Universitat Autònoma de Barcelona

A Circular Economy Approach to Urban Agriculture: an Environmental Assessment

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Doctoral thesis

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"Una nit de lluna plena
tramuntàrem la carena,
lentament, sense dir re.
Si la lluna feia el ple
també el féu la nostra pena"

Pere Quart – Corrandes d'Exili

The present thesis entitled *A Circular Economy Approach to Urban Agriculture: an Environmental Assessment* has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB)

Martí Rufí Salís

under the supervision of Dr. Anna Petit Boix, from the Chair of Societal Transition and Circular Economy at the Albert-Ludwigs-Universität Freiburg, Dr. Gara Villalba Méndez, from the ICTA and the Department of Chemical, Biological and Environmental Engineering at the UAB, and Dr. Xavier Gabarrell Durany, from the ICTA and the Department of Chemical, Biological and Environmental Engineering at the UAB.

Anna Petit Boix Gara Villalba Méndez Xavier Gabarrell Durany

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Abbreviations

1,4 DB eq.	1,4-Dichlorobenzene equivalent emissions
3R	Reuse, reduce, recycle
4R	Reuse, reduce, recycle, recover
9R	Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover
ACV	Ànalisi de Cicle de Vida / Análisis de Ciclo de Vida
AE	Auxiliary equipment
AMB	Àrea Metropolitana de Barcelona
BaU	Business as usual
BoM	Bill of Materials
Ca	Calcium
Ca^{2+}	Calcium ion
$Ca_3(PO_4)_2$	Calcium phosphate
$Ca(NO_3)_2$	Calcium nitrate
$CaCl_2$	Calcium chloride
CC	Climate Change impact category (ReCiPe 2008)
CE	Circular Economy
CED	Cumulative Energy Demand impact category
CP	Chemical precipitation
CS	Closed system,
DAP (1)	Diammonium Phosphate
DAP (2)	Days after planting / transplanting
DAT	Days after planting
DLR	Direct leachate recirculation
DOI	Digital Object Identifier
DUN	Declaració Única Agrària
EC	Electrical conductivity
EDAR	Estació depuradora d'aigües residuals / Estación depuradora de aguas residuales
EMF	Ellen MacArthur Foundation

ET	Ecotoxicity impact category (ReCiPe 2008 & 2016)
EU	European Union
FDP	Fossil Depletion impact category (ReCiPe 2008)
FE	Freshwater Eutrophication impact category (ReCiPe 2008 & 2016)
FRS	Fossil Resources Scarcity impact category (ReCiPe 2016)
FU	Functional unit
GFRP	Glass fibre reinforced plastic
GHG	Greenhouse Gas
GIS	Geographical Information Systems
GW	Global Warming impact category (ReCiPe 2016)
HDPE	High density polyethylene
HT	Human Toxicity impact category (ReCiPe 106)
IC	Impact category
ICTA	Institute of Environmental Science and Technology (UAB)
ICP	Catalan Palaeontological Institute (UAB)
ICP-OES	Inductively coupled plasma – optical emission spectroscopy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
i-RTG	Integrated Rooftop Greenhouse
K	Potassium
K_2SO_4	Potassium sulphate
kcal	kilocalorie
KNO_3	Potassium nitrate
KPO_4H_2	Monopotassium phosphate
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LFI	Linear Flow Index
LFI_{LCA}	LFI coupled with LCA

LFI_{LCA-R}	LFI coupled with LCA with relative values
LFI_{LCA-T}	LFI coupled with LCA with absolute/total values
LS	Linear system
MAP	Magnesium ammonium phosphate
MCI	Material Circularity Indicator
MCI_{LCA}	MCI coupled with LCA
ME	Marine Eutrophication impact category (ReCiPe 2008 & 2016)
MF	Membrane Filtration
Mg	Magnesium
Mg^{2+}	Magnesium ion
$Mg(NO_3)_2$	Magnesium nitrate
MJ.	Megajoules
MPP	Magnesium potassium phosphate
N	Nitrogen
N eq	Nitrogen equivalent emissions
N_2O	Nitrous oxide
NH_4^+	Ammonium ion
P	Phosphorus
P eq	Phosphorus equivalent emissions
PE	Polyethylene
PO_4^{3+}	Phosphate ion
PVC	Polyvinylchloride
RH	Relative humidity
RWHS	Rainwater harvesting system
RO	Reverse Osmosis
RTG	Rooftop Greenhouse
TA	Terrestrial Acidification impact category (ReCiPe 2008 & 2016)
S	Sulphur
S-LCA	Social Life Cycle Assessment
SO_2 eq.	Sulphur dioxide equivalent emissions
Sostenipra	Sustainability and Environmental Prevention research group
UA	Urban Agriculture

UAB	Universitat Autònoma de Barcelona
UK	United Kingdom
UNEP	United Nation Environment Programme
WCE	Water consumption efficiency
WUE	Water use efficiency
WWTP	Wastewater treatment plant

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Summary

Population growth in urban areas has turned cities in major hotspots of environmental impacts. These impacts are related to the massive flows of resources needed to meet the ever-growing demand of urban areas. This is specially the case of food, which is normally produced outside the city boundaries or even overseas and finally transported to urban areas, creating long and inefficient supply chains. To mitigate these impacts and diminish the linear tendency of the food flow, urban agriculture (UA) has attracted the attention of researchers and policymakers. UA can be implemented in unused areas such as building rooftops. This implementation is usually associated with social, economic and environmental benefits, including opportunities such as resource recovery or recycling. In this sense, the concept of circular economy (CE) applied to UA can improve the performance of these systems by enhancing the restoration of flows and creating a symbiosis between urban facilities and agricultural systems. However, the application of circular strategies must be strictly monitored in terms of environmental impacts to avoid the implementation of contradictory strategies. To ensure that circularity aligns with the principles of sustainability when applied to UA, the goal of this dissertation is to assess the environmental performance of circular strategies applied to UA systems. Considering this goal, this dissertation aims to answer the following research questions:

- **Question 1**: Which are the main environmental hotspots in UA systems resulting from different crop types?
- **Question 2**: How can existing nutrient recovery techniques contribute to improving the efficiency of nutrient use while diminishing the environmental impacts of UA?
- **Question 3**: Is the recovery and reuse of struvite a promising strategy to reduce the environmental impacts of UA and wastewater treatment in cities?
- **Question 4**: How should circular strategies be prioritized to improve the environmental and circularity performance of UA?

The following sections summarize the materials and methods used, the results obtained, and the further research proposed in this dissertation.

Materials and methods. Environmental assessment and complementary tools

The Life Cycle Assessment (LCA) methodology was used in this dissertation to analyze the environmental performance of the systems under study. However, since UA is based on complex systems that require a holistic approach, a series of complementary tools were used. Besides yield quantification, this dissertation conducted an assessment of

nutrient flows through analytical methods, an eco-efficiency assessment using wholesale market prices based on ISO standards or a novel circularity assessment through modifications of the Material Circularity Indicator (MCI). The mentioned methodologies were applied in a rooftop greenhouse based in the Universitat Autònoma de Barcelona campus, complementary to a regional study considering the Barcelona metropolitan area (AMB).

Environmental assessment of rooftop greenhouse crop production

We quantified the impact of 25 cycles of 7 different crops with three different functional units (kg, €, kcal) to detect the main environmental hotspots of rooftop agriculture resulting from different yearly crop combinations. Based on an eco-efficiency analysis combining the impact on climate change and the wholesale market price of horticultural products, we found that growing two consecutive tomato cycles was the best alternative with a functional unit based on yield (0.49 kg CO_2 eq. · kg^{-1}). On the other hand, a combination of a long spring tomato cycle followed by autumn bean and lettuce cycles had the best performance with functional units of price (0.70 kg CO_2 eq · $€^{-1}$) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2 eq · $kcal^{-1}$). Moreover, the fertilizers and their related emissions to water were identified as one of the main impacting items for all crops and impact categories analyzed.

Recovering nutrients in urban agriculture systems

The application of CE principles to UA was first addressed by focusing on the recovery of nutrients that are lost in UA systems. Of the three recovery strategies that could be applied in hydroponic set-ups, the analysis of theoretical applications unveiled that the direct recirculation of leachates (5.5 kg CO_2 eq.) was the preferable option to recover nutrients over alternatives such as chemical precipitation or membrane filtration, which exerted 3 and 5 times more impacts, respectively.

Considering this, we installed a recirculation system and analyzed its performance compared to a linear system using different methods. The results showed that recirculation systems can contribute to a reduction in the amount of water and nutrients used in urban agriculture, although detailed monitoring is required to avoid nutritional deficiencies. The main limitation of the recirculation system was the high impact exerted by the new infrastructure required, with a contribution of 45% on the total ecotoxicity impact of the system. However, four improvement scenarios unveiled the potential of these systems to overcome this limitation.

To avoid nutritional deficiencies in the main crop, another option is to use the residual flows of water and nutrients in other parallel crops in what is known as a cascade system. The assessment of this symbiosis was explored by using the leachates from a tomato crop to irrigate five successive lettuce cycles. The results showed that the evolution of the nutrient content of the tomato leachates is a key parameter to plan the size of the crop to be irrigated with this residual flow. Due to nitrogen deficiencies, the early stage of the tomato crop could only produce 0.1 lettuces per tomato plant, while the late stage increases this number up to 9 lettuces per tomato plant.

Improving the phosphorus cycle through the synergies between urban systems

The recovery of nutrients in other urban systems to be used in UA focused on phosphorus (P) in the form of struvite, given the urgency to find replacements for non-renewable phosphate rocks, which are depleting at an alarming rate. With the aim to determine the potential of struvite as a fertilizer in UA systems, we tested different quantities of struvite in a hydroponic set-up with two common bean cycles. The results showed that plants with more than 5g of struvite had higher yields than the control irrigated with mineral fertilizer (134.6 g/plant). Moreover, the low solubility of struvite demonstrated a great potential to diminish the P losses through the leachates.

The potential of struvite as a fertilizer was also evaluated at a regional scale. Considering the agricultural area within the limits of the AMB and the two main wastewater treatments plants (WWTP) of the region, we determined the feasibility of a regional struvite recovery and reuse strategy and quantified the environmental performance with three different system boundaries and functional units. The results showed that with only the recovery of P in one WWTP, we could meet the P demand of the agricultural area within the region (36.5t of P per year). However, we detected that identifying suitable WWTPs to install the recovery technologies is essential, since the decision may entail additional environmental impacts.

Combining environmental and circularity performance

To prioritize the application of circular strategies in UA based on environmental and circularity performances we defined 13 different circular strategies based on the use of struvite, closed-loop systems, compost, source of water, and source and end-of-life of the infrastructure materials. To do so, we used LCA to evaluate the environmental performance and the MCI to quantify the circularity of the system. The assessment of indicators unveiled the existence of relevant methodological limitations in the MCI to precisely evaluate agricultural systems. For instance, energy flows were not included, whereas the water flow contributed to more than 99% of the final MCI score. To proceed with the analysis, we proposed a new set of indicators that couple the Linear Flow Index (LFI) with one environmental indicator at a time, contributing to the search for new targets to optimize within the inventory and scenario comparison. With this set of indicators, nutrient recirculation, struvite fertilization or the use of recycled materials were the best strategies to improve the coupled performance of the UA system.

And now, what? Upcoming Challenges

This thesis paves the way towards the need to focus the further research in a series of detected upcoming challenges. It is essential to advance towards a precise standardization of the definition of CE and the related concepts to better define the limits and synergies between CE principles and sustainability goals. The alignment or decoupling between these two big frameworks must also be analyzed in further research. In this sense, academics should focus on assessing the environmental performance of circular strategies to make sure that improving the circularity does not significantly increase the environmental impacts exerted by the system.

Considering the complexity of agricultural systems, including other perspectives like the quantification of the nutrient flows or the recording of climatic variables can disclose hidden findings of the assessment.

Given that this dissertation analyzes UA as part of a more complex system (cities), the evaluation of the implementation of circular strategies should focus in assessing other urban systems that can unveil synergies within the urban context.

Resum

L'increment de la població en àrees urbanes ha provocat que les ciutats es converteixin en grans fonts d'impactes ambientals. Aquest impactes estan associats als fluxos de recursos necessaris per abastir la creixent demanda de les àrees urbanes. Aquest és especialment el cas de l'abastiment d'aliments, sovint produïts fora dels límits urbans o fins i tot en altres continents per finalment ser transportats a les ciutats, creant cadenes de subministrament llargues i ineficients. Per mitigar aquests impactes i disminuir la tendència lineal d'aquest flux, l'agricultura urbana ha guanyat el reconeixement d'acadèmics i legisladors. L'agricultura urbana pot ser implementada en àrees de baix ús com les cobertes d'edificis. Aquesta implementació sol venir acompanyada de beneficis econòmics, socials i ambientals, a més de generar oportunitats per al reaprofitament de recursos. En aquest sentit, el concepte d'economia circular aplicat a l'agricultura urbana pot millorar el comportament d'aquests sistemes mitjançant la restauració de fluxos i crear simbiosis entre l'agricultura i altres sistemes urbans. Tot i això, l'aplicació de les anomenades estratègies circulars ha d'estar monitoritzada estrictament en termes d'impacte ambiental per evitar la implementació d'estratègies contradictòries. Per assegurar que la circularitat s'alinea amb els objectius de sostenibilitat quan s'aplica a sistemes d'agricultura urbana, l'objectiu d'aquesta tesi és avaluar el comportament ambiental d'estratègies circulars en sistemes d'agricultura urbana. Tenint en compte aquest objectiu, aquesta tesi pretén respondre les següents preguntes d'investigació:

- **Pregunta 1**: Quines són les fonts principals d'impacte ambiental de l'agricultura urbana tenint en compte diferents cultius?
- **Pregunta 2**: Com poden les tecnologies de recuperació de nutrients contribuir a millorar l'eficiència dels l'ús de nutrients i a reduir l'impacte ambiental de l'agricultura urbana?
- **Pregunta 3**: És la recuperació i la reutilització d'estruvita una estratègia prometedora per reduir l'impacte ambiental de l'agricultura urbana i el tractament d'aigües residuals a les ciutats?
- **Pregunta 4**: Com s'haurien de prioritzar les estratègies circulars per millorar la circularitat i el comportament ambiental de l'agricultura urbana?

Els següents punts resumeixen els materials i mètodes utilitzats, els resultats obtinguts i la recerca futura que es proposa en aquesta tesi.

Materials i mètodes. Anàlisi ambiental i eines complementàries

L'Anàlisi de Cicle de Vida (ACV) ha estat utilitzat en aquesta tesi com el mètode principal per analitzar el comportament ambiental dels sistemes d'estudi. Tenint en compte que l'agricultura urbana està basada en sistemes complexos que necessiten un enfocament holístic, l'anàlisi global ha requerit una sèrie d'eines complementàries. A part de la quantificació de la producció, aquesta tesi ha utilitzat l'anàlisi de fluxos de nutrients a través de mètodes analítics, l'anàlisi d'eco-eficiència utilitzant preus de venda a l'engròs basant-nos en estàndards ISO o l'anàlisi de circularitat a través de modificacions de l'indicador de circularitat de materials (MCI). Aquestes metodologies han estat aplicades en un hivernacle en coberta del campus de la Universitat Autònoma de Barcelona, complementat per un estudi regional considerant l'Àrea Metropolitana de Barcelona (AMB).

Anàlisi ambiental de la producció en hivernacles en coberta

Hem quantificat l'impacte de 25 cicles de 7 cultius amb 3 unitats funcionals diferents (kg, €, kcal) per detectar les principals fonts d'impacte ambiental de l'agricultura en coberta i definir les combinacions de cultius amb menys impacte ambiental. Basant-nos en un anàlisi d'eco-eficiència que combina l'impacte en canvi climàtic i el preu de venda a l'engròs, hem observat que cultivar dos cicles consecutius de tomàquet és la millor alternativa amb una unitat funcional basada en la producció (0.49 kg CO_2 eq. · kg^{-1}). Tot i això, una combinació consistent en un cicle llarg de tomàquet a la primavera seguit de mongeta a la tardor i un cicle d'enciam per acabar l'any és la combinació amb un millor comportament ambiental amb unitats funcionals de preu (0.70 kg CO_2 eq · $€^{-1}$) i valor nutricional ($3.18 \cdot 10^{-3}$ kg CO_2 eq · $kcal^{-1}$). A més, els fertilitzants i les emissions a l'aigua associades han estat identificats com un dels elements més impactant del sistema per tots els cultius i totes les categories d'impacte analitzades.

Recuperació de nutrients en sistemes d'agricultura urbana

L'anàlisi de l'aplicació de principis d'economia circular en aquesta tesi s'ha centrat en primera instància en recuperar els nutrients que es perden en els sistemes d'agricultura urbana. L'anàlisi de l'aplicació teòrica de tres estratègies de recuperació de nutrients en sistemes hidropònics ha detectat que la recirculació directa dels lixiviats (5.5 kg CO_2 eq) és l'opció preferent per recuperar nutrients per sobre d'altres alternatives com la precipitació química o la filtració per membranes, les quals presenten 3 i 5 vegades més impacte ambiental, respectivament.

Tenint en compte els resultats obtinguts vam instal·lar un sistema de recirculació en l'hivernacle d'estudi i vam analitzar el seu comportament comparant-lo amb un sistema lineal utilitzant diferent mètodes. Els resultats mostren que els sistemes de recirculació poden contribuir a reduir la quantitat d'aigua i nutrients utilitzats en l'agricultura urbana, tot i que s'ha de realitzar un monitoreig constant d'aquests fluxos per evitar dèficits nutricionals. La limitació més gran del sistema de recirculació és l'elevat impacte produït per la nova infraestructura, contribuint en un 45% de l'impacte total del sistema en ecotoxicitat. Tot i això, quatre escenaris de millora mostren el potencial d'aquests sistemes per superar aquesta limitació.

Per evitar deficiències nutricionals al cultiu principal, una altra opció pot contemplar l'ús dels fluxos residuals d'aigua i nutrients en cultius paral·lels en el que és conegut com un sistema en cascada. L'anàlisi d'aquesta simbiosis ha estat explorada utilitzant els lixiviats d'un cultiu de tomàquet per regar cinc cultius consecutius d'enciam. Els resultats mostren que l'evolució del contingut nutricional dels lixiviats del tomàquet és un paràmetre clau per estructurar la mida del cultiu que utilitzarà aquest flux residual com a reg. Degut a un dèficit de nitrogen, el primer estadi del cultiu de tomàquet pot contribuir només a produir 0.1 enciams per planta de tomàquet, mentre que a finals de cultiu aquest número s'incrementa fins a 9 plantes d'enciam.

Millorant el cicle del fòsfor mitjançant sinèrgies entre sistemes urbans

La recuperació de nutrients en altres sistemes urbans per ser utilitzats en agricultura s'ha centrat en el fòsfor (P) en forma d'estruvita tenint en compte la necessitat de trobar alternatives a les roques fosfàtiques no-renovables, les qual s'estan esgotant a un ritme alarmant. Amb l'objectiu de determinar el potencial de l'estruvita com a fertilitzant en sistemes d'agricultura urbana, hem provat diferents quantitats d'estruvita en un sistema d'hidroponia amb dos cicles de mongeta verda. El resultats mostren que les plantes amb més de 5g d'estruvita produeixen més que les plantes control (134.6 g/planta) regades amb fertilitzant mineral. A més, la baixa solubilitat de l'estruvita presenta un elevat potencial per disminuir les pèrdues de P a través dels lixiviats.

El potencial de l'estruvita com a fertilitzant ha estat avaluat també a una escala regional. Considerant la zona agrària dins dels límits de l'AMB i les dues estacions depuradores d'aigües residuals (EDAR) principals de la zona, hem determinat la viabilitat d'una estratègia regional de recuperació i reutilització d'estruvita i el comportament ambiental del sistema mitjançant tres enfocaments diferents. Els resultats mostren que utilitzant una única EDAR podríem subministrar el P necessari per l'agricultura de l'AMB (36.5t de P anuals). Tot i això, s'ha de posar atenció en quina EDAR instal·lar les tecnologies de recuperació ja que aquesta decisió pot comportar impactes ambientals addicionals.

Combinant el comportament ambiental i la circularitat

Per prioritzar l'aplicació d'estratègies circulars basant-nos en el comportament ambiental i la circularitat vàrem definir 13 estratègies circulars diferents basades en l'ús d'estruvita, sistemes de cicle tancat, compostatge, fonts d'aigua i origen i destí dels materials emprats. Per a fer això utilitzem l'ACV per avaluar el comportament ambiental del sistema i el MCI per a quantificar la circularitat del sistema. L'anàlisi dels indicadors desvela severes limitacions del MCI per a avaluar de manera precisa els sistemes d'agricultura, com per exemple la no inclusió dels fluxos d'energia o un biaix en la quantificació dels fluxos d'aigua en els càlculs, contribuint en més del 99% del valor del MCI. Per continuar amb l'anàlisi proposem un ventall de nous indicadors que ajunten l'índex de flux lineal (LFI) amb un indicador ambiental cada vegada, contribuint a buscar nous elements a optimitzar dins l'inventari, a la vegada que comparem escenaris. Amb aquest nou ventall d'indicadors, la recirculació de nutrients, la fertilització amb estruvita o la utilització de materials reciclats han estat identificades com les millors estratègies per millorar el comportament conjunt del sistema en termes ambientals i de circularitat.

I ara què? Pròxims reptes

Els resultats obtinguts en aquesta tesi demostren la necessitat de dedicar la recerca futura en una sèrie de reptes detectats. És essencial avançar cap a una estandardització precisa de la definició d'economia circular i dels conceptes que té associats per definir millor els límits i les sinèrgies entre els principis de l'economia circular i els objectius de sostenibilitat. En aquest sentit, l'alineament o la desvinculació entre aquests dos marcs s'ha d'analitzar més profundament en la recerca futura. El món acadèmic hauria de centrar el seus esforços en analitzar els impactes ambientals derivats de l'aplicació d'estratègies circulars per assegurar que una millora en la circularitat del sistema no compromet el seu comportament ambiental.

Considerant la complexitat dels sistemes d'agricultura, la inclusió d'altres perspectives en l'anàlisi com la quantificació dels fluxos de nutrients o el registre de variables climàtiques pot desvelar resultats amagats.

Tenint en compte que aquesta tesi analitza l'agricultura urbana com a part de sistemes més complexos com les ciutats, la avaluació de la implementació d'estratègies circulars s'hauria enfocar en analitzar altres sistemes que poden presentar sinergies en el marc urbà.

Resumen

El incremento de la población en áreas urbanas ha provocado que las ciudades se conviertan en grandes fuentes de impacto ambiental. Estos impactos están asociados a los grandes flujos de recursos necesarios para abastecer la creciente demanda de las áreas urbanas. Este es espacialmente el caso del abastecimiento de alimentos. Los alimentos consumidos en las ciudades son normalmente producidos fuera de sus límites e incluso en otros continentes para ser finalmente transportados a las áreas urbanas, creando cadenas de subministro largas e ineficientes. Para mitigar estos impactos y la tendencia lineal de los flujos de alimentos, la agricultura urbana ha ganado reconocimiento entre académicos y legisladores. La agricultura urbana puede ser implementada en zonas de bajo uso como las cubiertas de los edificios. Esta implementación suele venir relacionada con beneficios económicos, sociales y ambientales, además de ofrecer oportunidades para el reaprovechamiento de recursos. En este sentido, el concepto de economía circular aplicado a la agricultura urbana puede mejorar el comportamiento de estos sistemas mediante la restauración de flujos, explotando simbiosis entre la agricultura y otros sistemas urbanos. A pesar de esto, la aplicación de las denominadas estrategias circulares debe estar monitorizada estrictamente en términos de impacto ambiental para evitar la implementación de estrategias contradictorias. Para asegurar que la circularidad se alinea con los objetivos de sostenibilidad en los sistemas de agricultura urbana, el objetivo de esta tesis es evaluar el comportamiento ambiental de estrategias circulares en este tipo de sistemas productivos. Teniendo en cuenta este objetivo, esta tesis pretende responder a las siguientes preguntas de investigación:

- **Pregunta 1**: ¿Cuáles son las fuentes principales de impacto ambiental de la agricultura urbana teniendo en cuenta distintos cultivos?
- **Pregunta 2**: ¿Cómo pueden las tecnologías de recuperación de nutrientes contribuir a mejorar la eficiencia de los flujos de nutrientes y a reducir el impacto ambiental de la agricultura urbana?
- **Pregunta 3**: ¿Es la recuperación y la reutilización de la estruvita una estrategia prometedora para reducir el impacto ambiental de la agricultura urbana y el tratamiento de aguas residuales en las ciudades?
- **Pregunta 4**: ¿Cómo se deberían priorizar las estrategias circulares para mejorar la circularidad y el comportamiento ambiental de la agricultura urbana?

Las siguientes secciones resumen los materiales y métodos utilizados, los resultados obtenidos y la investigación futura que se propone en esta tesis.

Materiales y métodos. Análisis ambiental y herramientas complementarias

El Análisis de Ciclo de Vida (ACV) ha sido utilizado en esta tesis como el método principal para analizar el comportamiento ambiental de los sistemas de estudio. Teniendo en cuenta que la agricultura urbana está basada en sistemas complejos que requieren un enfoque holístico, una serie de herramientas complementarias han sido incluidas en determinados capítulos. Aparte de la cuantificación de la producción, se han utilizado el análisis de flujos de nutrientes mediante métodos analíticos, el análisis de eco-eficiencia utilizando precios de venta al por mayor basándonos en estándares ISO o el análisis de circularidad a través de modificaciones del indicador de circularidad de materiales (MCI). Estas metodologías han sido aplicadas en un invernadero en cubierta del campus de la Universitat Autònoma de Barcelona, complementado con un estudio regional considerando el Área Metropolitana de Barcelona (AMB).

Análisis ambiental de la producción en invernaderos en cubierta

Hemos cuantificado el impacto de 25 ciclos de 7 cultivos con 3 unidades funcionales diferentes (k, €, kcal) para detectar las fuentes principales de impacto ambiental de la agricultura en cubierta y definir las combinaciones de cultivos con menos impacto. Basándonos en un análisis de eco-eficiencia combinando el impacto en cambio climático y el precio de venta al por mayor, hemos observado que cultivar dos ciclos consecutivos de tomate es la mejor alternativa con una unidad funcional basada en la producción (0.49 kg CO_2 eq · kg^{-1}). Por otro lado, una combinación consistente en un ciclo largo de tomate en la primavera seguido de judía en otoño y un ciclo de lechuga a final de año es la combinación con un mejor comportamiento ambiental con unidades funcionales de precio (0.70 kg CO_2 eq · $€^{-1}$) y valor nutricional ($3.18 \cdot 10^{-3}$ kg CO_2 eq · $kcal^{-1}$). Además, los fertilizantes y sus emisiones al agua asociadas han sido identificados como uno de los elementos más impactantes del sistema para todos los cultivos y todas las categorías de impacto analizadas.

Recuperando nutrientes en sistemas de agricultura urbana

El análisis de la aplicación de principios de economía circular en esta tesis se ha centrado en un primer momento en recuperar los nutrientes que se pierden en sistemas de agricultura urbana. El análisis de la aplicación teórica de tres estrategias de recuperación de nutrientes en sistemas hidropónicos ha detectado que la recirculación directa de los lixiviados (5.5 kg CO_2 eq.) es la opción preferente para recuperar nutrientes por delante de otras alternativas como la precipitación química o la filtración por membranas, las cuales presentan 3 y 5 veces más impacto, respectivamente.

Considerando esto, instalamos un sistema de recirculación en el invernadero de estudio y analizamos su comportamiento comparándolo con un sistema lineal utilizando distintos métodos. Los resultados muestran que los sistemas de recirculación pueden contribuir a reducir la cantidad de agua y nutrientes utilizados en la agricultura urbana, pero un monitoreo continuo es necesario para evitar déficits nutricionales. La limitación más grande del sistema de recirculación fue el elevado impacto producido por la nueva infraestructura, con una contribución del 45% sobre el impacto total del sistema en ecotoxicidad. A pesar de esto, cuatro escenarios de mejora desvelaron el potencial de estos sistemas para superar esta limitación.

Para evitar deficiencias nutricionales en el cultivo principal, otra opción puede consistir en el uso de los flujos residuales de agua y nutrientes en cultivos paralelos en lo que es conocido como un sistema en cascada. El análisis de esta simbiosis ha sido explorado utilizando los lixiviados de un cultivo de tomate para regar cinco cultivos consecutivos de lechuga. Los resultados muestran que la evolución del contenido nutricional de los lixiviados del tomate es un parámetro clave para planificar el tamaño del cultivo que utilizará este flujo residual como riego. Debido a un déficit de nitrógeno, el primer estadio del cultivo de tomate puede contribuir a producir solo 0.1 lechugas por planta de tomate, mientras que al final de cultivo este número se incrementa hasta 9 lechugas.

Mejorando el ciclo del fósforo mediante la sinergia entre sistemas urbanos

La recuperación de nutrientes en otros sistemas urbanos para ser utilizados en agricultura se ha centrado en el fósforo (P) en forma de estruvita teniendo en cuenta la necesidad de encontrar alternativas a las rocas fosfáticas no-renovables. Con el objetivo de determinar el potencial de la estruvita como fertilizante en sistemas de agricultura urbana, hemos analizado la aplicación de distintas cantidades de estruvita en un sistema de hidroponía con dos ciclos de judía verde. Los resultados muestran que las plantas con más de 5g de estruvita producen más que las plantas control (134.6 g/planta), regadas con fertilizante mineral. Además, la baja solubilidad de la estruvita presenta un elevado potencial para disminuir las pérdidas de P a través de los lixiviados.

El potencial de la estruvita como fertilizante ha sido evaluado también a escala regional. Considerando la zona agraria dentro de los límites de la AMB y las estaciones depuradoras de aguas residuales (EDAR) principales de la zona, determinamos la viabilidad de una estrategia regional de recuperación y reutilización de estruvita y cuantificamos el comportamiento ambiental del sistema mediante tres enfoques distintos. Los resultados muestran que utilizando una única EDAR podríamos proveer el P necesario para la agricultura de la región (36.5t de P anuales). A pesar de esto, se debe prestar atención en qué EDAR instalar las tecnologías de recuperación ya que esta decisión puede comportar impactos ambientales adicionales.

Combinando el comportamiento ambiental y la circularidad

Para priorizar la aplicación de estrategias circulares basándonos en el comportamiento ambiental y la circularidad, definimos 13 estrategias circulares diferentes basadas en el uso de estruvita, sistemas de ciclo cerrado, compostaje, fuentes de agua y origen y destino de los materiales utilizados. Para esto, utilizamos el ACV para evaluar el comportamiento ambiental y el MCI para cuantificar la circularidad el sistema. El análisis de los indicadores presenta grandes limitaciones del MCI para evaluar de forma precisa los sistemas agrícolas, como por ejemplo la omisión de los flujos de energía o un sesgo relacionado con la cuantificación de los flujos de agua en los cálculos, contribuyendo en más del 99% del valor del MCI. Para proseguir con el análisis, proponemos una serie de nuevos indicadores que juntan el índice de flujo lineal (LFI) con un indicador ambiental cada vez, contribuyendo a buscar nuevos elementos a optimizar dentro del inventario y a comparar escenarios. Con esta nueva serie de indicadores, la recirculación de nutrientes, la fertilización con estruvita o la utilización de materiales reciclados han sido identificadas como las mejores estrategias para mejorar el comportamiento conjunto del sistema en términos de impacto ambiental y circularidad.

¿Y ahora qué? Próximos retos

Los resultados obtenidos en esta tesis demuestran la necesidad de dedicar la investigación futura a una serie de retos. En este sentido, es esencial avanzar hacia una estandarización de la definición de economía circular y sus conceptos asociados para definir mejor los límites y sinergias entre les principios de la economía circular y los objetivos de sostenibilidad. El alineamiento o la desvinculación entre estos dos marcos se debe analizar más profundamente en la investigación futura. Para esto, el mundo académico debería centrar sus esfuerzos en analizar los impactos ambientales derivados de la aplicación de estrategias circulares para asegurar que una mejora en la circularidad del sistema no compromete su comportamiento ambiental.

Considerando la complejidad de los sistemas agrícolas, la inclusión de otras perspectivas en el análisis como la cuantificación de los flujos de nutrientes o el registro de las variables climáticas puede desvelar resultados escondidos.

Teniendo en cuenta que esta tesis analiza la agricultura urbana como parte de sistemas más complejos como las ciudades, la evaluación de la implementación de estrategias circulares se debería focalizar en analizar otros sistemas que puedan generar sinergias en el marco del metabolismo urbano.

Preface

This thesis was developed during the period from October 2017 to November 2020 in compliance with the PhD program in Environmental Science and Technology of the Universitat Autònoma de Barcelona (UAB). This training period took place within the Sostenipra research group at the Institute of Environmental Science and Technology (ICTA), including an international mobility at the Albert-Ludwigs-Universität Freiburg (Baden-Württemberg, Germany), and teaching assistance at the Department of Chemical, Biological and Environmental Engineering (DEQBA). The thesis was supported by a pre-doctoral fellowship awarded by the UAB at the DEQBA. In addition, research was conducted in a "María de Maeztu" Unit of Excellence in R&D (MDM-2015-0552 / CEX2019-000940-M) thanks to the support of the Spanish Ministry of Economy and Competitiveness.

This dissertation addresses the application of circular strategies in urban agricultural systems from an environmental perspective. The novelty of this research is the assessment of the environmental performance of circular strategies to unveil if circular economy principles applied to real case studies align with environmental improvements. Additionally, complementary methods such as the assessment of nutrient balances, eco-efficiency or circularity assessment were applied in different chapters of this dissertation.

Different parts of this dissertation were elaborated in the framework of a funded research project. The development of most crop cycles was conducted within the Fertilecity II project (CTM2016-75772-C3-1-R) "Invernaderos integrados en azoteas: simbiosis de energía, agua y emisiones de CO2 con el edificio - Hacia la seguridad alimentaria urbana en una economía circular".

This thesis is composed of 6 parts with at least one chapter, as illustrated in Figure X1.

Structure of the doctoral thesis

P1 BACKGROUND AND METHODOLOGICAL FRAMEWORK

- C1 Introduction and objectives
- C2 Materials and Methods

P2 ENVIRONMENTAL ASSESSMENT OF ROOFTOP GREENHOUSE PRODUCTION FOR A MORE SUSTAINABLE URBAN AGRICULTURE

- C3 Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture

P3 CLOSING WATER AND NUTRIENT CYCLES IN URBAN AGRICULTURE THROUGH ON-SITE RECOVERY STRATEGIES

- C4 Exploring nutrient recovery from hydroponics in urban agriculture: an environmental assessment
- C5 Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency?
- C6 Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities

P4 TACKLING PHOSPHORUS SCARCITY THROUGH RECOVERY AND REUSE OF STRUVITE IN URBAN FOOD PRODUCTION

- C7 Recovered phosphorus for a more resilient urban agriculture: assessment of the fertilizer potential of struvite in hydroponics
- C8 Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions

P5 ENVIRONMENTAL AND CIRCULAR IMPLICATIONS OF APPLYING MULTI-SCALE CLOSED-LOOP STRATEGIES IN URBAN AGRICULTURE

- C9 Combining LCA and circularity assessments in complex production systems: the case of urban agriculture

P6 FINAL REMARKS AND FUTURE RESEARCH

- C10 Discussion of the main contributions
- C11 Conclusions
- C12 Future research

Figure X1 Structure of this dissertation

Part I. Background and methodological framework

Part I includes the first two chapters of the dissertation. **Chapter 1** [*Introduction and objectives*] introduces the theoretical background around the topics of cities, urban agriculture (UA) and circular economy (CE). The motivations of this dissertation are explained right after. Finally, the research questions and the objectives laid out are formulated. **Chapter 2** [*Materials and Methods*] summarizes the main methods used in this dissertation along with the two case studies.

Part II. Environmental assessment of rooftop greenhouse production for a more sustainable urban agriculture

Part II is composed of **Chapter 3** [*Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture*]. This chapter addresses the environmental and eco-efficient performance of rooftop greenhouse agriculture through the Life Cycle Assessment (LCA) to define the best yearly crop combinations and detect targets to optimize within the system. It sets the stage for the subsequent analyses (Parts III, IV and V)

Part III. Closing water and nutrient cycles in urban agriculture through on-site recovery strategies

Part III addresses the application of CE principles to recover nutrients in UA systems and includes 3 chapters. **Chapter 4** [*Exploring nutrient recovery from hydroponics in urban agriculture: an environmental assessment*] quantifies the environmental performance of the theoretical application of three recovery strategies (direct leachate recirculation, chemical precipitation and membrane filtration) that could be applied in a real tomato cycle. **Chapter 5** [*Recirculating water and nutrients in urban agriculture: an opportunity towards environmental sustainability and water use efficiency?*] explores the direct recirculation of the leachates flow within a same crop from an environmental and nutritional perspective. Finally, **Chapter 6** [*Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities*] examines the nutritional and production implications of using the leachates drained by a long tomato cycle (donor crop) in successive lettuce cycles (receiving crop).

Part IV. Tackling phosphorus scarcity through recovery and reuse of struvite in urban food production

Part IV assesses the application of CE principles to recover phosphorus (P) in wastewater treatment plants (WWTP) with the aim of using the recovered nutrients in UA systems. Specifically, **Part IV** focuses on the recovery and reuse of struvite, a P secondary fertilizer obtained in WWTP. This part includes two chapters. **Chapter 7** [*Recovered phosphorus for a more resilient urban agriculture: assessment of the fertilizer potential of struvite in hydroponics*] analyzes the performance of applying different quantities of struvite in a common bean crop (*Phaseolus vulgaris*) to determine the potential associated yield and quantify the P balances. **Chapter 8** [*Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions*] seeks to determine the feasibility and environmental performance of recovering and reusing struvite in the Àrea Metropolitana de Barcelona (AMB), by considering the agricultural area and the two main WWTP of the AMB.

Part V. Environmental and circular implications of applying multi-scale closed-loop strategies in urban agriculture

Part V comprises only **Chapter 9** [*Combining LCA and circularity assessments in complex production systems: the case of urban agriculture*]. This chapter combines LCA and circularity assessment to prioritize circular strategies in UA. Moreover, the limitations of the Material Circularity Indicator (MCI) are explored to examine further indicator development to combine MCI with environmental indicators.

Part VI. Final remarks and future research

Part VI is the final section of this dissertation, including 3 chapters. **Chapter 10** [*Discussion of the main contributions*] discusses the results obtained in the previous chapters and presents the main contributions of this dissertation. **Chapter 11** [*Conclusions*] presents the conclusions of this work, providing an answer to each research question presented in **Chapter 1**. Finally, **Chapter 12** [*Future research*] outlines future research directions based on the results obtained in this dissertation, along with the main research challenges that the application of circular strategies in UA systems may face in the future.

Dissemination and training

This thesis is based on a set of peer-reviewed articles:

- **Rufí-Salís, M**; Petit-Boix, A; Villalba, G; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Parada, F.; Arcas, V; Muñoz-Liesa, J & Gabarrell, X (2020). Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. *The International Journal of Life Cycle Assessment.* (doi: 10.1007/s11367-019-01724-5)
- **Rufí-Salís, M**; Calvo, MJ; Petit-Boix, A; Villalba, G & Gabarrell, X (2020). Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resources, Conservation & Recycling.* (doi: 10.1016/j.resconrec.2020.104683)
- **Rufí-Salís, M**; Petit-Boix, A; Villalba, G; Sanjuan-Delmás, D; Parada, F; Ercilla-Montserrat, M; Arcas-Pilz, V; Muñoz-Liesa, J; Rieradevall, J & Gabarrell, X (2020). Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? *Journal of Cleaner Production* (doi: 10.1016/j.jclepro.2020.121213)
- **Rufí-Salís, M**; Brunnhofer, N; Petit-Boix, A; Gabarrell, X; Guisasola, A & Villalba, G (2020). Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions. *Science of the Total Environment* (doi: 10.1016/j.scitotenv.2020.139783)
- **Rufí-Salís, M**; Parada, F; Arcas-Pilz, V; Petit-Boix, A; Villalba, G & Gabarrell, X (2020). Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities. *Frontiers in Plant Science* (doi: 10.3389/fpls.2020.596550)

In addition, some preliminary results were presented in international conferences of interest:

- **Rufí-Salís, M**; Sanjuan-Delmás, D; Ercilla-Montserrat, M; Josa, A; Montero, JI; Muñoz, P; Gabarrel, X & Rieradevall, J. Vertical Farming reduces environmental impacts of food in cities. Case Study of common bean crop. Oral presentation. CILCA 2017 - VII International Conference on Life Cycle Assessment in Latin America. Medellín (Colombia).
- Petit-Boix, A; **Rufí-Salís, M**; Villalba, G; Rieradevall, J; Gabarrell, X; Moliné, E & Suárez-Ojeda, ME. Upgrading wastewater treatment technologies in the framework of current renewable energy policies - an environmental assessment. Poster presentation. SETAC 2018. Responsible and Innovative Research for Environmental Quality. Rome (Italy)

- **Rufí-Salís, M**; Petit-Boix, A; Villalba, G & Gabarrell X. Building - Rooftop Symbiosis at the next level. Improving urban agriculture through circular economy strategies. Oral presentation. SETAC 2018. Responsible and Innovative Research for Environmental Quality. Rome (Italy)
- Ercilla-Monserrat, M; Parada, F; Arcas, V; **Rufí-Salís, M**; Villalba, G; Gabarrell, X & Muñoz, P. Substrate selection in urban agriculture, water holding capacity and resilience to water stress. (2019). Oral presentation. Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers (France)
- Muñoz, P; Arcas, V; **Rufí-Salís, M**; Parada, F; Petit-Boix, A; Villalba, G & Gabarrell, X. Different treatments for the availability of Phosphorus with Struvite for Soilless systems. (2019). Poster presentation. Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers (France)
- Muñoz-Liesa, J; Parada, F; **Rufí-Salís, M**; Zambrano, P; Cuerva, E; Jarauta, E; Hervada, C; Jibergans, J & Josa, A. Energy performance through forced and natural ventilation systems in building integrated rooftop greenhouses. (2019). Oral presentation. Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers (France)
- **Rufí-Salís, M**; Parada, F; Arcas, V; Muñoz, P; Villalba, G; Petit-Boix, A & Gabarrell, X. Improving urban agriculture sustainability with Life Cycle Assessment (LCA). (2019). Poster presentation. Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers (France)
- **Rufí-Salís, M**; Petit-Boix, A; Villalba, G; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Parada, F; Arcas, V; Muñoz-Liesa, J; Rieradevall, J & Gabarrell, X. Intercropping, urban agriculture and circular economy. A first approach using LCA to determine best-annual crop combination. (2019). Oral presentation. ANQUE-ICCE 2019 – 3rd International Congress of Chemical Engineering – Mediterranean Symposium of Life Cycle Assessment. Santander (Spain)
- **Rufí-Salís M**; Petit-Boix, A; Villalba, G; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Parada, F; Arcas, V & Gabarrell, X. Recirculating water and nutrients in urban agriculture – an opportunity towards environmental sustainability and water use efficiency? (2019). Oral presentation. ANQUE-ICCE 2019 – 3rd International Congress of Chemical Engineering – Mediterranean Symposium of Life Cycle Assessment. Santander (Spain)
- **Rufí-Salís, M**; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Petit-Boix, A; Arcas, V; Parada, F; Toboso-Chavero, S; Muñoz, J; Rovira, MR; Rieradevall, J; Villalba, G & Gabarrell, X. Intercropping, urban agriculture and circular economy. A first

approach using Life Cycle Assessment to determine best annual crop combination. Oral presentation. CILCA 2019 - Conferencia Internacional Análisis de Ciclo de Vida 2019 ACV para la Competitividad Global. Cartago (Costa Rica)

- Parada, F; Gabarrell, X; **Rufí-Salís, M**; Arcas-Pilz, V; Muñoz, P & Villalba, G. Water management strategies for a food production in circular cities. Oral presentation. ISIE Americas 2020. Lima (Perú)
- **Rufí-Salís, M**; Petit-Boix, A; Villalba, G; Gabarrell; X & Leipold, S. Does the promotion of circular economy in urban agricultural systems align with its improvement in life cycle environmental performance? Oral presentation. Interdisciplinary Circular Economy Conference 2020. Freiburg (Germany).

Furthermore, additional training and knowledge was obtained through collaborations in a number of projects, articles, conferences, books, and scientific activities during the PhD training process.

Participation in projects:

- Fertilecity II (CTM2016-75772-C3-1-R, AI/UE-Feder). Agrourban sustainability through rooftop greenhouses. Integrated rooftop greenhouses: symbiosis of energy, water and CO2 emissions with the building – Towards urban food security in a circular economy. MINECO funds
- LIFE SAVING-E (LIFE14-ENV_ES_000633). Two-Stage Autotrophic N-remoVal for maINstream sewaGe treatment. EU funds
- Desdemona: DESarrollo de una DEpuradora urbana autosuficiente energéticamente Mediante la eliminación autOtrófica de Nitrógeno en la línea principal de Aguas y la recuperación de fósforo. MINECO funds
- Interreg V NWE - GROOF: Greenhouses to Reduce CO2 on rooFs. EU funds
- Collaborative Research: IRES (International Research Experience for Undergraduates) - Life Cycle Management and Ecosystem Services Applied to Urban Agriculture. National Science Foundation funds
- URBAG: Integrated System Analysis of Urban Vegetation and Agriculture. EU funds

The author of this dissertation did a research stay in the Albert-Ludwigs-Universität Freiburg in Germany from February to June 2020, under the supervision of Junior Professor Sina Leipold, coordinator of the Chair of Societal Transition and Circular Economy.

The author of this dissertation is a participant of the Working Group 3 "Measuring Circularity" from the ISO TC/323 "Circular Economy" committee representing the Comité Técnico de Normalización 323 from the Spanish Association for Standardization and Certification. ISO TC/323 technical committee works on the "*standardization in the field of Circular Economy to develop frameworks, guidance, supporting tools and requirements for the implementation of activities of all involved organizations, to maximize the contribution to Sustainable Development*."

Participation in articles that complement this dissertation:

- Boneta, A; **Rufí-Salís, M**; Ercilla-Montserrat, M; Gabarrell, X & Rieradevall, J (2019). Agronomic and environmental assessment of a polyculture rooftop soilless urban home garden in a Mediterranean city. *Frontiers in Plant Science*, *10*, 341 (doi: 10.3389/fpls.2019.00341)
- **Rufí-Salís, M**; Garcia-Orellana, J; Cantero, G; Castillo, J; Hierro, A; Rieradevall, J & Bach, J (2019). Influence of land use changes on submarine groundwater discharge. *Environmental Research Communications* (doi: 10.1088/2515-7620/ab1695)
- Mason, B; **Rufí-Salís, M**; Parada, F; Gabarrell, X & Gruden, C (2019). Intelligent urban irrigation systems: Saving water and maintaining crop yields. *Agricultural Water Management* (doi: 10.1016/j.agwat.2019.105812)
- Muñoz-Liesa, J; Royapoor, M; López-Capel, E; Cuerva, E; **Rufí-Salís, M**; Gassó-Domingo, S & Josa, A (2020). Quantifying energy symbiosis of building-integrated agriculture in a Mediterranean rooftop greenhouse. *Renewable Energy* (doi: 10.1016/j.renene.2020.04.098)

Collaboration in journals

- From October, 2017, until October, 2018, the abstracts of the Journal of Industrial Ecology were translated into Spanish.

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- A total of 9 peer-reviews were done for the following journals: *Resources, Conservation and Recycling*; *Journal of Cleaner Production*; *Journal of Agricultural Science and Food Research*; *Environmental Pollution*; *Environment; Development and Sustainability*; *Journal of Urban Affairs* and *Asian Journal of Soil Science and Plant Nutrition*.

Participation in university modules as lecturer:

- "Industrial Ecology" in the Master's Degree "Interdisciplinary Studies in Environmental, Economic and Social Sustainability". Academic years: 2017-2018, 2018-2019; 2019-2020.
- "Matter and Energy Flows" in the Bachelor's Degree "Management of Smart and Sustainable Cities". Academic years: 2018-2019, 2019-2020.
- "Chemical Engineering Experiments" in the Bachelor's Degree "Chemical Engineering". Academic years: 2017-2018, 2018-2019.

Participation as supervisor in Master's Thesis:

- "Agronomic and environmental assessment of a polyculture rooftop soilless urban home garden in a Mediterranean city" by Anna Boneta. Supervisors: Ercilla-Montserrat, M; **Rufí-Salís, M**; Rieradevall, J. Academic year: 2017-2018.

- “Nutrient recovery comparison of an integrated rooftop greenhouse using life cycle assessment – Case Study: i-RTG building at Universitat Autònoma de Barcelona” by Milena Calvo Juárez. Supervisors: **Rufí-Salís, M**; Gabarrell, X. Academic year: 2017-2018.
- “Economic and Environmental Analysis of Hydroponic Benches” by Benedikt Flock. Supervisors: Toboso-Chavero, S; **Rufí-Salís, M**; Gabarrell, X. Academic year: 2017-2018
- “Urban planning strategies: implementation of open-air farming on hotel rooftops” by María Alexandra Poveda. Supervisors: **Rufí-Salís, M**; Toboso-Chavero, S; Gabarrell, X. Academic year: 2018-2019.
- “Comparative environmental assessment of polyculture rooftop home urban gardens in the Mediterranean region” by Jai Verma. Supervisors: **Rufí-Salís, M**; Parada, F; Rieradevall, J; Gabarrell, X. Academic year: 2018-2019.
- “Assessing the circularity potential of the Wood industry in Catalonia” by Alex Mate. Supervisors: **Rufí-Salís, M**; Gabarrell, X. Academic year: 2018-2019.
- “Cigarette butt littering: causes, impacts and possible solutions. Experiences from a survey in Catalonia” by Laura Sanz. Supervisors: **Rufí-Salís, M**; Cabrera, A; Gabarrell, X. Academic year: 2019-2020.

Part 1

Background and methodological framework

Chapter 1

Picture: Green bean grown in a hydroponic rooftop greenhouse

Introduction and objectives

Chapter 1. Introduction and objectives

This chapter introduces the background of urban agriculture (UA) and its drivers, and justifies why circular economy (CE), life cycle thinking (LCT) and urban metabolism can contribute to study the potential of improvement and the main limitations of urban food production.

1.1 The growing importance of cities and the food flow

For the first time ever, urban population surpassed rural population in 2007 (UN, 2014). In the period from 1950 to 2018, 68% of the world's population was classified as urban, with an expected additional increase of 1.69% for the 2018-2030 period and of 1.28% for the 2030-2050 period (UN, 2018), exceeding the prospects published by the United Nations (UN) in 2014 (1.66 and 1.13%). Despite this increase in urban population (and the one that is yet to come), cities only cover 3% of Earth's surface area (SEDAC, 2016).

It is thus not surprising that urban populations consume a vast amount of the world's resources. In this regard, cities have become large contributors to a variety of environmental impacts at different scales (Kennedy et al., 2012). Specifically, the food supply chain has been labeled as one of the largest contributors to global environmental impacts for being long and inefficient (Spiertz, 2010). Some of the reported impacts are related to water depletion or greenhouse gas emissions (GHG) (Foley et al., 2011). Combined with population growth, the rising demand for food has also increased the pressures on natural resources and land availability (Schade and Pimentel, 2010). The Intergovernmental Panel on Climate Change (IPCC) quantified that agriculture, forestry and land use contribute to 24% of the global GHG, with agriculture on its own emitting between 5.0 and 5.8 Gt CO_2 eq/year considering the 2000-2010 period (IPCC, 2014). Data for the European Union (EU-28) show that agriculture contributes to 10% of the EU-28 GHG (Eurostat, 2011). Considering the amount of urban population, it is unavoidable to allocate the impact of global agriculture to the food supply to cities. As cities rely on its hinterland to sustain urban life, understanding how to reduce the pressures arising from urban food consumption is vital (Lenzen and Peters, 2010). In this sense, new approaches to mitigate these impacts focus on providing cities with fresh and local food (Brock, 2008).

1.2 Recent development of urban agriculture

1.2.1 Background and forms

Urban agriculture (UA) can be an alternative to our common perception of food production for cities (Specht et al., 2014). However, a standard definition for this concept does not exist (FAO, 2007). Lohrberg et al. (2016) classifies the current institutional definitions of UA into different components: spatial, origin, functional, actors, stakeholders, market, motivation and process. In this dissertation we embrace the definition provided by Smit et al. (2001) in the book "*Urban Agriculture: Food, Jobs and Sustainable Cities*" funded by the United Nations Development Programme. The authors consider that UA systems are those within or at the edge of a metropolitan or urban area, with the function of food provision, environmental enhancement and disaster management. Stakeholders can be defined based on their motivations within the complexity of UA systems, ranging from food security and nutrition to increasing income or leisure. Smit et al. (2001) also emphasize that these systems should be efficient in terms of use of space, water and other resources. Finally, the authors highlight the potential contribution of UA to close ecological loops. Although some UA definitions in the literature include the production of livestock (e.g. Lovell, 2010; Zezza and Tasciotti, 2010) or ornamental plants (Lin et al., 2015), this dissertation will only consider the production of horticultural products.

Considering the described scope, we can find different classifications of UA systems. For example, Lin et al. (2015) classifies UA systems into community gardens, private gardens, easement gardens, rooftop gardens and community orchards. From a more technical perspective, Goldstein et al. (2016b) consider 4 UA types: ground-based-non-conditioned, ground-based-conditioned, building-integrated-non-conditioned and building-integrated-conditioned. With a multi-parameter classification, Llorach-Massana (2017) proposes a division between soil and building-based UA. Among the building-based options, vertical farming is one of the forms that needs further exploring (Despommier, 2013), since it is expected to involve a higher development of technology, such as the use of hydroponics (Al-Chalabi, 2015; Kalantari et al., 2018). Vertical farming embraces edible walls, skyfarming and rooftop farming (Llorach-Massana, 2017). The latter can be developed in two different forms: open air or using greenhouses (Thomaier et al., 2015). The use of rooftop greenhouses (RTGs) has been gaining interest in the literature in the last few years. Besides making use of unused rooftop spaces, RTGs benefit from the concept and implications of building-integrated agriculture, an innovative form of farming with a high potential of urban symbiosis. RTGs can benefit from the building residual heat (Muñoz-Liesa et al., 2020; Nadal et al., 2017) without compromising the air quality in terms of aerobiology (Ercilla-Montserrat et al., 2017) or heavy metals (Ercilla-Montserrat et al., 2018). Moreover, the installation of rainwater harvesting systems (RWHS) is also an element frequently mentioned in the literature (e.g. De Zeeuw, 2011; Lin et al., 2015; Toboso-Chavero et al., 2018), contributing to the water self-sufficiency of the system.

1.2.2 General benefits and detected constraints

The benefits of UA can be classified in the three dimensions of sustainability: economic, social and environmental (Specht et al., 2014; Thomaier et al., 2015) (Figure 1.1).

From an economic perspective, previous literature has highlighted the power of UA to promote the development of local economies (De Zeeuw, 2011; Kortright and Wakefield, 2011; Lovell, 2010) and to provide fresh food on demand to the local market (Despommier, 2013). However, UA must compete with other urban uses that entail a higher economic revenue such as solar energy systems (Thomaier et al., 2015). In terms of social benefits, UA contributes to the food security of urban regions (Mok et al., 2014) by increasing the resilience of food supply chains. According to Zezza and Tasciotti (2010), UA may be associated to a more diverse diet and greater calorie availability by providing healthier food (Müller and Sukhdev, 2019). From an educational perspective, UA can increase the levels of self-awareness and the feeling of belonging in urban areas (Ferreira et al., 2018). Other benefits such as job creation or social equality are also highlighted by previous literature (Orsini et al., 2013).

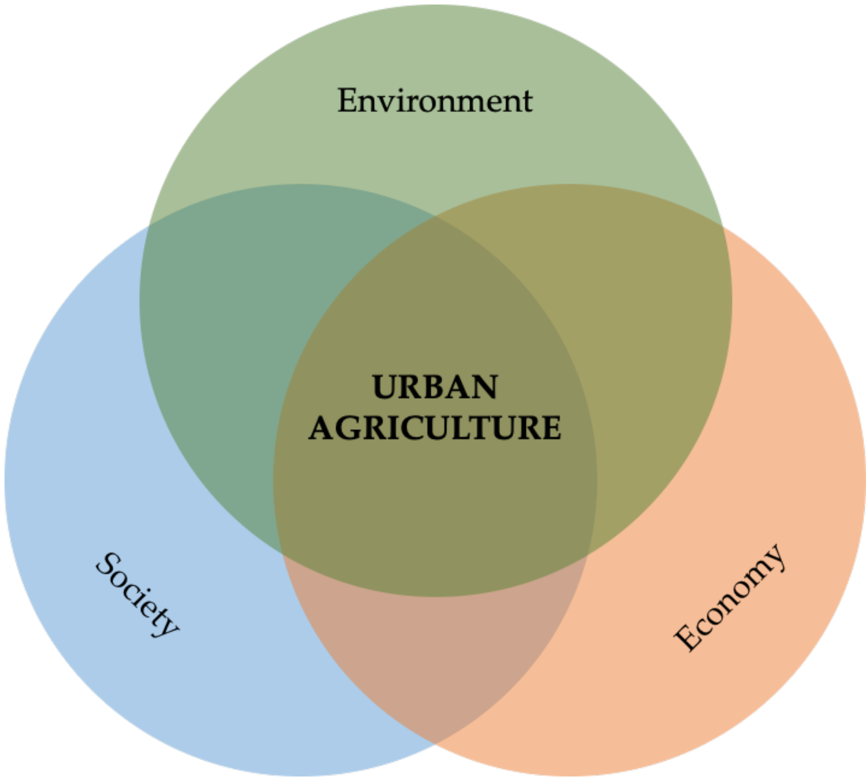


Figure 1.1 Dimensions of sustainability applied to urban agriculture

The environmental perspective of UA is the least explored, despite being one of its main drivers. As stated by Taylor et al. (2012), the development of UA should be classified as a top strategy towards sustainable global cities. The most apparent environmental benefit of the expansion of UA is the reduction of transportation distances of the vegetables that are consumed in cities (Jones, 2002). Moreover, UA releases pressure from agricultural land (Specht et al., 2014), while offering opportunities to contribute to urban resilience (Barthel and Isendahl, 2013) and ecosystem services (Artmann et al., 2018). Other studies have also targeted UA systems as a possible actor in synergy with insect pollination (Matteson and Langellotto, 2010). A summary of environmental benefits of vertical farming is outlined by Kalantari et al. (2018), highlighting an increase in productivity, more available land use, resilience to climate change and reductions of water demand. The latter two variables are also highlighted by Lin et al. (2015). The authors underline the need for further research on how UA can contribute to the resilience to climate change while diminishing the water used. In this sense, Kulak et al. (2013) highlights the importance of selecting the most suitable crops and cultivation set-ups to tap the full potential of UA to contribute to climate targets.

To do so, it is essential to recognize the main environmental hotspots within the analysed UA systems. In this sense, life cycle thinking (LCT) can give a more accurate assessment of the environmental performance of UA. By using the Life Cycle Assessment (LCA) methodology, previous literature detected the life cycle of fertilizers as one of the most impacting contributors. Different authors highlighted the relative contribution of the production stage of the fertilizers to different impact categories (Muñoz et al., 2008; Sanjuan-Delmás et al., 2018). Moreover, the impact of the fertilizers is also critical in the end-of-life. In this stage, the environmental implications are related to the eutrophication potential related to the release of nitrogen (N) and phosphorus (P) into aquatic environments in the urban context (Boneta et al., 2019; Sanjuan-Delmás et al., 2018), which is also an issue detected in conventional agriculture (Muñoz et al., 2008; Romero-Gámez et al., 2012). The application of hydroponics, where the fertilizers are supplied through the irrigation system to plants in soilless substrates, can provide a better control of the plant's nutrition and manage nutrient dynamics (Christie, 2014; Sanjuan-Delmás et al., 2020). In addition to hydroponic irrigation systems, there is a need to identify and evaluate novel concepts and strategies that effectively enhance the environmental sustainability of UA through the restoration of flows. One of them is the circular economy (CE).

1.3 The young concept of circular economy

The concept of CE has gained importance in the last years, not only among academics, but also among policymakers. The European Commission recently released a new "Circular Economy Action Plan" *for a cleaner and more competitive Europe* (European Commission, 2020a), which updates the one released in 2015 (European Commission, 2015), titled "*Closing the loop – An EU action plan for the Circular Economy*". A few years back, China released "The Law for the Promotion of the Circular Economy" (People's Republic of China, 2008). Its Article 1 describes the main purpose of the law: "*promoting the development of the circular economy, improving the resource utilization efficiency, protecting and improving the environment and realizing sustainable development*".

However, there is still no standard definition for CE. The Ellen MacArthur Foundation (one of the main organizations working around CE) states that a CE rests on three principles: preserving and enhancing natural capital, optimizing resource yields, and fostering system effectiveness (EMF et al., 2015). However, a review published in 2017 by researchers from the Utrecht University found up to 114 definitions (Kirchherr et al., 2017). Of the papers revised by the authors, almost half of the sample mentioned "economic prosperity", while less than 40% talked about "environmental quality" and near 20% mentioned "social equity". The authors also found different approaches to the 3R/4R framework (reuse, reduce, recycle and recover) and to the scale perspective (micro, meso and macro).

In this dissertation we address the CE concept considering the environmental dimension of sustainable development. To this end, and following literature recommendations on adopting a single definition in CE studies (Kirchherr et al., 2017), we use the CE definition proposed by Geissdoerfer et al. (2017):

"*CE is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops*".

One could argue that the concept "circularity" is more precise than CE, since the selected CE definition is more related to the application of closed-loop principles adapated from the Material Flow Analysis (MFA) (Eurostat, 2001). However, since there is no glossary of concepts around CE, the literature keeps referring to circularity and CE without specifying the particularities of each concept. For example, we can observe these imprecisions in the literature around indicators, where we can either find the concept of "CE indicators" (e.g. Haupt et al., 2017; Helander et al., 2019; Niero and Kalbar, 2019; Pauliuk, 2018; Saidani et al., 2019b; Santagata et al., 2020) or "circularity indicators" (e.g. Cobo et al., 2018; EMF, 2015; Linder et al., 2020; Saidani et al., 2019a).

The practical implementation of CE principles in specific systems is referred to as "circular strategies". Although this concept has gained importance in the literature, academics have focused on developing the concept and establishing a classification and defining implementation levels (e.g. Elia et al., 2017; Kalmykova et al., 2018; Moraga et al., 2019). Nevertheless, the implementation in specific systems and its environmental evaluation remain mostly unexplored.

1.4 A life cycle perspective to circular economy

LCT is "*a holistic approach that considers sustainability factors over the entire life of a product*" (Mcconville and Mihelcic, 2007). The life cycle of a product encompasses interlinked or consecutive stages, from the extraction of raw materials to its end-of-life (ISO, 2006). LCT's ultimate application is the Life Cycle Sustainability Assessment (LCSA), which combines the results of the assessment of a product's social implications (Social Life Cycle Assessment or S-LCA), economical costs and value (Life Cycle Costing or LCC) and environmental performance (Environmental Life Cycle Assessment or just Life Cycle Assessment or LCA). The latter is the most broadly used methodology to analyze the environmental impacts of products and systems.

Traditionally, an analysis involving LCT or LCA concepts could have different approaches, such as cradle-to-gate, gate-to-gate or assessment of specific parts of the life cycle (ISO, 2012). However, the most common approach involves the linear process between the extraction of raw materials and the end-of-life of a product, known as a Cradle-to-Grave (C2G) approach. Several authors relate C2G with the concept of a linear economy (e.g. Bocken et al., 2016; Qiao and Qiao, 2013; UNIDO, 2008), which follows the traditional model of continuously turning resources into waste after their lifetime. The meeting point between LCT and CE is the Cradle-to-Cradle (C2C) approach, a system that mimetizes nature's highly effective functioning (McDonough and Braungart, 2002) in which wastes are converted into new resources and disposal of goods is minimized. A graphical representation of the ultimate stage of a CE (as opposed to a linear economy) with a LCT approach is shown in Figure 1.2. The recent Circular Economy Action Plan for the EU (European Commission, 2020a) mentions that "*this legislative initiative […] will be developed in a way to improve the coherence with existing instruments regulating products along various phases of their life cycle*". In this sense, the application of LCT principles to CE through LCA is vital to detect weaknesses and environmental hotspots of circular strategies not only at the end-of-life, but also among different stages of the life cycle of a product or system. As expressed in the last Life Cycle Initiative's position paper titled "*Using Life Cycle Assessment to achieve a circular economy*", LCA should be used as a methodology to promote more robust circular strategies that include all relevant resources and indicators, leading to better decisions for sustainability (Peña et al., 2020).

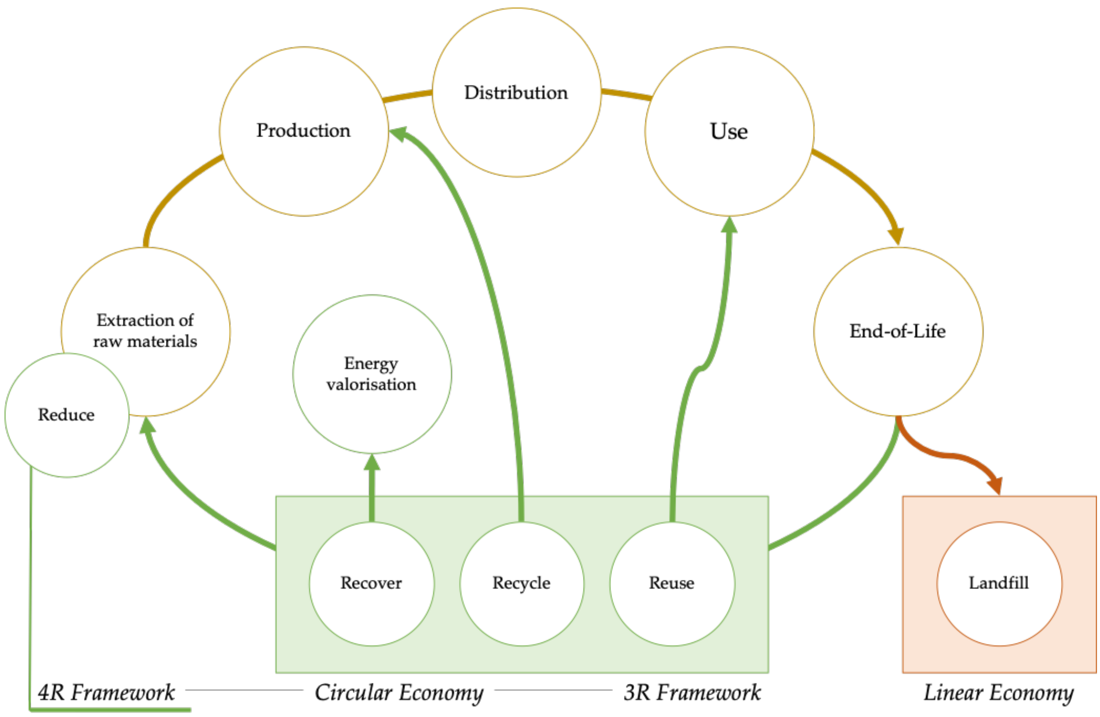


Figure 1.2 Life cycle stages of a linear and circular economies

1.5 Motivation of this dissertation

This dissertation is based on the potential that the CE principles could have in improving urban food production systems. The promotion of CE principles in UA can help mitigate the environmental impact generated by these systems and move towards a circular agriculture (e.g. Gangnibo et al. 2010; Cao et al. 2011; Trendov 2017; Fan et al. 2018). According to Ferreira et al. (2018), "*agriculture is central to any territorial based circular economy strategy*". Closing the nutrient cycles in UA can produce a regenerative effect on the environment (EMF, 2015a), contributing to utility and value preservation of scarce resources (Bocken et al., 2017). In this sense, the application of CE principles in systems within the city boundaries is strictly related to the concept of urban metabolism, as first conceived by Wolman (1965) as "the metabolism of cities". Kennedy et al. (2007) defines urban metabolism as "*the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*". In this sense, the application of CE principles in urban systems creates what could be called a circular urban metabolism (Ferrao and Fernandez, 2012), in which waste (outputs) generated in urban areas is transformed into valuable products (inputs) that can be used again within urban limits.

Given the potential of UA as an opportunity to use wastes as resources within city limits (Ferreira et al., 2018; Smit and Nasr, 1992), the application of circular strategies in UA systems is a promising path towards a more circular urban metabolism, as schematized in Figure 1.3. To do so, there is a need to analyze the environmental performance of different kinds of crops in order to identify the environmental hotspots within different forms of UA that follow a linear behavior (Figure 1.3 – Linear UA). In particular, RTG systems remain mostly unexplored although offering additional synergies at a building scale. Once the environmental hotspots are detected, the application of suitable circular strategies can be defined, targeting specific items in the system. Notwithstanding, the application of circular strategies must be strictly monitored in terms of environmental impacts. This analysis will shed light on the alignment or decoupling between CE and environmental sustainability principles, helping to avoid the implementation of contradictory strategies. However, it is essential that the optimization of the circularity or the sustainability of UA does not contradict the ultimate function of these systems: to produce vegetables.

Recovering nutrients in UA systems

Focusing on UA systems, the use of hydroponic cultivation in rooftop farming intrinsically improves the nutrient supply efficiency by allowing for a better control of plant's nutrition. Moreover, hydroponic cultivation also allows a precise monitoring of the leachates and increases the flexibility of the UA system to manage the residual water and nutrient flows. In this sense, different environmental targets with a linear behavior can be defined with UA at the core. Considering the high demand for fertilizers of

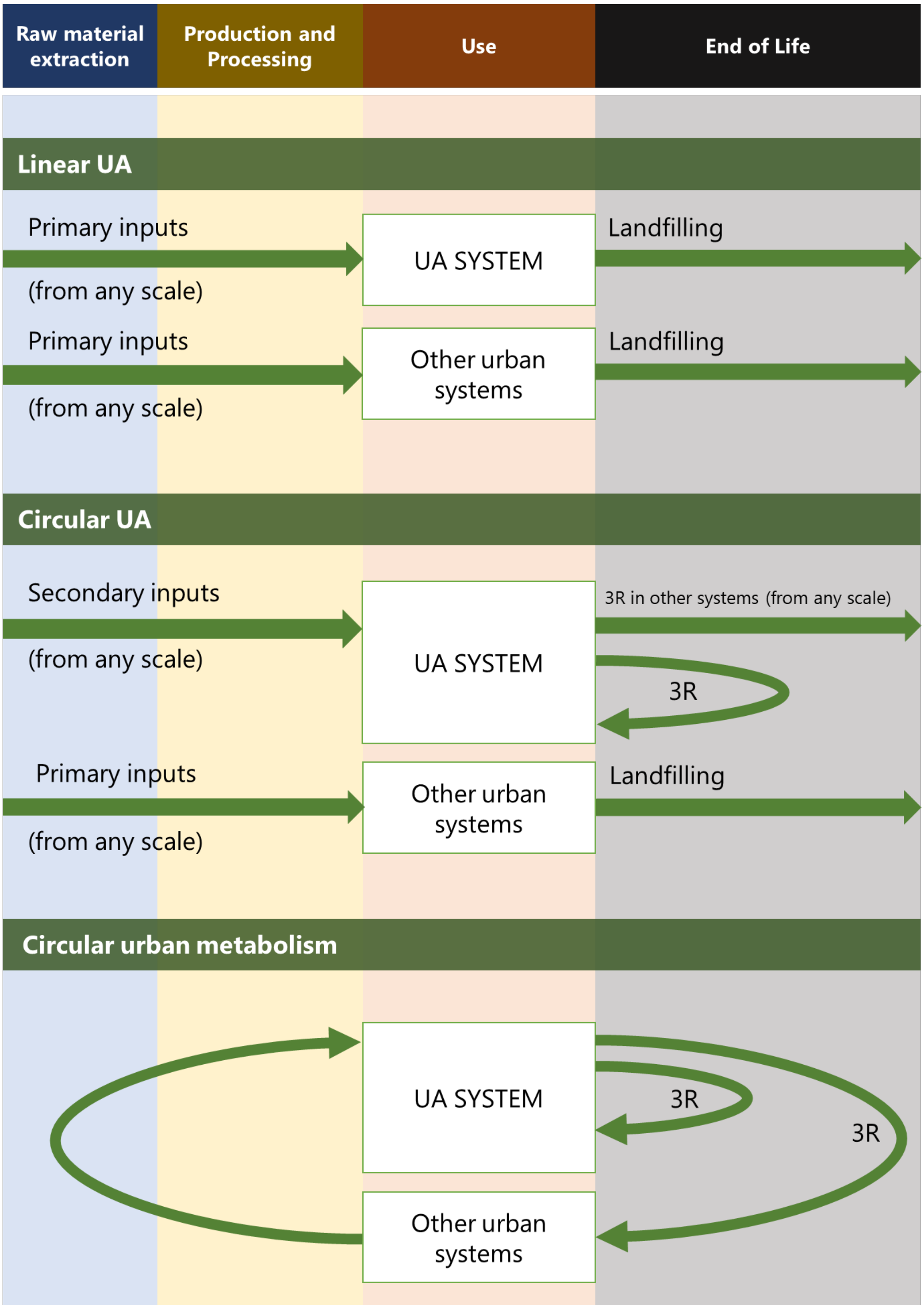


Figure 1.3 Metabolism of urban agriculture (UA) from a linear perspective to a circular urban metabolsim

agricultural systems and the depletion of nutrients through the leachates, we need to define strategies to improve the metabolism of nutrient flows in newly implemented UA systems. To this end, finding the best strategy for nutrient recovery in UA systems is a priority, while considering the feasibility and environmental performance of the implemented strategies, among others. From a reuse perspective (Figure 1.3 – Circular UA), this dissertation will assess the real implementation of strategies such as leachates recirculation, which uses the leached flows to irrigate the same crop, or cascade systems, which uses the nutrients lost from a donor crop to irrigate a receiving crop. However, these strategies only focus on recovering the nutrients lost in UA systems. Applying CE principles within the urban metabolism framework must go beyond this and exploit possible synergies with other urban systems.

Exploiting the synergy between urban systems through phosphorus recovery

Phosphorus (P) is primarily obtained from phosphate rocks, a non-renewable resource given the slowness of the P cycle. Due to the increasing demand for P to produce fertilizers for agriculture (Figure 4.1) (80% of the available stock of phosphate rocks is being used in the production of fertilizers (Shu et al., 2006)), half of the world's current phosphate resources will have been used up by the end of the 21st century (Steen, 1998), although more pessimistic predictions have been recently reported (Li et al., 2016). For this reason, the EU-28 labels P as a critical resource (European Comission, 2014).

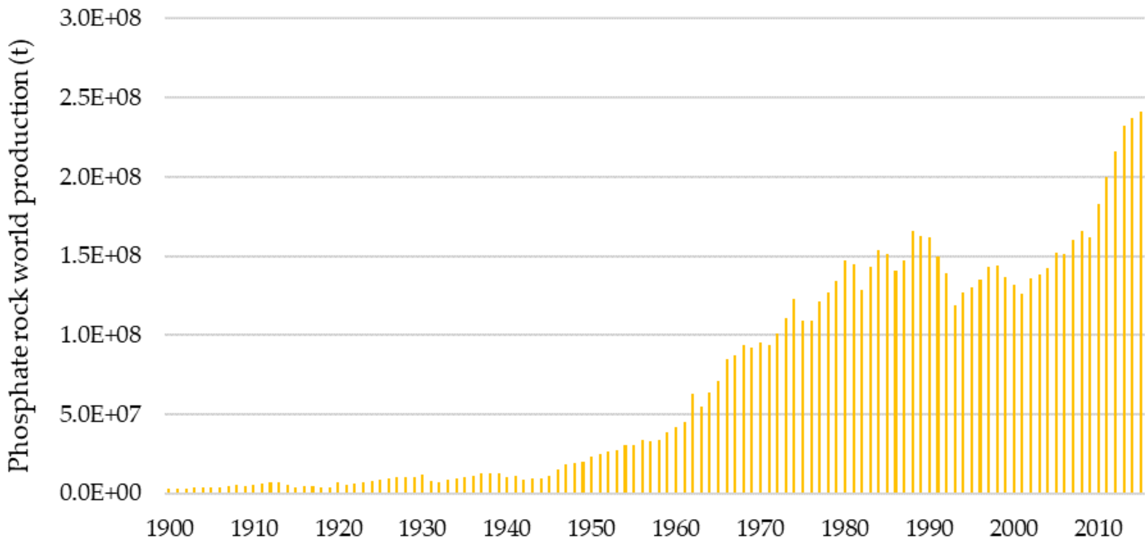


Figure 1.4 Annual world production of phosphate rock (t) in the 1990-2015 period. Own elaboration with data from USGS (2015)

In this sense, the European Commission encourages P recovery from local sources by enforcing a shift towards a more circular use of nutrients (European Comission, 2016). Struvite can contribute to this shift. Magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$), commonly called MAP struvite or simply struvite, is a mineral with a low solubility in water ($0.018 g \cdot 100 ml^{-1}$ at 25ºC) (Bridger et al., 1961). Due to this parameter, struvite spontaneous precipitation is a regular problem in urban wastewater treatment plants (WWTPs) with a high P load, since it precipitates in ducts and pipes causing operational problems and additional costs (Stratful et al., 2004). However, the development of technologies aimed to avoid this problem by removing P has offered an unexpected opportunity. Intentionally precipitated struvite can be used as a P secondary fertilizer with clear reported benefits. Its low solubility makes struvite a slow-release fertilizer, improving its supply efficiency, with most experimental tests reporting competitive yields compared to mineral fertilizers (Li et al., 2019). However, two main aspects regarding struvite recovery in urban WWTPs and its application in UA systems remain barely explored.

First, the application of struvite in hydroponics set-ups. Alike soil-based systems, soilless hydroponics allow a precise monitoring of all input and output flows. Apart from analysing its agronomic performance, this dissertation assesses how the application of struvite changes the behaviour of the P flows through experimental tests and analytical methods.

Second, the environmental evaluation of struvite recovery and reuse strategies on a regional scale is still missing from the literature. In this sense, we analyze the environmental performance of struvite recovery and reuse with a regional perspective that treats a metropolitan area like a self-sufficient entity, tapping the full potential of the synergy between urban WWTPs and UA systems (Figure 1.3 – Circular urban metabolism).

The need for a combined assessment

A full system with a maximum circularity is not necessarily a system with an optimized environmental performance. Although the application of circular strategies may entail a reduction in the environmental impacts of a system, it is important not to get the concepts mixed up. The recent position paper by the Life Cycle Initiative calls for precaution: "*there is yet no harmonised method to assess whether a specific CE strategy contributes towards sustainable consumption and production*" (Peña et al., 2020). To add to this pool of knowledge, this dissertation aims to study all possible circular strategies that could be applied in UA systems considering an urban metabolism perspective. This study needs to include an analysis of the environmental performance of the system, but also an analysis of circularity. The results obtained will help in two different ways. First, to prioritize circular strategies in UA systems. Second, to move towards the combined analysis of sustainability and circularity of production systems through the development of new indicators to define the alignment between the goals of these two big frameworks.

1.6 Research questions and objectives

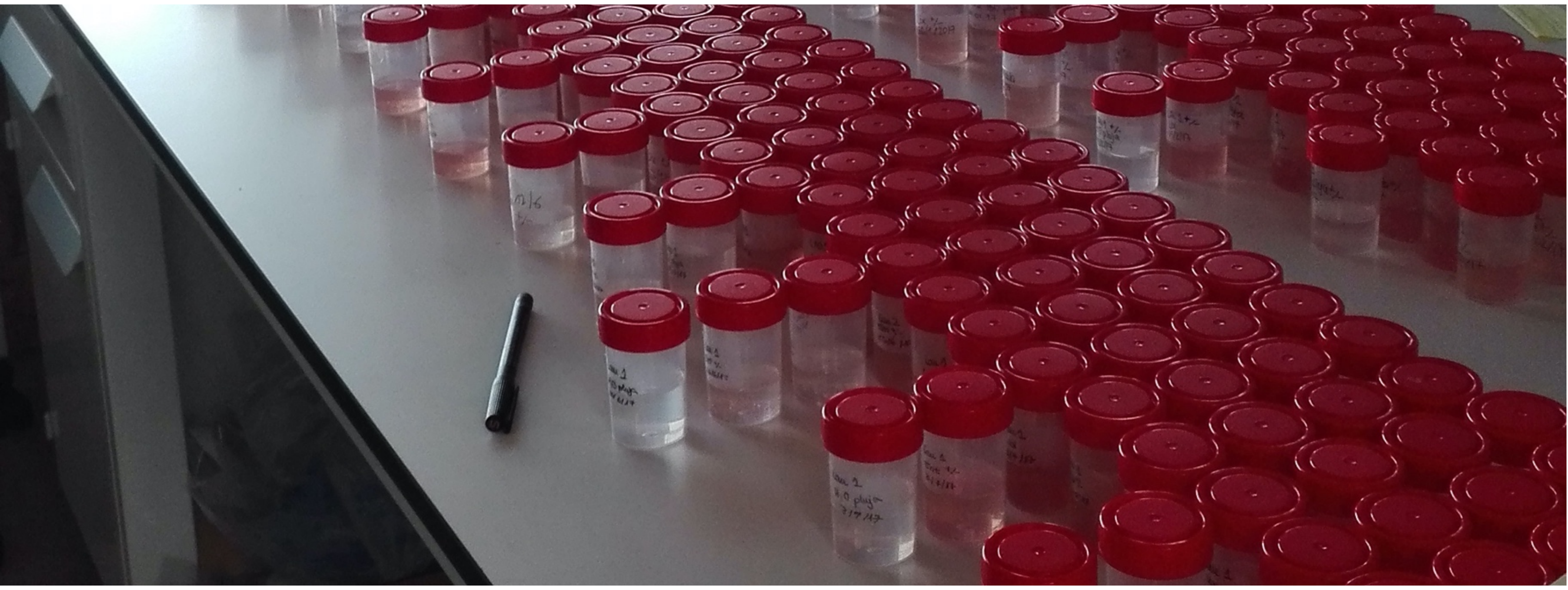
The goal of this dissertation is to assess the environmental performance of circular strategies in UA systems. To do so, we formulated the following research questions:

- **Question 1**: Which are the main environmental hotspots in UA systems resulting from different crop types?
- **Question 2**: How can existing nutrient recovery techniques contribute to improve the efficiency of nutrient flows while diminishing the environmental impacts of UA?
- **Question 3**: Is the recovery and reuse of struvite a promising strategy to reduce the environmental impacts of UA and wastewater treatment in cities?
- **Question 4**: How can circular strategies be prioritized to improve the environmental and circularity performance of UA?

To answer these questions, we set different objectives that were addressed in different chapters of this dissertation:

<table>
<tr><th colspan="2">Objective</th><th>RQ</th><th>Chapter</th></tr>
<tr><td>I</td><td>To identify the best yearly crop combinations based on their environmental performance</td><td rowspan="2">Q1</td><td>C3</td></tr>
<tr><td>II</td><td>To detect the environmental hotspots of an UA system in order to define the target areas to optimize while defining the most eco-efficient year-round crop combinations</td><td>C3</td></tr>
<tr><td>III</td><td>To determine the less environmentally intensive strategy to recover nutrients in hydroponic UA systems</td><td rowspan="3">Q2</td><td>C4</td></tr>
<tr><td>IV</td><td>To compare the environmental performance of closed-loop systems with linear systems in a hydroponic UA system</td><td>C5</td></tr>
<tr><td>V</td><td>To evaluate the potentials and limitations of cascade systems to produce locally grown vegetables in the framework of UA while diminishing the nutrient load by closing nutrient cycles.</td><td>C6</td></tr>
<tr><td>VI</td><td>To assess the potential of struvite precipitated in a WWTP as a fertilizer within the framework of urban metabolism.</td><td rowspan="2">Q3</td><td>C7</td></tr>
<tr><td>VII</td><td>To quantify the environmental burdens and benefits of regional struvite recovery and reuse to feed agricultural fields for urban food production.</td><td>C8</td></tr>
<tr><td>VIII</td><td>To analyze the environmental and circularity performance of applying circular strategies in UA systems and to explore indicators that support decision-making and prioritization in the urban context.</td><td>Q4</td><td>C9</td></tr>
</table>

Chapter 2



Picture: Organisation of water samples at the end of the crop

Materials and Methods

Chapter 2. Materials and Methods

This chapter presents the materials and methods used in this dissertation and the case studies used to perform the analysis.

2.1 Methodology overview

Different methods were used in this dissertation to assess the performance of urban agriculture (UA) and the different circular strategies applied (Table 2.1). Life Cycle Assessment (LCA) was applied to quantify the environmental performance of the systems analyzed in **Chapters 3, 4, 5, 8 and 9**. LCA was combined with wholesale market prices of vegetables to determine the eco-efficiency of different crops in **Chapter 3**. In **Chapter 8**, LCA was combined with geographical information systems (GIS) to determine the environmental impacts of the distribution of struvite within the region under analysis. Both experimental and analytical data were analyzed in all chapters except in **Chapter 8**.

Table 2.1 Methodologies applied in each of the chapters

Chapter	LCA	Eco-efficiency	GIS	Experimental	Analytical
C3	X	X		X	X
C4	X			X	X
C5	X			X	X
C6				X	X
C7				X	X
C8	X		X		
C9	X			X	X

2.2 Life Cycle Assessment

LCA was used in most of the chapters to quantify the environmental impacts of production systems. LCA is based on ISO 14040, and is used "*to address the environmental aspects and potential environmental impacts […] throughout a product's life cycle from raw material acquisition […] to final disposal*" (ISO, 2006). To do so, LCA is divided in four main phases, outlined in Figure 2.1.

2.2.1 Goal and scope definition

The first phase is the basis for a correct development of a LCA. The goal of the study entails the application, audience and reasons to carry the analysis. Meanwhile, the scope encompasses a set of key parameters that will be used as reference for the following phases. Among these, the functional unit (FU) is the reference quantity of product that will be used to normalize the input and outputs of the analysis, while the system boundaries define the processes included in the assessment and the ones that are to be

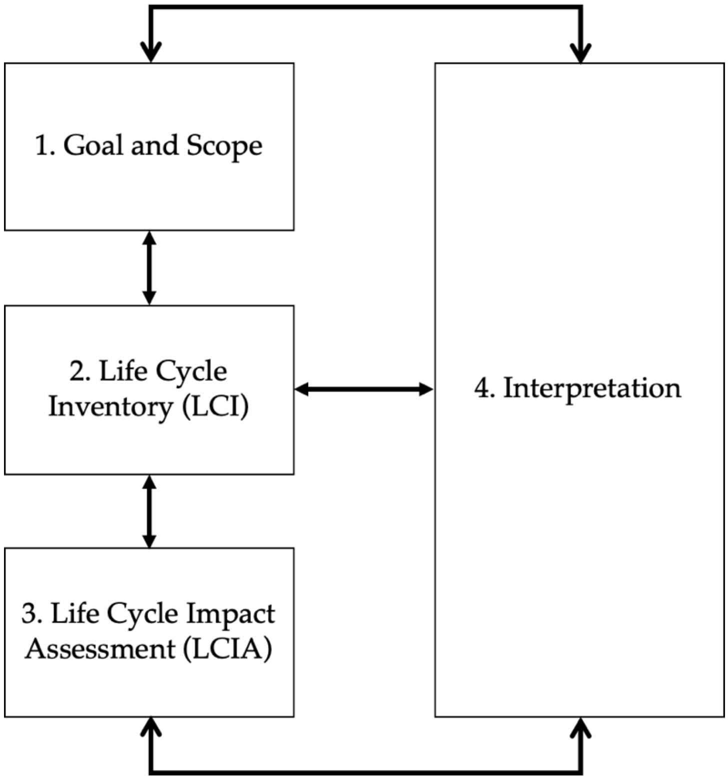


Figure 2.1 Steps of LCA. Adapted from ISO (2006)

left out. Quality of data, assumptions used and potential limitations are also part of the goal and scope phase.

Specific FUs are used in every chapter. With the aim to respond to the functions of producing food, generating monetary value and supplying nutritional value, **Chapter 3** uses FUs of kg of yield, € of wholesale market value and kcal of nutritional quality.

Since the goal of **Chapter 4** is related to the recovery of nutrients while exploring their possible reuse, two functional units were used. FU A was defined as the recovery of the total phosphorus leached (446.6 g) in a hydroponic tomato crop cycle that produced 1084 kg of tomatoes and lasted 187 days, with the purpose of reusing the phosphorus in the same growing system. FU B was defined as meeting the nutrient demand of a tomato crop cycle by reusing the recovered nutrients leached from a previous crop cycle through the applied recovery strategies, i.e. the results from FU A plus the nutritional adjustments needed to meet the nutritional requirements of the entire tomato crop.

The FU in **Chapter 5** is based on 1 kg of edible beans, considering that the final goal of both linear and closed systems is to produce.

Chapter 8 uses 3 different FUs to encompass different approaches to the recovery and reuse of struvite. In a preliminary evaluation which goal is to determine whether a technology is suitable within the operation of an existing wastewater treatment plant (WWTP), we use 1 m3 of wastewater as the FU, which strictly refers to the function of cleaning wastewater. Second, a FU of 1 kg of P is used to respond to the function of recover and apply P in the form of struvite, prioritizing recovery strategies. Finally, a more complex FU is used with the aim of analyzing the environmental performance of the recovery and reuse of all required P of the region under study: a combination of the yearly wastewater treatment of the area (considering the two main WWTPs) and meeting the P demand as fertilizer in the region.

The FU in **Chapter 9** is again based on yield. Since the cycle used in this study is tomato, the FU refers to 1 kg of the fruit produced by this crop.

2.2.2 Life Cycle Inventory (LCI)

The second phase of the LCA involves the collection and calculation of data to meet the goal of the study. According to ISO (2006), data in the LCI can be classified in four major groups: (I) energy, raw materials and other physical inputs, (II) products, co-products and waste, (III) emissions and discharges to various environmental compartments and (IV) other environmental aspects.

The process of collecting the data for the LCI is dynamic and resource-intensive: as limitations and hidden aspects of the system may appear, different sources and types of data may be required. This dissertation used both primary data (collected through experimental tests, analytical methods or fieldwork, among others) and secondary data (generated by others and retrieved from reports, scientific papers or book chapters, among others).

A final section of the LCI is the use of allocation when unavoidable. The process of allocation is the splitting of specific flows between the system under study and other systems, mainly due to the multifunctional nature of these specific flows or elements within the LCI. For example, some chapters of this dissertation include the life cycle stages of a rainwater harvesting system (RWHS). Since this RWHS may supply water for different uses, its impact may be divided among the uses that are benefitting from it, splitting the impacts based on mass, economic value or other parameters that may be relevant (water supplied in the case of the RWHS). When allocations are used, they must be stated and explained very carefully to avoid confusion and allow other LCA practitioners to replicate the results. Specific allocations in this dissertation are detailed in each specific chapter.

2.2.3 Life Cycle Impact Assessment (LCIA)

The LCIA is the final calculation step of the LCA, encompassing the classification, characterization, normalization and weighting phases. The first two are mandatory, while the other are optional and relevant for specific cases. By using the flows gathered in the LCI in reference to the FU, the environmental impacts of the system are calculated for a set of impact categories, normally classified using impact methods. Once these categories are chosen by the LCA practitioner, the elementary flows of the LCI are allocated to each impact category, with the possibility of one flow contributing to multiple impact categories (classification). Then, each flow is multiplied by characterization factors accounting for how harmful is that emission in that impact category (characterization). Finally, the product of the aggregated multiplications is summed to yield the final score of a specific impact category in a specific unit (e.g. kg P equivalents for freshwater eutrophication or kg SO_2 equivalents for terrestrial acidification). The optional phases of LCIA, i.e. normalization (comparing the values of the impact categories to a reference information) and weighting (aggregation of impact categories into single values based on weighting factors) were not included in this dissertation.

The main impacting method used in this dissertation is the ReCiPe, which includes multiple impact categories and was recently updated to a global scale (Huijbregts et al., 2016). The ReCiPe method includes three perspectives that are used to group specific assumptions. Among the three perspectives included in the ReCiPe (Egalitarian, Hierarchist and Individualist), Hierarchist (H) was used as "*it is based on the most common policy principles with regard to time frame and other issues*" (Goedkoop et al., 2009).

The ReCiPe includes midpoint and endpoint indicators. Midpoint indicators were chosen over endpoint indicatoris because the formers have a stronger relation with environmental flows and imply lower uncertainty levels (Hauschild and Huijbregts, 2015). During the elaboration of this thesis, the ReCiPe method was updated by its creators, changing and updating some impact categories. Therefore, **Chapter 3** uses impact categories included in ReCiPe 2008 (Goedkoop et al., 2009), while the remaining chapters use impact categories within the ReCiPe 2016 (Huijbregts et al., 2016). As an example, the Climate Change (CC) and Fossil Depletion (FDP) impact categories in ReCiPe 2008 are called Global Warming (GW) and Fossil Resources Scarcity (FRS) in ReCiPe 2016.

CC / GW was included in all chapters since it is commonly used in LCA studies while their results are easy to communicate. FDP / FRS was included as the energy-related impact category. However, some chapters replaced this indicator for the single issue impact category Cumulative Energy Demand (CED), which includes energy supply through other renewable and non-renewable sources. Ecotoxicity (ET) was included in the assessment as the indicator to quantify the toxicity of the assessed flows to the environment. ET is not a category itself in the ReCiPe, but was constructed by summing the scores of Freshwater, Marine and Terrestrial Ecotoxicity (FET, MET and TET, respectively) midpoint indicators. Freshwater Eutrophication (FE) and Marine Eutrophication (ME) were included in the LCIA for their known relationship with agricultural systems based on phosphorus (P) and nitrogen (N) depletion, respectively. Finally, Terrestrial Acidification (TA) was included in the first chapters for its quantification of soil changes that harm plant species. However, TA was only included in the first two chapters because the report about this impact category does not explicitly mention a significance related to hydroponic cultivation. Although TA impacts are still quantifiable, we assumed that the use hydroponics decreased the relevancy of this indicator. The ReCiPe version and the description of the impact categories used in this dissertation are described in Table 2.2.

Table 2.2 List of impact categories used in the dissertation.

Acronym	Name	Units	Definition
ReCiPe 2008 (H) (Goedkoop et al., 2009)			
Climate Change	CC	kg CO_2 eq	Impacts derived from the integrated infrared radiative forcing increase of greenhouse gases.
Terrestrial Acidification	TA	kg SO_2 eq	Atmospheric deposition of inorganic substances that cause a change in soil's acidity, harming plants species
Freshwater Eutrophication	FE	kg P eq	Eutrophication impacts derived from discharges of P in freshwater environments (where P is the limiting nutrient)
Marine Eutrophication	ME	kg N eq	Eutrophication impacts derived from discharges of N in marine environments (where N is the limiting nutrient)
Fossil Depletion	FDP	kg oil eq	Reduction of the available resources of fossil fuels (in energy content terms) due to its extraction
Ecotoxicity	ET	kg 1,4-DB eq	Impact of chemicals in the environment based on its environmental persistence, toxicity and accumulation in the human food chain. ET is the sum of the values obtained for freshwater (FET), marine (MET) and terrestrial ecotoxicity (TET)
ReCiPe 2016 (H) (Huijbregts et al., 2016)			
Global Warming	GW	kg CO_2 eq	Equivalent to ReCiPe 2008 CC, updating emission factors from IPCC among others
Terrestrial Acidification	TA	kg SO_2 eq	Equivalent to ReCiPe 2008 TA, updating emission factors from Roy et al. (2014) among others
Freshwater Eutrophication	FE	kg P eq	Equivalent to ReCiPe 2008 FE, updating emission factors from Helmes et al. (2012) among others
Marine Eutrophication	ME	kg N eq	Equivalent to ReCiPe 2008 ME, added in later reports, with no reported changes.
Human Toxicity	HT	kg 1,4-DB eq	Impact of chemicals in human health based on its environmental persistence, toxicity and accumulation in the human food chain.
Fossil Resource Scarcity	FRS	kg oil eq	Equivalent to ReCiPe 2008 FDP, with changes from Huijbregts et al. (2016)
Ecotoxicity	ET	kg 1,4-DB eq	Equivalent to ReCiPe 2008 ET, with changes from (Van Zelm et al., 2009)
Single Issue (Frischknecht et al., 2007; Hischier et al., 2010)			
Cumulative Energy Demand	CED	MJ	Energy use throughout the life cycle of a good or a service, divided by its origin.

Due to the large amount of elementary flows and impact categories involved, the LCIA is usually performed using a software linked to databases with background environmental information. In this dissertation, we used the Simapro software developed by PRé Consultants. Simapro is coupled with Ecoinvent (Wernet et al., 2016), one of the biggest life cycle environmental databases, developed by ETH Zurich.

Versions of Simapro, Ecoinvent, and the method and impact categories used are linked to each chapter of this dissertation in Table 2.3.

2.2.4 Interpretation

The final step of the LCA is the interpretation of the outcomes. This phase is used to identify environmental hotspots and define targets to optimize, always depending on the goal previously defined. Since LCA is an iterative process, there is not only one interpretation phase: the outcome of the LCIA can provide results that weren't expected, which could trigger a further analysis, like drawing scenarios or defining new objectives.

2.3 Eco-efficiency analysis

An eco-efficiency assessment is a quantitative tool that combines the environmental impacts of a product or system with its value for a specific stakeholder. This combination is performed through plot drawing (eco-efficiency portfolio), with environmental impacts in the Y-axis and the value in the X-axis. The process is standardized by ISO 14045 (ISO, 2012). The environmental impacts are calculated based on ISO 14040 (ISO, 2006) using LCA, and thus the steps for this part of the process are the same as described in the previous sections. On the other hand, the value for a stakeholder may be expressed in monetary terms, giving room for choosing between a set of variables. Eco-efficiency analysis is used in **Chapter 3** of this dissertation, using the wholesale market value of vegetables as the monetary value parameter. We considered that a desired best-case eco-efficiency performance combines low environmental impacts and high market prices, as the system under analysis is providing low-impacting vegetables with added economic value to the market.

Table 2.3 Software, database, impact method and impact categories used in the dissertation. Climate Change (CC); Terrestrial Acidification (TA); Freshwater Eutrophication (FE – kg P eq); Marine Eutrophication (ME – kg N eq); Fossil Depletion (FDP); Ecotoxicity (ET), Global Warming (GW); Human Toxicity (HT); Fossil Resource Scarcity (FRS); Cumulative Energy Demand (CED).

<table>
<tr><td>Chapter</td><td>SimaPro v.</td><td>Ecoinvent v.</td><td>Impact Method</td><td>Impact categories</td></tr>
<tr><td>C3</td><td>8.5</td><td>3.4 (Moreno Ruiz et al., 2017)</td><td>ReCiPe 2008 (Goedkoop et al., 2009)</td><td>CC, TA, FE, ME, FDP, ET</td></tr>
<tr><td>C4</td><td rowspan="4">9.0</td><td rowspan="4">3.5 (Moreno Ruiz et al., 2018)</td><td rowspan="4">ReCiPe 2016 (Huijbregts et al., 2016) and Cumulative Energy Demand</td><td>GW, TA, FE, HT, FRS</td></tr>
<tr><td>C5</td><td>GW, FE, ME, FRS, ET</td></tr>
<tr><td>C8</td><td>GW, FE, ME, ET, CED</td></tr>
<tr><td>C9</td><td>GW, FE, ME, ET, CED</td></tr>
</table>

2.4 Circularity assessment

The aim of a circularity assessment is to define to which degree a product or a system (among others) is "circular". However, there is not yet standardized methodology to perform a circularity assessment, and therefore a great diversity of indicators are available in the literature (e.g. Helander et al., 2019; Pauliuk, 2018; Saidani et al., 2019a). In this dissertation a circularity assessment is performed in **Chapter 9** through the quantification of the Material Circularity Indicator (MCI) (EMF, 2015b). MCI has a value between 0 (100% linear) and 1 (100% circular), with a complete calculation requiring 27 sub-parameters (EMF, 2015b). In terms of inputs, flows are classified between virgin feedstock and other origins. In terms of outputs, flows are split between unrecoverable waste and other end-of-life scenarios. Because MCI is applied across life cycle phases (Helander et al., 2019), it is complementary to LCA (EMF, 2015b). We exploited this characteristic in **Chapter 9** to analyze the circularity and environmental performance of applying circular strategies in UA through the process shown in Figure 2.2. Since we are applying both LCA and MCI in the same assessment, we adapted the established steps for LCA (goal and scope, inventory and impact assessment) (ISO, 2006) to the application of the MCI. Since the combined assessment in this dissertation include a part related to indicator development, the methodology to reach the final coupled indicators is included in the results section of **Chapter 9**.

2.5 Experimental and analytical data

This section describes the procedure and devices used to gather the different types of experimental and analytical data complementary to the environmental assessment: climatic variables (Section 2.5.1), water (Section 2.5.2 for volume and basic control and Section 2.5.3 for nutrient content) and biomass and substrate (Section 2.5.4).

2.5.1 Climatic variables

Climatic variables in this dissertation encompass temperature, radiation and relative humidity. One or more of these variables were explicitly analyzed in **Chapters 5 and 6**, although they were used in most of the chapters for monitoring and validation of experimental tests. The temperature was measured hourly using T107, CS215 and 110 PV automatic sensors by Campbell Scientific. The relative humidity was also measured hourly through CS215 sensor by Campbell Scientific, while the radiation was measured using a LP02 pyranometer by Hukseflux. All these sensors were attached to a CR3000 Datalogger by Campbell Scientific to keep the records.

2.5.2 Water – Volume and basic control

Keeping track of the water flows in hydroponic set-ups is key to ensure a correct water and nutrient management and to have a proper data quality to quantify nutrient balances and specific parts of the LCA. Volume of the water flows was quantified using analogic flowmeters for the crops analyzed in most of the chapters of this dissertation. Other systems were used only to quantify the leachates in specific chapters, and was explicitly stated and described accordingly.

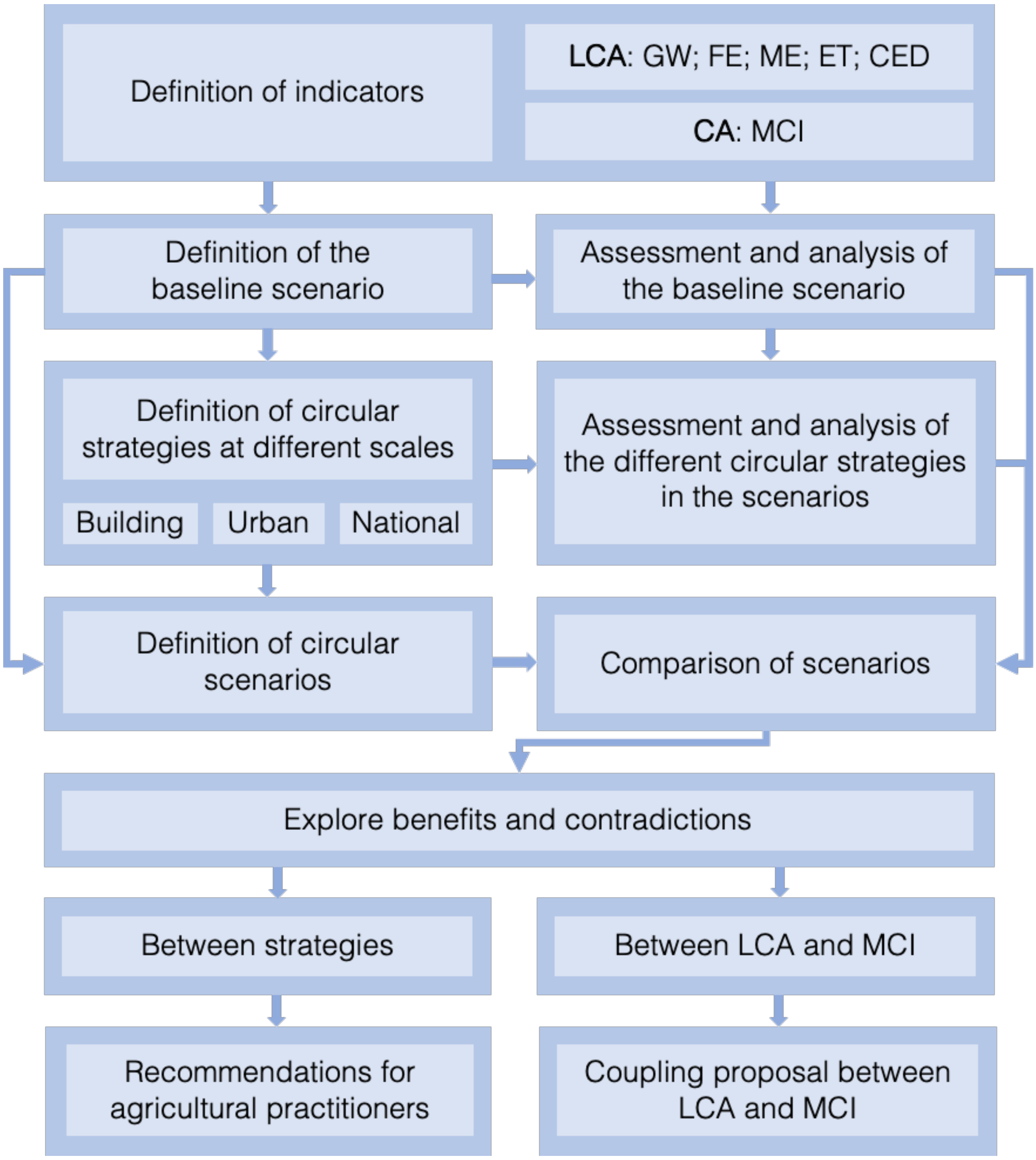


Figure 2.2 Methodological steps used to combine MCI and LCA

We monitored the pH (sensor G-PHT1 by XS instruments) and electrical conductivity (EC) (sensor G-CONDT5 by XS instruments) of the irrigation, leachates and rainwater on a daily basis to prevent anomalies. EC and pH values were analyzed in-depth in **Chapter 6** for the evaluation of cascade systems.

2.5.3 Water – Nutrient content

The nutrient content of the different water flows was measured using different equipment. Nitrogen content was analyzed through Ion Chromatography with a set-up to quantify anions. The device used was a ICS-2000 by Dionex coupled to an autosampler with 120 spaces for 1.5-mm vials. Using the Chromeleon software by Thermo-Fisher Scientific, we obtained readings for nitrite (NO_2^-) and nitrate (NO_3^-). P, K, Ca, Mg and S content was determined externally using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Optima 4300DV by PerkinElmer).

2.5.4 Biomass and substrate – Nutrient content

After being dried and shredded according to the type of sample (this process is described in every specific chapter), the nutrient content of biomass organs and substrate was externally determined using ICP-OES (Optima 4300DV by PerkinElmer) for P, K, Ca, Mg and S and using elemental analysis (Flash EA 2000 CHNS by Thermo-Fisher Scientific) for C, H, N and S.

2.6 Case Studies

Two main case studies were used in this dissertation. Considering a building scale, the ICTA-ICP rooftop greenhouse was used in **Chapters 3, 4, 5, 6, 7 and 9** as the system under analysis. Considering a regional scale, the metropolitan area of Barcelona (Àrea Metropolitana de Barcelona - AMB) was used in **Chapter 8** to study the regional implications of struvite recovery and reuse in urban regions. A summary of the case studies and their location within the region of Catalunya is displayed in Figure 2.3.

2.6.1 ICTA-ICP rooftop greenhouse

The ICTA-ICP building (41.497681N, 2.108834E) is located in the campus of the Universitat Autònoma de Barcelona (UAB), 15 km away from the city of Barcelona (Catalunya) and in the West Mediterranean region of the Iberian Peninsula. The building is used for research activities, hosting the Environmental Science and Technology Institute (ICTA) and the Catalan Paleontology Institute (ICP). The rooftop greenhouse (RTG) is located at the top of the building, with four areas that can be dedicated to growing crops. The RTG has a bioclimatic outer skin that regulates itself based on a combination of climatic parameters (temperature, radiation or CO_2 concentration, among others), allowing suitable conditions to grow crops throughout the year. Additionally, four big atriums contribute to a thermal inertia that accumulates heat in the rooftop, increasing its temperature by 9ºC on average (Nadal et al., 2017). Moreover, the RTG enhances resource optimization through the use of rainwater. A surface totaling 900 m^2 collects rainwater and store it in a 100 m^3 tank located underground. This

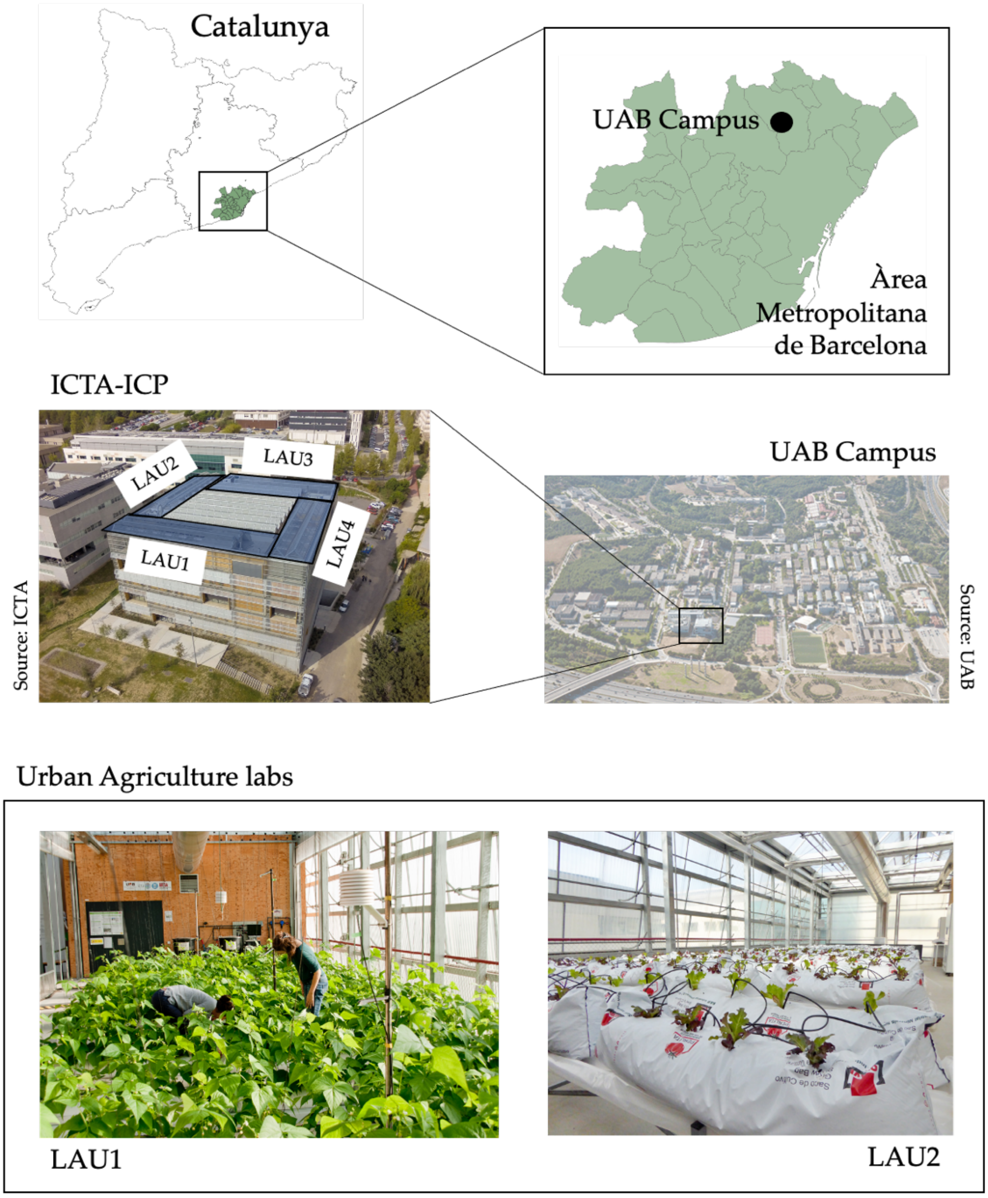


Figure 2.3. Scheme of the case studies used in this dissertation

rainwater is then used to irrigate the crops on the rooftop and the ornamental plants of the building.

In this dissertation, two areas (LAU-1 and LAU-2) out of the four available in the RTG were used in the different chapters, as shown in Table 2.4.

Table 2.4 Sections of the rooftop greenhouse used in this dissertation per chapter. SE: southeasterly; SO: southwesterly.

Section	LAU-1	LAU-2
Facing	Southeast	Southwest
Chapters	C3, C4, C5, C6, C9	C3, C6, C7
Growing Trays	Single	Double
Plant per bag	3	4
Plant density	2.0 plants/m^2	4.6 plants/m^2

The irrigation system used in all chapters was hydroponics, i.e. adding the fertilizers through the water flow. Most crop cycles used only rainwater supplied by the RWHS. Rainwater was stored in two 300-L tanks in the RTG. Using an automated irrigation system resulting from the combination of Hunter® programmers and electrovalves, rainwater was mixed with mineral fertilizers using a Dosatron® injection system calibrated at a 1:100 ratio. Finally, water was supplied to the plants through 2 L/h drippers. The substrate used in all chapters was perlite with a pH of 7, an EC of 0.09 $dS \cdot m^{-1}$ and a granulometry of [0-6], distributed in bags with a volume of 40 L and 1 m of length.

The choice of this system to analyze the application of circular strategies is based on the preexistent RWHS, which is a targeted element towards urban sustainability (Petit-Boix et al., 2017) and circular economy (Toboso-Chavero et al., 2018), as well as the hydroponic cultivation, which allows a precise control over the nutrient and water supply. Moreover, its modularity makes it easy to apply nutrient targeted strategies.

2.6.2 Àrea Metropolitana de Barcelona

The AMB is the administrative region around the city of Barcelona (Catalunya) that comprises 36 municipalities and a population of 5.4 million inhabitants. The AMB was used in **Chapter 8** to study the environmental implications of struvite recovery and reuse in a regional scale. For this purpose, we analyzed the two main wastewater treatment plants (WWTPs) in the region (Besós and Llobregat) and the total agricultural land of the AMB to estimate the yearly P demand. The choice of this area is based on two parameters. First, that is the same area that contains the RTG under study. Second, that it contains both urban WWTPs and a significant extension of agricultural area, which can synergize through the recovery and reuse of struvite.

Part 2

Environmental assessment of rooftop greenhouse production for a more sustainable urban agriculture

Chapter 3

Picture: Harvest of green pepper and arugula

Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture

Chapter 3. Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture

This chapter is based on the following journal paper:

Rufí-Salís, M; Petit-Boix, A; Villalba, G; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Parada, F.; Arcas, V; Muñoz-Liesa, J; & Gabarrell, X (2020). Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. *The International Journal of Life Cycle Assessment.* (doi: 10.1007/s11367-019-01724-5)

Abstract

Rooftop greenhouses (RTGs) are agricultural systems that can improve the food supply chain by producing vegetables in unused urban spaces. However, to date, environmental assessments of RTGs have only focused on specific crops, without considering the impacts resulting from seasonality, combinations of crops and non-operational time. We analyze vegetable production in a RTG over 4 years to determine the crop combinations that minimize yearly environmental impacts while diversifying food supply.

The system under study consists of an integrated RTG (i-RTG) with a hydroponic system in Barcelona, in the Mediterranean region. By using life cycle assessment (LCA), we evaluate the environmental performance of 25 different crop cycles and 7 species cultivated during the period 2015–2018. Three functional units are used: 1 kg of edible fresh production, 1 unit of economic value (€) in the wholesale market and 1 kcal of nutritional value. The system boundaries consider two subsystems: infrastructure (greenhouse structure, rainwater harvesting system and auxiliary equipment) and operation (fertilizers and their emissions into water and substrate). In addition, we perform an eco-efficiency analysis, considering the carbon footprint of the crop cycles and their value at the wholesale market during their harvesting periods.

Spring tomato cycles exerted the lowest impacts in all categories, considering all three functional units, due to the high yields obtained. In contrast, spinach and arugula had the highest impacts. Regarding relative impact, the greenhouse structure presented a large impact, while fertilizer production had notable relative contributions in tomato cycles. Moreover, nitrogen and phosphorus emissions from fertigation are the main causes of freshwater and marine eutrophication. By combining the most eco-efficient cycles, we can see that growing two consecutive tomato cycles is the best alternative with the functional unit of yield (0.49 kg CO_2eq./kg), whereas a long spring tomato cycle combined with bean and lettuce cycles in the autumn/winter is the best scenario when using market (0.70 kg CO_2 eq./€) and nutritional value ($3.18 \cdot 10^{-3}$ kg CO_2/ kcal).

Part 3

Closing water and nutrients cycles in urban agriculture through on-site recovery strategies

Chapter 4

Picture: Interior of an irrigation programmer

Exploring nutrient recovery from hydroponics in urban agriculture: an environmental assessment

Chapter 4. Exploring nutrient recovery from hydroponics in urban agriculture: an environmental assessment

This chapter is based on the following journal paper:

Rufí-Salís, M; Calvo, MJ; Petit-Boix, A; Villalba, G; & Gabarrell, X (2020). Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resources, Conservation & Recycling* (doi: 10.1016/j.resconrec.2020.104683)

Abstract

In light of global population growth and the increasing food demand in cities, new food production strategies have been developed to promote a more resource-efficient urban agriculture. Greenhouses with hydroponic systems have been proposed as sustainable systems for growing food in urban areas with a better control of plant growth. However, nutrient management in hydroponic agricultural systems is an environmental challenge and its efficiency could be improved from a circular economy standpoint. The goal of this study is to analyze the potential implementation of three nutrient recovery alternatives that promote re-use for urban hydroponics, i.e. direct leachate recirculation (DLR), chemical precipitation (CP) and membrane filtration (MF), and to study their environmental performance through life cycle assessment. The study focuses on the recovery of phosphorus (P), magnesium, potassium and calcium in a hydroponic tomato crop cycle carried out in an integrated rooftop greenhouse (i-RTG), located in the Metropolitan Area of Barcelona. The assessment shows that DLR was the most environmentally friendly option in terms of global warming (5.5 kg CO_2 eq. to recover 447 g of P) as opposed to CP and MF, which had 3 and 5 times more impact, respectively. Moreover, all three alternatives showed less eutrophication potential than the baseline scenario, which considered that 447 g of P were discharged into the environment. Meeting the crop's nutritional requirements through recovered nutrients helped save between 44–52% of global warming impacts with respect to new fertilizers when using DLR and MF. Oppositely, CP showed a 2% impact increase in global warming because this technology was only able to recover P and part of the magnesium. This study informs practitioners and decision-makers about the environmental benefits of applying circular thinking to nutrient management in urban agriculture to promote urban sustainability.

Keywords: Nutrient recovery, Urban agriculture, Industrial ecology, P-peak, Circular economy, LCA

Chapter 5

Picture: Headboard of a recirculation system

Recirculating water and nutrients in urban agriculture: an opportunity towards environmental sustainability and water use efficiency?

Chapter 5. Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency?

This chapter is based on the following journal paper:

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

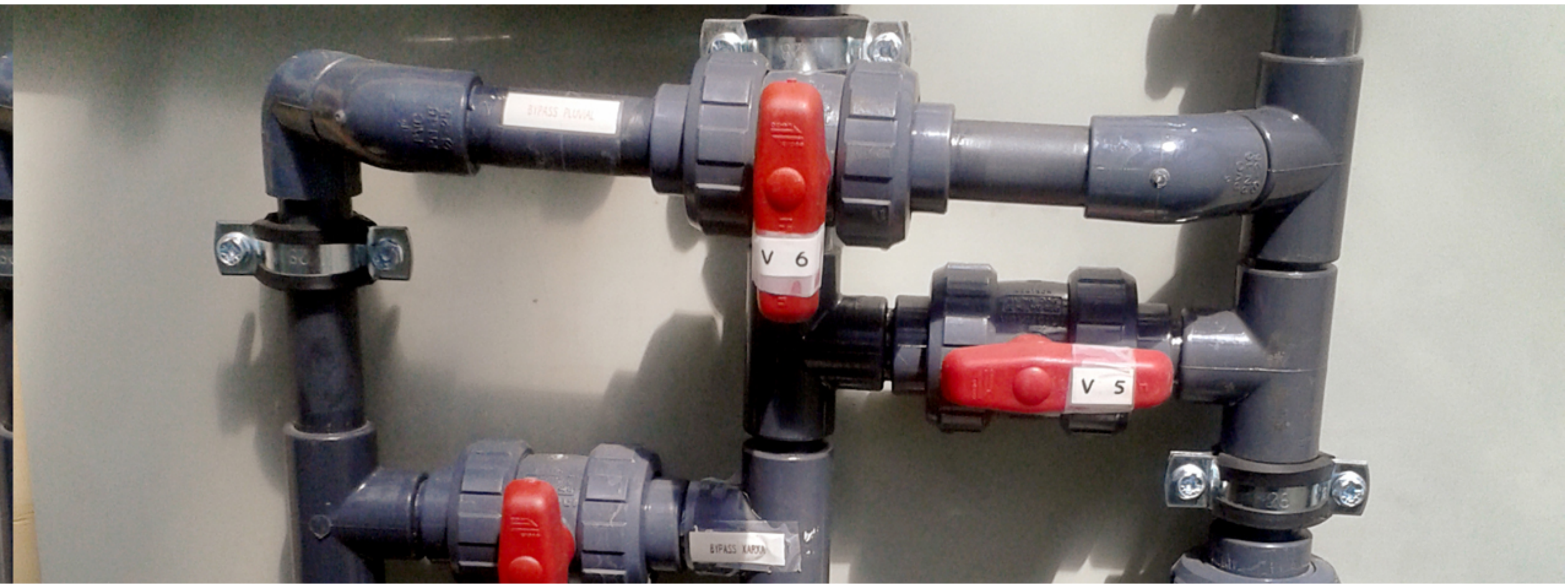
Abstract

Urban agricultural systems, such as rooftop greenhouses, are attractive alternatives for mitigating the impacts of the extensive food supply chains that currently feed cities. In this study, we study the opportunity that nutrient recirculation offers to improve the environmental performance of agricultural systems. In particular, we analyze the environmental burdens of a hydroponic closed-loop production system that recovers nutrients and reduces water demand by recirculating the irrigation water leaching from the substrate bags along with nutrients that have not been assimilated by the plant. The closed-loop system is compared to a linear system in which there is no nutrient or water recovery. Based on two green bean crop cycles in a Mediterranean rooftop greenhouse, we analyze the yield, climatic variables and water and nutrient balances, and apply life cycle assessment (LCA) to study the environmental impacts.

The results of this study indicate that closed-loop systems save daily 40% of irrigation water and between 35 and 54% of nutrients. Moreover, leachate reuse leads to reduced eutrophication impacts, but it can entail nutrient deficiencies. However, implementing a closed-loop system requires additional infrastructure causing larger impacts than linear systems in terms of global warming and fossil resource scarcity. The results of the LCA were highly sensitive to the yield, the crop production period and the meteorological conditions. Based on these results, we design improved scenarios, providing recommendations for reducing the impacts of closed-loop systems for more sustainable cities.

Keywords: Life cycle assessment, Closed-loop, Industrial ecology, Rooftop agriculture, Phaseolus vulgaris, Circular economy

Chapter 6



Picture: Pipes and valves

Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities

Chapter 6. Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities

This chapter is based on the following journal paper:

Rufí-Salís, M; Parada, F; Arcas-Pilz, V; Petit-Boix, A., Villalba, G & Gabarrell, X (2020). Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities. *Frontiers in Plant Science* (doi: 10.3389/fpls.2020.596550)

Abstract

Urban agriculture (UA) can significantly contribute towards mitigating the impacts of inefficient and complex food supply chains and increase urban food sovereignty. Moreover, improving these UA systems in terms of nutrient management can lead to a better environmental performance. Based on a rooftop greenhouse in the Barcelona region, we propose a cascade system where the leachates of a tomato cycle from January to July (donor crop) are used as the main irrigation source for five successive lettuce cycles (receiving crop). By determining the agronomic performance and the nutrient metabolism of the system, we aimed to define the potential of these systems to avoid nutrient depletion and mitigate eutrophication, while scaling the system in terms of nutrient supply between the donor and the receiving crops. The results showed that low yields (below 130g per lettuce plant) are obtained if a cascade system is used during the early stage of the donor crop, as the amount of nutrients in donor's leachates, specially nitrogen (N) (62.4 mg irrigated per plant in the first cycle), was not enough to feed the lettuce receiving crop. This effect was also observed in the nutrient content of the lettuce, which increased with every test until equaling the control (4.4% of N content) as the leachates got richer, although too high electrical conductivity values (near 3 dS/m) were reached at the end of the donor crop cycle. Findings on the uptake of the residual nutrient flows showed how the cascade system was able to take advantage of the nutrients to produce local lettuce while mitigating the effect of N and phosphorus (P) in the freshwater and marine environments. Considering our case study, we finally quantified the scale between the donor and receiving crops and proposed three major ideas to optimize the nutrient flows while maintaining the yield and quality of the vegetables produced in the receiving crop.

Keywords: Cascade systems, nutrient recycling, urban agriculture, industrial ecology, urban metabolism

Part 4

Tackling phosphorus scarcity through recovery and reuse of struvite in urban food production

Chapter 7

Picture: Treatment with 15 grams of struvite per plant

Recovered phosphorus for a more resilient urban agriculture: assessment of the fertilizer potential of struvite in hydroponics

Chapter 7. Recovered phosphorus for a more resilient urban agriculture: assessment of the fertilizer potential of struvite in hydroponics

This chapter had the following collaborators:

Rufi-Salís, M; Arcas-Pilz, V; Parada, F; Petit-Boix, A; Villalba, G; Gabarrell, X.

Abstract

Urban agriculture (UA) is a mean for cities to become more resilient in terms of food sovereignty while shortening the distance between production and consumption. However, UA still intensively depends on the use of fertilizers, which is problematic because of the depletion of non-renewable resources as is the case of phosphorus (P). With the aim to reduce such impacts associated to UA, this study assesses the feasibility of using struvite precipitated from an urban wastewater treatment plant as the unique source of P fertilizer. To do so, we apply various quantities of struvite (ranging from 1 to 20 g/plant) to the substrate of a hydroponic *Phaseolus vulgaris* crop and determine the yield, water flows and P balances. The results show that treatments with more than 5g of struvite per plant produced a higher yield (maximum of 181.41 g/plant) than the control (134.6 g/plant) with mineral fertilizer (KPO4H2). On the other hand, P concentration in all plant organs was always lower when using struvite compared to when using mineral fertilizer. Finally, the fact that different amounts of struvite remained undissolved in all treatments denotes the importance to balance between a correct P supply to the plant and a decrease of P lost through the leachates, based on the amount of struvite and the irrigated water. The findings of this study show that it is feasible for UA to use locally recovered nutrients to produce local food.

Keywords: Phosphorus, Struvite, Fertilizer substitution, Circular economy, Industrial ecology, Urban agriculture

7.1 Introduction

Meeting the food demand of the ever-growing urban population is a global challenge. Since food provision to cities is highly dependent on long and complex supply chains, the distance between production and consumption points has extensively increased. This prevents nutrient recycling, while emitting huge amounts of greenhouse gases (GHG) due to long-distance transport (Rees and Wackernagel, 1996; Thomaier et al., 2015). In this sense, moving towards more robust and resilient food systems should be a priority in the following years (European Commission, 2020b). To do so, alternatives that narrow the distance between production and consumption points have already been reported, being urban agriculture (UA) one of the most prominent (Deelstra, 1987). However, this implies that the resources required to produce food, mainly fertilizers and water, must now be imported to cities. In the case of water, the use of rainwater harvesting systems (RWHS) combined with hydroponics can help meet the irrigation requirements without compromising the yield (Astee and Kishnani, 2010; Martí Rufí-Salís et al., 2020b). Oppositely, the use of local fertilizers is still very limited, and often reduced to the use of compost (Thomaier et al., 2015).

The case of phosphorus (P) fertilizers is of great relevance, since P is primarily obtained from non-renewable phosphate rocks. Moreover, previous studies have quantified that 80% of the available stock of phosphate rocks is being used in the production of fertilizers (Shu et al., 2006). Since half of the world's current economic phosphate resources will have been used up by the end of the 21st century (Steen, 1998) the European Union recognizes P as a critical resource (European Comission, 2014). Among its recommendations, a planned amendment of the fertilizer regulation encourages P recovery from local sources by enforcing a shift towards a more circular use of nutrients (European Comission, 2016).

In this sense, urban wastewater treatment plants (WWTPs) are well-known sources of secondary P. WWTPs. have already been addressed as a potential alternative to importing mineral fertilizers (e.g. de-Bashan and Bashan, 2004; Kern et al., 2008; Shu et al., 2006). P can be recovered from wastewater in different forms, being magnesium ammonium phosphate (MAP with the formula $NH_4MgPO_4{\cdot}6H_2O$), commonly called struvite, one of the most prominent. Struvite precipitates in a molar ratio of magnesium (Mg^{2+}), ammonium (NH_4^+) and phosphate (PO_4^{3-}) of 1:1:1 and under suitable pH conditions (8.5-9.5) (Bouropoulos and Koutsoukos, 2000; J. R. Buchanan et al., 1994; Le Corre et al., 2009). Since precipitation of struvite in a WWTP was first documented in Los Angeles (Borgerding, 1972), this process has been gaining concern (Doyle et al., 2003), as the purging of uncontrolledly precipitated struvite can be the cause of additional expenses due to damaged equipment that need replacement or increased labour costs (Stratful et al., 2004). However, since the 90's, struvite forced precipitation has gained attraction as a possible way for P recovery (Doyle et al., 2003). At the same time, academia has focused on studying different recovery technologies and trying to improve the efficiency of the precipitation process (Le Corre et al., 2009; Li et al., 2019; Sena and Hicks, 2018).

In terms of application, the properties of struvite as an effective source of nutrients (P-PO_4^{3-}, N-NH_4^+ and Mg-Mg^{2+}) for plants (Li and Zhao, 2003) and its low solubility in water (0.018g·$100ml^{-1}$ at 25ºC) (Bridger et al., 1961) make it a slow-releasing valuable fertilizer that can reduce economic costs in agriculture (Rahman et al., 2014). However, only limited literature has explored the application of struvite in agricultural facilities. For example, Antonini et al. (2012), Uysal et al. (2014), Gell et al. (2011) and Liu et al. (2011) assessed the maize performance of struvites with different characteristics and origins in different soils. In a review made by Li et al. (2019) we can see that almost all struvite trials found that vegetables grown with struvite had the same -or even improved-performance compared to controls with conventional fertilizers.

Creating a closed-loop, waste-to-resource system such as that of struvite recovery within the city limits and not applying it at this scale seems contradictory within the concept of urban metabolism. In this sense, the synergy between struvite precipitation in urban WWTPs and UA seems worth exploring considering the potential of the latter to blurry the lines between waste and resource within urban areas (Ferreira et al., 2018; Smit and Nasr, 1992). This article aims to assess the potential of struvite precipitated in a WWTP as a fertilizer within the framework of urban metabolism. Based on experimental and analytical results performed on a *Phaseolus vulgaris* crop grown in a hydroponic rooftop greenhouse, we determine the implications of fertilization with struvite in terms of yield, water flows and P balances and provide recommendations to further improve the performance of this waste-to-resource fertilizer.

7.2 Methodology

This section describes the materials and methods used in our analysis. We first present the system under study (section 2.1) along with the fertilization and experimental set-up (section 2.2). The experimental and analytical assessment of the P balances is defined in section 2.3, whereas sections 2.4 and 2.5 present the validation test set-up and its most relevant results, respectively. Finally, section 2.6 presents the configuration of the determination test, which will finally provide the results for this study.

7.2.1 Characterization of the system

The present study was conducted in a rooftop greenhouse on the ICTA-ICP building, located in the campus of the Universitat Autònoma de Barcelona (UAB), 15km away from Barcelona. The building is equipped with a $900m^2$ rainwater harvesting system (RWHS) that stores water in a $100m^3$ tank. Most of this rainwater is used in the rooftop greenhouse ($122.8m^2$) to irrigate crops with a hydroponic system, i.e. mixing water with nutrients before providing the solution through a dripping system (2 L/h) to the perlite substrate bags (40L capacity). The perlite substrate has a pH of 7, an electrical conductivity of 0.09 $dS \cdot m^{-1}$, a granulometry of [0-6] mm and 4 plants can be planted in each bag.

7.2.2 Fertilization and experimental set-up

Struvite granules were obtained from Aarhusvand A/S company from Aarhus, Denmark. This company distributes fertiliser grade struvite under the name PhosphorCare™, recovered using the Phosphogreen™ technology. This technology is based on a fluidized bed reactor that creates the specific conditions to precipitate struvite through the addition of magnesium chloride, sodium hydroxide and air. The final struvite granules have a size range of 0.5-1.5 mm.

Common bean plant (*Phaseolus vulgaris* var. Pongo) was chosen as the crop for this study, planting nursery plants (approximately 10-14 days old). To apply the struvite to the plants, we considered different possibilities. Mixing it with the nutrient solution was discarded because the system could not benefit from the slow-release characteristics of struvite. Thus, we chose to directly apply the granules to the plant roots. Considering this option, we designed a system that consisted on mixing perlite with struvite inside a low-density polyethylene perforated bag with holes of no more than 1 mm diameter (see Appendix 5.1). At the same time, this system allows the interaction between struvite granules and roots and avoids the depletion of undissolved struvite into the leachates.

Two different experiments were carried out: the validation test and the determination test, both of them using double growing lines with 8 substrate bags each. For control treatments, the nutrient solution applied to the crops in milligrams per litre was KPO_4H_2 – 136, KNO_3 – 101, K_2SO_4 – 217.5, $Ca(NO_3)_2$ – 164, $CaCl_2 \cdot H_2O$ – 111, $Mg(NO_3)_2$ – 148.3, Hortilon – 10, and Sequestrene – 10. In treatments with struvite, the mineral P source, KPO_4H_2 in this case, was excluded from the initial nutrient solution. All other mineral fertilizers were maintained.

7.2.3 Phosphorus balances

To account for the P balances, Equation 7.1 was calculated on a plant basis for every control and struvite treatment. Appendix 5.1 shows a diagram of the perforated bag with the elements displayed in Equation 1.

$$P_{NS} + P_{SI} = P_{LV} + P_{ST} + P_{BN} + P_{SF} + P_{LIX} + P_{AC} \ (Equation\ 7.1)$$

In Equation 1, P represents mass of phosphorus. P_{NS} is the amount of mineral P supplied through the irrigation system during all the crop cycle. P_{SI} is the amount of P in the form of struvite applied at the beginning of the test. P_{LIX} is the amount of P in the leachates during all the crop cycle. P_{LV}, P_{ST}, and P_{BN}, represent P uptake by leaves, stem and beans, respectively. P_{SF} is the amount of remaining undissolved P in the form of struvite at the end of the test, plus the P adsorbed in the perlite granules. Finally, P_{AC} is the amount of dissolved P accumulated in the water retained in the substrate at the end of the crop. Three different biomass and substrate sampling dates were used in every test: 26, 54 and 78 days after planting (DAP) for the validation test and 23, 51 and 72 DAP for the determination test.

The initial nutrient concentration of the substrate was verified to be negligible at the beginning of the experiment through atomic spectroscopy and elemental analysis. Samples of the fertilizer solution were collected directly from the drippers placed in the perlite bags. Leachate samples were taken from plastic drainage buckets placed on one side of each line. To determine the P_{NS} and P_{LIX}, the respective samples were collected three times per week and externally analyzed using ICP-OES atomic spectroscopy (Optima 4300DV by Perkin-Elmer). P_{SI} was quantified summing the amount of perlite in a specific bag with the amount of struvite that was applied, considering weights obtained by drying two struvite samples and two perlite samples at 105°C in a furnace until reaching constant weight (reached after 3 days). P_{SF} was quantified differently in each test. In the validation test, all 4 samples for a specific treatment were homogenized after extracting the roots, using distilled water to separate the struvite granules from the roots. After this process, two random samples were dried at 105°C in a furnace until reaching constant weight and externally analyzed using ICP-OES atomic spectroscopy. On the other hand, in the determination test, roots were shredded, homogenized and integrated within every individual substrate sample. Then, a fraction of these samples was dried and analyzed using the same method as in the validation test.

P_{LV}, and P_{ST} were determined based on the nutrient content of every plant separately. Leaves and stem were separated, sorted into paper envelopes and dried in a furnace at 65°C until reaching constant weight (reached after 7 days) before analyzing externally the concentration of P through ICP-OES atomic spectroscopy. The same methodology was applied to determine the P_{BN}, with randomly chosen 500-gram bean samples being processed for every treatment. The P analytical results obtained for the beans were multiplied by the production obtained in every treatment to comply with the balances in a plant basis.

7.2.4 Validation test set-up and justification

From September 13th until December 3rd, 2018, 10 double growing lines were used (totalling 320 plants), distributing the treatments as showed in Appendix 5.2. The aim of this experiment was to validate and keep track of different parameters of the system. First, to check that the small, perforated bag did not have negative consequences to crop development. To do so, we split the control lines into two different treatments, VCB and VC0, using standard nutrient solution with and without the bags, respectively. Secondly, to check the correct development of bean plants with struvite in a hydroponic system, we applied different struvite amounts per plant: 5, 10, 15, 20 and 25g corresponding to the treatments tagged as V5, V10, V15, V20 and V25, respectively. Additionally, a treatment with no struvite was tagged as V0. These amounts of struvite were based on previous experiments done with the same crop species and variety in hydroponic cultivation that accounted for P uptake (Rufí-Salís et al., 2020c). One week after the first harvest, KPO_4H_2 was added in the nutrient solution of struvite treatments until the end of the harvest to ensure a good nutrition to the plants during the production period, which is highly demanding in P (e.g. Bender et al. 2015; Kouki et al. 2016; da Silva et al. 2019).

7.2.5 Validation test results

7.2.5.1 PRODUCTION AND PHENOLOGICAL STAGES

The production results for the control treatments VCB and VC0 showed that the perforated bag did not have any effect on the correct crop development and yield (Figure 7.1), as the yields from the different lines do not differ between them (VC0_2 187.54±69.35; VCB_1 186.15±84.01 g/plant). Even though treatment VC0_1 exerted more yield (224.84±91.84 g/plant), it could be attributed to the fact it was a line that had half of its plants facing the exterior border and thus received more radiation. Similarly, VCB_2 also exerted more yield (195.45±88.63 g/plant) than its replicate (VCB_1)

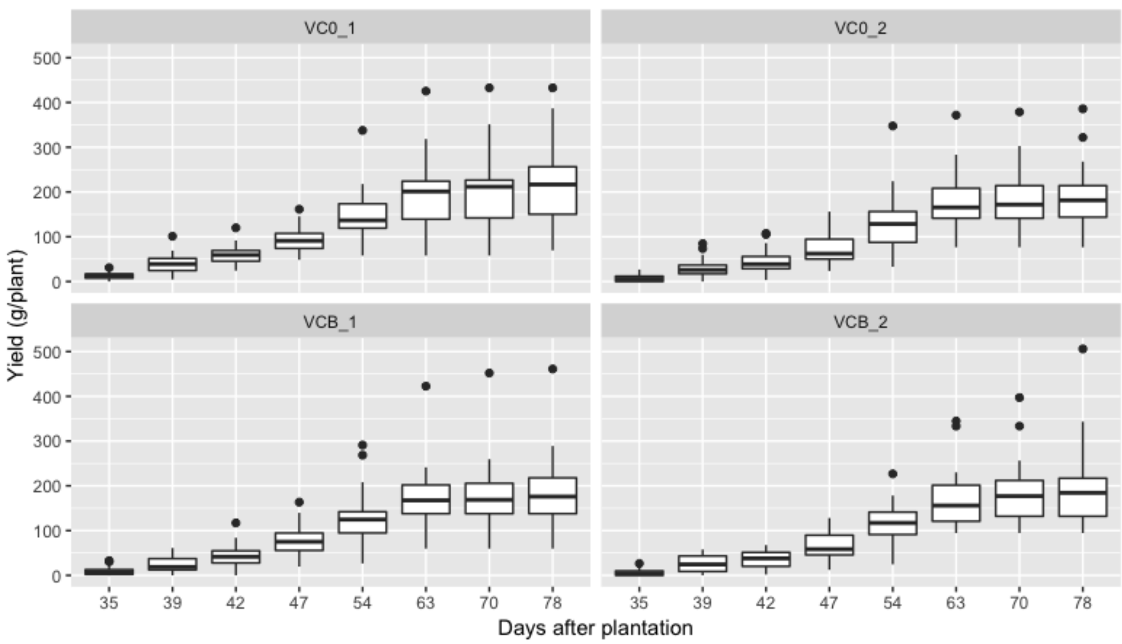


Figure 7.1 Production of the control treatments in the validation test, with (VCB) and without (VC0) perforated bags.

On the other hand, treatments with struvite (see Appendix 5.3) exerted a similar yield than the control treatments at the end of the crop. The treatment with the highest quantity of struvite (V25) had the highest production median (203.85 g/plant), while the treatment with the lowest quantity of struvite (V5) had the highest mean (216.15±93.54 g/plant). On the other hand, the treatment without struvite produced a really low yield (7.19±4.49 g/plant).

The similarities in terms of yield between all struvite treatments at the end of the cycle may be related to the additional mineral fertilization during the production phase. Moreover, we can see that struvite treatments produced more than the control in the first 3 harvests (35, 39 and 42 DAP). This effect is similarly observed for the phenological stages (see Appendix 5.4 to 5.8). For the parameters that were quantified in different dates (number of leaves (Appendix 5.4), side shoots (Appendix 5.5) and floral buttons (Appendix 5.7)), we can see that the treatments with struvite not only had a correct early stage development, but also seemed to develop plant organs earlier than in control treatments.

7.2.5.2 WATER

We applied more water in struvite treatments (125 L/plant) than to the control (94.76 L/plant) to ensure a proper dissolution of this fertilizer (see Appendix 5.9). However, we can see in Appendix 5.10 that if no control is taken over the water that is being irrigated, leachates emitted by the struvite treatments with higher concentrations (28.9 mg/L – V25) of this fertilizer tend to be similar to those of the control treatments. Obviously, this behaviour can only be observed before the irrigation with mineral P added during the harvesting process. Parallelly, we can see that the perforated bag mechanism did not affect the P concentration in the leachates between the control treatment C0 and CB.

7.2.5.3 PHOSPHORUS CONTENT

Appendix 5.11 shows the P content in the different plant organs. P concentration in the stem show low variability along all treatments, with VCB having the highest (7.61±0.38 mgP/g) and V10 the lowest (6.03±0.94 mgP/g) at the end of the crop cycle. The treatment without struvite (V0) was the only exception: when P was not supplied from any source, its concentration was the lowest in the stem (2.11±1.25 mgP/g - 26 DAP). However, when P was supplied through the fertigation, V0 plants concentrated the P in high concentration in the stem (18.35±2.96 mgP/g – 78 DAP). This effect was also observed in the beans, with a concentration of 25.56±1.79 mgP/g (54 DAP), which was much higher than the highest observed in the control for VCB (9.81±0.96 mgP/g –54 DAP) and struvite treatments for V15 (10.09±0.07 mgP/g - 54 DAP). V0 don’t show P results in leaves for 54 and 78 DAP because no leaves remained in the plant at the sampling time. This same reason is related to the lack of data in beans for 78 DAP. Finally, concentration in beans for struvite treatments was similar to the one observed in the control.

7.2.6 Determination test set-up

From September 16th until November 27th, 2019, 8 double growing lines were used (totalling 256 plants), distributing the treatments as showed in Apendix 5.12. The determination test was designed based on the results of the validation test. Thus, the struvite treatments were recalculated, applying per plant: 1, 2.5, 5, 7.5, 10, 15 and 20g corresponding to the treatments tagged as S1, S2.5, S5, S7.5, S10, S15 and S20, respectively. Struvite amounts below 5g were applied based on the yield and P content performance in the validation test for V5. Since we found that the perforated bag did not affect plant development, we only used one control treatment, tagged as CB, which used the same perforated bag as the struvite treatments. Moreover, considering the yield and phenological findings in the validation test, we decided not to apply mineral P fertilizer to the struvite treatments at any point, being struvite the only source of P to the plants.

7.3 Results

This section presents the results of the determination test. Section 3.2 shows the production of the control and struvite treatments. Section 3.2 presents the results in terms of amount and concentration of the water flows. Section 3.3 displays the findings related to the P amount in the substrate and the undissolved struvite. Finally, Section 3.4 zooms in and shows the P concentration in the different plant organs.

7.3.1 Yield

Appendix 5.13 shows the results of the accumulated yield per number of harvests, being the sixth harvest (71 DAP) the final one before uprooting the plants. Only treatments S1 (78.9 g/plant) and S2.5 (128.1 g/plant) had lower yields than the control treatment (134.6 g/plant). On the other hand, all other treatments with 5g of struvite or above produced more than the control treatment, demonstrating the potential of struvite to produce similar or even higher yields than with mineral fertilizer, as reported by Li et al. (2019).

As we can see in Figure 7.2, it was not until the second harvest (42 DAP) that great differences were observed between the S1 yield and the other treatments, while a decrease in S2.5 yield was observed between the 3rd and 4th harvest, 49 and 57 DAP, respectively. Regarding the control treatment, the first harvest produced lower yield (6.31±5.71 g/plant) than even the S1 struvite treatment (9.98±8.51 g/plant). This fact reinforces the idea that the application of struvite could be beneficial for early stage plant development, as the validation test showed better behaviour in struvite than in control in phenological variables. This fact could be related to the NH_4^+ supply by struvite, which could benefit the plant root balance when combined with nitrate supply

(Marschner, 1995). The fact that previous literature suggests that NH_4^+ supply to common bean could be harmful for plant development (Chaillou et al., 1986; Guo et al., 2007) could be related to the amount of NH_4^+ supplied. Because struvite does not only enable a slow release of P but also of NH_4^+, reaching NH_4^+ accumulation to harmful levels seems improbable.

In terms of distribution, yields show an asymptote behaviour among treatments, where S20 produces the highest yield (g/plant) (181.41±66.16) and S1, the lowest (78.94±34.23). Appendix 5.13 shows how treatment S10 was detected as the exception for this tendency in terms of mean production (150.50±56.10), probably related to bias parameters like shapes in the greenhouse or a non-homogenic distribution of struvite in the perlite bag. However, boxplots represented in Figure 7.2 shows how the median of the final amount of yield harvested for S10 (155.70) follows the tendency, while not presenting outliers in the distribution.

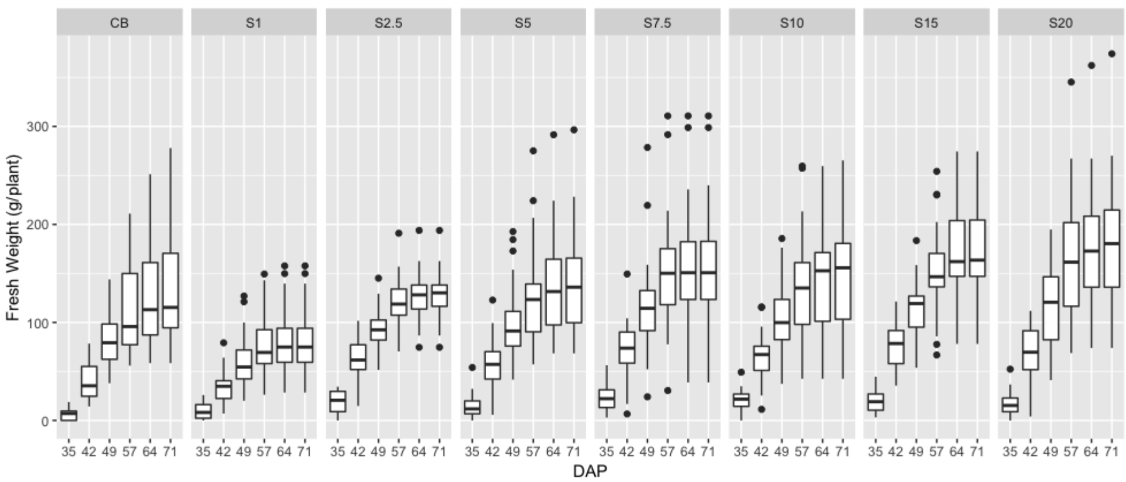


Figure 7.2 Distribution of accumulated production per plant per harvest of different treatments.

7.3.2 Water

Appendix 5.14 shows that the irrigated water in the control and the struvite treatments was the same (42.5 litres per plant), while Figure 7.3 shows the accumulated P during the entire cycle in the different water streams. The quantity of P present in the control streams is much bigger than the one in the struvite streams, with the former irrigating and leaching 2.07 and 1.41 g of P per plant for the entire crop cycle, respectively. The fact that the P leachates are one order of magnitude smaller when using struvite (maximum of 0.03 g of P per plant in S20) could be related to the slow-release characteristic of struvite reported in the literature. A clear benefit of this finding is a decrease in both P depletion and freshwater eutrophication related to the leachates flow. Moreover, if the leachates of struvite treatments do not contain a large amount of P, it means that most of the struvite has been whether taken up by the plant or remains undissolved in the substrate.

When comparing Appendix 5.11 and Appendix 5.15, we can see that P release by struvite is highly dependent on the input water flow, represented in Appendix 5.10 and Appendix 5.14 for the validation and determination test, respectively. Because the irrigated water was three times less in the determination test (125.2 against 42.5 litres per plant, respectively), the P observed in the leachates is less than in the validation test, considering the period where P was not supplied through mineral fertilizer in the validation test.

Differences are observed within the struvite treatments in Figure 7.3, highly dependent on the quantity of struvite that was applied at the beginning of the crop. Treatments S1 and S2.5 stopped emitting P in the leachates just 14 DAP, which could have triggered P deficiencies. On the other hand, treatments S15 and S20 were the only struvite treatments that did not stop emitting P to the leachates flow.

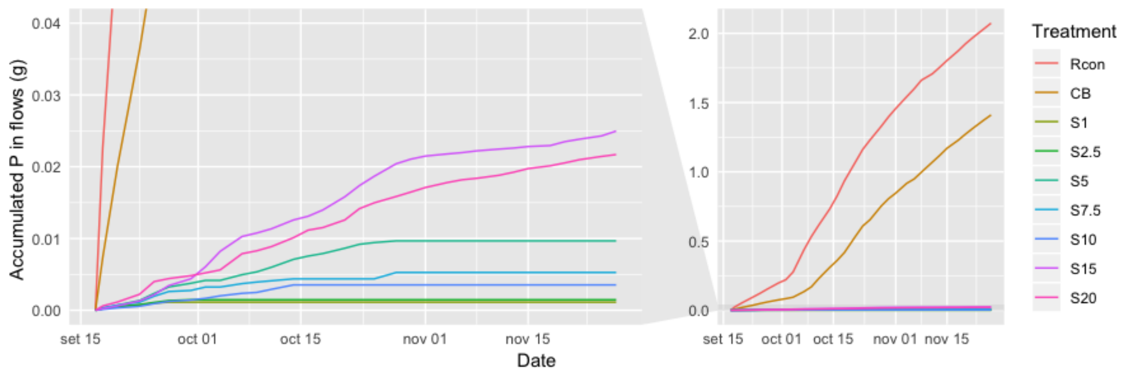


Figure 7.3 Distribution of accumulated phosphorus in the irrigation and leachates of different treatments. Rcon: P in the control irrigation stream

7.3.3 Substrate and undissolved struvite

Figure 7.4 shows the distribution of P among all possible input and outputs considered in the system. At the end of the crop, the control treatment supplied more P (2.07 g of P per plant) than the treatment with the highest amount of struvite (S20 - 1.90 g of P per plant). Most of the P supplied in the control treatments is discharged (68%), while in the struvite treatments still remains in the substrate. This amount of struvite at the end of the crop could be recovered, or the same substrate with struvite could be used for a successive crop.

7.3.4 Biomass

In terms of biomass, we can see that the concentration in percentage (see Appendix 5.16) in all organs increases with the quantity of struvite applied to the treatment, having S15 and S20 similar concentrations in the leaves (0.70±0.13 and 0.67±0.18, respectively) and stem (0.50±0.09 and 0.44±0.12, respectively). However, the control treatment with mineral fertilizer presented higher concentrations of P than all struvite treatments, also in beans (0.73±0.04). This is especially relevant in the case of beans, where the P deficiency in this organ directly affects the nutritional value of the product that is going to reach the market.

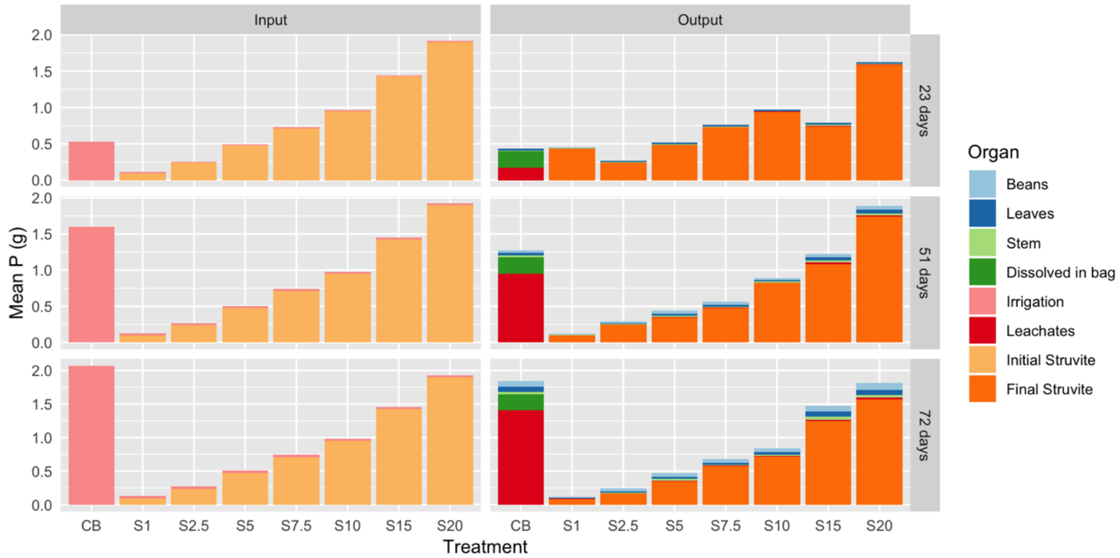


Figure 7.4 P distribution among all water, biomass and substrate flows and compartments

7.4 Discussion

Studying isolated parameters in agriculture only shows part of the big picture. In this sense, this section will discuss the results and tendencies that were found regarding the inputs and outputs for the control and struvite treatments and provide recommendations to practitioners based on our findings.

Treatments S1 and S2.5 had lower yields than the control treatments, establishing a clear relationship between the yield and possible P deficiencies in these treatments. However, an specific amount of struvite remained undissolved in all treatments, even though the production and the distribution of P among plant organs was different between treatments (see Appendix 5.15). The fact that we have undissolved struvite even in treatments S1 and S2.5 shows that the limitation is not only related to the quantity of struvite available, but also its dissolution.

Because the irrigated water was three times lower in the determination test, the P observed in the leachates is lower than in the validation test, considering the period where P was not supplied through mineral fertilizer. Moreover, there is a significant amount of P accumulated in the substrate bag at the end of the treatment in the control test. This stored P will be depleted if a successive crop is planted, since the small nursery plants will not benefit from it due to the difference in volume between their roots and the substrate bag, and therefore the water stream would move it to the leachates. By applying struvite (and verified by the small amount of P in the leachates in struvite treatments) this P is not stored and thus, not lost.

Based on the findings of this study, a well-designed struvite crop cycle needs to take into account two essential parameters. First, the quantity of struvite, considering that the quantity that remains undissolved at the end of the crop can be used again for a successive cycle. Second, the irrigation management, considering that if we modify this variable to increase the dissolution of struvite granules, we would also be increasing the P lost through the leachates. Moreover, since previous studies highlighted the effect of the surface area of the granules on the solubility of slow-release fertilizers (Chien and Menon, 1995; Gell et al., 2011; Li et al., 2019), the size used in our study (0.5-1.5mm) seems adequate for the balance between P supply and P lost through the leachates. Literature with higher sizes reported solubility problems that affected early plant development (Talboys et al., 2016), while studies using lower sizes or powder do not report these problems (Achat et al., 2014; Antonini et al., 2012; Bonvin et al., 2015; Gell et al., 2011). Additionally, the use of nursery plants is preferable since struvite cannot provide enough P to feed the transition from seeds to nursery plants (Talboys et al., 2016).

Struvite supply per plant should always be above 5g for *Phaseolus vulgaris*, considering that more quantity of struvite would release more P into the leachates, but ensure that P is available for plants. On the other hand, we should also account for the nutritional value of the beans, considering the ultimate function of producing yield. In this sense, P in the biomass was a variable where the control treatment had a better performance than struvite treatments. Only S15 and S20 reach a similar P amount to the control in all plant organs. For this reason, a quantity between 15 and 20g of struvite, a responsible irrigation management and growing successive crops with the same substrate constitute the best option to grow a well-designed struvite bean crop cycle.

7.5 Conclusions

On the way towards resilient cities, the recovery of scarce resources that can be utilised within the urban boundaries will play an important role, especially in the food vector. This study assessed the performance of the potential application of struvite recovered from WWTPs in hydroponic bean crops to diminish the need for external resources in urban agriculture. Three main conclusions could be drawn from this analysis.

First, applying struvite in hydroponics crops equals and even increases the yield compared to mineral fertilizer while diminishing P losses in the leachates, contributing to both less nutrient depletion and eutrophication potential. In this sense, a quantity above 5g/plant of struvite was observed to be enough for correct bean plant development.

Second, the input water flow was relevant in supplying enough P to the plants through dissolution using struvite. On the other hand, a correct water irrigation management is relevant to diminish P losses through overdissolution. Therefore, a balance between these two potential problems should be one of the key parameters when growing crops with struvite.

Third, a great quantity of struvite remains undissolved at the end of the crop in all treatments. In this sense, planting a successive cycle or recovering the struvite from the substrate could be alternatives to not losing this valuable fertilizer.

Based on the findings presented in this paper, we believe that future research should focus on three different aspects. First, the role of NH_4^+ supplied by struvite on plant development during the first production phase. Second, the performance of crops if successive cycles are grown using the same undissolved struvite in hydroponic systems. Third and finally, the modelling of P release by struvite based on quantity applied and input water flow.

Chapter 8

Picture: Section of the SHP file with agricultural areas

Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions

Chapter 8. Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions

This chapter is based on the following journal paper:

Rufí-Salís, M; Brunnhofer, N; Petit-Boix, A; Gabarrell, X; Guisasola, A & Villalba, G (2020). Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions. *Science of the Total Environment* (doi: 10.1016/j.scitotenv.2020.139783)

Abstract

Phosphorus (P) resources are decreasing at an alarming rate due to global fertilizer use and insufficient nutrient recovery strategies. Currently, more circular approaches are promoted, such as recovering P from wastewater in the form of struvite. This is especially attractive for urban areas, where there is a growing trend of local crop production and large volumes of wastewater are treated in centralized wastewater treatment plants (WWTPs). This research aims to assess the technical and environmental feasibility of applying a struvite recovery and reuse strategy to meet the P requirements to fertilize the agricultural fields of an urban region. To do so, we analyze the potential P recovery and the environmental impacts of integrating three recovery technologies (REM-NUT®, Ostara® and AirPrex®) in the two biggest WWTPs of the Àrea Metropolitana de Barcelona. The results show that all technologies are able to recover between 5 and 30 times the amount of P required to fertilize the agricultural area of the region annually (36.5 t). As can be expected, including P recovery technologies result in additional impacts per m3 of wastewater due to increased electricity consumption and chemicals required for the struvite precipitation. However, struvite recovery results in less eutrophication potential, especially in the REM-NUT® case, with an average reduction of 5.4 times. On the other hand, Ostara®, that recovers P from the digestate, had the lowest impacts (9 kgCO_2eq/kgP), even compared to the production of mineral fertilizer. When we apply our findings to the whole region, we can see that chemical use for struvite precipitation and energy consumption during the wastewater treatment process are the elements with the greatest impact. Thus, choosing the most appropriate technology in the most suitable WWTP is the most efficient strategy to diminish the environmental impacts of the system.

Keywords: Life cycle assessment, Phosphorus recovery, Urban agriculture, Nutrient recirculation, Fertilizer substitution, Circular economy

Part 5

Environmental and circular implications of applying multi-scale closed-loop strategies in urban agriculture

Chapter 9

Picture: Urban farmers working on rooftop agriculture

Combining LCA and circularity assessments in complex production systems: the case of urban agriculture

Chapter 9. Combining LCA and circularity assessments in complex production systems: the case of urban agriculture

This chapter had the following collaborators:

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Abstract

Local food production through urban agriculture (UA) is promoted as a means to make cities more sustainable. However, UA does not come free of environmental impacts. In this sense, optimizing urban resources through circular economy (CE) principles offers the opportunity to close loops and improve production systems, but an assessment of these systems through a combination of circularity and environmental tools is missing from the literature. The goal of our study is to analyse the environmental and circularity performance of applying circular strategies in UA systems. We use Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI) to assess the baseline scenario of a Mediterranean rooftop greenhouse and the application of 13 circular strategies. The results show that the MCI score for all strategies was biased by overweighting of the water subsystem in the mass balance. Based on this finding, we propose a series of modifications to the circularity assessment, calculating specific MCI scores for every subsystem before coupling them with environmental life cycle indicators. The outcome is a set of indicators that use the Linear Flow Index (LFI), where decreasing the values as much as possible will correspond to a decrease both in environmental impact and linearity of the system (the inverse of circularity). The use of these indicators provides a simple understanding of the circular and environmental performance of these systems while being fully adaptable. With these indicators, the uses of nutrient recirculation, struvite fertilizer or recycled materials were the best strategies to improve UA.

Keywords: Circular economy, Life Cycle Assessment, Industrial ecology, Urban agriculture, Urban metabolism, Circularity Indicators

9.1 Introduction

In recent years, the circular economy (CE) has become a popular topic on policy agendas as a promising, innovative avenue to enhance resource efficiency and economic prosperity (e.g., People's Republic of China 2008; The White House 2012; European Commission 2020). Given the high expectations for a circular future, research has been devoted to understanding the conceptual and practical implications of promoting circular strategies at different scales (from countries to products) through different principles (e.g., 3Rs, 9Rs) and in different sectors (e.g., Ghisellini et al. 2016; Kirchherr et al. 2017). Whether CE is a precondition to achieve sustainability goals or a source of potential trade-offs is still open to debate (Geissdoerfer et al., 2017). Indicators are thus needed to measure and trace the progress of circular strategies towards sustainable development. Examples of circularity indicators are abundant (e.g., Saidani et al. 2019b; Moraga et al. 2019), such as the Material Circularity Indicator (MCI) (EMF, 2015a), the longevity indicator (Franklin-Johnson et al., 2016), and the reuse potential (Park and Chertow, 2014). Nevertheless, there is a need to generate a monitoring framework that measures not only the degree of circularity of a system but also the extent to which circularity reduces environmental impacts and pressures (Helander et al., 2019).

A systems perspective can help shed light on the relationship between circular and environmental indicators. In particular, a life cycle approach enables a systematic evaluation of the environmental impacts and benefits resulting from the implementation of circular strategies in different life cycle stages of a product, system or service (Haupt and Zschokke, 2017; Niero and Kalbar, 2019; Pauliuk, 2018; Sauvé et al., 2016). In fact, increased circularity does not necessarily result in reduced environmental impact (Niero and Kalbar, 2019), which creates a conflict for decision-making when selecting suitable circular innovations and practices. When moving from theory to practice, this conflict becomes a challenge that demands more attention. Given the large number of circular strategies available and their potential effects on the environment, there is a need to prioritize the ones that promote circularity while minimizing environmental impacts and trade-offs. Testing monitoring frameworks in real case studies is thus paramount for adjusting the indicators to the inherent complexity of human activities.

Cities provide an excellent background for studying the environmental effects of circular strategies and identifying monitoring needs. Resources are produced worldwide to be consumed in cities. Global unidirectional flows end up in urban areas, generating a number of environmental impacts before reaching the point of consumption, such as nutrient depletion, environmental pollution and waste (Lin et al., 2014). Most of these phenomena are related to food, which is one of the biggest unidirectional flows to cities. Linear behaviour is a well-known feature of food systems (EMF et al., 2015); food is produced outside of the cities, sometimes even overseas, thus creating long and ineffective supply chains. Urban agriculture (UA), especially when using unused rooftop spaces, has raised as a promising partial alternative. UA produces food near the point of consumption, thus reducing food transportation impacts and developing local economies (Kortright and Wakefield, 2011; Specht et al., 2014). According to Taylor et al. (2012), the promotion of UA should be labelled as a top strategy towards sustainable global cities.

UA has been extensively studied from different perspectives, and a number of challenges related to resource use have been identified, which demands a holistic understanding of the full CE potential of UA. As reported by Deelstra and Girardet (2001), the process of waste management and nutrient recycling is inherent to urban metabolism, and UA could contribute to its improvement. Although previous literature states that the reuse of local resources for UA is limited to rainwater harvesting and composting (Thomaier et al., 2015), embedding UA in the urban context can help identify a larger variety of opportunities. For instance, resources required to grow food, such as fertilizers, are not usually available at a reasonable distance and are therefore imported. Their environmental impacts usually play a major role in the UA system (Boneta et al., 2019; Martí Rufí-Salís et al., 2020b; Sanjuan-Delmás et al., 2018). Additionally, nutrients are lost in production facilities and after consumption since recovery strategies are still very limited (M. Rufí-Salís et al., 2020; Sanjuan-Delmás et al., 2018). These deficiencies are contradictory to the potential of UA as an opportunity to use waste as a resource within city limits (Ferreira et al., 2018; Smit and Nasr, 1992) and move from a linear to a circular agriculture, a concept already defined in previous literature (e.g., Gangnibo et al. 2010; Cao et al. 2011; Trendov 2017; Fan et al. 2018). Some of these deficiencies may be a result of the relatively young analysis of real applications of circular strategies in terms of their environmental benefits. However, applying circular strategies to agricultural systems does not necessarily result in environmental benefits (e.g., Fan et al. 2018; Rufí-Salís et al. 2020b), which calls for monitoring tools that support prioritization.

Based on these challenges, our goal is to analyse the environmental and circularity performance of applying circular strategies in UA systems and to explore indicators that support decision-making and prioritization in the urban context. We tap into the full circular potential of UA as a waste-to-resource system in urban areas. To do so, we define a series of strategies based on the literature and analyse their feasibility, circularity and environmental performance in an actual UA facility. With this multi-perspective assessment, we develop recommendations on both the best way to analyse an urban system from a circularity and environmental perspective and the most efficient way to improve circularity in UA facilities through feasible practices without compromising environmental goals.

9.2 Methodology

This section describes the configuration of our analysis. We first present the circularity and environmental assessments (Section 9.2.1) and describe the baseline system that we use for the analysis (Section 9.2.2). We then define the goal and scope (Section 9.2.3), the inventory (Section 9.2.4) to perform the analysis of the baseline scenario and the indicators for the impact assessment (Section 9.2.5). Finally, Section 9.2.6 outlines and describes the strategies aimed at improving the indicator scores and the required adaptations to define 13 different scenarios.

9.2.1 Combined Circularity - Life Cycle Assessment

Since academics are still discussing the many definitions of the CE concept, Kirchherr et al. (2017) recommend that CE studies clearly indicate the definition used in the analysis. We have adopted the CE definition by Geissdoerfer et al. (2017): "*CE is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops*". For the purpose of this study, this definition mostly focuses on the environmental dimension of sustainability, leaving social and economic aspects out of scope.

The environmental impacts are analysed through life cycle assessment (LCA) (ISO, 2006). LCA is a widely used methodology to assess the environmental performance of products, services and systems and to compare different processes according to their environmental impacts by accounting for their entire life cycle.

Circularity assessments are yet to be standardized. Therefore, we used the most common approach found in the CE literature. Given its widespread application in theoretical and empirical analyses (Saidani et al., 2019b), we evaluated circularity through the Material Circularity Indicator (MCI) (EMF, 2015a), which was defined as an ambitious attempt to develop a product-level circularity metric (Linder et al., 2017). The MCI focuses on the restoration of material flows (EMF, 2015b) and is adaptable to materials, products and companies (Saidani et al., 2019a), thus being classified as a micro-scale indicator (Saidani et al., 2019b). Unlike the majority of circularity metrics, the MCI is applied across life cycle phases (Helander et al., 2019), making it complementary to LCA (EMF, 2015b). Moreover, the Bill of Materials (BoM) required for MCI can be easily structured in the form of a life cycle inventory (LCI) given their similar data requirements (Valencia, 2017).

MCI has a range of values of 0 (100% linear) to 1 (100% circular). The final step for calculating the MCI is based on the Linear Flow Index (LFI), which has an opposite range from the MCI, with values from 0 (100% circular) to 1 (100% linear). After calculating the LFI, the value is multiplied by a Utility factor, which accounts for the lifespan or the amount of times that the product will be used. A complete calculation requires 27 sub-parameters (EMF, 2015b), but the most relevant ones can be classified between inputs and outputs. For inputs, flows are classified between virgin feedstock and other origins, and for outputs, flows are divided between unrecoverable waste and other possible end-of-life scenarios, such as reuse, recycling or energy valorisation.

Similar to other indicators, the MCI only focuses on environmental aspects of CE (Walker et al., 2018), fitting in our scope and chosen definition of CE. Because we are using both LCA and MCI in the same analysis, we adapted the methodological steps suggested by ISO (2006) for LCA (goal and scope, inventory and impact assessment) to the application of MCI. We showed these adjustments through a UA case study.

9.2.2 Definition of the baseline scenario – The rooftop greenhouse

A complete system definition is vital for indicator development (Pauliuk, 2018). To analyse the performance of circular strategies with real data, we used a rooftop greenhouse (RTG) as the UA case study. RTGs are greenhouses located on buildings that usually benefit from building integration at several levels (Muñoz-Liesa et al., 2020; Pons et al., 2015). This 122.8 m^2 RTG is located on the top floor of the Institute of Environmental Science and Technology (ICTA-ICP) on the campus of the Universitat Autònoma de Barcelona (41.497681N, 2.108834E) in the Mediterranean region and the north-eastern part of the Iberian Peninsula. The system already has two elements that make it suitable for the purpose of this study. First, the building includes a rainwater harvesting system (RWHS), a targeted element towards urban sustainability (Petit-Boix et al., 2017) and CE (Toboso-Chavero et al., 2018). Second, the irrigation system is hydroponic, i.e. soilless growing media plus nutrient delivery through water. Hydroponics enable a fully controllable nutrient and water supply (Christie, 2014). This type of irrigation system is modular, allowing control of the water flows and application of different water-targeted strategies.

For more information, see previous literature on the same system (Manríquez-Altamirano et al., 2020; Nadal et al., 2017; Martí Rufí-Salís et al., 2020b; Sanjuan-Delmás et al., 2018). Here, we studied a tomato crop grown from January 12th to July 18th, 2017 with a yield of 1084 total kg / 12.3 $kg \cdot m^{-2}$ / 6.3 $kg \cdot plant^{-1}$.

9.2.3 Goal and scope definition

The analysis considered all processes from extraction of raw materials to the end of life of all elements in the greenhouse. The system was divided into two main subsystems, infrastructure and operation, based on the lifespan of the materials, which was higher or lower than 5 years, respectively. A cut-off criterion for recycling was used, where the impacts of a recycling process were allocated to the product that benefits from it. The functional unit (FU) selected was the production of 1 kg of tomatoes in the RTG. However, since the MCI generated a value within a specific range and no units, doing the MCI analysis without a FU would not affect the final outcome as long as the function of the system is maintained. Since the MCI was designed to be applied at the product-level, we considered that all inputs and outputs in the greenhouse system had the ultimate function of producing a product (tomatoes in this case).

9.2.4 Life Cycle Inventory and Bill of Materials

Given their similar data requirements, the LCI for the LCA and the BoM for the MCI could be easily integrated in this step with specific assumptions for some elements.

The infrastructure subsystem included the production, transportation, installation, use, and waste management of the RTG, the RWHS, and the auxiliary equipment (AE). Data from previous literature on materials, transport and lifespan assumptions were used for the RTG structure (Sanyé-Mengual et al., 2015b) and the RWHS (Sanjuan-Delmás et al., 2018).

The operation subsystem for tomato production included the use of substrate bags, energy, fertilizers, pesticides and water. Wastewater was assumed to be directly discharged to the environment because the local wastewater treatment plant does not include nutrient removal processes. Direct emissions to air (NH_3, NO_x and N_2O) were calculated according to standard emission factors (IPCC, 2019). Direct emissions to water were quantified using ion chromatography for nitrate (NO_3^-) (ICS-2000 by Dionex) and atomic spectroscopy for phosphorus (P) (Optima 4300DV by Perkin-Elmer), which was then transformed to phosphate (PO_4^{3-}).

Allocation was applied to estimate the share of impacts of infrastructure and substrate bags by considering their use in the crop in relation to its lifespan. Similarly, the share of impacts of the RWHS allocated to the crop was based on the quantity of water used with respect to other uses in the building (Rufí-Salís et al., 2020b; Sanjuan-Delmás et al., 2018).

The waste management stage of the infrastructure included the landfilling of the RTG structure, the RWHS and the AE. The waste management of the operation included the transport and landfilling of the perlite bags after 3 years of use. Biomass gathered at the end of the crop was assumed to be landfilled. All recycled elements were transported to the nearest facility (6.8 km), whereas all discarded elements were transported to the nearest landfill (2.7 km).

Additional adjustments and assumptions were needed at this stage to ensure compatibility between the LCA and MCI. These adjustments were needed to comply with MCI mass balances since some elements in the inventory were usually omitted in the LCA calculations if no impact was generated in the impact categories under analysis. For example, direct emissions to water with no eutrophication impacts should be included in the BoM to comply with the mass balances of the fertilizers, and they are considered unrecoverable waste. In this sense, discharge of potassium (K^+), sulphate (SO_4^{2-}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) was calculated using leachates data from previous literature (Sanjuan-Delmás et al., 2020), whereas we assumed all chloride (Cl^-) applied was discharged. The aquatic part of the leachates (i.e. only the water), which does not have any impact in most of the LCA impact categories, should be quantified for the MCI calculations to ensure that the water balance of the system is closed. Since this water is lost, we assumed it to be unrecoverable waste. Tap water was considered virgin feedstock as opposed to rainwater, which was assumed to come from a "recycling" source.

Carbon (C) used by plants for photosynthesis was included in the calculations to comply with the material balances and was labelled input from a "recycled" source as it was considered a renewable source. It was quantified externally by elemental analysis (6890 by Agilent Technologies and 5973 by HP) of all plant organs.

Since the FU is related to the production of tomatoes, its consumption was out of the scope of the system analysis. Therefore, our approach for tomatoes was to quantify them as an element that would be reused because it is going to be consumed in a short period of time. In other words, the consumption of tomatoes by another system (humans, in this case) implies a reuse allocated to the production system. Although this labelling is not fully comprehensive for this element, it is required to fit the MCI terminology. To understand it better, one could argue that tomatoes would be labelled unrecoverable waste if food losses were 100%.

9.2.5 Impact Assessment

The software used to perform the life cycle impact assessment was Simapro 9.0 by PRé Consultants, and we applied the ReCiPe 2016 v1.1 Midpoint (H) method (Huijbregts et al., 2016). We conducted the mandatory classification and characterization steps. The following impact categories were selected: (1) global warming (GW – kg CO_2 eq), (3) freshwater eutrophication (FE – kg P eq), marine eutrophication (ME – kg N eq) and ecotoxicity (ET – kg 1,4-DB eq), which is the sum of freshwater, marine and terrestrial ecotoxicity impact categories. Additionally, the single-issue impact category (5) cumulative energy demand (CED - MJ) was included in the analysis.

In the MCI, the utility factor of the product was omitted from the calculations since we accounted for the lifespan allocation considering the length of the crop under analysis. Moreover, the terms E_C and E_F, corresponding to the efficiencies of the recycling process of the products and the recycling process used to produce the recycled feedstock, were set to the upper limit (100%) due to lack of data. Gathering these data for a system analysis may entail a complex and long process due to the quantity of materials and elements in the analysis compared to a product-level analysis.

9.2.6 Strategies and Scenarios

After assessing the baseline scenario with LCA and MCI, we defined a set of strategies aimed at evaluating the effects of CE implementation in the system based on the CE definition chosen for this study. A scale classification was used, sorting the strategies between building, urban or national scales (see Figure 9.1).

In the following sections, we described the scenarios defined in each strategy and their target, scale, aim and implications. In parallel, Appendix 7.1 shows the literature used to support the application of these strategies. To make the results comparable with other UA facilities, we only included strategies that could be implemented in most crop configurations (e.g., open-air or ground level) and elsewhere in the world, but one should first explore if the synergies between UA and other systems are plausible at the defined scales. For example, the use of locally recovered struvite is only feasible in large urban wastewater treatment plants (WWTPs) within the urban areas under study. Moreover, strategies with a high degree of associated uncertainty were left out of the analysis. As an example, one could argue that minimizing the space between growing lines could increase production, and therefore, diminish the environmental impacts per FU. However, this outcome would be uncertain since the radiation received per plant would be altered. Another example of a strategy left out of the analysis is the use of greywater to irrigate the crops, since it would require new infrastructure for which we lack data. Each strategy was then transformed into a scenario by considering the modification of the baseline LCI of our case study, obtaining different MCI and LCA values. The scores of these indicators showed the degree of improvement/worsening of a specific strategy in terms of circularity or environmental performance. While defining the scenarios, we also discussed their feasibility from both a technical and a practical perspective (considering the geographical specificities).

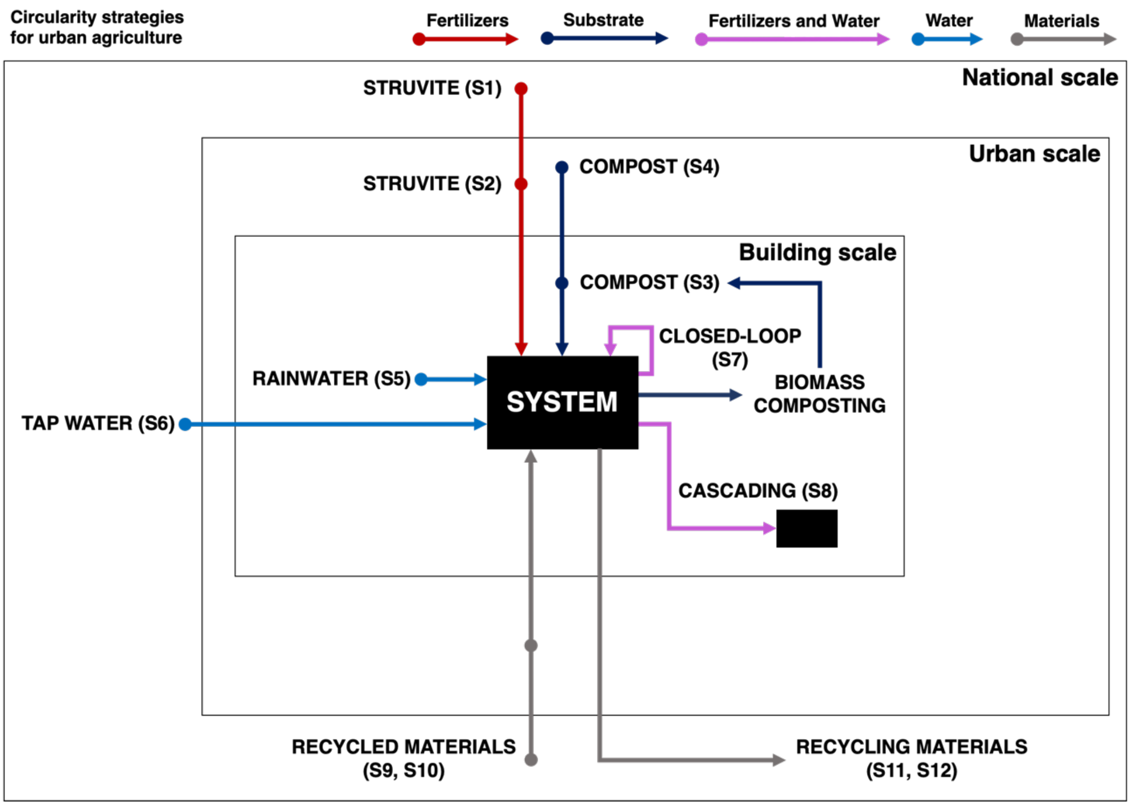


Figure 9.1 Circular scenarios under assessment

9.2.6.1 STRUVITE (S1 AND S2)

Struvite ($NH_4MgPO_4 * 6H_2O$) is a promising new fertilizer that is recovered in WWTPs through a broad range of chemical precipitation processes. Since P has been catalogued as a scarce resource (European Comission, 2014), the use of struvite is seen as a potential alternative to traditional fertilizers manufactured from phosphate rocks (Latifian et al., 2012; Li et al., 2019). There are different recovery technologies that precipitate struvite in a WWTP. In this study, we considered the use of Ostara® technology by Ostara (2019), which recovers struvite from the digestate (aqueous phase obtained in the anaerobic digester of sludge). This strategy is only plausible if the WWTP has an enhanced biological phosphorus removal (EBPR) that extracts the P from the wastewater stream and concentrates it in the sludge line.

Two different scenarios were defined according to different scales. First, contemplating the urban scale (S1), we considered that the struvite is obtained from WWTP located in el Prat de Llobregat, in the south of Barcelona, 38 km away from the UA system under study. Since this WWTP already has nutrient removal modules, we only considered the impacts triggered by the struvite precipitation process (chemicals and electricity use), as given my Amann et al. (2018). Second, contemplating the national scale (S2), we considered that the struvite is obtained from a WWTP in Madrid, 607 km away from the RTG. In both strategies, we assumed that the crop's P demand is fully covered through struvite. Thus, no mineral P was required as opposed to the baseline scenario where all the P was provided through potassium phosphate. Moreover, we considered that the P leachates are diminished 10 times compared to when mineral phosphorus is applied, according to the findings outlined in **Chapter 7**.

9.2.6.2 COMPOST (S3 AND S4)

Compost was used as a substrate substitute for perlite. Two different scenarios were defined according to different scales. First, contemplating the building scale (S3), we considered that the compost was primarily made from the biomass generated in a previous tomato crop with the same characteristics (260 kg of residual biomass). Since the C/N relationship in tomato biomass was approximately 10:1 (Sanjuan-Delmás et al., 2020), we assumed the addition of 100 kg of wood chips with 25% moisture content, 37.5% C content (Forest Research, 2020) and a 100:1 C/N ratio (Dickson et al., 1991) to increase aeration (Rynk et al., 1992) and reach a final C/N of 25:1, which was within the optimal range for first-stage compost (Finck, 1988). The composting process was assumed to start when the pile reached 55% humidity (Román et al., 2013). Considering that the composting process would be completed at approximately 35% humidity and a density of 650 kg/m^3 (Román et al., 2013), we could obtain approximately 205 kg of compost, which would fill only 8 40L-HDPE bags, 5% of the total used in the system. To solve this issue, we mixed the obtained compost with perlite homogeneously in all bags. Second, contemplating the urban scale (S4), we considered that the compost was made from organic municipal solid waste. We assumed that no limitation existed in the amount of compost that the system could obtain, and all substrate bags were filled with compost without the need to use perlite. The same compost parameters considered in S3 were used in S4. In both strategies, we omitted the possible extra fertilization that could be provided by compost to simplify the effects of this strategy in the substrate subsystem.

9.2.6.3 WATER SUPPLY (S5 AND S6)

Two different scenarios were defined for the water supply according to different sources. First, we considered only the use of rainwater (S5). To do so, the tomato crop was prioritized among other crops and ornamental plants. Since the impact of the RWHS was calculated on an allocation based on water supply, the impacts of this item were expected to increase. Second, we considered only the use of tap water (S6). To do so, we considered that the system did not benefit from water captured by the RWHS. Thus, the impacts and materials of this item were no longer included in the inventory of the tomato crop for this scenario. Since the crop was already benefitting from 89% of rainwater out of total water input in the baseline scenario, S5 would increase this percentage to 100%, whereas S6 would bring it down to 0%.

9.2.6.4 ON-SITE NUTRIENT REUSE (S7 AND S8)

Based on the findings from **Chapters 4 and 5**, we considered two direct leachate recirculation scenarios at the building scale. First, a closed-loop irrigation system (S7) reintroduces the leached water and nutrients back into the same system after simple filtration and disinfection treatment. Although this strategy implies both nutrients and water savings, new infrastructure is required and is entirely allocated to the tomato crop. Second, a cascading (S8) system considers that the leached water and nutrients are used in a parallel crop with less nutritional requirements. To do so, new infrastructure is also required. However, in contrast to S7, the materials required for this infrastructure are entirely allocated to the crop benefitting from the leached nutrients based on a cut-off criterion. Moreover, since we were not introducing the leachates back into the tomato crop, the water and fertilizer input were the same as in the baseline scenario.

9.2.6.5 USE OF RECYCLED MATERIALS (S9 AND S10)

Two different scenarios were defined for the use of recycled materials according to different data. First, contemplating the national scale, we assumed that all the input material used to manufacture the infrastructure items came from recycled sources (S9). Second, contemplating the national scale, part of the input material used to manufacture the infrastructure items came from recycled sources according to actual rates of recycled materials usage (S10) (see references in Appendix 7.1).

9.2.6.6 MATERIAL RECYCLING (S11 AND S12)

Two different scenarios were defined according to different approaches and scales for the end-of-life of materials used in the system. First, contemplating the national scale, we considered the maximum recycling efficiency of all materials (S11). Second, contemplating the national scale, we considered the actual recycling rates based on publicly reported data for every material (S12) (see references in Appendix 7.1).

9.2.6.7 COMBINED SCENARIO (S13)

In addition, we considered a combined scenario (S13) that aggregated the majority of the circular strategies described in the previous sections. First, all materials came from recycled sources (S9) and were recycled at the end of their service life (S11). In addition, all the water consumed by the system was supplied by the RWHS (S5), and a closed-loop system was installed (S7). Compost supplied by the urban waste management network replaced perlite as the substrate (S4), and local struvite was used as the source of P in the fertilizers (S1).

9.3 Results and Discussion

This section presents the results of our analysis and discusses the main findings. We first present the environmental and circularity results of the baseline scenario (Section 9.3.1) and the improvement scenarios (Section 9.3.2). Finally, Section 9.3.3 presents a series of proposals for a more suitable analysis of circularity in agricultural systems, combining the circularity indicator with environmental indicators.

9.3.1 Assessment of the baseline scenario

Table 9.1 shows the scores of the indicators for the baseline scenario. A detailed inventory and the complete results of the calculations can be found in Appendix 7.2. As reported in previous literature, fertilization is the main source of impacts in agricultural systems in most impact categories (Boneta et al., 2019; Muñoz et al., 2008; Romero-Gámez et al., 2014, 2012; Rufí-Salís et al., 2020b, 2020c; Sanjuan-Delmás et al., 2018; Torrellas et al., 2012). This situation is especially the case in eutrophication, where the N and P emissions contribute to 72 and 93% of impact in freshwater and marine eutrophication, respectively. Apart from the fertilizers, the greenhouse structure exerts significant impacts on global warming (1.6 kg CO_2 eq/kg) and ecotoxicity (0.6 kg 1,4-DB eq/kg), whereas the RWHS and energy exert high relative impacts in cumulative energy demand (1.2 and 1.4 MJ/kg).

For the circularity assessment, the fact that the MCI (nor any other circularity indicator) has not yet been applied to agricultural systems makes it difficult to put its score (0.46 out of 1) in context. However, the final score of the MCI is highly influenced by the water used since it is the biggest mass flow in the system (Columns V and W – Table 9.1). Since the MCI is based on a mass balance, it makes sense that the score is highly influenced by the mass distribution among all subsystems under analysis. This limitation is also reported for economy-wide material flow analysis (MFA) where water and air flows are often one order of magnitude above other flows and are left out of the material analysis (Eurostat, 2001). In our system and for the purpose of our study, this bias generated by the water can also be considered a limitation of the indicator and will be further discussed when applying the strategies in the next section.

Table 9.1 Indicator results for the baseline scenario. Subsys: Subsystem; GW: Global Warming (kg CO_2 eq); FE: Freshwater Eutrophication (kg P eq); ME: Marine Eutrophication (kg N eq); ET: Ecotoxicity (kg 1,4-DB eq); CED: Cumulative Energy Demand (MJ); V: Virgin Feedstock (kg); W: Unrecoverable Waste (kg); LFI: Linear Flow Index; MCI: Material Circularity Indicator; AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System.

		LCA					MCI			
Subsys	Item	GW	FE	ME	ET	CED	V	W	LFI	MCI
-	Total	5.3E-01	5.3E-04	3.7E-04	1.9E+00	7.7E+00	7.1E+03	60595	0.54	0.46
Operation	Substrate	3.7E-02	1.0E-05	7.4E-07	8.7E-02	4.8E-01	3.6E+01	35.8	-	-
	Fertilizers	1.6E-01	3.8E-04	3.4E-04	8.1E-01	1.3E+00	9.3E+01	60.0	-	-
	Pesticides	2.1E-04	1.3E-07	6.6E-08	8.6E-04	3.8E-03	3.1E-02	0.0	-	-
	Energy	5.2E-02	2.4E-05	2.0E-06	1.4E-01	1.4E+00	-	-	-	-
	Nursery	4.9E-04	1.0E-07	5.8E-09	2.2E-03	8.5E-03	0.0E+00	0.0	-	-
	Water	1.7E-06	1.3E-09	1.0E-10	4.5E-06	3.5E-05	6.9E+03	60391	-	-
Infrastructure	Structure	1.6E-01	7.1E-05	8.2E-06	5.6E-01	2.3E+00	8.6E+01	85.7	-	-
	AE	5.5E-02	2.1E-05	3.0E-06	1.6E-01	9.4E-01	5.7E+00	5.7	-	-
	RWHS	6.2E-02	2.2E-05	1.0E-05	1.5E-01	1.2E+00	1.7E+01	17.5	-	-

9.3.2 Assessment of the improvement scenarios and interpretation

Figure 9.2 shows the impact contribution in the analysed impact categories and the MCI scores for all circular strategies and for the baseline (BS) scenario. As expected, avoiding leachates disposal through nutrient recirculation in S7 and S8 produces large impact reductions in freshwater and marine eutrophication. Moreover, the application of P through slow release struvite (S1 and S2) also shows similar improvements in freshwater eutrophication, where units are related to P equivalents. The combined scenario (S13) shows the best performance in both freshwater and marine eutrophication, since it also takes the S9 strategy to use recycled materials. The use of recycled instead of virgin steel has less eutrophication potential, especially in freshwater, which is why the total use of recycled materials (S9) was the strategy with the least freshwater eutrophication impact apart from the ones using struvite or recirculation systems. In terms of global warming, the scenario that uses compost from the urban network (S4) is the one with the largest impact. Despite the fact that perlite has more global warming impact per kg than compost, the large amount needed to fill all substrate bags makes urban compost a less promising strategy in global warming than mixing perlite and compost obtained from crop biomass (S3). Because S13 uses the S4 approach, it exerted more impact than S9, which was the scenario with the lowest carbon footprint. A similar behaviour is observed in ecotoxicity and cumulative energy demand, but in this case the combined scenario (S13) has better environmental performance than S9 due to higher ecotoxicity potential and energy requirements for perlite production compared to compost. Moreover, applying nutrient recirculation in the same crop (S7), which shows great savings in eutrophication, exerts the largest impact on cumulative energy demand due to the amount of materials required under the assumption that they all come from virgin sources.

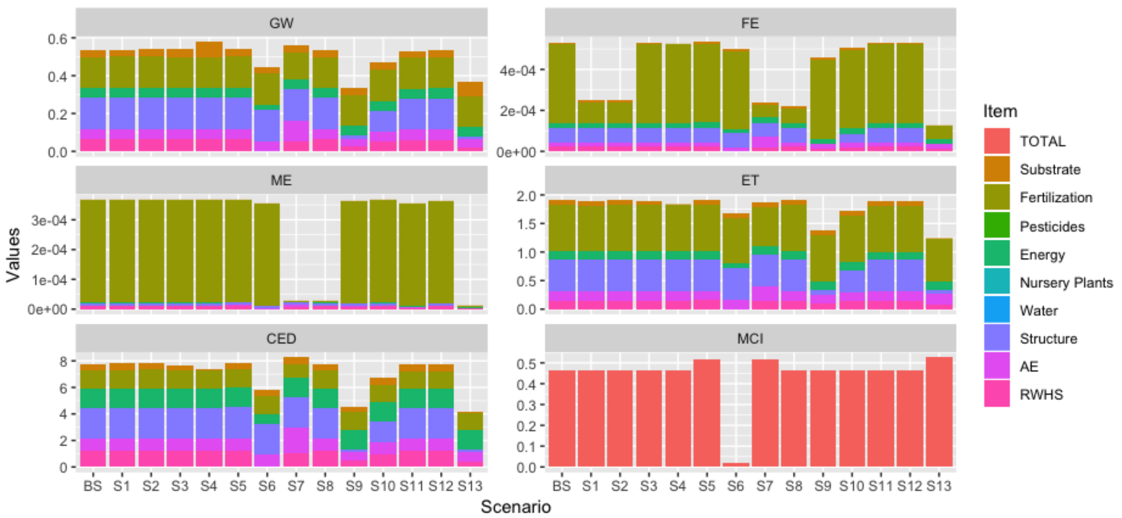


Figure 9.2 Indicator scores for all scenarios. GW: Global Warming (kg CO_2 eq); FE: Freshwater Eutrophication (kg P eq); ME: Marine Eutrophication (kg N eq); ET: Ecotoxicity (kg 1,4-DB eq); CED: Cumulative Energy Demand (MJ); MCI: Material Circularity Indicator; AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System. Strategy abbreviations are described in previous sections.

When analysing the outcomes of the model regarding the MCI, we can observe the same limitation that we detected during the assessment of the baseline scenario because the water flow is the largest in mass terms. The changes in this flow are the only ones that significantly modify the MCI score. This fact is reinforced by looking at scenario S6, where the use of only tap water brought the MCI score close to 0, making it the most "linear". Moreover, since the use of rainwater was predominant (89% of all input water) in the baseline scenario, the degree of improvement that we can get in strategies using rainwater (S5), compost at the building scale (S3) or the combined scenario (S13) is limited. These results do not allow for a comparison between the change in circularity of a specific strategy and its consequent environmental benefits or trade-offs. This situation leaves no room for an accurate dual assessment of circular strategies. To solve these problematic findings, we propose a series of modifications of the MCI in the following section.

9.3.3 Towards more complex circularity assessments

We propose a series of modifications of the MCI that set the basis for evaluating the circularity with additional parameters complying with the mass balance (Table 9.2). The step-by-step calculations are detailed in the following sections and shown in Appendix 7.3 in the form of a script from R programming software. In systems other than agricultural facilities, the use of mass as a weighting factor to assess the circular performance of the system may be the most adequate. However, the weight allocated to water in agricultural systems opens the door for exploring other parameters that could give a better perspective on the circularity of these systems. Already Razza et al. (2020) proposed an MCI modification to adapt the indicator to the specificities of biodegradable products, and Niero and Kalbar (2019) coupled different types of environmental and circularity indicators using multi-criteria decision analysis (MCDA) to assess alternatives for beer packaging. Niero and Kalbar (2019) used different weighting factors and a specific MCDA method to calculate a single score that involved multiple environmental and circularity indicators. In our study, wesuggest the coupling of MCI or LFI with one environmental indicator at a time. To do so, we use the relative contributions to a specific environmental indicator of every subsystem in the inventory as weighting factors. These weighting factors are finally applied to the modified MCI or LFI to generate the final set of coupled indicators. The final coupled indicators give an overview of how a circular strategy performs in terms of environmental performance and circularity.

9.3.3.1 MCI_{NW} – ADAPTING THE MCI FOR FURTHER INDICATOR DEVELOPMENT

Figure 9.3 shows the first step in the modified MCI calculation proposed. In this calculation, separated MCIs are calculated for every subsystem or item in the inventory. This step is different than the one proposed by EMF (2015b), in which parameters for every subsystem are aggregated before the calculation of the LFI. In the proposed modification, because every subsystem obtains an MCI value between 0 and 1, the aggregated scores of all subsystems would probably exceed the upper limit of 1 for the global MCI. To correct that issue, each individual value will be divided by the total number of subsystems or items (*n*) that we considered in the inventory, as shown in

Equation 9.1. These values are the values displayed in Figure 9.3, and this preliminary indicator was labelled "MCI without weighting factors" (MCI_{NW}). In our case, since the number of subsystems is 9, every subsystem has a specific percentage weight equal to 11.1%. With this modification in the MCI, we can see which subsystems score better in circularity with respect to others without the need to look at previous parameters in the calculations, such as amount of mass, virgin materials or unrecoverable waste. These values are interesting if we want to focus our attention only on a specific subsystem, and they allow us to solve the limitation of the overweighting of the water subsystem.

Table 9.2 Proposed modifications to couple MCI and environmental indicators

Name	Basic definition	Utility	Limitations
MCI_{NW}	MCI without weighting factors	Avoid the bias related to the mass flows. Can be coupled with other indicators	Same weight is given to every subsystem (arbitrary)
MCI_{LCA}	Couples MCI with one life cycle environmental indicator at a time using relative environmental contributions	Maximize the circularity of most impacting subsystems (can be controversial). Include the energy flows and the transportation processes in the calculations	Not fair for scenario comparison: if a circular strategy diminishes the environmental impact of a subsystem, it will be underrepresented
LFI_{LCA-R}	Couples LFI with one life cycle environmental indicator at a time using relative environmental contributions	Independent evaluation of strategies to analyse which are the subsystems to be targeted in the future	Not fair for scenario comparison: if a circular strategy diminishes the environmental impact of a subsystem, the other subsystems will increase their relative contribution
LFI_{LCA-T}	Couples LFI with one life cycle environmental indicator at a time using absolute environmental contributions	Integrated evaluation of strategies to prioritize them in the decision-making process. The best strategy will be the one with the lowest value	Partial limitation: a set of indicators hinders the selection of a unique strategy, but give more information to the decision-maker

However, the same importance is given to each of the subsystems (11.1%), which would be arbitrary. In this sense, the application of weighting factors should be opened to debate. Here, we discuss some ideas.

$$\mathrm{MCI_{NW}} = \sum_{i=1}^{n} \left(\frac{MCI_i}{n}\right) \quad (Equation\ 9.1)$$

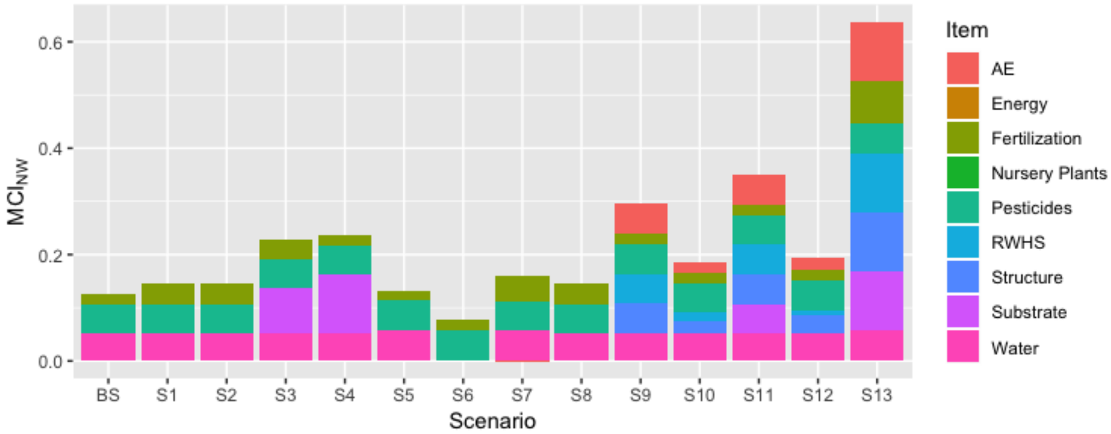


Figure 9.3 Scores for the modified MCI. AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System. Strategies abbreviations are described in previous sections.

9.3.3.2 MCI_{LCA} – COUPLING CIRCULARITY AND ENVIRONMENTAL INDICATORS

As proposed by other authors, scarcity should play a role when evaluating circular measures (Linder et al., 2017; Niero et al., 2014). Co-driven by phosphorus scarcity problems worldwide, struvite use as a fertilizer is being studied from different perspectives but was not well represented in the standard MCI. Thus, coupling MCI with scarcity databases or the Mineral Resource Scarcity impact category reported in the ReCiPe impact method (Huijbregts et al., 2016) could partially solve the problem. If the latter is used, attention should be given to the datasets to avoid double-counting. Moreover, since every subsystem in the case study is composed of different materials, scarcity weighting factors should be applied before aggregating the data. Other problems that would probably arise regarding scarcity could be the fluctuation and perception of scarcity by different stakeholders and practitioners (Linder et al., 2017).

Since one of the prominent objectives of published literature is to find ways of coupling circularity and environmental performance (Haupt and Hellweg, 2019; Niero and Kalbar, 2019), coupling the MCI values with one specific environmental indicator could be seen as a simple and efficient way of including an environmental perspective into circularity measurement. In this sense, we propose the MCI_{LCA}, a set of indicators that couple environmental impact categories with the MCI of every subsystem. To do so, environmental impacts for all subsystems are divided by the total impact exerted by the system. This process produces the relative impact exerted by every subsystem. These percentage values could then substitute the fixed percentages in the MCI shown in Figure 9.3 (11.1%) for the MCI_{NW}. Equation 2 exemplifies the basis for the calculation using the global warming impact category, where "i" is a specific subsystem.

$$\mathrm{GW} - \mathrm{MCI}_{LCA} = \sum_{i=1}^{n} \left[\left(\frac{GW_i}{\sum GW} \right) \times MCI_i \right] \qquad (Equation\ 9.2)$$

A limitation that cannot be solved by mixing circularity with environmental indicators is the predefined exclusion of specific flows in the MCI, such as energy (Lonca et al., 2018). Although EMF (2015a) proposes a complementary indicator that includes energy usage, the fact that the energy flows are not included in the MCI calculations is a big limitation when trying to apply MCI modifications since these flows will not be represented even though they have an impact in the LCA. Our suggestion is to consider both the impact of energy in a specific impact category plus the electricity mix percentages of the geographical area of the case study. The electricity mix percentages define the degree of circularity of the energy subsystem within the inventory according to the ratio of renewable versus non-renewable electricity sources. In this case, we used the electricity mix in Spain, with 40.1% renewable sources (REE, 2018). With this calculation, we can add energy as a subsystem in Equation 9.2 and calculate its contribution to the final indicators.

Results mixing environmental indicators with the MCI are represented in Figure 9.4. As seen in Figure 9.3, where MCI is not weighted, scenarios such as struvite use (S1 and S2) did not produce any differences even though they considered different scales. This limitation, related to the non-inclusion of location and transportation (Saidani et al., 2019a), is partially solved since the impact from the transport life cycle stages is already included in the impact assessment of the LCA. However, differences between strategies at different scales will only have a big repercussion in the MCI_{LCA} if the transport or import of the targeted resources has a significant relative impact in the inventory.

Another drawback detected in this study is the limitation of MCI to fairly evaluate water-related strategies. The original MCI value of the scenario with nutrient recirculation in the same crop (S7) was higher than the one considering crop-cascading (S8) because of the amount of water saved in the former, but it required a certain amount of extra materials. Similarly, the benefits obtained through less nutrient inputs in S7 were not reflected in the original MCI. With the indicator coupling proposal, this limitation is solved since it includes both the benefits and trade-offs quantified in the environmental assessment in the final score of the indicators.

On the other hand, when a subsystem in the inventory has a large impact on a specific indicator in the MCI_{LCA}, maximizing its circularity will be a priority because the goal is to reach the highest possible value. However, MCI_{LCA} shows severe limitations in terms of evaluation and comparison of strategies. For example, one would expect that the application of nutrient recirculation (S7 and S8) increases the circularity of the fertilization subsystem while decreasing its eutrophication potential. This situation is true if we evaluate the score of the MCI_{NW} and eutrophication impact categories separately. However, when coupling the MCI with the freshwater and marine eutrophication impact categories, we can see that the contribution of the fertilization subsystem to the score of the coupled indicators is the lowest among all scenarios because, since N and P are no longer emitted to the aquatic environment, no impact is generated in eutrophication from direct emissions, and therefore the coupled indicator does not give relative importance to the fertilization subsystem.

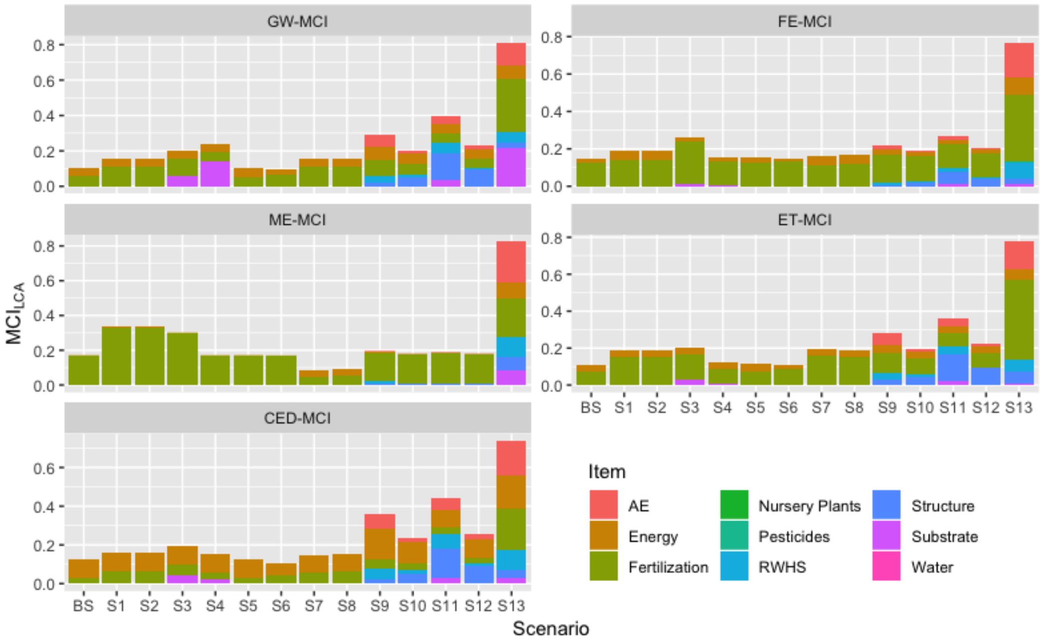


Figure 9.4 Scores for the modified MCIs with the environmental indicators. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; ET: Ecotoxicity; CED: Cumulative Energy Demand; MCI: Material Circularity Indicator; AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System.

9.3.3.3 $LFI_{LCA\text{-}R}$ AND $LFI_{LCA\text{-}T}$ – IMPLICATIONS FOR DECISION-MAKING

Given the outlined limitations related to the MCI_{LCA}, our final proposal for coupling circularity and environmental indicators is the combination of two groups of indicators: Linear Flow Index (LFI) with relative values ($LFI_{LCA\text{-}R}$ and no units) and LFI with absolute values ($LFI_{LCA\text{-}T}$ and units related to each specific environmental indicator). As shown in Equation 9.3 for the global warming indicator, we use the LFI to adjust Equation 9.2 for MCI_{LCA}. Since the LFI minimum score of 0 means that the circularity of the subsystem is the best possible, diminishing the score of the LFI aligns with the goal of minimizing the score of the environmental indicators.

$$\mathrm{GW} - \mathrm{LFI}_{LCA-R} = \sum_{i=1}^{n} \left[\left(\frac{GW_i}{\sum GW} \right) \times LFI_i \right] \quad (Equation\ 9.3)$$

As we can see in Figure 9.5, $LFI_{LCA\text{-}R}$ provides relative values for all subsystems. As an example, we can see how nutrient recirculation scenarios (S7 and S8) substantially decrease their eutrophication score for the fertilization subsystem. However, because the relative impacts from fertilization on eutrophication decrease due to the cessation of emissions of nitrogen and phosphorus, other elements such as the RWHS, structure or auxiliary equipment increase their relative impacts. Since nutrient recirculation strategies do not target these items, the final score for these strategies in eutrophication is increased. For this reason, $LFI_{LCA\text{-}R}$ can only be used for independent evaluation of strategies to evaluate which subsystems should be targeted in the future, but not for comparison between strategies and the baseline scenario.

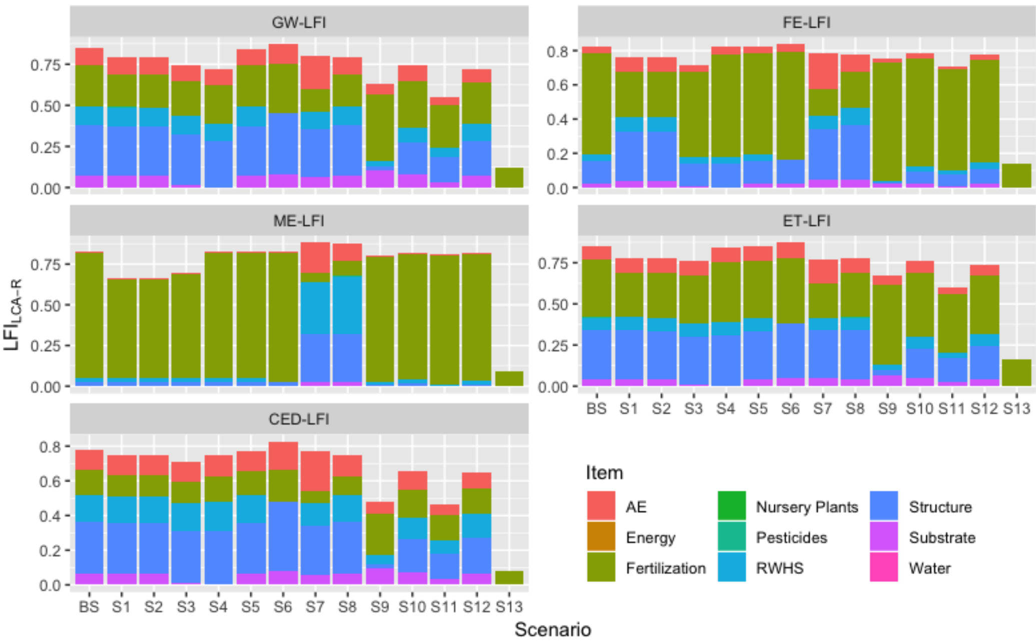


Figure 9.5 Scores for the $LFI_{LCA\text{-}R}$. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; ET: Ecotoxicity; CED: Cumulative Energy Demand; LFI: Linear Flow Index; AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System.

To compare the score obtained among strategies, we use $LFI_{LCA\text{-}T}$, as shown in Equation 9.4 for the global warming indicator.

$$\mathrm{GW} - \mathrm{LFI}_{LCA-T} = \sum_{i=1}^{n} [GW_i \times LFI_i] \quad (Equation\ 9.4)$$

As shown in Figure 9.6, values can be higher than 1 for the LFI_{LCA-T} since we are using the total impact per subsystem obtained in the environmental indicators instead of the relative impact for every subsystem. Using the same example, now nutrient recirculation strategies (S7 and S8) exert the lowest impacts on freshwater and marine eutrophication. In this sense, the use of closed-loop systems combined with phosphorus fertilization through struvite shows the largest improvement in terms of a combined eutrophication and circularity assessment, clearly putting the focus on the use and management of nutrients. On the other hand, using recycled materials in the infrastructure shows great improvements in global warming, ecotoxicity and cumulative energy demand. Considering that the use of recycled materials for the infrastructure or the RWHS is one of the most prominent strategies, the decision on whether we use recycled materials and to which extent should be made at the construction stage. Notwithstanding, attention should be paid to both the availability of recycled materials to be used and their degree of recyclability, which greatly affects the results as shown in the difference between scenarios S9 and S10 and S11 and S12.

Figure 9.6 Scores for the LFI_{LCA-T}. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; ET: Ecotoxicity; CED: Cumulative Energy Demand; LFI: Linear Flow Index; AE: Auxiliary Equipment; RWHS: Rainwater Harvesting System.

However, the selection of strategies is not as straightforward as in MCI_{NW}. The reason for that finding is the same problematic that an LCA practitioner encounters in every analysis: each impact category has its own tendency. This issue is why a set of indicators is preferable over a single indicator (Moraga et al., 2019), and thus we recommend comparing the values of the coupled indicators with the raw values of the environmental indicators and the MCI_{NW} before making decisions. Moreover, other relevant indicators for the area under study should be considered. As an example, we can see that the only use of tap water (S6) showed better environmental performance than the use of rainwater (S5). This situation is due to the impacts exerted by the materials used for the RWHS, which should be optimized. However, considering that the system is within urban limits, water scarcity should also be brought into the decision-making process. In this sense, the final decision on the strategies that best suit a specific agricultural system must include the goal of the farmer or the company and the alignment with sustainable development goals.

9.4 Conclusions

This study aimed to evaluate the circularity and environmental performance of applying circular strategies in UA systems in the framework of urban metabolism and to explore how we can define more suitable metrics to evaluate these systems. Three main conclusions can be drawn from this analysis.

First, the score of the MCI applied to agricultural systems was dominated by water, representing more than 99% of the mass flow. This fact blurred potential benefits of applying circular strategies related to fertilizers, use of recycled materials or substrate.

Second, the application of circular strategies presented both potential benefits and trade-offs in terms of environmental performance depending on the impact category analysed. A scenario combining different strategies showed great impact reduction compared to the baseline scenario in all environmental indicators, with impact reductions ranging from 30.8% in global warming to 96.9% in marine eutrophication. Hence, such a scenario would likely be the preferred option for practitioners in terms of environmental performance if resources and capacities are available to combine several strategies. However, the use of closed-loop systems (impact reductions of 55.3% in freshwater eutrophication and 92.4% in marine eutrophication), fertilization with struvite (impact reduction of 53.4% in freshwater eutrophication, as well as reduced use of secondary P) and the use of recycled materials (impact reductions of 37.5% in global warming and 41.0% in cumulative energy demand) should be prioritized if limited resources are available. Moreover, every case study should be evaluated independently to comprehend both the hotspots to target and the feasible strategies that could be applied.

Third, coupling environmental and circularity indicators helped solve reported limitations related to the latter, such as the exclusion of energy flows and transport processes. However, we recommend the use of the coupled indicators combined with the raw impact categories to provide a broader perspective and transparency prior to decision-making to account for biases in impact categories and include other possibly relevant indicators considering the area under study. Most importantly, any final decision on which strategies best suit a specific agricultural system must include local goals and needs and broader sustainable development goals.

Given that this paper applies environmental and circular metrics at the micro-level, we encourage the academic field to follow this direction, especially considering complex systems to identify benefits and trade-offs of applying CE principles. We have shown that such a metric indeed helps to identify potential trade-offs between CE and environmental impacts (as suggested by Lonca et al. (2018)). Furthermore, it could help to link circular strategies to sustainability targets (as suggested by Pauliuk, (2018)). Most importantly, it provides a viable basis for local decision-makers to prioritize circularity strategies based on their environmental benefits and shows them options on how to best combine feasible strategies.

Finally, we observed that numerous assumptions were required to develop these metrics and while adapting the MCI for agricultural systems. In this sense, we recommend that future methodology work includes sector-specific adaptation tools to reduce the uncertainties and move towards uniformity among studies.

Part 6

Final Remarks and Future Research

Chapter 10

Picture: Harvested lettuce

Discussion of the main contributions

Chapter 10. Discussion of the main contributions

This chapter discusses the main contributions of this dissertation, with the aim to provide a comprehensive understanding of the research conducted in the previous chapters. This chapter is structured in six sections integrating the main four topics of this thesis: Urban Agriculture (UA), Cities and Urban Areas, Life Cycle Assessment (LCA) and Circular Economy (CE), as shown in Figure 10.1.

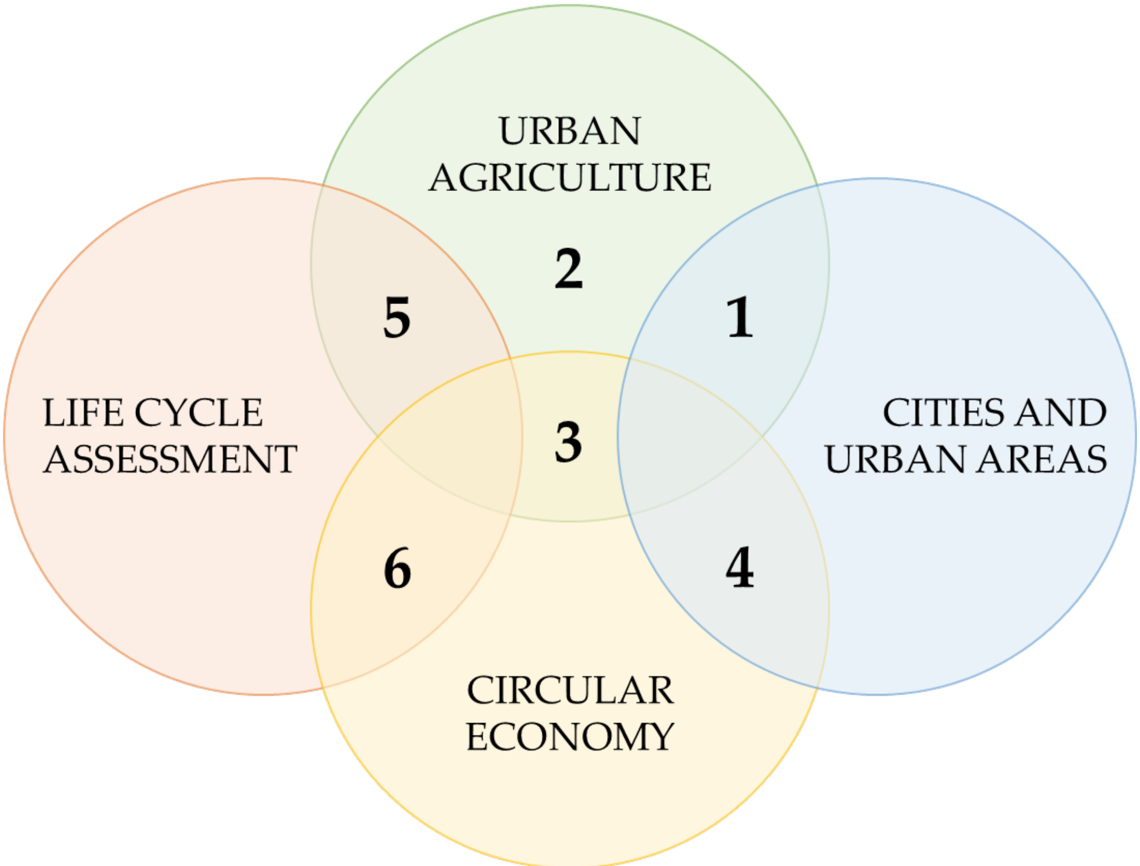


Figure 10.1 Sections in Chapter 10 and how they relate to the main topics addressed in this dissertation.

10.1 Urban agriculture to improve urban metabolism at different scales

This dissertation analysed a series of circular strategies following different goals according to each chapter, highlighting the potential that UA systems can have to improve the circularity of resources within urban limits and considering multiple perspectives. Considering the pivotal role of the environmental impacts of the food supply chain as one of the main drivers for UA, this dissertation has focused on the environmental performance of UA and its relationship with other urban systems.

To tap the full potential of UA, the main contribution of this dissertation is the assessment of UA systems within a bigger system: the urban region. This approach enables the understanding of multiple bidirectional strategies within UA and between

UA and other urban systems to close flows at an urban scale. Considering CE principles, all strategies analysed were designed to recover resources that will be consumed within the urban limits. In this sense, the case-study (rooftop greenhouse) presented great synergies at different scales. Recirculation of leachates (**Chapter 5**) or cascade systems (**Chapter 6**) unveiled a potential to regenerate nutrient and water flows within the building scale. The optimization of P flows through struvite showed a great synergy between UA and wastewater treatment plants (WWTPs) in **Chapter 7**, obtaining high yields while optimizing the P flows in the hydroponic configuration, and a feasible scaling between recovery and reuse at the urban scale in **Chapter 8**, estimating that the WWTPs of the area under study would meet the P demand of the agricultural fields of the region. Finally, **Chapter 9** classified all the potential strategies within the detected scales: building, urban or national. Thus, analysing UA by looking into the bigger picture can help find a larger variety of circular strategies at different scales and understand their environmental feasibility.

10.2 Agronomic contributions

Since most chapters included experimental analysis of crops, this dissertation presents significant contributions to the agronomical pool of knowledge of UA. **Chapter 3** focused on the environmental assessment of multiple crops, which demands an understanding of the role of agronomic variables to ensure their technical feasibility. One of the most notable contributions of this dissertation is the generation of average yield data for 25 cycles of 7 different species such as tomato, lettuce, bean or spinach (Table 3.1). This data can be used by future researchers aiming to compare the potential yield that can be obtained in similar growing systems or other crops that were not included in this dissertation. This process of comparing data from different forms of UA provides urban farmers with extremely precise information about the best configurations and crops depending on a wide range of variables: season, environmental impact, yield potential or water requirements, among others.

From another perspective, the analysis of the nutrient and water flows with different recirculation strategies (**Chapters 4, 5 and 6**) in hydroponic set-ups can also be useful for future researchers aiming to tap the full potential of these recovery strategies from a nutritional point of view considering that little data is available in the literature.

Moreover, in **Chapters 5** (recirculation of leachates) **and 6** (cascade systems)**,** the relationship between the nutrient flows and the potential yield obtained was one of the main detected issues. Since the nutrient content of the residual water flows was not modified to meet the specific demand of the plants, the response of crops in terms of production was altered. In this sense, both chapters presented different strategies aiming to work towards the best management practices in the implementation of these systems in the urban context.

Finally, the results obtained in the experiments using struvite (**Chapter 7**) are a big step forward in terms of using locally recovered fertilizers in the framework of urban metabolism. The yields obtained have highlighted the potential of struvite to substitute traditional P fertilizers, while providing benefits related to the wastewater treatment (as observed in **Chapter 8**). The nutrient metabolism of hydroponic set-ups, diminishing the P losses and the required input of this valuable and limiting nutrient is a novel contribution of this dissertation considering that little data is available in the literature on the use of struvite in this kind of systems.

10.3 Unveiling the potentials and limitations of nutrient recovery strategies in urban agricultural systems

This dissertation brings together different nutrient recovery strategies in UA systems, included in **Chapters 4, 5 and 6**. **Chapters 5 and 6** analysed the performance of direct recirculation and cascade systems from different perspectives, but independently from each other. Here, we discuss and compare the main potentials and limitations of both systems.

As outlined in **Chapter 4**, the direct recirculation of leachates exerted the lowest impact among the considered strategies. As opposed to chemical precipitation and membrane filtration, the recirculation of leachates was the only feasible technology that could be applied on-site. However, **Chapter 4** did not account for the installation of aluminium benches. The use of these benches was detected as one of the biggest environmental hotspots in **Chapter 5**. Although this infrastructure exerts a great impact in categories such as global warming and ecotoxicity (**Chapter 5**), the installation of benches was also linked to a more comfortable, ergonomic and sanitized working space for the urban farmers, highlighting the importance of avoiding isolated environmental assessments and accounting for external benefits.

Another limitation regarding the recirculation of leachates in the same crop was related to the nutrient supply. The established nutrient ratio to recirculate the leachates was not sufficient to meet the crop demand (e.g. for N), and it entailed yield slowness. In this sense, strict monitoring is needed to avoid nutritional deficiencies that could compromise the entire crop. If the resources are limited and this monitoring is not feasible, a cascade system (the configuration analysed in **Chapter 6**) would be more appropriate. By reusing the leachates in another crop, the possible nutritional deficiencies in the donor crop are no longer a concern, since the nutritional input will be the same as in a linear configuration. Nonetheless, **Chapter 6** also unveiled the nutritional concerns that arise in the receiving crop due to highly unstable nutrient concentrations in the leachates of the donor crop. Although a series of strategies to improve the cascade configuration are proposed in **Chapter 6**, the consequences that a soft monitoring can have in a short-cycle receiving crop in a cascade system compared to a long-cycle crop in a recirculation system are different in terms of crop development.

Nutritional deficiencies in a lettuce cycle entail short-period consequences that can be solved by planting the next lettuce cycle shortly after the end of the first cycle, thus narrowing down the losses to a single short-cycle. On the other hand, nutritional deficiencies due to an imprecise ratio calculation in the recirculation system can endanger the development of the whole long-cycle crop, which may not be uprooted and planted again due to the climatic variables. In this sense, the findings provided in **Chapter 3** related to the potential yield and nutrient requirements in different seasons from different crops can provide a valuable insight on how to define the implementation of the systems analysed in both **Chapters 5 and 6**.

If none of the improvement strategies proposed in **Chapter 6** related to the scaling between the donor and the receiving crops are applied to cascade systems, the consequences in terms of nutrient cycling for cascade set-ups are worse than in recirculation systems. As the nutrient content of the leachates of the donor crop increases, the removal of nutrients from this flow diminishes if the donor and the receiving crops are not scaled accordingly. This fact is a disadvantage compared to recirculation set-ups, since these configurations can recover and reuse all nutrients, as they are part of a completely closed-loop system.

In this sense, one could argue that the most desirable configuration would include a cascade system with a long-cycle donor crop and successive cycles of a low-demanding receiving crop that in turn reuses the nutrients that leach, leading to a complex closed-loop system with a complete nutrient cycling that does not compromise the development of the donor crop.

10.4 Exploring the synergies between urban systems through the P cycle

The slowness of its cycle, along with the anthropogenic demand to produce fertilizers, makes P a scarce and valuable resource. CE principles were applied in **Chapters 4 to 8** to recover this nutrient. Specifically, **Chapters 7 and 8** consider the recovery of P in WWTPs in the form of struvite to be used as a secondary fertilizer in UA systems from two different perspectives. This utilization of locally recovered resources is desirable when designing urban systems, i.e. maximizing the recovery of secondary resources to be used within the urban limits. Moreover, this synergy should be prioritized if it can produce benefits for both systems involved. Benefits were reported in this dissertation for UA systems, as plants fed with struvite produced more yield and diminished P losses compared to plants irrigated with mineral fertilizer. But benefits were also reported for WWTPs. **Chapter 8** presented the first reported environmental performance of a regional struvite recovery and reuse strategy, finding that the impacts of recovering struvite are lower than those exerted by the production of conventional P fertilizers if technologies are applied based on their environmental performance. From a CE perspective, the recovered struvite can be used to feed all the agricultural areas located in the metropolitan area of Barcelona. This synergy taps the full potential of synergies between urban systems by avoiding the demand for external P resources and thus mitigating both P depletion and the linear behaviour of fertilizer flows.

10.5 Multi-perspective environmental assessment of urban agricultural systems: integration of tools

The studies developed in the present dissertation, especially in **Chapters 3, 4, 5, 8 and 9**, had a common aim of contributing to the LCA literature on food production systems. Although the classic environmental assessment of agricultural facilities is a complementary tool used by many researchers (e.g. Kulak et al., 2013; Martínez-Blanco et al., 2011; Romero-Gámez et al., 2012), this dissertation included other perspectives and additional items, responding to different goals. The integration of other tools complementary to LCA is represented in Figure 10.2.

In **Chapter 3**, LCA was combined with market price data to determine the eco-efficiency of different crops and cycles, which helped determine the best annual crop combinations for the system under study. To do so, we also used three different functional units (FUs) (yield, price and nutritional value) that lead to different results, highlighting the sensitivity of this parameter in the assessment of agricultural systems.

In **Chapter 4**, LCA was used to determine the best strategy within different options. Based on these results, a real recirculation set-up was installed and analysed in **Chapter 5**. In this chapter, LCA was one of the parameters within the global analysis, complemented with nutrient balances, climatic variables and production. In **Chapter 8**, LCA was used again to determine the best strategy within different options, as done in **Chapter 4**. In this case, three different FUs were used, as done in **Chapter 3**, although the justification for their use was based on different LCA goals and system boundaries. Apart from the results outlined in **Chapter 8**, the LCA methodology in this chapter highlighted the importance of considering different perspectives and core LCA elements (FU and system boundaries) when analysing the environmental performance of a system, even though this implies a more complex and probably uncertain process of decision-making. In this chapter, data related to geographical information systems (GIS) was used as a complementary tool to LCA to estimate distribution distances.

10.6 The role of Life Cycle Assessment in moving towards a more circular economy

LCA does not directly evaluates the degree of circularity of a system. The degree of circularity can *a priori* be assessed by circularity metrics, such as the MCI used in **Chapter 9**, or the metrics that will be the result of the current works of the ISO/TC323 "Circular economy" (ISO, 2020), created in 2018. The role of LCA must be complementary to the evaluation of circularity. To this end, this dissertation has highlighted the importance of incorporating a parallel environmental evaluation to the implementation of circular

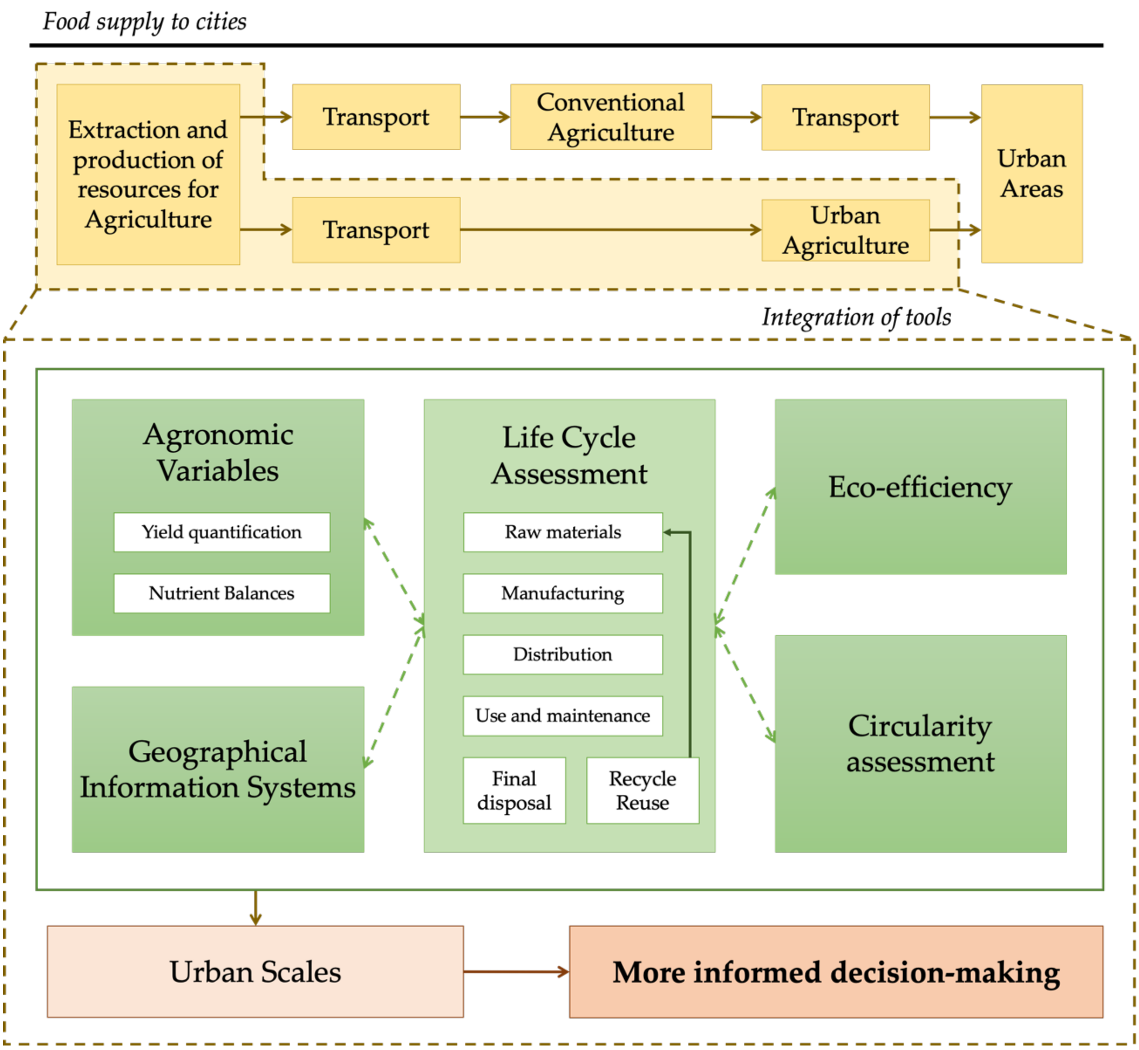


Figure 10.2 Sumary of the main contributions of this dissertation

strategies. This statement is also made by relevant literature around the CE and LCA topics (Peña et al., 2020; Petit-Boix and Leipold, 2018). As observed in **Chapters 3 and 4**, the application of circular strategies in UA systems (e.g. the restoration of water and nutrient flows through the recirculation of leachates) can lead to contradictory results in terms of environmental impacts. This fact has also been observed by previous literature assessing agricultural systems (Fan et al., 2018). Although recovering non-renewable P helps to mitigate the depletion of this nutrient, attention must be paid to the environmental performance of these circular strategies. Some impact categories may align with an improvement in circularity, especially those strictly related to nutrient pollution such as freshwater or marine eutrophication. However, some others can show the inverse behaviour, such as global warming in **Chapter 4** due to the addition of new infrastructure. To this end, this dissertation contributes to the assessment of circular strategies by proposing a series of coupled indicators (**Chapter 9**) that use the circularity metrics and any other environmental indicator to jointly evaluate the degree of advancement towards environmental sustainability and circularity of a system.

Chapter 11

Picture: Flowes of a green bean plant

Conclusions

Chapter 11. Conclusions

This chapter presents the global conclusions of this dissertation, providing individual answers to the Research Questions outlined in **Chapter 1**.

Question 1. Which are the main environmental hotspots in UA systems resulting from different crop types?

Based on a rooftop greenhouse (RTG) case study, we determined that these systems improve urban agriculture (UA) by allowing year-round production in the Mediterranean climate (**Chapter 3**). In harsher seasons, crops such as bean, lettuce or pepper produced competitive yields.

Considering a functional unit (FU) of yield, two successive tomato cycles was the best yearly set-up in terms of environmental performance, while a combination of a tomato, bean and lettuce cycle exerted the lowest impacts compared to other combinations with FUs of economic and nutritional value. These two FUs were useful to demonstrate the capability of the growing system to produce added-value vegetables in harsher conditions while complying with the function of providing nutritional value through local food production. In this sense, increasing the diversity of the system leads to a better environmental performance of RTGs if suitable crops are selected.

Moreover, we determined that three main elements were responsible for the environmental impact of the system: the greenhouse structure, the rainwater harvesting system (RWHS) and the fertilizers. Considering that the greenhouse structure and the RWHS are elements that may not be present in other forms of UA and can be linked to other uses within the building, the fertilizers were detected to be the element with the greatest potential for improvement. The fertilizers exerted more than 25% of impacts in climate change for tomato crops, although their contribution in crops with shorter cycles was reduced and similar to the impacts generated by the RWHS. On the other hand, the impacts exerted by the depletion of nitrogen (N) and phosphorus (P) species contributed to the majority of the impact in freshwater and marine eutrophication impact categories, emphasizing the need to design strategies that mitigate the impact of the entire life cycle of the fertilizers.

Question 2. How can existing nutrient recovery techniques contribute to improve the efficiency of nutrient flows while diminishing the environmental impacts of UA?

Given the urgency of diminishing eutrophication impacts while tackling nutrient depletion (with a special focus on non-renewable P), we assessed different recovery strategies that could be applied in UA systems (Figure 11.1). Considering a hydroponic set-up, we identified direct leachate recirculation to be the best strategy to recover nutrients in urban food production systems. This statement was based on the easy implementation of these systems at a building scale and their environmental performance across different indicators. For the opposite reasons, chemical precipitation and membrane filtration (that exerted 3 and 5 times more impact, respectively) were discarded (**Chapter 4**).

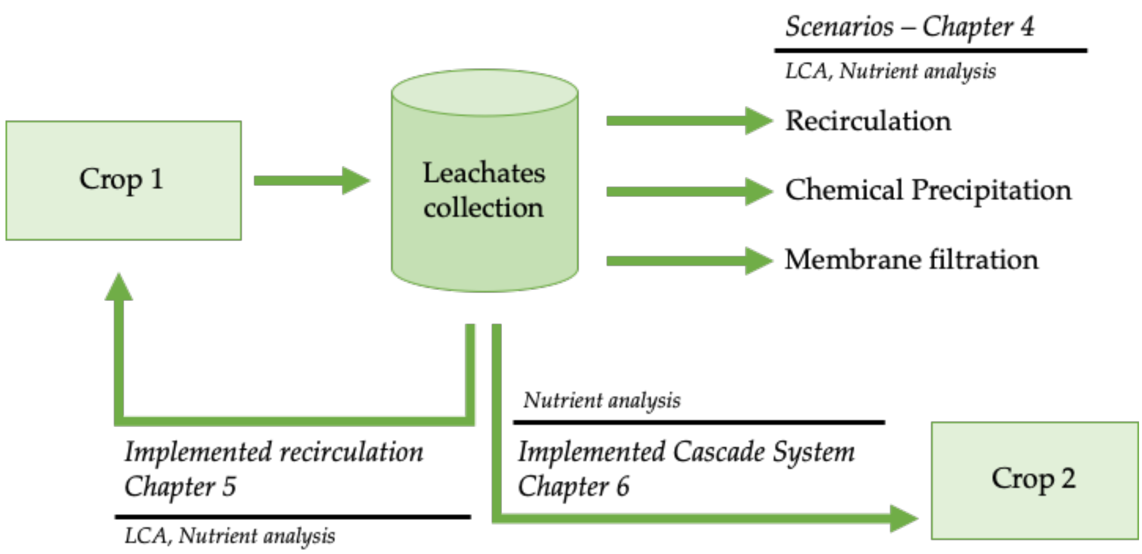


Figure 11.1 Scheme of the set-up to answer Research Question 2: *"How can existing nutrient recovery techniques contribute to improve the efficiency of nutrient flows while diminishing the environmental impact of UA?"*

Based on the results obtained, a more in-depth analysis was done in specific recirculation strategies to tap their full potential, but also to detect possible limitations. In this sense, we assessed the performance of the recirculation of leachates in the same crop with a real implementation in two common bean cycles (**Chapter 5**). The analysis showed an immediate optimization of residual water flows, thus diminishing the water needed for the system, the depletion of nutrients and the eutrophication impacts derived. However, two main limitations were detected. First, the direct recirculation of the leachates can trigger nutritional deficiencies without a daily nutrient monitoring. This deficiency (combined with a negative effect triggered by less radiation received) affected the daily yield of the closed system, which took a month longer than the linear system to produce the same amount of yield. Second, the environmental performance of the recirculation set-up presented higher impacts than the linear system in impact categories such as global warming or fossil resource scarcity due to the use of primary aluminum substrate benches. Considering this, we designed and evaluated four scenarios and observed that there is still room for improvement for these systems in terms of environmental performance.

Considering the limitations in using the leachates in the same crop and the effort that it may require in terms of constant monitoring, we evaluated a cascade system (**Chapter 6**). By using a long-cycle tomato crop we determined the evolution of the nutrient content of the tomato leachates and how these nutrients can contribute to grow parallel lettuce cycles that are only fed by these residual nutrients. The results showed that 10 tomato plants were needed in the early stage to produce 1 plant of lettuce, mainly due to the low quantity of drained N. However, a single tomato plant in its late stage can produce up to 9 lettuces with the amount of nutrients that are being leached. From the opposite perspective, although the yield of the lettuce crop was extremely low in the early stage of the tomato crop, marine eutrophication was totally mitigated, since lettuce took up all N. In this same stage, 28% of P leached by the tomato crop was taken up by the lettuce crop in the cascade system.

Based on the results of **Chapters 4, 5 and 6** we can determine that the different nutrient recovery strategies assessed are effective to avoid nutrient depletion and the consequent eutrophication impacts. However, the limitations detected with the real implementation of direct recirculation and cascade systems are as important. Considering these limitations, we can state that the best nutrient recovery set-up in hydroponic UA would include a cascade system with a long-cycle donor crop and successive cycles of a low-demanding receiving crop that uses a recirculation system to reuse the nutrients that leaches, completely closing the nutrient flows within the system.

Question 3. Is the recovery and reuse of struvite a promising strategy to reduce the environmental impacts of UA and wastewater treatment in cities?

Given the slowness of its cycle, P is considered a non-renewable nutrient. Due to P demand for the fertilizer manufacturing industry, phosphate reserves are being depleted at an alarming rate. To partially close the P cycle at the urban level and to enhance a more nutrient resilient urban production systems, we assessed the performance of struvite recovery and reuse at two different levels as shown in Figure 11.2. Considering two experiments in a hydroponic set-up, we determined the potential yield and P balances of a bean crop using struvite as the P source for the plants (**Chapter 7**). The tests showed that struvite has a great potential as P source above 5 g/plant, since yields were increased compared to the control using mineral fertilizer. Additionally, P depletion through the leachates is drastically diminished when using struvite due to its slow-release characteristic. However, incorrect irrigation management and monitoring hamper the positive effects of struvite. Finding a balance between ensuring the precise supply while diminishing the residual losses is critical to maximise the efficiency of struvite fertilization.

From a different perspective, we assessed the feasibility of a struvite recovery and reuse strategy at a regional level to determine the environmental burdens of converting a waste generated by wastewater treatment plants (WWTPs) to an efficient resource for agriculture (**Chapter 8**). Considering the metropolitan area of Barcelona (Àrea Metropolitana de Barcelona - AMB) as a case study, we determined that selecting the most suitable WWTP to recover struvite and prioritizing the technologies that best suit the selected facilities are two key parameters, since the decisions may have consequences in terms of additional impacts. Nonetheless, struvite recovery presented great savings in eutrophication, since a great amount of P and part of the N were extracted from the effluent from the WWTP, thus preventing substantial emissions to the freshwater and marine environments when this effluent is discharged. Accounting for all the impact categories and P recovery processes analyzed, we determined that Ostara® technology had the lowest environmental impacts. Our empirical findings support the need for paradigm shifts in WWTPs, considering wastewater flows as a source of nutrients that must be recovered and used locally to improve the resilience of future cities. Moreover, considering the burdens at a regional level can contribute to enhance the circularity of resources, a key variable to improve the urban metabolism of future cities and urban areas.

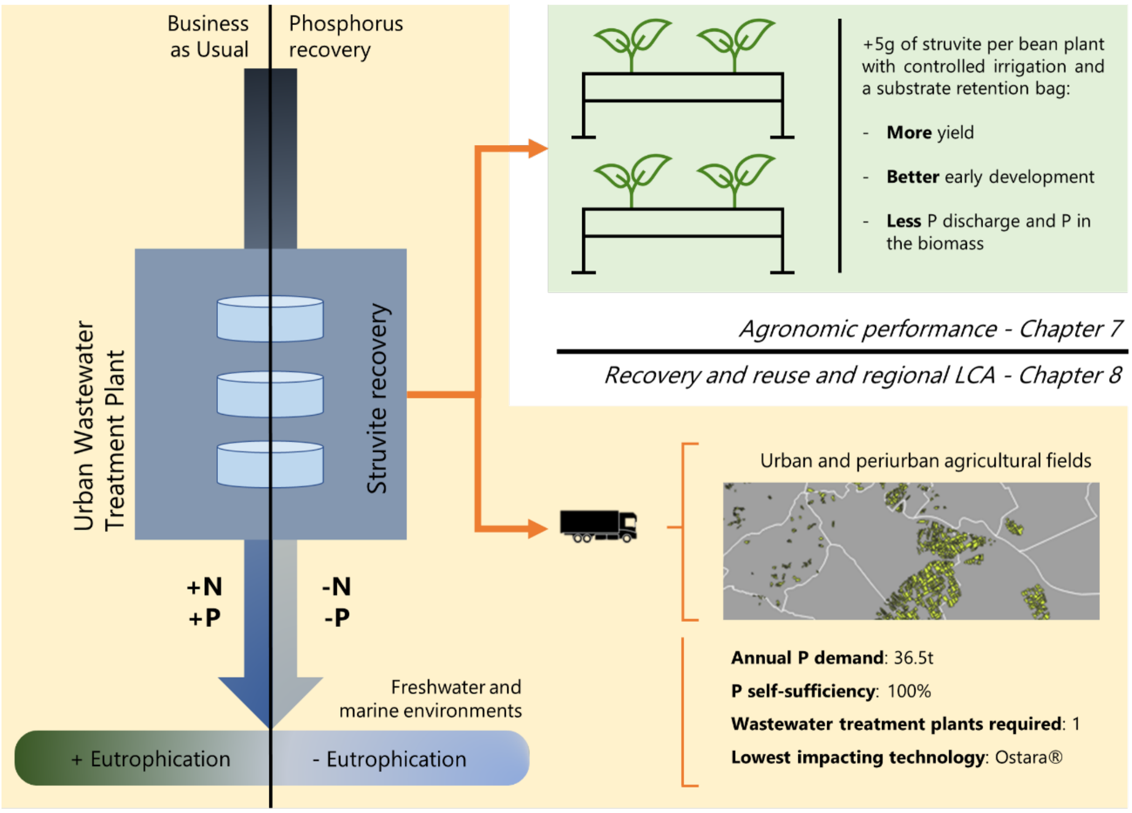


Figure 11.2 Experimental set-up to answer Research Question 3: *"Is the recovery and reuse of struvite a promising strategy against phosphorus depletion and close its cycle?"*

Question 4. How should circular strategies be prioritized to improve the environmental and circularity performance of UA?

The environmental assessment of the application of circular strategies in UA presented both potential benefits and trade-offs, depending on the impact category analyzed (**Chapter 9**). However, when we quantified the circularity degree for the RTG through the Material Circularity Indicator (MCI), we observed that the final score was dominated by the amount of mass that the water flow represented (more than 99%) compared to the other elements in the inventory. This fact hided the potential benefits of other included strategies. To solve this, we presented a series of modifications to the MCI, while also mitigating already reported limitations of this indicator, like the non-inclusion of energy flows or transport processes. Coupling environmental and circularity indicators helped solve these reported limitations and link circular strategies to sustainability targets. Most importantly, it provided a viable basis for local decision makers to prioritize circular strategies based on their environmental benefits, as well as presenting options on how to best combine feasible strategies.

In our case study, a scenario combining different strategies showed a great impact reduction in all environmental indicators. Hence, such a scenario would likely be the preferred option for practitioners, if resources and capacities are available to combine several strategies. However, the use of closed-loop systems, fertilization with struvite and the use of recycled materials should be prioritized if limited resources are available. Moreover, every case study should be evaluated independently to comprehend both the hotspots to target and the feasible strategies that could be applied.

Chapter 12

Picture: Lettuce zoom-in

Future Research

Chapter 12. Future research

This dissertation has tried to answer the relevant questions regarding the environmental performance of circular strategies applied to urban agriculture (UA). While doing this, more specific questions emerged that could be the object of study for further research. Chapter-specific recommendations for further research are detailed below.

C3	**Increase** the diversity of crops, especially in cold months, to present different options of crop combinations for urban farmers.
	Perform similar analysis in areas with different climatic conditions to provide a precise quantification of the behavior of the system under study.
C4	**Test** the analyzed technologies in real case studies to better identify their potentials and limitations and not only from an environmental perspective.
C5	**Study** the feasibility of a big-scale implementation of recirculation systems to quantify the recovery potential of cities of the future.
	Analyze the performance of different crops in recirculation systems to detect the main drawbacks related to nutrient management.
	Compare recirculation with linear systems considering other perspectives, such as life cycle costing.
C6	**Evaluate** different kinds of horticultural crops and other combinations of donor and receiving crops to outline potential synergies.
	Quantify the degree of improvement of the strategies presented to identify the benefits and limitations of all of them and establish a prioritization
C7	**Explore** the role of NH_4^+ supplied through struvite in plant development when struvite is the only source of this cation.
	Plant successive cycles that could benefit from the remaining struvite in the substrate and quantify how struvite is depleted based on the initial quantity and irrigation changes.
C8	**Replicate** the methodology in other densely inhabited urban areas that could contribute to avoiding P depletion.
C9	**Extend** the application of circular and environmental metrics in complex systems to identify potential trade-offs related to the application of circular strategies
	Involve sector-specific adaptation tools to reduce uncertainties and detect limitations of circular metrics

Additionally, more general research lines have also been detected:

Standardization of circular economy metrics and concepts

A general clarification of concepts is the most urgent matter related to the circular economy (CE). The variability in the number of CE definitions calls for a standardization process that dots the I's and crosses the T's. In this dissertation, we assumed that the ultimate goal of CE relies on the restoration of flows while minimizing the residual outputs. This assumption has allowed us to define clear circular strategies as actions that aim to minimize the linear behavior of one or more flows within a system.

However, other definitions of CE include social and economic aspects. Therefore, it would seem appropriate that the so-called circular strategies also include these dimensions within their aim. Giving this variability among the CE and related concepts, future work should urgently standardize the boundaries of the implications that CE principles entail and where are the limits or synergies between CE and sustainability goals.

Alignment between circularity and environmental performance

This dissertation has highlighted the need to environmentally assess the performance of circular strategies since their application may entail additional impacts. Therefore, we recommend that academics working on the real implementation of circular strategies do not omit the environmental perspective in the assessment.

The inclusion of an environmental perspective must entail different impact categories. This dissertation has underlined the different tendencies among environmental indicators like global warming, eutrophication or ecotoxicity. Even though an increase in the circularity of the system caused by the implementation of a specific circular strategy can align with decreasing the score of a specific environmental indicator, it can also increase the value of another one for a specific reason. The detection of this drawback is relevant to improve the implementation of circular strategies from an environmental perspective and thus something that further research should consider.

Integration of different perspectives in the assessment of UA systems

Agricultural facilities are complex systems. An analysis from an environmental perspective may require data that may not be essential for an agronomic or a circularity analysis and the other way around. Moreover, the assessment with a single perspective of an agricultural system in this dissertation was demonstrated to hinder relevant findings. Without the analysis of the nutrient flows in **Chapter 5**, the yield obtained or some of the environmental results would lack sense. In this context, we highlight the need for multidisciplinary approaches to the analysis of UA systems to have a more complete quantification of their performance.

Explore and evaluate new strategies in UA systems… and elsewhere

This dissertation has evaluated a series of circular strategies that can be applied to UA systems considering the restoration of flows at different scales. The system and flows under study were selected based on the urgency to move towards more resilient, circular, and environmentally sustainable urban food systems. Apart from the strategies analyzed in this dissertation and the further research outlined in every chapter, further research trying to improve the performance of UA through CE principles should explore new strategies that maximize the potential synergies with other urban systems in terms of materials, energy or waste.

But the evaluation of circular strategies must not be narrowed to specific systems. Since the debate around the CE has merely focused on concept definition, the practical implementation of circular strategies and their implications remains barely explored in all urban systems, being this limitation one of the main motivations of this dissertation. In this sense, further research in the urban context should explore the implications of applying circular strategies to other relevant urban systems (e.g. wastewater treatment plants, household waste recycling centers or industrial parks). These parallel analyses will help advance towards the assessment of cities as complex networks composed of different urban systems. Additionally, more synergies may arise between urban systems and UA, triggering the emergence of new circular strategies that will need further evaluation from multiple perspectives.

References

Abad, D., Garrido, J., Fernández, E., 2009. Ensayo de cultivares de judía de mata baja en invernadero bajo control biológico. XXXVII Semin.

Abeliotis, K., Detsis, V., Pappia, C., 2013. Life cycle assessment of bean production in the Prespa National Park, Greece. J. Clean. Prod. 41, 89–96. https://doi.org/10.1016/j.jclepro.2012.09.032

Aber, J.D., Nadelhoffer, K.J., Steudler, P., Melillo, J.M., 1989. Nitrogen Saturation in Northern Forest Ecosystems.

Abou-Hadid, A.F., Abd-Elmoniem, E.M., El-Shinawy, M.Z., Abou-Elsoud, M., 1996. Electrical conductivity effect on growth and mineral composition of lettuce plants in hydroponic system. Acta Hortic. https://doi.org/10.17660/ActaHortic.1996.434.6

Achat, D.L., Sperandio, M., Daumer, M.-L., Santellani, A.-C., Prud'Homme, L., Akhtar, M., Morel, C., 2014. Plant-availability of phosphorus recycled from pig manures and dairy effluents as assessed by isotopic labeling techniques. Geoderma 232–234, 24–33. https://doi.org/10.1016/J.GEODERMA.2014.04.028

Agung Putra, P., Yuliando, H., 2015. Soilless Culture System to Support Water Use Efficiency and Product Quality: A Review. https://doi.org/10.1016/j.aaspro.2015.01.054

Ahmed, A.K., Cresswell, G.C., Haigh, A.M., 2000. Comparison of sub-irrigation and overhead irrigation of tomato and lettuce seedlings. J. Hortic. Sci. Biotechnol. 75, 350–354. https://doi.org/10.1080/14620316.2000.11511249

Al-Chalabi, M., 2015. Vertical farming: Skyscraper sustainability? Sustain. Cities Soc. 18, 74–77. https://doi.org/10.1016/j.scs.2015.06.003

Amani, P., Schiefer, G., 2011. Review on Suitability of Available LCIA Methodologies for Assessing Environmental Impact of the Food Sector. Int. J. Food Syst. Dyn. 2, 194–206.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resour. Conserv. Recycl. 130, 127–139. https://doi.org/10.1016/j.resconrec.2017.11.002

AMB, 2019. Instal·lacions i equipaments - Aigua - Depuradora - EDAR [WWW Document]. URL http://www.amb.cat/ca/web/ecologia/aigua/instalacions-i-equipaments/llistat?p_p_id=EquipamentSearchListPortlet_WAR_AMBSearchPortletportlet&p_p_lifecycle=1&p_p_state=normal&_EquipamentSearchListPortlet_WAR_AMBSearchPortletportlet_pageNum=1&_EquipamentSearc (accessed 2.17.20).

Andrade, J.M., Estévez-Pérez, M.G., 2014. Statistical comparison of the slopes of two regression lines: A tutorial. Anal. Chim. Acta 838, 1–12. https://doi.org/10.1016/j.aca.2014.04.057

Angel, R., 1999. Removal of Phosphate from Sewage as Amorphous Calcium Phosphate. Environ. Technol. 20, 709–720. https://doi.org/10.1080/09593332008616865

Angrill, S., Farreny, R., Gasol, C.M., Gabarrell, X., Viñolas, B., Josa, A., Rieradevall, J., 2012. Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Int. J. Life Cycle Assess. 17, 25–42. https://doi.org/10.1007/s11367-011-0330-6

Antonini, S., Arias, M.A., Eichert, T., Clemens, J., 2012. Greenhouse evaluation and environmental impact assessment of different urine-derived struvite fertilizers as phosphorus sources for plants. Chemosphere 89, 1202–1210. https://doi.org/10.1016/J.CHEMOSPHERE.2012.07.026

Artmann, M., Sartison, K., Artmann, M., Sartison, K., 2018. The Role of Urban Agriculture as a Nature-Based Solution: A Review for Developing a Systemic Assessment Framework. Sustainability 10, 1937. https://doi.org/10.3390/su10061937

Ashley, K., Cordell, D., Mavinic, D., 2011. A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. Chemosphere 84, 737–746. https://doi.org/10.1016/j.chemosphere.2011.03.001

Astee, L.Y., Kishnani, N.T., 2010. Building Integrated Agriculture: Utilising Rooftops for Sustainable Food Crop Cultivation in Singapore. J. Green Build. 5, 105–113. https://doi.org/10.3992/jgb.5.2.105

Audsley, E., Brander, M., Chatterton, J.C., Murphy-Bokern, D., Webster, C., Williams, A.G., 2010. How low can we go? An assessment of greenhouse gas emissions from the UK foodsystem and the scope reduction by 2050. Report for the WWF and Food ClimateResearch Network.

Bach, V., Finkbeiner, M., 2017. Approach to qualify decision support maturity of new versus established impact assessment methods—demonstrated for the categories acidification and eutrophication. Int. J. Life Cycle Assess. 22, 387–397. https://doi.org/10.1007/s11367-016-1164-z

Baker, R.W., 2012. Membrane Technology and Applications, Membrane Technology. https://doi.org/10.1016/S0958-2118(96)90133-0

Baker, R.W., Cussler, E.L., Eykamp, W., Koros, W.J., Riley, R.L., Strathman, R.H., 1991. Membrane separation systems.

Ball, P., 2000. Scale-up and scale-down of membrane-based separation processes. Membr. Technol. 2000, 10–13. https://doi.org/10.1016/S0958-2118(00)86634-3

Barthel, S., Isendahl, C., 2013. Urban gardens, Agriculture, And water management:

Sources of resilience for long-term food security in cities. Ecol. Econ. 86, 224–234. https://doi.org/10.1016/j.ecolecon.2012.06.018

Bender, R.R., Haegele, J.W., Below, F.E., 2015. Nutrient uptake, partitioning, and remobilization in modern soybean varieties. Agron. J. 107, 563–573. https://doi.org/10.2134/agronj14.0435

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bocken, N.M.P., Olivetti, E.A., Cullen, J.M., Potting, J., Lifset, R., 2017. Taking the Circularity to the Next Level: A Special Issue on the Circular Economy. J. Ind. Ecol. 21, 476–482. https://doi.org/10.1111/jiec.12606

Boneta, A., Rufí-Salís, M., Ercilla-Montserrat, M., Gabarrell, X., Rieradevall, J., 2019. Agronomic and Environmental Assessment of a Polyculture Rooftop Soilless Urban Home Garden in a Mediterranean City. Front. Plant Sci. 10, 341. https://doi.org/10.3389/fpls.2019.00341

Bonvin, C., Etter, B., Udert, K.M., Frossard, E., Nanzer, S., Tamburini, F., Oberson, A., 2015. Plant uptake of phosphorus and nitrogen recycled from synthetic source-separated urine. Ambio 44, 217–227. https://doi.org/10.1007/s13280-014-0616-6

Borgerding, J., 1972. Phosphate deposits in digestion systems. J. Water Pollut. Control Fed. 44, 813–819.

Bouchaaba, Z., Santamaria, P., Choukr-Allah, R., Lamaddalena, N., Montesano, F.F., 2015. Open-cycle drip vs closed-cycle subirrigation: Effects on growth and yield of greenhouse soilless green bean. Sci. Hortic. (Amsterdam). 182, 77–85. https://doi.org/10.1016/j.scienta.2014.11.007

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31, 757–777. https://doi.org/10.1007/s13593-011-0031-3

Bouropoulos, N.C., Koutsoukos, P.G., 2000. Spontaneous precipitation of struvite from aqueous solutions. J. Cryst. Growth 213, 381–388. https://doi.org/10.1016/S0022-0248(00)00351-1

Bradford-Hartke, Z., Lane, J., Lant, P., Leslie, G., 2015. Environmental Benefits and Burdens of Phosphorus Recovery from Municipal Wastewater. Environ. Sci. Technol. 49, 8611–8622. https://doi.org/10.1021/es505102v

Brechner, M., Both, A.J., 2013. Hydroponic Lettuce Handbook, Cornell University CEA

Program.

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production. Eur. J. Agron. 20, 247–264.

Briassoulis, D., Hiskakis, M., Babou, E., 2013. Technical specifications for mechanical recycling of agricultural plastic waste. Waste Manag. 33, 1516–1530. https://doi.org/10.1016/j.wasman.2013.03.004

Bridger, G.L., Salutsky, M.L., Starostka, R.W., 1961. Metal Ammonium Phosphates as Fertilizers. 140th Meet. Am. Chem. Soc. 1–19.

Brock, A., 2008. Room to Grow: Participatory Landscapes and Urban Agriculture at NYU. Agriculture 13.

Brugnoli, E., Lauteri, M., 1991. Effects of Salinity on Stomatal Conductance, Photosynthetic Capacity, and Carbon Isotope Discrimination of Salt-Tolerant (Gossypium hirsutum L.) and Salt-Sensitive (Phaseolus vulgaris L.) C(3) Non-Halophytes. Plant Physiol. 95, 628–35. https://doi.org/10.1104/PP.95.2.628

Bryld, E., 2003. Potentials, problems, and policy implications for urban agriculture in developing countries. Agric. Human Values 20, 79–86. https://doi.org/10.1023/A:1022464607153

Buckwell, A., Nadeu, E., 2016. Nutrient Recovery and Reuse (NRR) in European agriculture. RISE, Rural Invest. Support Eur. 92.

Burrage, S.W., 2014. Soilless Culture and Water Use Efficiency for Greenhouses in Arid, Hot Climates.

Buytaert, W., De Bièvre, B., 2012. Water for cities: The impact of climate change and demographic growth in the tropical Andes. Water Resour. Res. 48, W08503. https://doi.org/10.1029/2011WR011755

Cakmak, I., 2013. Magnesium in crop production, food quality and human health. Plant Soil 368, 1–4. https://doi.org/10.1007/s11104-013-1781-2

Cao, J., Li, M., Li, S., 2011. Development strategy research of modern eco-agriculture on the basis of constructing the rural circular economy-for the example of Shandong province. Energy Procedia 5, 2504–2508. https://doi.org/10.1016/j.egypro.2011.03.430

Carmassi, G., Incrocci, L., Maggini, R., Malorgio, F., Tognoni, F., Pardossi, A., 2005. Modeling Salinity Build-Up in Recirculating Nutrient Solution Culture. J. Plant Nutr. 28, 431–445. https://doi.org/10.1081/PLN-200049163

Çelen, I., Buchanan, J.R., Burns, R.T., Bruce Robinson, R., Raj Raman, D., 2007. Using a chemical equilibrium model to predict amendments required to precipitate phosphorus as struvite in liquid swine manure. Water Res. 41, 1689–1696. https://doi.org/10.1016/j.watres.2007.01.018

Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. J. Clean. Prod. 28, 56–62. https://doi.org/10.1016/J.JCLEPRO.2011.10.021

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.-I., Rieradevall, J., 2012. Barriers and Opportunities Regarding the Implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean Cities of Europe. J. Urban Technol. 19, 87–103. https://doi.org/10.1080/10630732.2012.717685

Chaillou, S., Morot-Guadry, J., Lesaint, C., Salsac, L., Jolivet, E., 1986. Nitrate or ammonium nutrition in french bean. Plant Soil 91, 363–365.

Chatzisymeon, E., Foteinis, S., Borthwick, A.G.L., 2017. Life cycle assessment of the environmental performance of conventional and organic methods of open field pepper cultivation system. Int. J. Life Cycle Assess. 22, 896–908. https://doi.org/10.1007/s11367-016-1204-8

Chien, S.H., Menon, R.G., 1995. Factors affecting the agronomic effectiveness of phosphate rock for direct application. Fertil. Res. 41, 227–234. https://doi.org/10.1007/BF00748312

Childers, D.L., Corman, J., Edwards, M., Elser, J.J., 2011. Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle. Bioscience 61, 117–124. https://doi.org/10.1525/bio.2011.61.2.6

Choi, B.-S., Lee, S.-S., Ok, Y.-S., 2011. Effects of Waste Nutrient Solution on Growth of Chinese Cabbage (Brassica campestris L.) in Korea. Korean J. Environ. Agric. 30, 125–131. https://doi.org/10.5338/kjea.2011.30.2.125

Christie, E., 2014. Water and Nutrient Reuse within Closed Hydroponic Systems. Electron. Thesis Disseratations.

CNP-Technology Water GmbH and Biosolids, 2017. Main P-REX deliverables - Factsheets.

Cobo, S., Dominguez-Ramos, A., Irabien, A., 2018. Trade-Offs between Nutrient Circularity and Environmental Impacts in the Management of Organic Waste. Environ. Sci. Technol. 52, 10923–10933. https://doi.org/10.1021/acs.est.8b01590

Cohen and Kirchmann, 2004. INCREASING THE pH OFWASTEWATER TO HIGH LEVELS WITH DIFFERENT GASES —CO2 STRIPPING. Water. Air. Soil Pollut. 159, 265–275.

Comission, E., 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives (Waste framework, European Comission. https://doi.org/2008/98/EC.; 32008L0098

Conijn, J.G., Bindraban, P.S., Schröder, J.J., Jongschaap, R.E.E., 2018. Can our global food system meet food demand within planetary boundaries? Agric. Ecosyst. Environ. 251, 244–256. https://doi.org/10.1016/j.agee.2017.06.001

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Chang. 19, 292–305. https://doi.org/10.1016/J.GLOENVCHA.2008.10.009

Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L., 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere 84, 747–758. https://doi.org/10.1016/J.CHEMOSPHERE.2011.02.032

Cordell, D., White, S., 2011. Peak phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability 3, 2027–2049. https://doi.org/10.3390/su3102027

Corominas, L., Foley, J., Guest, J.S.S., Hospido, A., Larsen, H.F.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: state of the art. Water Res. 47, 5480–92. https://doi.org/10.1016/j.watres.2013.06.049

da Silva, D.A., Tsai, S.M., Chiorato, A.F., da Silva Andrade, S.C., de Fatima Esteves, J.A., Recchia, G.H., Carbonell, S.A.M., 2019. Analysis of the common bean (Phaseolus vulgaris L.) transcriptome regarding efficiency of phosphorus use. PLoS One 14, 1–27. https://doi.org/10.1371/journal.pone.0210428

DARPA-GENCAT, 2017. Declaració única agrària (dun-web) 2020.

de-Bashan, L.E., Bashan, Y., 2004. Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). Water Res. 38, 4222–4246. https://doi.org/10.1016/J.WATRES.2004.07.014

De Pascale, S., Maggio, A., 2005. SUSTAINABLE PROTECTED CULTIVATION AT A MEDITERRANEAN CLIMATE. PERSPECTIVES AND CHALLENGES. Acta Hortic. 29–42. https://doi.org/10.17660/ActaHortic.2005.691.1

De Zeeuw, H., 2011. Cities, climate change and urban agriculture. Urban Agric. Mag. 25, 39–42.

Deelstra, T., 1987. Urban Agriculture and the Metabolism of Cities. Food Nutr. Bull. 9, 1–3. https://doi.org/10.1177/156482658700900210

Deelstra, T., Girardet, H., 2001. Urban agriculture and sustainable cities. Urban Agric. Sustain. Cities 4, 43–65. https://doi.org/10.1177/095624789200400214

Despommier, D., 2013. Farming up the city: The rise of urban vertical farms. Trends Biotechnol. 31, 388–389. https://doi.org/10.1016/j.tibtech.2013.03.008

Dickson, N., Richard, T., Kozlowski, R., 1991. Composting To Reduce The Waste Stream-A Guide To Small Scale Food And Yard Waste Composting, NorthEast Regional Agricultural Engineering Service, Cornell University.

Doyle, J.D., Oldring, K., Churchley, J., Price, C., Parsons, S.A., 2003. Chemical Control of Struvite Precipitation. J. Environ. Eng. 129, 419–426. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:5(419)

Duke, J.A., 1983. Handbook of energy crops.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. Sci. Total Environ. 571, 522–542. https://doi.org/10.1016/J.SCITOTENV.2016.07.019

Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. Resour. Conserv. Recycl. 105, 325–346. https://doi.org/10.1016/J.RESCONREC.2015.09.016

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: A critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/J.JCLEPRO.2016.10.196

Elser, J., Bennett, E., 2011. A broken biogeochemical cycle. Nature 478, 29–31. https://doi.org/10.1038/478029a

EMF, 2015a. Circularity Indicators: An Approach to Measuring Circularity - Project Overview. Ellen MacArthur Found. 12. https://doi.org/10.1016/j.giq.2006.04.004

EMF, 2015b. Circularity Indicators: An Approach to Measuring Circularity - Methodology 1–64.

EMF, Foundation, D.P., McKinsey Center for Business and Environment, 2015. Growth within: a circular economy vision for a competitive europe. https://doi.org/Article

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

Ercilla-Montserrat, M., Muñoz, P., Montero, J.-I.I., Gabarrell, X., Rieradevall, J., Villalba, G., 2018. A study on air quality and heavy metals content of urban food produced in a Mediterranean city (Barcelona). J. Clean. Prod. 195, 385–295. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.05.183

EuRIC AISBL, 2015. Metal Recycling Factsheet.

European Comission, 2016. Paket zur Kreislaufwirtschaft. Verordnung des Europäischen Parlaments und des Rates mit Vorschriften für die Bereitstellung von

Düngeprodukten mit CE-Kennzeichnung auf dem Markt und zur Änderung der Verordnungen 0084.

European Comission, 2014. Critical raw materials | Internal Market, Industry, Entrepreneurship and SMEs [WWW Document]. URL http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en (accessed 6.25.19).

European Commission. Directorate-General for Research and Innovation, 2018. Sustainable & circular bioeconomy, the European way. Brussels, 22 October 2018. Outcome report. https://publications.europa.eu/en/publication-detail/-/publication/f57a0695-04d9-11e9-adde-01aa75ed71a1/language-en/format-PDF/source-search.

European Commission, 2020a. Circular Economy Action Plan - For a cleaner and more competitive Europe.

European Commission, 2020b. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system 1–13.

European Commission, 2020c. Circular Economy Action Plan. For a cleaner and more competitive Europe. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf.

European Commission, 2015. Closing the loop - An action plan for the circular economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels. doi:10.1017/CBO9781107415324.004.

Eurostat, 2011. Archive:Agriculture - greenhouse gas emission statistics - Statistics Explained [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Agriculture_-_greenhouse_gas_emission_statistics&oldid=158401 (accessed 7.14.20).

Eurostat, 2001. Economy-wide material flow accounts and derived indicators, Fuel.

Fan, W., Zhang, P., Xu, Z., Wei, H., Lu, N., Wang, X., Weng, B., Chen, Z., Wu, F., Dong, X., 2018. Life cycle environmental impact assessment of circular agriculture: A case study in Fuqing, China. Sustain. 10, 1–19. https://doi.org/10.3390/su10061810

FAO, 2018. Transforming Food and Agriculture To Achieve the SDGs.

FAO, 2011. The State of the World's land and water resources for Food and Agriculture. Managing systems at risk, Food and Agriculture Organization. https://doi.org/978-1-84971-326-9

FAO, 2007. AGRICULTURAL MANAGEMENT, MARKETING AND FINANCE OCCASIONAL PAPER. Profitability and sustainability of urban and peri-urban agriculture.

Feir-Walsh, B.J., Toothaker, L.E., 1974. AN EMPIRICAL COMPARISON OF THE ANOVA F-TEST, NORMAL SCORES TEST AND KRUSKAL-WALLIS TEST UNDER VIOLATION OF ASSUMPTIONS. Educ. physchological Meas. 34, 789–799.

Ferrao, P., Fernandez, J.E., 2012. Sustainable Urban Metabolism. Massachusetts Institute of Technology.

Ferreira, A.J.D., Guilherme, R.I.M.M., Ferreira, C.S.S., Oliveira, M. de F.M.L. de, 2018. Urban agriculture, a tool towards more resilient urban communities? Curr. Opin. Environ. Sci. Heal. 5, 93–97. https://doi.org/10.1016/J.COESH.2018.06.004

Finck, A., 1988. Abonos para mejorar el suelo (enmiendas) y activar el crecimiento general, in: Editorial Reverté, S.A. (Ed.), Fertilizantes y Fertilización. Fundamentos y Métodos Para La Fertilización de Los Cultivos. Barcelona, p. 442.

Foley, J., de Haas, D., Hartley, K., Lant, P., 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems. Water Res. 44, 1654–1666. https://doi.org/10.1016/j.watres.2009.11.031

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O ʼconnell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478. https://doi.org/10.1038/nature10452

Forest Research, 2020. Carbon emissions of different fuels - Forest Research [WWW Document]. URL https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/ (accessed 4.3.20).

Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023

Frischknecht, R., Editors, N.J., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Köllner, T., Loerincik, Y., Margni, M., 2007. Implementation of Life Cycle Impact Assessment Methods. Am. Midl. Nat. 150, 1–151.

Fusi, A., Castellani, V., Bacenetti, J., Cocetta, G., Fiala, M., Guidetti, R., 2016. The environmental impact of the production of fresh cut salad: a case study in Italy. Int. J. Life Cycle Assess. 21, 162–175. https://doi.org/10.1007/s11367-015-1019-z

Gangnibo, C.N., Cheng, S., Huang, L., Sambou, A., 2010. Sustainable Agriculture in Benin: Strategies for Applying the Chinese Circular Agriculture Model. J. Sustain. Dev. 3, 69–80. https://doi.org/10.5539/jsd.v3n1p69

García-Caparrós, P., Llanderal, A., El-Tarawy, A., Correia, P.J., Pestana, M., Lao, M.T., 2016. Irrigation with drainage solutions improves the growth and nutrients uptake in Juncus acutus. Ecol. Eng. 95, 237–244. https://doi.org/10.1016/j.ecoleng.2016.06.090

García-Caparrós, P., Llanderal, A., Maksimovic, I., Lao, M., 2018. Cascade Cropping System with Horticultural and Ornamental Plants under Greenhouse Conditions. Water 10, 125. https://doi.org/10.3390/w10020125

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gell, K., Ruijter, F.J. d., Kuntke, P., Graaff, M. de, Smit, A.L., 2011. Safety and Effectiveness of Struvite from Black Water and Urine as a Phosphorus Fertilizer. J. Agric. Sci. 3, p67. https://doi.org/10.5539/jas.v3n3p67

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.09.007

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Strujis, J., van Zelm, R., 2009. ReCiPe 2008.

Goldstein, B., Hauschild, M., Fern??ndez, J., Birkved, M., 2016a. Testing the environmental performance of urban agriculture as a food supply in northern climates. J. Clean. Prod. 135, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004

Goldstein, B., Hauschild, M., Fernández, J., Birkved, M., 2016b. Urban versus conventional agriculture, taxonomy of resource profiles: a review. Agron. Sustain. Dev. 36, 1–19. https://doi.org/10.1007/s13593-015-0348-4

Goonan, T.G., 2004. Copper Recycling in the United States in 2004. Flow Stud. Recycl. Met. Commod. United States 1–16.

Grange, R.I., Hand, D.W., 1987. A review of the effects of atmospheric humidity on the growth of horticultural crops. J. Hortic. Sci. 62, 125–134. https://doi.org/10.1080/14620316.1987.11515760

Gress, S.E., Nichols, T.D., Northcraft, C.C., Peterjohn, W.T., 2007. NUTRIENT LIMITATION IN SOILS EXHIBITING DIFFERING NITROGEN AVAILABILITIES: WHAT LIES BEYOND NITROGEN SATURATION?, Ecology.

Grewal, H.S., Maheshwari, B., Parks, S.E., 2011a. Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: An Australian case study. Agric. Water Manag. 98, 841–846. https://doi.org/10.1016/j.agwat.2010.12.010

Grewal, H.S., Maheshwari, B., Parks, S.E., 2011b. Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: An Australian case study. Agric. Water Manag. 98, 841–846. https://doi.org/10.1016/j.agwat.2010.12.010

Grieve, C.M., Suarez, D.L., 1997. Purslane (Portulaca oleracea L.): A halophytic crop for drainage water reuse systems. Plant Soil 192, 277–283. https://doi.org/10.1023/A:1004276804529

Guadie, A., Xia, S., Jiang, W., Zhou, L., Zhang, Z., Hermanowicz, S.W., Xu, X., Shen, S., 2014. Enhanced struvite recovery from wastewater using a novel cone-inserted fluidized bed reactor. J. Environ. Sci. (China) 26, 765–774. https://doi.org/10.1016/S1001-0742(13)60469-6

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D., Love, N.G., 2009. A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater. Environ. Sci. Technol. 43, 6126–6130. https://doi.org/10.1021/es9010515

Guo, S., Kaldenhoff, R., Uehlein, N., Sattelmacher, B., Brueck, H., 2007. Relationship between water and nitrogen uptake in nitrate- and ammonium-supplied Phaseolus vulgaris L. plants. J. Plant Nutr. Soil Sci. 170, 73–80. https://doi.org/10.1002/jpln.200625073

Haghighi, M., Barzegar, M.R., da Silva, J.A.T., 2016. The effect of municipal solid waste compost, peat, perlite and vermicompost on tomato (Lycopersicum esculentum L.) growth and yield in a hydroponic system. Int. J. Recycl. Org. Waste Agric. 5, 231–242. https://doi.org/10.1007/s40093-016-0133-7

Halberg, N., Dalgaard, R., Rasmussen, M.D., 2006. Miljøvurdering af konventionel og økologisk avl af grøntsager Livscyklusvurdering af produktion i væksthuse og på.

Hancock, N.T., Black, N.D., Cath, T.Y., 2012. A comparative life cycle assessment of hybrid osmotic dilution desalination and established seawater desalination and wastewater reclamation processes. Water Res. 46, 1145–1154. https://doi.org/10.1016/j.watres.2011.12.004

Hasler, K., Bröring, S., Omta, S.W.F., Olfs, H.-W., 2015. Life cycle assessment (LCA) of different fertilizer product types. Eur. J. Agron. 69, 41–51. https://doi.org/10.1016/j.eja.2015.06.001

Haupt, M., Hellweg, S., 2019. Measuring the environmental sustainability of a circular economy. Environ. Sustain. Indic. 1–2, 100005. https://doi.org/10.1016/j.indic.2019.100005

Haupt, M., Vadenbo, C., Hellweg, S., 2017. Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. J. Ind. Ecol. 21, 615–627. https://doi.org/10.1111/jiec.12506

Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. 22, 832–837. https://doi.org/10.1007/s11367-017-1267-1

Hauschild, M.Z., Huijbregts, M.A.J., 2015. Introducing Life Cycle Impact Assessment. pp. 1–16. https://doi.org/10.1007/978-94-017-9744-3_1

Helander, H., Petit-Boix, A., Leipold, S., Bringezu, S., 2019. How to monitor environmental pressures of a circular economy: An assessment of indicators. J. Ind. Ecol. https://doi.org/10.1111/jiec.12924

Helmes, R.J.K., Huijbregts, M.A.J., Henderson, A.D., Jolliet, O., 2012. Spatially explicit fate factors of phosphorous emissions to freshwater at the global scale. Int. J. Life Cycle Assess. 17, 646–654. https://doi.org/10.1007/s11367-012-0382-2

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods Data v2.2 (2010). ecoinvent Rep. No. 3 176.

Huijbregts, M.A.J., Steinmann, Z.J.N.N., Elshout, P.M.F.M.F., Stam, G., Verones, F., Vieira, M.D.M.D.M., Zijp, M., van Zelm, R., 2016. ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and enpoint level - Report 1: characterization. Natl. Inst. Public Heal. Environ. https://doi.org/10.1007/s11367-016-1246-y

Incrocci, L., Pardossi, A., Malorgio, F., Maggini, R., Campiotti, C.A., 2003. Cascade cropping system for greenhouse soilless culture. Acta Hortic. 609, 297–301.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories — IPCC.

IPCC, 2014. AR5 Climate Change 2014: Mitigation of Climate Change — IPCC.

IPNI, 2007. Diammonium Phosphate. Nutr. Source Specifics. https://doi.org/10.1007/978-3-540-71095-0_2853

ISO, 2020. ISO - ISO/TC 323 - Circular economy [WWW Document]. URL https://www.iso.org/committee/7203984.html (accessed 10.7.20).

ISO, 2012. ISO 14045: Environmental management — Eco-efficiency assessment of product systems — Principles, requirements and guidelines Management 2012.

ISO, 2006. ISO 14040: Environmental management – life cycle assessment – principles and framework.

ISO (2006a) ISO 14040, ISO, 2006. Environmental management — Life cycle assessment — Principles and framework Management environnemental — Principles and Framework. Int. Organ. Stand.

J. R. Buchanan, J.R., C. R. Mote, C.R., R. B. Robinson, R.B., 1994. Thermodynamics of Struvite Formation. Trans. ASAE 37, 617–621. https://doi.org/10.13031/2013.28121

Jaffer, Y., Clark, T.A., Pearce, P., Parsons, S.A., 2002. Potential phosphorus recovery by struvite formation. Water Res. 36, 1834–1842. https://doi.org/10.1016/S0043-1354(01)00391-8

Jones, A., 2002. An environmental assessment of food supply chains: A case study on dessert apples. Environ. Manage. 30, 560–576. https://doi.org/10.1007/s00267-002-2383-6

Kalantari, F., Tahir, O.M., Joni, R.A., Fatemi, E., 2018. Opportunities and challenges in sustainability of vertical farming: A review. J. Landsc. Ecol. Republic) 11, 35–60. https://doi.org/10.1515/jlecol-2017-0016

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy - From review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034

Kataki, S., West, H., Clarke, M., Baruah, D.C., 2016. Phosphorus recovery as struvite: Recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. Resour. Conserv. Recycl. 107, 142–156. https://doi.org/10.1016/J.RESCONREC.2015.12.009

Kennedy, C., Baker, L., Dhakal, S., Ramaswami, A., 2012. Sustainable Urban Systems: An Integrated Approach. J. Ind. Ecol. 16, 775–779. https://doi.org/10.1111/j.1530-9290.2012.00564.x

Kennedy, C., Cuddihy, J., Engel-yan, J., 2007. The Changing Metabolism of Cities. J. Ind. Ecol. 11.

Kern, J., Heinzmann, B., Markus, B., Kaufmann, A.C., Soethe, N., Engels, C., 2008. Recycling and Assessment of Struvite Phosphorus from Sewage Sludge. Agric. Eng. Int. CIGR J. 10, 13.

Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., Clark, S., 2014. Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. J. Clean. Prod. 73, 183–192. https://doi.org/10.1016/J.JCLEPRO.2013.09.057

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kofina, A.N., Koutsoukos, P.G., 2005. Spontaneous precipitation of struvite from synthetic wastewater solutions. Cryst. Growth Des. 5, 489–496. https://doi.org/10.1021/cg049803e

Kortright, R., Wakefield, S., 2011. Edible backyards: A qualitative study of household food growing and its contributions to food security. Agric. Human Values 28, 39–53. https://doi.org/10.1007/s10460-009-9254-1

Kouki, S., Abdi, N., Hemissi, I., Bouraoui, M., Sifi, B., 2016. Phosphorus fertilization effect on common bean (Phaseolus vulgaris L .) -rhizobia symbiosis 25, 1130–1137.

Kruskal, W.H., Wallis, W.A., 1952. Use of Ranks in One-Criterion Variance Analysis. J. Am. Stat. Assoc. 47, 583–621. https://doi.org/10.1080/01621459.1952.10483441

Kulak, M., Graves, A., Chatterton, J., 2013. Reducing greenhouse gas emissions with urban agriculture: A Life Cycle Assessment perspective. Landsc. Urban Plan. 111, 68–78. https://doi.org/10.1016/J.LANDURBPLAN.2012.11.007

Kumar, M., Badruzzaman, M., Adham, S., Oppenheimer, J., 2007. Beneficial phosphate recovery from reverse osmosis (RO) concentrate of an integrated membrane system using polymeric ligand exchanger (PLE). Water Res. 41, 2211–2219. https://doi.org/10.1016/j.watres.2007.01.042

Kumar, R.R., Cho, J.Y., 2014. Reuse of hydroponic waste solution. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-014-3024-3

La Vanguardia, 2019. Economía verde: Las infinitas vidas del aluminio, el verdadero rey del reciclado [WWW Document]. URL https://www.lavanguardia.com/economia/20191031/471280612959/aluminio-reciclaje-reciclar-latas-espana.html (accessed 4.20.20).

Latifian, M., Liu, J., Mattiasson, B., 2012. Struvite-based fertilizer and its physical and chemical properties. Environ. Technol. 33, 2691–2697. https://doi.org/10.1080/09593330.2012.676073

Le Corre, K.S., Valsami-Jones, E., Hobbs, P., Parsons, S.A., 2009. Phosphorus recovery from wastewater by struvite crystallization: A review, Critical Reviews in Environmental Science and Technology. Taylor & Francis Group . https://doi.org/10.1080/10643380701640573

Lenth, R., Buerkner, P., Herve, M., Love, J., Riebl, H., Singmann, H., 2020. Package "emmeans." https://doi.org/10.1080/00031305.1980.10483031

Lenzen, M., Peters, G.M., 2010. How City dwellers affect their resource Hinterland. J. Ind. Ecol. 14, 73–90. https://doi.org/10.1111/j.1530-9290.2009.00190.x

Levene, H., 1961. Robust tests for equality of variances. Contrib. to Probab. Stat. Essays Honor Harold Hotell. 279–292.

Li, B., Boiarkina, I., Young, B., Yu, W., Singhal, N., 2016. Prediction of Future Phosphate Rock: A Demand Based Model. J. Environ. Informatics. https://doi.org/10.3808/jei.201700364

Li, B., Boiarkina, I., Yu, W., Huang, H.M., Munir, T., Wang, G.Q., Young, B.R., 2019. Phosphorous recovery through struvite crystallization: Challenges for future design. Sci. Total Environ. 648, 1244–1256. https://doi.org/10.1016/j.scitotenv.2018.07.166

Li, X.., Zhao, Q.L., 2003. Recovery of ammonium-nitrogen from landfill leachate as a multi-nutrient fertilizer. Ecol. Eng. 20, 171–181. https://doi.org/10.1016/S0925-8574(03)00012-0

Liberti, L., Limoni, N., Lopez, A., Passing, R., Boari, G., 1986. The rim-nut process at West Bari for removal of nutrients from wastewater: First demonstration. Resour. Conserv. 12, 125–136. https://doi.org/10.1016/0166-3097(86)90022-2

Lin, B.B., Philpott, S.M., Jha, S., 2015. The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. Basic Appl. Ecol. 16, 189–201. https://doi.org/10.1016/j.baae.2015.01.005

Lin, T., Gibson, V., Cui, S., Yu, C.P., Chen, S., Ye, Z., Zhu, Y.G., 2014. Managing urban nutrient biogeochemistry for sustainable urbanization. Environ. Pollut. 192, 244–250. https://doi.org/10.1016/j.envpol.2014.03.038

Linder, M., Boyer, R.H.W., Dahllöf, L., Vanacore, E., 2020. Product-level inherent circularity and its relationship to environmental impact. J. Clean. Prod. 121096. https://doi.org/10.1016/j.jclepro.2020.121096

Linder, M., Sarasini, S., van Loon, P., 2017. A Metric for Quantifying Product-Level Circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552

Liu, Y., Rahman, M.M., Kwag, J.-H., Kim, J.-H., Ra, C., 2011. Eco-friendly Production of Maize Using Struvite Recovered from Swine Wastewater as a Sustainable Fertilizer Source. Asian-Australasian J. Anim. Sci. 24, 1699–1705. https://doi.org/10.5713/ajas.2011.11107

Liu, Y.H., Kwag, J.H., Kim, J.H., Ra, C.S., 2011. Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater. Desalination 277, 364–369. https://doi.org/10.1016/j.desal.2011.04.056

Llorach-Massana, P., 2017. Mitigating the environmental impacts of Urban Agriculture: innovative materials, GHG emissions analysis and new by-products.

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

Lohrberg, F., Lička, L., Scazzosi, L., Timpe, A., 2016. Urban agriculture Europe. Jovis.

Lonca, G., Muggéo, R., Tétreault-Imbeault, H., Bernard, S., Margni, M., 2018. A Bi-dimensional Assessment to Measure the Performance of Circular Economy: A Case Study of Tires End-of-Life Management, in: Benetto, E., Gericke, K., Guiton, M. (Eds.), Designing Sustainable Technologies, Products and Policies: From Science to Innovation. Springer International Publishing, Cham, pp. 33–42. https://doi.org/10.1007/978-3-319-66981-6_4

Lorenzo-Toja, Y., Alfonsín, C., Amores, M.J.M.J., Aldea, X., Marin, D., Moreira, M.T.M.T., Feijoo, G., Marín-Navarro, D., Moreira, M.T.M.T., Feijoo, G., 2016. Beyond the conventional life cycle inventory in wastewater treatment plants. Sci. Total Environ. 553, 71–82. https://doi.org/http://dx.doi.org/10.1016/j.scitotenv.2016.02.073

Lovell, S.T., 2010. Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States. Sustainability 2, 2499–2522. https://doi.org/10.3390/su2082499

Lundin, M., Magnus Bengtsson, A., Molander, S., 2000. Life Cycle Assessment of Wastewater Systems: Influence of System Boundaries and Scale on Calculated Environmental Loads. https://doi.org/10.1021/ES990003F

Machado, A.P., Urbano, L., Brito, A.G., Janknecht, P., Salas, J.J., Nogueira, R., 2007. Life cycle assessment of wastewater treatment options for small and decentralized communities. Water Sci. Technol. 56, 15–22. https://doi.org/10.2166/wst.2007.497

Magán, J.J., Gallardo, M., Thompson, R.B., Lorenzo, P., 2008. Effects of salinity on fruit yield and quality of tomato grown in soil-less culture in greenhouses in Mediterranean climatic conditions. Agric. Water Manag. 95, 1041–1055. https://doi.org/10.1016/j.agwat.2008.03.011

Manríquez-Altamirano, A., Sierra-Pérez, J., Muñoz, P., Gabarrell, X., 2020. Analysis of urban agriculture solid waste in the frame of circular economy: Case study of tomato crop in integrated rooftop greenhouse. Sci. Total Environ. 734, 139375. https://doi.org/10.1016/j.scitotenv.2020.139375

MAPAMA, 2014. Inventarios nacionales de emisiones a la atmósfera 1990-2012. Volumen 2: Análisis por Actividades SNAP. Tratamiento y eliminación de residuos. http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/temas/sistema-espanol-de-inventario-sei-/09%20Tratami.

Marschner, H., 1995. Mineral nutrition of higher plants. San Diego Academic P, 889. https://doi.org/http://dx.doi.org/10.1006/anbo.1996.0155

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

Martínez, M.., Sánchez, S., Jiménez, J.., El Yousfi, F., Muñoz, L., 2000. Nitrogen and phosphorus removal from urban wastewater by the microalga Scenedesmus obliquus. Bioresour. Technol. 73, 263–272. https://doi.org/10.1016/S0960-8524(99)00121-2

Matteson, K.C., Langellotto, G.A., 2010. Determinates of inner city butterfly and bee species richness. Urban Ecosyst. 13, 333–347. https://doi.org/10.1007/s11252-010-0122-y

Maurer, M., Abramovich, D., Siegrist, H., Gujer, W., 1999. Kinetics of biologically induced phosphorus precipitation in waste-water treatment. Water Res. 33, 484–493. https://doi.org/10.1016/S0043-1354(98)00221-8

Mazuela, P., Salas, C., 2005. Vegetable Waste Compost as Substrate for Melon. Commun. Soil Sci. Plant Anal. 36, 1557–1572.

Mcconville, J.R., Mihelcic, J.R., 2007. Adapting Life-Cycle Thinking Tools to Evaluate Project Sustainability in International Water and Sanitation Development Work. Environ. Eng. Sci. 24. https://doi.org/10.1089/ees.2006.0225

McDonald, R.I., Green, P., Balk, D., Fekete, B.M., Revenga, C., Todd, M., Montgomery, M., 2011. Urban growth, climate change, and freshwater availability. Proc. Natl. Acad. Sci. U. S. A. 108, 6312–7. https://doi.org/10.1073/pnas.1011615108

McDonough, W., Braungart, M., 2002. Cradle to Cradle: Remaking the Way We Make Things [WWW Document]. North Point Press. URL https://books.google.es/books?hl=ca&lr=&id=KFX5RprPGQ0C&oi=fnd&pg=PP1&ots=isCiv5qbJe&sig=Cn76GJ5PutLk6VwUnVmlWIGhsZU&redir_esc=y#v=onepage&q=cradle&f=false (accessed 9.28.20).

McLaren, S.J., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/J.JCLEPRO.2016.06.071

Mehta, C.M., Khunjar, W.O., Nguyen, V., Tait, S., Batstone, D.J., 2015. Technologies to recover nutrients from waste streams: A critical review. Crit. Rev. Environ. Sci. Technol. https://doi.org/10.1080/10643389.2013.866621

Mercabarna, 2018. Mercabarna [WWW Document]. URL http://www.mercabarna.es/ (accessed 4.20.17).

Mercadé, L., Delgado, M. del M., Gil, J.M., 2010. Pràctiques de Fertilització a Catalunya Enquesta 2010.

Meseguer-Lloret, S., 2017a. Ensayos estadísticos para comparar las pendientes de 2 rectas de calibrado: Caso práctico para varianzas NO homogéneas. [WWW Document]. URL https://riunet.upv.es/handle/10251/84444 (accessed 10.13.20).

Meseguer-Lloret, S., 2017b. Ensayos estadísticos para comparar las pendientes de 2 rectas de calibrado: Caso práctico para varianzas homogéneas. [WWW Document]. URL https://riunet.upv.es/handle/10251/84323 (accessed 10.13.20).

Miceli, A., Moncada, A., D’Anna, F., 2003. Effect of salt stress in lettuce cultivation. Acta Hortic. 609, 371–375. https://doi.org/10.17660/ActaHortic.2003.609.56

Mikkelsen, R.L., 2007. Managing potassium for organic crop production, in: HortTechnology. pp. 455–460.

Milà i Canals, L., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans, Centre for Environmental Strategy. https://doi.org/1464-8083

Milton, J.S., Tsokos, J.O., 1983. Statistical methods in the biological and health sciences.

Mok, H.-F., Williamson, V.G., Grove, J.R., Burry, K., Barker, S.F., Hamilton, A.J., 2014. Strawberry fields forever? Urban agriculture in developed countries: a review. Agron. Sustain. Dev. 34, 21–43. https://doi.org/10.1007/s13593-013-0156-7

Möller Nielsen, J., 2007. Rapport - Energin i svensk växthusodling 2007 - TOMAT.

Monteiro, A., 1994. OUTLOOK ON GROWING TECHNIQUES OF GREENHOUSE SOLANACEA IN MILD-WINTER CLIMATES. Acta Hortic. 21–32. https://doi.org/10.17660/ActaHortic.1994.366.1

Montero, J.I., Antón, A., Torroellas, M., Ruijs, M., Vermeulen, P., 2011. EUPHOROS deliverable 5. Report on environmental and economic profile of present greenhouse production systems in Europe. European Comssion FP7 RDT Project Euphoros (Reducing the need for external inputs in high value protected horticultural and ornament).

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: What do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/J.RESCONREC.2019.03.045

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., Fitzgerald, D., Treyer, K., Bourgault, G., Wernet, G., 2017. Documentation of changes implemented in the ecoinvent database v3.4 (2018.08.23). Ecoinvent V3 4, 1–97.

Moreno Ruiz, E., Valsasina, L., Brunner, F., Symeonidis, A., FitzGerald, D., Treyer, K., Bourgault, G., Wernet, G., 2018. Documentation of changes implemented in ecoinvent database v3.5. Ecoinvent, Zürich, Switzerland. 5, 1–97.

MRWA, 2009. Chapter 19: Membrane Filtration. Minnessota.

Mulder, E.G., 1956. Plant and Soil VII, no 4 NITROGEN-MAGNESIUM RELATIONSHIPS IN CROP PLANTS.

Müller, A., Sukhdev, P., 2019. Measuring what matters in agriculture and food systems.

Munch, E. V., Barr, K., 2001. Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. Water Res. 35, 151–159. https://doi.org/10.1016/S0043-1354(00)00236-0

Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Josa, A., Rufí-Salís, M., Gassó, S., Gassó-Domingo, S., Josa, A., 2020. Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. Renew. Energy 156, 696–709. https://doi.org/10.1016/j.renene.2020.04.098

Muñoz, P., Antón, A., Nuñez, M., Paranjpe, A., Ariño, J., Castells, X., Montero, J.I., Rieradevall, J., 2008. COMPARING THE ENVIRONMENTAL IMPACTS OF GREENHOUSE VERSUS OPEN-FIELD TOMATO PRODUCTION IN THE MEDITERRANEAN REGION. Acta Hortic. 1591–1596. https://doi.org/10.17660/ActaHortic.2008.801.197

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

Muñoz, P., Paranjpe, A., Montero, J.I., Antón, A., 2012. Cascade crops: An alternative solution for increasing sustainability of greenhouse tomato crops in mediterranean zone. Acta Hortic. 927, 801–805. https://doi.org/10.17660/actahortic.2012.927.99

Nadal, A., Cuerva, E., Ji, M., Josa, A., Rieradevall, J., Royapoor, M., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017. Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. Appl. Energy 187, 338–351. https://doi.org/10.1016/j.apenergy.2016.11.051

Nelson, N.O., Mikkelsen, R.L., Hesterberg, D.L., 2003. Struvite precipitation in anaerobic swine lagoon liquid: Effect of pH and Mg:P ratio and determination of rate constant. Bioresour. Technol. 89, 229–236. https://doi.org/10.1016/S0960-8524(03)00076-2

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

Niero, M., Pizzol, M., Bruun, H.G., Thomsen, M., 2014. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. J. Clean. Prod. 68, 25–35. https://doi.org/10.1016/J.JCLEPRO.2013.12.051

Nziguheba, G., Smolders, E., 2008. Inputs of trace elements in agricultural soils via phosphate fertilizers in European countries. Sci. Total Environ. 390, 53–57. https://doi.org/10.1016/J.SCITOTENV.2007.09.031

Orsini, F., Gasperi, D., Marchetti, L., Piovene, C., Draghetti, S., Ramazzotti, S., Bazzocchi, G., Gianquinto, G., 2014. Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. Food Secur. 6, 781–792. https://doi.org/10.1007/s12571-014-0389-6

Orsini, F., Kahane, R., Nono-Womdim, R., Gianquinto, G., 2013. Urban agriculture in the developing world: A review. Agron. Sustain. Dev. https://doi.org/10.1007/s13593-013-0143-z

Ostara, 2019. Technology | Ostara Nutrient Recovery [WWW Document]. URL https://ostara.com/nutrient-management-solutions/ (accessed 3.16.20).

Owen, G., Bandi, M., Howell, J.A., Churchouse, S.J., 1995. Economic assessment of membrane processes for water and waste water treatment. J. Memb. Sci. 102, 77–91. https://doi.org/10.1016/0376-7388(94)00261-V

Park, J.Y., Chertow, M.R., 2014. Establishing and testing the "reuse potential" indicator for managing wastes as resources. J. Environ. Manage. 137, 45–53. https://doi.org/10.1016/j.jenvman.2013.11.053

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87, 139–148. https://doi.org/10.1016/J.JCLEPRO.2014.10.007

Peña, C., Civit, B., Gallego-schmid, A., Druckman, A., 2020. Using Life Cycle Assessment to achieve a circular economy. Life Cycle Initiat. 1–2.

People's Republic of China, 2008. Circular Economy Promotion Law of the People's Republic of China.

Pérez-González, A., Urtiaga, A.M., Ibáñez, R., Ortiz, I., 2012. State of the art and review on the treatment technologies of water reverse osmosis concentrates. Water Res. https://doi.org/10.1016/j.watres.2011.10.046

Petit-Boix, A., Devkota, J., Phillips, R., Vargas-Parra, M.V., Josa, A., Gabarrell, X., Rieradevall, J., Apul, D., 2018. Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: Implications of urban form and water demand patterns in the US and Spain. Sci. Total Environ. 621, 434–443. https://doi.org/10.1016/j.scitotenv.2017.11.206

Petit-Boix, A., Leipold, S., 2018. Circular economy in cities: Reviewing how environmental research aligns with local practices. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.05.281

Petit-Boix, A., Llorach-Massana, P., Sanjuan-Delmás, D., Sierra-Pérez, J., Vinyes, E., Gabarrell, X., Rieradevall, J., Sanyé-Mengual, E., 2017. Application of life cycle thinking towards sustainable cities: A review. J. Clean. Prod. 166, 939–951. https://doi.org/10.1016/j.jclepro.2017.08.030

Petruzzelli, D., Dell'Erba, A., Liberti, L., Notarnicola, M., Sengupta, A.., 2004. A phosphate-selective sorbent for the REM NUT® process: field experience at Massafra Wastewater Treatment Plant. React. Funct. Polym. 60, 195–202. https://doi.org/10.1016/j.reactfunctpolym.2004.02.023

Piekema, P., Giesen, A., 2001. Phosphate recovery by the crystallisation process: experience and developments. Environ. Technol. 21.

Pons, O., Nadal, A., Sanyé-Mengual, E., Llorach-Massana, P., Cuerva, E., Sanjuan-Delmàs, D., Muñoz, P., Oliver-Solà, J., Planas, C., Rovira, M.R., 2015. Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism. Procedia Eng. 123, 441–448. https://doi.org/10.1016/j.proeng.2015.10.084

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science (80-.). 360, 987–992. https://doi.org/10.1126/science.aaq0216

Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. Eur. J. Agron. 10, 23–36. https://doi.org/10.1016/S1161-0301(98)00047-1

Postel, S., 1993. Facing water scarcity. TT -. New York New York W.W. Norton 1993., pp. 21-41,204-209.

Prasad, P.V. V., Staggenborg, S.A., Ristic, Z., 2008. Impacts of Drought and/or Heat Stress on Physiological, Developmental, Growth, and Yield Processes of Crop Plants, in: Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, pp. 301–355. https://doi.org/10.2134/advagricsystmodel1.c11

Qiao, F., Qiao, N., 2013. Circular Economy: An Ethical and Sustainable Economic Development Model. Prakseologia 253–272.

Qiu, G., Ting, Y.P., 2014. Direct phosphorus recovery from municipal wastewater via osmotic membrane bioreactor (OMBR) for wastewater treatment. Bioresour. Technol. 170, 221–229. https://doi.org/10.1016/j.biortech.2014.07.103

Rahman, M.M., Salleh, M.A.M., Rashid, U., Ahsan, A., Hossain, M.M., Ra, C.S., 2014. Production of slow release crystal fertilizer from wastewaters through struvite crystallization – A review. Arab. J. Chem. 7, 139–155. https://doi.org/10.1016/j.arabjc.2013.10.007

Razza, F., Briani, C., Breton, T., Marazza, D., 2020. Metrics for quantifying the circularity of bioplastics: the case of bio-based and biodegradable mulch films. Resour. Conserv. Recycl. In press. https://doi.org/10.1016/j.resconrec.2020.104753

REE, 2018. El sistema eléctrico español, El sistema eléctrico español.

Rees, W., Wackernagel, M., 1996. Urban ecological footprints: Why cities cannot be sustainable - and why they are a key to sustainability. Environ. Impact Assess. Rev. 16, 223–248. https://doi.org/10.1016/S0195-9255(96)00022-4

Rittmann, B.E., Mayer, B., Westerhoff, P., Edwards, M., 2011. Capturing the lost phosphorus. Chemosphere 84, 846–853. https://doi.org/10.1016/J.CHEMOSPHERE.2011.02.001

Robles, Á., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Giménez, J.B., Martí, N., Ribes, J., Ruano, M.V., Serralta, J., Ferrer, J., Seco, A., 2020. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy. Bioresour. Technol. 300, 122673. https://doi.org/10.1016/j.biortech.2019.122673

Román, P., Martínez, M.M., Pantoja, A., 2013. Manual de compostaje del agricultor, Oficina Regional de la FAO para América Latina y el Caribe.

Romero-Gámez, M., Audsley, E., Suárez-Rey, E.M., 2014. Life cycle assessment of cultivating lettuce and escarole in Spain. J. Clean. Prod. 73, 193–203. https://doi.org/10.1016/J.JCLEPRO.2013.10.053

Romero-Gámez, M., Suárez-Rey, E.M.M., Antón, A., Castilla, N., Soriano, T., 2012. Environmental impact of screenhouse and open-field cultivation using a life cycle analysis: The case study of green bean production. J. Clean. Prod. 28, 63–69. https://doi.org/10.1016/j.jclepro.2011.07.006

Roy, P.O., Azevedo, L.B., Margni, M., van Zelm, R., Deschênes, L., Huijbregts, M.A.J., 2014. Characterization factors for terrestrial acidification at the global scale: A systematic analysis of spatial variability and uncertainty. Sci. Total Environ. 500–501, 270–276. https://doi.org/10.1016/j.scitotenv.2014.08.099

Royal Haskoning DHV, 2019. Crystalactor Water Technology [WWW Document]. URL https://www.royalhaskoningdhv.com/crystalactor (accessed 3.5.19).

Rufí-Salís, Martí, Brunnhofer, N., Petit-Boix, A., Gabarrell, X., Guisasola, A., Villalba, G., 2020a. Can wastewater feed cities? Determining the feasibility and environmental burdens of struvite recovery and reuse for urban regions. Sci. Total Environ. 737, 139783. https://doi.org/10.1016/J.SCITOTENV.2020.139783

Rufí-Salís, M., Calvo, M.J., Petit-Boix, A., Villalba, G., Gabarrell, X., 2020. Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. Resour. Conserv. Recycl. 155. https://doi.org/10.1016/j.resconrec.2020.104683

Rufí-Salís, Martí, Petit-Boix, A., Villalba, G., Ercilla-Montserrat, M., Sanjuan-Delmás, D., Parada, F., Arcas, V., Muñoz-Liesa, J., Gabarrell, X., 2020b. Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. Int. J. Life Cycle Assess. 25, 564–576. https://doi.org/10.1007/s11367-019-01724-5

Rufí-Salís, Martí, Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020c.

Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? J. Clean. Prod. 261, 121213. https://doi.org/10.1016/J.JCLEPRO.2020.121213

Rynk, R., van de Kamp, M., Willson, G.B., Singley, M.E., Richard, T.L., Kolega, J.J., Gouin, F.R., Laliberty, L., Kay, D., Murphy, D.W., Hoitink, H.A., Brinton, W.F., 1992. On-Farm Composting Handbook. Monogr. Soc. Res. Child Dev. 77, 132. https://doi.org/10.1111/j.1540-5834.2012.00684.x

Saidani, M., Cluzel, F., Leroy, Y., Yannou, B., 2019a. Testing the robustness of circularity indicators: Empirical insights from workshops on an industrial product. Proc. Int. Conf. Eng. Des. ICED 2019-Augus, 3401–3410. https://doi.org/10.1017/dsi.2019.347

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019b. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/J.JCLEPRO.2018.10.014

Samarakoon, U.C., Fyffe, C., Bale, J., Ling, P., Basnagala, S., Donley, N., Altland, J., 2019. Effect of electrical conductivity on the productivity and nutrient uptake of Lactuca sativa L. Grown using nutrient film technique (NFT). Acta Hortic. 1266, 137–143. https://doi.org/10.17660/ActaHortic.2019.1266.19

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

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

Sanjuan Delmás, D., 2017. Environmental assessment of water supply: cities and vertical farming buildings.

Santagata, R., Zucaro, A., Viglia, S., Ripa, M., Tian, X., Ulgiati, S., 2020. Assessing the sustainability of urban eco-systems through Emergy-based circular economy indicators. Ecol. Indic. 109, 105859. https://doi.org/10.1016/j.ecolind.2019.105859

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015a. Integrating Horticulture into Cities: A Guide for Assessing the Implementation Potential of Rooftop Greenhouses (RTGs) in Industrial and Logistics Parks. J. Urban Technol. 22, 87–111. https://doi.org/10.1080/10630732.2014.942095

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

Sanyé-Mengual, E., Gasperi, D., Michelon, N., Orsini, F., Ponchia, G., Gianquinto, G., Sanyé-Mengual, E., Gasperi, D., Michelon, N., Orsini, F., Ponchia, G., Gianquinto, G., 2018. Eco-Efficiency Assessment and Food Security Potential of Home Gardening: A Case Study in Padua, Italy. Sustainability 10, 2124. https://doi.org/10.3390/su10072124

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

Sanyé-Mengual, E., Orsini, F., Oliver-Solà, J., Rieradevall, J., Montero, J.I., Gianquinto, G., 2015c. Techniques and crops for efficient rooftop gardens in Bologna, Italy. Agron. Sustain. Dev. 35, 1477–1488. https://doi.org/10.1007/s13593-015-0331-0

Sarvajayakesavalu, S., Lu, Y., Withers, P.J.A., Pavinato, P.S., Pan, G., Chareonsudjai, P., 2018. Phosphorus recovery: a need for an integrated approach. Ecosyst. Heal. Sustain. 4, 48–57. https://doi.org/10.1080/20964129.2018.1460122

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environ. Dev. 17, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Savvas, D., Gianquinto, G., Tuzel, Y., Gruda, N., 2013. Soilless culture, Good Agricultural Practices for greenhouse vegetable crops. https://doi.org/10.1201/b13737-8

Scarascia-Mugnozza, G., Sica, C., Russo, G., 2012. Plastic Materials in European Agriculture: Actual Use and Perspectives. J. Agric. Eng. 42, 15. https://doi.org/10.4081/jae.2011.28

Schachtman, D.P., Reid, R.J., Ayling, S.M., 1998. Update on Phosphorus Uptake Phosphorus Uptake by Plants: From Soil to Cell.

Schade, C., Pimentel, D., 2010. Population crash: Prospects for famine in the twenty-first century. Environ. Dev. Sustain. 12, 245–262. https://doi.org/10.1007/s10668-009-9192-5

Schmid, D., 2019. Recycling of plastic packaging waste in the EU 2017 | Statista [WWW Document]. URL https://www.statista.com/statistics/812510/plastic-packaging-waste-recycling-eu-by-country/ (accessed 4.20.20).

Seckler, M.M., Bruinsma, O.S.L., Van Rosmalen, G.M., 1996. Calcium phosphate precipitation in a fluidized bed in relation to process conditions: A black box approach. Water Res. 30, 1677–1685. https://doi.org/10.1016/0043-1354(96)00043-7

SEDAC, 2016. Gridded Population of the World (GPW), v4 [WWW Document]. URL http://sedac.ciesin.columbia.edu/data/collection/gpw-v4 (accessed 11.27.17).

Seemann, J.R., Critchley, C., 1985. Effects of salt stress on the growth, ion content, stomatal behaviour and photosynthetic capacity of a salt-sensitive species, Phaseolus vulgaris L. Planta 164, 151–162. https://doi.org/10.1007/BF00396077

Sena, M., Hicks, A., 2018. Life cycle assessment review of struvite precipitation in wastewater treatment. Resour. Conserv. Recycl. 139, 194–204. https://doi.org/10.1016/j.resconrec.2018.08.009

Sengupta, S., Pandit, A., 2011. Selective removal of phosphorus from wastewater combined with its recovery as a solid-phase fertilizer. Water Res. 45, 3318–3330. https://doi.org/10.1016/J.WATRES.2011.03.044

Serio, F., Elia, A., 2001. Electrical Conductivity of Nutrient Solution. Acta 559, 563–568.

Shannon, M.C., Grieve, C.M., Lesch, S.M., Draper, J.H., 2000. Analysis of salt tolerance in nine leafy vegetables irrigated with saline drainage water. J. Am. Soc. Hortic. Sci. 125, 658–664. https://doi.org/10.21273/JASHS.125.5.658

Shapiro, S.S., Wilk, M.B., 1965. An Analysis of Variance Test for Normality (Complete Samples). Biometrika 52, 591. https://doi.org/10.2307/2333709

Shiina, T., Hosokawa, D., Roy, P., Nakamura, N., Thammawong, M., Orikasa, T., 2011. LIFE CYCLE INVENTORY ANALYSIS OF LEAFY VEGETABLES GROWN IN TWO TYPES OF PLANT FACTORIES. Acta Hortic. 115–122. https://doi.org/10.17660/ActaHortic.2011.919.14

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

Siddiqi, M.Y., Kronzucker, H.J., Britto, D.T., Glass, A.D.M., 1998. Growth of a tomato crop at reduced nutrient concentrations as a strategy to limit eutrophication. J. Plant Nutr. 21, 1879–1895. https://doi.org/10.1080/01904169809365530

Singh, H., Dunn Bruce, 2016. Electrical Conductivity and pH Guide for Hydroponics.

Smit, J., Nasr, J., 1992. Urban agriculture for sustainable cities: using wastes and idle land and water bodies as resources. Environ. Urban. 4, 141–152. https://doi.org/10.1177/095624789200400214

Smit, J., Nasr, J., Ratta, A., 2001. Urban Agriculture Food, Jobs and Sustainable Cities 2001 Edition Cities That Feed Themselves.

Song, Y., Yuan, P., Zheng, B., Peng, J., Yuan, F., Gao, Y., 2007. Nutrients removal and recovery by crystallization of magnesium ammonium phosphate from synthetic swine wastewater. Chemosphere 69, 319–324. https://doi.org/10.1016/j.chemosphere.2007.06.001

Song, Y.H., Qiu, G.L., Yuan, P., Cui, X.Y., Peng, J.F., Zeng, P., Duan, L., Xiang, L.C., Qian, F., 2011. Nutrients removal and recovery from anaerobically digested swine wastewater by struvite crystallization without chemical additions. J. Hazard. Mater. 190, 140–149. https://doi.org/10.1016/j.jhazmat.2011.03.015

Sostenipra, 2016. Fertilecity [WWW Document]. URL http://www.fertilecity.com/ (accessed 4.20.17).

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2014. Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. Agric. Human Values 31, 33–51. https://doi.org/10.1007/s10460-013-9448-4

Spiertz, H., 2010. Food production, crops and sustainability: Restoring confidence in science and technology. Curr. Opin. Environ. Sustain. https://doi.org/10.1016/j.cosust.2010.10.006

Steen, I., 1998. Phosphorus availability in the 21st Century: Management of a non-renewable resource. Phosphorus and Potassium 25–31.

Stoughton, K.M., Duan, X., Wendi, E., 2013. Reverse Osmosis Optimization. U.S. Dep. Energy 9–17. https://doi.org/10.1002/9780470882634

Stratful, I., Scrimshaw, M.D., Lester, J.N., 2004. Removal of Struvite to Prevent Problems Associated with its Accumulation in Wastewater Treatment Works. Water Environ. Res. 76, 437–443. https://doi.org/10.2175/106143004X151491

Talboys, P.J., Heppell, J., Roose, T., Healey, J.R., Jones, D.L., Withers, P.J.A., 2016. Struvite: a slow-release fertiliser for sustainable phosphorus management? Plant Soil 401, 109–123. https://doi.org/10.1007/s11104-015-2747-3

Taylor, R.W., Carandang, J.S., Alexander, C., Calleja, J.S., 2012. Making Global Cities Sustainable: Urban Rooftop Hydroponics for Diversified Agriculture in Emerging Economies. OIDA Int. J. Sustain. Dev. 05, 17–28.

Tchobanoglous, G., Burton, F.L., Stensel, H.D., 2003. Wastewater Engineering: Treatment and Reuse. Metcalf & Eddy, Inc., Engineering. https://doi.org/10.1016/0309-1708(80)90067-6

The White House, 2012. National bioeconomy blueprint.

Theodorou, M.E., Plaxton, W.C., 1993. Metabolic Adaptations of Plant Respiration to Nutritional Phosphate Deprivation. Plant Physiol. 101, 339–344. https://doi.org/10.1104/PP.101.2.339

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B., Sawicka, M., 2015. Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). Renew. Agric. Food Syst. 30, 43–54. https://doi.org/10.1017/S1742170514000143

Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., Rieradevall, J., 2018. Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. J. Ind. Ecol. https://doi.org/10.1111/jiec.12829

Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P., Montero, J.I., 2012. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17, 863–875. https://doi.org/10.1007/s11367-012-0409-8

Trendov, N.M., 2017. Index of Circular Agriculture Development in the Republic of Macedonia. Visegr. J. Bioeconomy Sustain. Dev. 6, 35–38. https://doi.org/10.1515/vjbsd-2017-0006

UN, 2018. World Urbanization Prospects, Demographic Research. https://doi.org/10.4054/demres.2005.12.9

UNEP, 2011. Recycling Rates of Metals, a status report, Recycling Rates of Metals, a status report.

UNIDO, 2008. Public goods for economic development.

United Nations, 2014. 2014 revision of the World Urbanization Prospects.

United Nations, 2004. WORLD POPULATION TO 2300.

Urrestarazu, M., Mazuela, P.C., Martínez, G.A., 2008. Effect of substrate reutilization on yield and properties of melon and tomato crops. J. Plant Nutr. 31, 2031–2043. https://doi.org/10.1080/01904160802405420

USDA, 2019. FoodData Central [WWW Document]. URL https://fdc.nal.usda.gov/index.html (accessed 10.15.19).

Uysal, A., Demir, S., Sayilgan, E., Eraslan, F., Kucukyumuk, Z., 2014. Optimization of struvite fertilizer formation from baker's yeast wastewater: Growth and nutrition of maize and tomato plants. Environ. Sci. Pollut. Res. 21, 3264–3274. https://doi.org/10.1007/s11356-013-2285-6

Valencia, E., 2017. 7 steps to a combined circular economy and LCA in SimaPro [WWW Document]. PRé Sustain. URL https://simapro.com/2017/7-steps-to-a-combined-circular-economy-lca-study-in-simapro/ (accessed 3.3.20).

van Dijk, J.C., Braakensiek, H., 1985. Phosphate Removal by Crystallization in a Fluidized Bed. Water Sci. Technol. 17.

Van Kauwenbergh, S.J., 2010. World Phosphate Rock Reserves and Resources Technical Bulletin IFDC-T-75, IFDC. https://doi.org/ISBN 978-9-88999-167-3

Van Os, E.A., 1999. Closed soilless growing systems: a sustainable solution for dutch greenhouse horticulture. Water Sci. Technol. 39, 105–112.

https://doi.org/10.2166/wst.1999.0228

Van Zelm, R., Huijbregts, M.A.J., Van De Meent, D., 2009. USES-LCA 2.0-a global nested multi-media fate, exposure, and effects model. Int. J. Life Cycle Assess. 14, 282–284. https://doi.org/10.1007/s11367-009-0066-8

Vanham, D., Mak, T.N., Gawlik, B.M., 2016. Urban food consumption and associated water resources: The example of Dutch cities. Sci. Total Environ. 565, 232–239. https://doi.org/10.1016/j.scitotenv.2016.04.172

Villarín, M.C., Merel, S., 2020. Paradigm shifts and current challenges in wastewater management. J. Hazard. Mater. 390, 122139. https://doi.org/10.1016/j.jhazmat.2020.122139

Voogt, W., Sonneveld, C., 1997. Nutrient Management in Closed Growing Systems for Greenhouse Production, in: Plant Production in Closed Ecosystems. Springer Netherlands, Dordrecht, pp. 83–102. https://doi.org/10.1007/978-94-015-8889-8_6

Vox, G., Teitel, M., Pardossi, A., Minuto, A., Tinivella, F., Schettini, E., 2010. Sustainable agriculture : technology, planning and management. Nova Science Publishers.

Walker, S., Coleman, N., Hodgson, P., Collins, N., Brimacombe, L., 2018. Evaluating the environmental dimension of material efficiency strategies relating to the circular economy. Sustain. 10, 1–14. https://doi.org/10.3390/su10030666

Wang, M., Zheng, Q., Shen, Q., Guo, S., 2013. The critical role of potassium in plant stress response. Int. J. Mol. Sci. https://doi.org/10.3390/ijms14047370

Wang, T., Müller, D.B., Graedel, T.E., 2007. Forging the Anthropogenic Iron Cycle. https://doi.org/10.1021/ES062761T

Wang, X., Wang, C., Tang, C.Y., Hu, T., Li, X., Ren, Y., 2017. Development of a novel anaerobic membrane bioreactor simultaneously integrating microfiltration and forward osmosis membranes for low-strength wastewater treatment. J. Memb. Sci. 527, 1–7. https://doi.org/10.1016/j.memsci.2016.12.062

Weber, C.F., 2016. Nutrient Content of Cabbage and Lettuce Microgreens Grown on Vermicompost and Hydroponic Growing Pads. J. Hortic. 03, 1–6. https://doi.org/10.4172/2376-0354.1000190

Welch, B.L., 1938. THE SIGNIFICANCE OF THE DIFFERENCE BETWEEN TWO MEANS WHEN THE POPULATION VARIANCES ARE UNEQUAL. Biometrika 29, 350–362. https://doi.org/10.1093/biomet/29.3-4.350

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

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Vara Prasad, P.., 2000.

Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159–167. https://doi.org/10.1016/S0167-8809(00)00224-3

Willett, W.C., Sacks, F., Trichopoulou, A., Drescher, G., Ferro-Luzzi, A., Helsing, E., Trichopoulos, D., 1995. Mediterranean diet pyramid: a cultural model for healthy eating. Am. J. Clin. Nutr. 61, 1402S-1406S.

Wilsenach, J.A., Schuurbiers, C.A.H., van Loosdrecht, M.C.M., 2007. Phosphate and potassium recovery from source separated urine through struvite precipitation. Water Res. 41, 458–466. https://doi.org/10.1016/j.watres.2006.10.014

Wolman, A., 1965. The Metabolism of Cities Author (s): Abel Wolman Source : Scientific American , Vol . 213 , No . 3 (September 1965), pp . 178-193 Published by : Scientific American , a division of Nature America , Inc . Stable URL : https://www.jstor.org/stable/10.23 213, 178–193.

Worku, W., Skjelvåg, A.O., Gislerød, H.R., 2004. Responses of common bean (Phaseolus vulgaris L.) to photosynthetic irradiance levels during three phenological phases. Agronomie 24, 267–274. https://doi.org/10.1051/agro:2004024

WRF, EPRI, 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries - 4454 [WWW Document]. URL http://www.waterrf.org/Pages/Projects.aspx?PID=4454 (accessed 6.25.19).

Xie, M., Shon, H.K., Gray, S.R., Elimelech, M., 2016. Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction. Water Res. https://doi.org/10.1016/j.watres.2015.11.045

Xu, K., Wang, C., Liu, H., Qian, Y., 2011. Simultaneous removal of phosphorus and potassium from synthetic urine through the precipitation of magnesium potassium phosphate hexahydrate. Chemosphere 84, 207–212. https://doi.org/10.1016/j.chemosphere.2011.04.057

Xu, K., Wang, C., Wang, X., Qian, Y., 2012. Laboratory experiments on simultaneous removal of K and P from synthetic and real urine for nutrient recycle by crystallization of magnesium-potassium-phosphate-hexahydrate in a draft tube and baffle reactor. Chemosphere 88, 219–223. https://doi.org/10.1016/j.chemosphere.2012.02.061

Yetilmezsoy, K., Ilhan, F., Kocak, E., Akbin, H.M., 2017. Feasibility of struvite recovery process for fertilizer industry: A study of financial and economic analysis. J. Clean. Prod. 152, 88–102. https://doi.org/10.1016/J.JCLEPRO.2017.03.106

Yuan, P., Kim, Y., 2017. Increasing phosphorus recovery from dewatering centrate in microbial electrolysis cells. Biotechnol. Biofuels 10. https://doi.org/10.1186/s13068-017-0754-8

Zabaniotou, A., Rovas, D., Libutti, A., Monteleone, M., 2015. Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill. Environ. Dev. 14, 22–36. https://doi.org/10.1016/j.envdev.2014.12.002

Zezza, A., Tasciotti, L., 2010. Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. Food Policy 35, 265–273. https://doi.org/10.1016/j.foodpol.2010.04.007

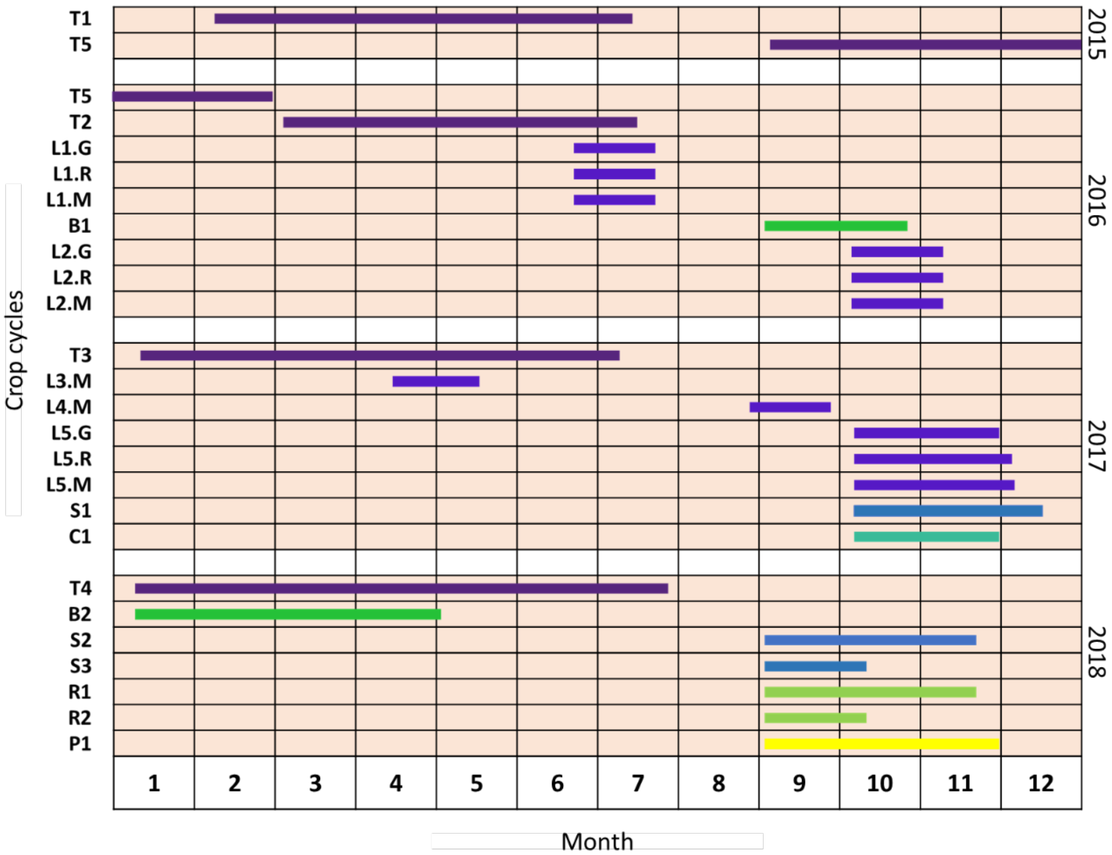
Zhang, C.H., Kang, H.-M., Kim, I.S., 2006. Effect of Using Waste Nutrient Solution Fertigation on the Musk Melon and Cucumber Growth. Prot. Hortic. Plant Fact.

Appendix

Appendix

Appendix 1. Supporting data related to Chapter 3

Appendix 1.1 Crop cycles considered in the study. T – Tomato; L – Lettuce; .G – Green oak variety; .R – Red oak variety; .M – Maravilla variety; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.

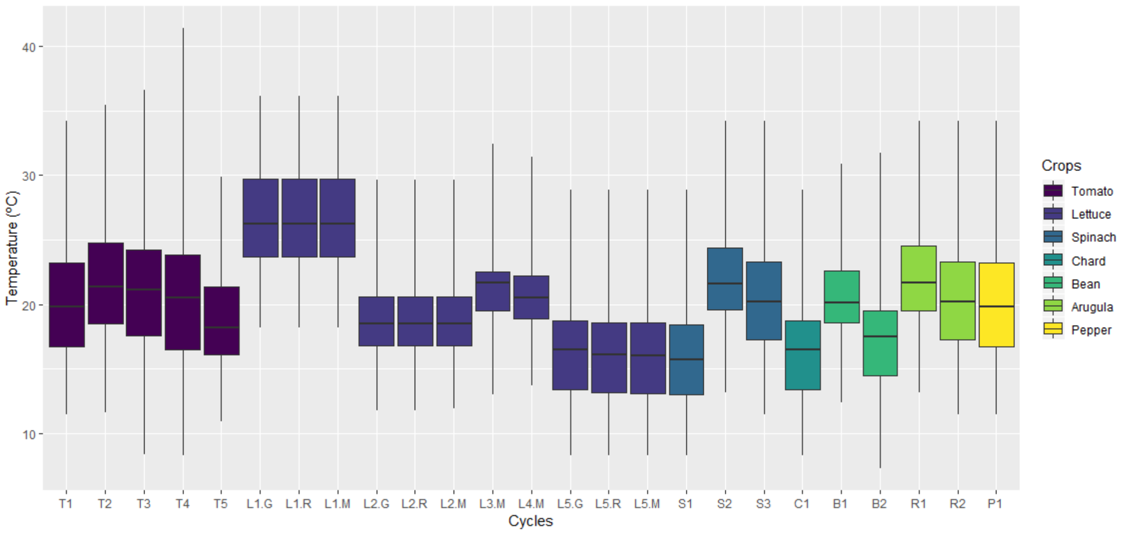


Appendix 1.2 Energy content of different vegetables. Source: USDA (2019)

Energy content of different vegetables. Source: USDA (2019)

Vegetables	Kcal/100g
Tomatoes, raw	18
Iceberg lettuce, raw	14
Green leaf lettuce, raw	15
Red leaf lettuce, raw	13
Spinach, raw	23
Chard, raw	19
Green bean, raw	31
Arugula, raw	25
Green pepper, raw	20

Appendix 1.3 Representation of maximum, minimum and median temperatures for all crop cycles grown in the i-RTG. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.



Appendix 1.4 Kg of fertilizer applied to every crop cycle considering the normalization value of 171 plants per cycle. T: Tomato; L: Lettuce; .G: Green Oak Lettuce; .R:Red Oak Lettuce; .M: Maravilla Lettuce; B: Green Bean; S: Spinach; C: Chard; R: Arugula; P: Green Pepper.

CYCLE	KPO_4H_2	KNO_3	K_2SO_4	$Ca(NO_3)_2$	$CaCl_2$	$Mg(NO_3)_2$	Hortrilon	Sequestrene
T1	11.20	18.60	26.90	34.60	10.90	22.90	0.80	0.80
T2	5.70	12.70	10.90	13.70	4.60	9.30	0.40	0.40
T3	8.50	9.90	27.20	31.80	9.50	4.90	0.60	0.60
T4	10.58	7.86	16.92	19.14	8.64	11.54	0.78	0.78
T5	5.19	11.55	9.95	12.51	4.23	8.48	0.38	0.38
L1.G	0.28	0.00	1.08	1.02	0.00	0.31	0.02	0.02
L1.R	0.28	0.00	1.08	1.02	0.00	0.31	0.02	0.02
L1.M	0.29	0.00	1.09	1.02	0.00	0.31	0.02	0.02
L2.G	0.50	1.12	0.96	1.21	0.41	0.82	0.04	0.04
L2.R	0.51	1.12	0.97	1.22	0.41	0.82	0.04	0.04
L2.M	0.51	1.13	0.97	1.22	0.42	0.83	0.04	0.04
L3.M	0.47	1.06	0.91	1.14	0.39	0.77	0.03	0.03
L4.M	0.45	0.99	0.85	1.08	0.36	0.73	0.03	0.03
L5.G	0.80	1.77	1.53	1.92	0.65	1.30	0.06	0.06
L5.R	0.87	1.93	1.66	2.09	0.71	1.41	0.06	0.06
L5.M	0.88	1.96	1.69	2.12	0.72	1.43	0.06	0.06
S1	1.16	2.58	2.22	2.79	0.95	1.89	0.09	0.09
S2	0.56	0.41	0.89	0.67	0.46	0.61	0.04	0.04
S3	1.16	0.86	1.86	1.40	0.95	1.26	0.09	0.09
C1	0.80	1.77	1.53	1.92	0.65	1.30	0.06	0.06
B1	0.91	0.67	1.45	1.09	0.74	0.99	0.07	0.07
B2	1.66	1.23	2.66	2.00	1.36	1.81	0.12	0.12
R1	0.56	0.41	0.89	0.67	0.46	0.61	0.04	0.04
R2	1.16	0.86	1.86	1.40	0.95	1.26	0.09	0.09
P1	1.28	0.95	2.06	1.55	1.05	1.40	0.09	0.09

Appendix 1.5 Temperature statistics of all crop cycles. . T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.

Cycle	Year	Mean	Median	Minimum	Maximum	P_{25}	P_{75}	St. Dev.	Variance
T1	2015	20.3	19.8	11.5	34.2	16.7	23.2	4.6	21.4
T2	2016	21.7	21.4	11.6	35.4	18.5	24.8	4.2	17.3
T3	2017	21.1	21.1	8.4	36.6	17.6	24.2	4.7	21.9
T4	2018	20.3	20.5	8.3	41.4	16.5	23.8	5.0	25.2
T5	2015	18.8	18.2	10.9	29.9	16.1	21.4	3.4	11.5
L1.G	2016	26.7	26.2	18.2	36.1	23.7	29.7	3.8	14.1
L1.R	2016	26.7	26.2	18.2	36.1	23.7	29.7	3.8	14.1
L1.M	2016	26.7	26.2	18.2	36.1	23.7	29.7	3.8	14.1
L2.G	2016	18.9	18.5	11.8	29.6	16.8	20.6	3.2	10.2
L2.R	2016	18.9	18.5	11.8	29.6	16.8	20.6	3.2	10.2
L2.M	2016	18.9	18.5	11.9	29.6	16.8	20.6	3.2	10.2
L3.M	2017	21.3	21.7	13.0	32.4	19.5	22.5	2.8	8.1
L4.M	2017	20.7	20.5	13.7	31.4	18.9	22.2	2.7	7.1
L5.G	2017	16.4	16.5	8.3	28.9	13.4	18.7	3.8	14.1
L5.R	2017	16.2	16.1	8.3	28.9	13.2	18.6	3.7	14.0
L5.M	2017	16.1	16.0	8.3	28.9	13.1	18.6	3.7	14.0
S1	2017	15.9	15.7	8.3	28.9	13.0	18.4	3.6	12.9
S2	2018	22.2	21.6	13.2	34.2	19.6	24.4	3.8	14.8
S3	2018	20.6	20.2	11.5	34.2	17.3	23.3	4.5	19.9
C1	2017	16.4	16.5	8.3	28.9	13.4	18.7	3.8	14.1
B1	2016	20.7	20.1	12.4	30.9	18.6	22.6	2.8	7.5
B2	2018	17.4	17.5	7.3	31.7	14.5	19.5	4.1	16.7
R1	2018	22.2	21.7	13.2	34.2	19.5	24.5	4.0	15.7
R2	2018	20.6	20.2	11.5	34.2	17.3	23.3	4.5	19.9
P1	2018	20.3	19.8	11.5	34.2	16.7	23.2	4.6	21.4

Appendix 1.6 Summary of impact per different functional units of the crop cycles. IC: Impact Category; FU: Functional Unit; CC: Climate Change; TA: Terrestrial Acidifaction; FE: Freshwater Eutrophication; ME: Marine Eutrophication; FDP: Fossil Depletion; ET: Ecotoxicity; T: Tomato; L: Lettuce; .G: Green Oak Lettuce; .R:Red Oak Lettuce; .M: Maravilla Lettuce; B: Green Bean; S: Spinach; C: Chard; R: Arugula; P: Green Pepper.

IC [UNITS]	CC [kg CO2 eq]		TA [kg SO2 eq]		FE [kg P eq]		ME [kg N eq]		FDP [kg oil eq]		ET [kg 1,4-DB eq]	
FU	kg	€	Kg	€	kg	€	Kg	€	kg	€	Kg	€
T1	4.57E-01	4.56E-01	2.23E-03	2.23E-03	1,87E-01	1,52E-04	1,52E-04	1,68E-01	1.15E-01	1.14E-01	1.40E-02	1.40E-02
T2	4.19E-01	5.26E-01	1.94E-03	2.44E-03	1,14E-01	1,29E-04	1,62E-04	1,03E-01	1.14E-01	1.43E-01	1.07E-02	1.35E-02
T3	3.76E-01	4.86E-01	1.85E-03	2.38E-03	1,74E-01	1,21E-04	1,56E-04	1,66E-01	1.02E-01	1.31E-01	1.02E-02	1.32E-02
T4	4.97E-01	4.32E-01	2.37E-03	2.06E-03	1,83E-01	1,70E-04	1,48E-04	1,56E-01	1.41E-01	1.23E-01	1.32E-02	1.15E-02
T5	1.12E+00	1.30E+00	5.12E-03	5.93E-03	1,24E-01	3,35E-04	3,89E-04	1,13E-01	3.17E-01	3.68E-01	2.69E-02	3.12E-02
L1.G	1.30E+00	2.24E+00	5.49E-03	9.47E-03	1,45E-02	3,66E-04	6,31E-04	1,17E-02	3.94E-01	6.79E-01	2.65E-02	4.57E-02
L1.R	1.73E+00	2.98E+00	7.31E-03	1.26E-02	1,45E-02	4,86E-04	8,38E-04	1,17E-02	5.25E-01	9.05E-01	3.46E-02	5.96E-02
L1.M	1.06E+00	1.83E+00	4.49E-03	7.74E-03	1,46E-02	2,99E-04	5,16E-04	1,17E-02	3.22E-01	5.55E-01	2.17E-02	3.74E-02
L2.G	1.89E+00	3.26E+00	8.22E-03	1.42E-02	1,99E-02	5,17E-04	8,91E-04	1,85E-02	5.67E-01	9.78E-01	3.72E-02	6.41E-02
L2.R	1.69E+00	2.92E+00	7.37E-03	1.27E-02	1,99E-02	4,63E-04	7,98E-04	1,85E-02	5.08E-01	8.76E-01	3.33E-02	5.74E-02
L2.M	1.91E+00	3.30E+00	8.33E-03	1.44E-02	2,00E-02	5,23E-04	9,02E-04	1,87E-02	5.74E-01	9.90E-01	3.76E-02	6.49E-02
L3.M	1.06E+00	1.77E+00	4.61E-03	7.68E-03	1,88E-02	2,90E-04	4,83E-04	1,75E-02	3.18E-01	5.30E-01	2.08E-02	3.47E-02
L4.M	2.10E+00	2.48E+00	9.07E-03	1.07E-02	1,70E-02	5,80E-04	6,84E-04	1,52E-02	6.26E-01	7.38E-01	4.13E-02	4.87E-02
L5.G	2.91E+00	4.85E+00	1.26E-02	2.11E-02	3,15E-02	7,95E-04	1,33E-03	2,93E-02	8.73E-01	1.45E+00	5.72E-02	9.53E-02
L5.R	3.21E+00	5.42E+00	1.40E-02	2.36E-02	3,42E-02	8,79E-04	1,48E-03	3,19E-02	9.64E-01	1.63E+00	6.32E-02	1.07E-01
L5.M	2.37E+00	5.55E+00	1.03E-02	2.41E-02	3,48E-02	6,48E-04	1,52E-03	3,24E-02	7.11E-01	1.67E+00	4.66E-02	1.09E-01
S1	7.22E+00	8.39E+00	3.13E-02	3.63E-02	4,46E-02	1,99E-03	2,31E-03	4,03E-02	2.16E+00	2.51E+00	1.42E-01	1.65E-01
S2	8.44E+00	1.13E+01	3.70E-02	4.94E-02	2,26E-02	2,34E-03	3,12E-03	2,19E-02	2.64E+00	3.52E+00	1.63E-01	2.18E-01
S3	4.85E+00	5.50E+00	2.11E-02	2.39E-02	4,39E-02	1,37E-03	1,56E-03	3,94E-02	1.51E+00	1.71E+00	9.39E-02	1.06E-01
C1	2.05E+00	3.16E+00	8.92E-03	1.37E-02	3,15E-02	5,61E-04	8,64E-04	2,93E-02	6.15E-01	9.48E-01	4.03E-02	6.21E-02
B1	2.43E+00	8.79E-01	1.06E-02	3.85E-03	3,07E-02	7,01E-04	2,54E-04	2,74E-02	7.50E-01	2.72E-01	4.84E-02	1.75E-02

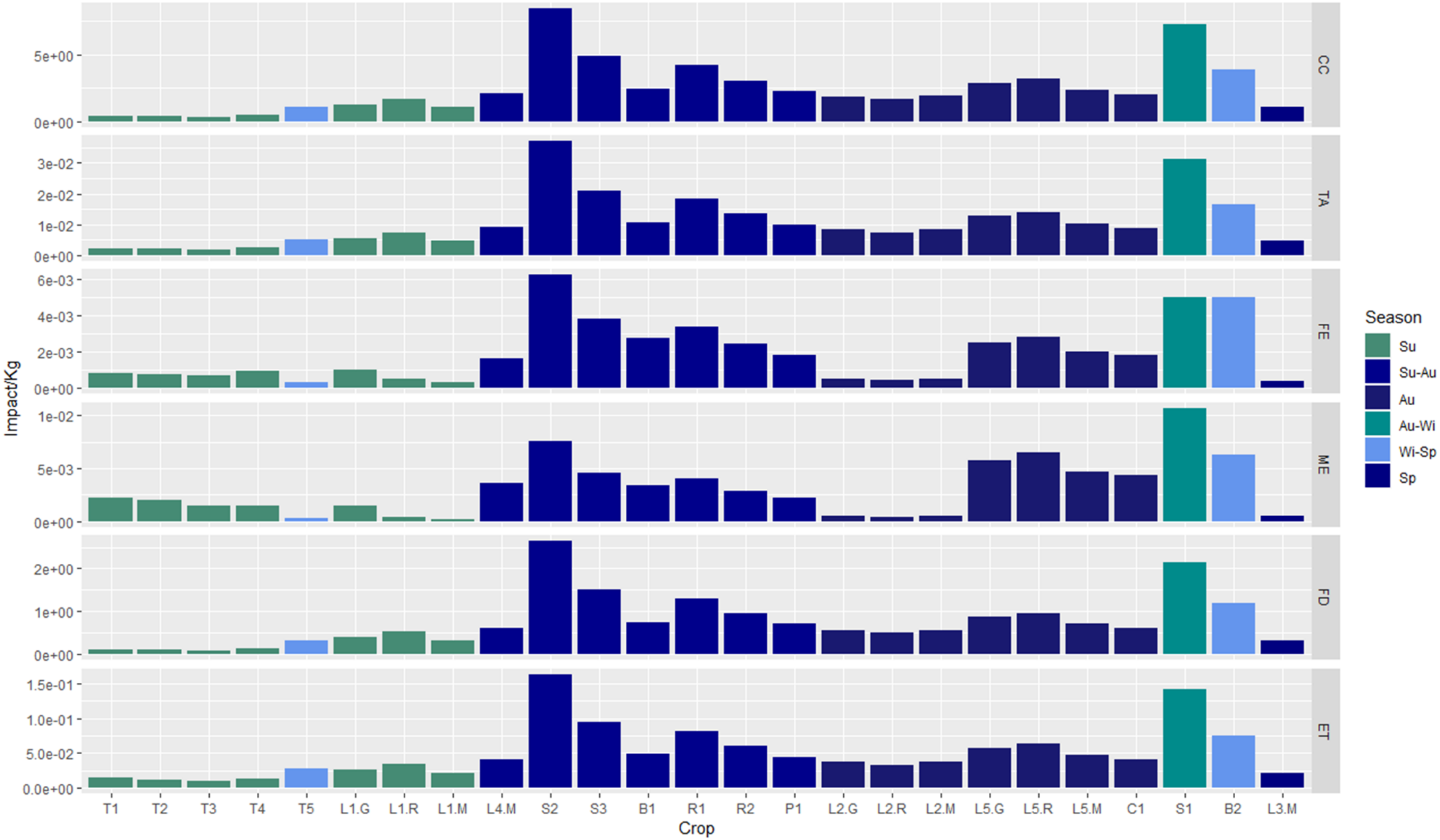
B2	3.86E+00	1.38E+00	1.65E-02	5.92E-03	5,89E-02	1,11E-03	3,99E-04	4,89E-02	1.20E+00	4.28E-01	7.44E-02	2.66E-02
R1	3.60E+00	4.29E+00	1.56E-02	1.86E-02	1,78E-02	1,02E-03	1,22E-03	1,57E-02	1.12E+00	1.33E+00	6.97E-02	8.30E-02
R2	3.08E+00	3.73E+00	1.34E-02	1.62E-02	4,39E-02	8,71E-04	1,05E-03	3,94E-02	9.55E-01	1.16E+00	5.96E-02	7.21E-02
P1	2.30E+00	2.05E+00	9.97E-03	8.89E-03	4,87E-02	6,50E-04	5,79E-04	4,37E-02	7.13E-01	6.36E-01	4.45E-02	3.96E-02

IC [UNITS]	**CC [kg CO2 eq]**				**TA [kg SO2 eq]**				**FE [kg P eq]**			
FU	**Total**	**Kg**	**€**	**Kcal**	**Total**	**Kg**	**€**	**Kcal**	**Total**	**Kg**	**€**	**Kcal**
T1	5,62E+02	4,57E-01	4,56E-01	2,54E-03	2,74E+00	2,23E-03	2,23E-03	1,24E-05	1,05E+00	8,56E-04	8,55E-04	4,76E-06
T2	3,71E+02	4,19E-01	5,26E-01	2,33E-03	1,72E+00	1,94E-03	2,44E-03	1,08E-05	6,85E-01	7,74E-04	9,72E-04	4,31E-06
T3	5,45E+02	3,76E-01	4,86E-01	2,09E-03	2,67E+00	1,85E-03	2,38E-03	1,03E-05	1,04E+00	7,22E-04	9,32E-04	4,01E-06
T4	5,34E+02	4,97E-01	4,32E-01	2,76E-03	2,54E+00	2,37E-03	2,06E-03	1,32E-05	1,05E+00	9,78E-04	8,50E-04	5,43E-06
T5	4,17E+02	1,12E+00	1,30E+00	6,26E-03	1,90E+00	5,12E-03	5,93E-03	2,85E-05	5,02E-01	1,35E-03	1,57E-03	7,54E-06
L1.G	5,15E+01	1,30E+00	2,24E+00	1,33E-02	2,18E-01	5,49E-03	9,47E-03	5,64E-05	4,05E-02	1,02E-03	1,76E-03	1,05E-05
L1.R	5,14E+01	1,73E+00	2,98E+00	2,67E-02	2,18E-01	7,31E-03	1,26E-02	1,13E-04	4,06E-02	1,36E-03	2,35E-03	2,11E-05
L1.M	5,16E+01	1,06E+00	1,83E+00	1,14E-02	2,18E-01	4,49E-03	7,74E-03	4,85E-05	4,09E-02	8,40E-04	1,45E-03	9,08E-06
L2.G	7,27E+01	1,89E+00	3,26E+00	1,50E-02	3,16E-01	8,22E-03	1,42E-02	6,51E-05	5,42E-02	5,17E-04	2,43E-03	1,12E-05
L2.R	7,27E+01	1,69E+00	2,92E+00	1,60E-02	3,16E-01	7,37E-03	1,27E-02	6,97E-05	5,44E-02	4,63E-04	2,19E-03	1,20E-05
L2.M	7,30E+01	1,91E+00	3,30E+00	1,83E-02	3,18E-01	8,33E-03	1,44E-02	7,95E-05	5,48E-02	1,43E-03	2,47E-03	1,37E-05
L3	6,87E+01	1,06E+00	1,77E+00	2,81E-02	2,99E-01	4,61E-03	7,68E-03	1,22E-04	2,48E-02	3,82E-04	6,37E-04	1,02E-05
L4	6,17E+01	2,10E+00	2,48E+00	5,67E-02	2,67E-01	9,07E-03	1,07E-02	2,45E-04	4,75E-02	1,62E-03	1,91E-03	4,37E-05
L5	1,15E+02	2,91E+00	4,85E+00	5,18E-02	5,01E-01	1,26E-02	2,11E-02	2,25E-04	9,88E-02	2,50E-03	4,16E-03	4,45E-05
L6	1,25E+02	3,21E+00	5,42E+00	6,79E-02	5,44E-01	1,40E-02	2,36E-02	2,95E-04	1,10E-01	2,81E-03	4,75E-03	5,95E-05
L7	1,27E+02	2,37E+00	5,55E+00	6,67E-02	5,53E-01	1,03E-02	2,41E-02	2,90E-04	1,09E-01	2,02E-03	4,74E-03	5,70E-05
S1	1,62E+02	7,22E+00	8,39E+00	1,38E-01	7,01E-01	3,13E-02	3,63E-02	5,96E-04	1,13E-01	5,03E-03	5,84E-03	9,58E-05

S2	8,17E+01	8,44E+00	1,13E+01	4,48E-01	3,59E-01	3,70E-02	4,94E-02	1,97E-03	6,07E-02	6,28E-03	8,37E-03	3,33E-04
S3	1,55E+02	4,85E+00	5,50E+00	2,58E-01	6,73E-01	2,11E-02	2,39E-02	1,12E-03	1,23E-01	3,85E-03	4,36E-03	2,04E-04
C1	1,15E+02	2,05E+00	3,16E+00	2,88E-02	5,01E-01	8,92E-03	1,37E-02	1,25E-04	1,04E-01	1,86E-03	2,86E-03	2,61E-05
B1	1,06E+02	2,43E+00	8,79E-01	7,84E-03	4,66E-01	1,06E-02	3,85E-03	3,43E-05	1,21E-01	2,76E-03	9,98E-04	8,89E-06
B2	2,04E+02	3,86E+00	1,38E+00	3,32E-02	8,75E-01	1,65E-02	5,92E-03	1,43E-04	2,67E-01	5,04E-03	1,81E-03	4,35E-05
R1	7,36E+01	4,24E+00	5,04E+00	2,23E-01	3,19E-01	1,84E-02	2,19E-02	9,66E-04	5,90E-02	3,40E-03	4,05E-03	1,79E-04
R2	1,55E+02	3,08E+00	3,73E+00	1,62E-01	6,73E-01	1,34E-02	1,62E-02	7,03E-04	1,23E-01	2,44E-03	2,96E-03	1,28E-04
P1	1,72E+02	2,30E+00	2,05E+00	7,27E-02	7,47E-01	9,97E-03	8,89E-03	3,16E-04	1,36E-01	1,82E-03	1,62E-03	5,77E-05

IC [UNITS]	**ME [kg N eq]**				**FDP [kg oil eq]**				**ET [kg 1,4-DB eq]**			
FU	**Total**	**Kg**	**€**	**Kcal**	**Total**	**Kg**	**€**	**Kcal**	**Total**	**Kg**	**€**	**Kcal**
T1	2,78E+00	2,26E-03	2,26E-03	2,54E-03	2,74E+00	2,23E-03	2,23E-03	1,24E-05	1,05E+00	8,56E-04	8,55E-04	4,76E-06
T2	1,78E+00	2,01E-03	2,52E-03	2,33E-03	1,72E+00	1,94E-03	2,44E-03	1,08E-05	6,85E-01	7,74E-04	9,72E-04	4,31E-06
T3	2,21E+00	1,53E-03	1,97E-03	2,09E-03	2,67E+00	1,85E-03	2,38E-03	1,03E-05	1,04E+00	7,22E-04	9,32E-04	4,01E-06
T4	1,53E+00	1,42E-03	1,24E-03	2,76E-03	2,54E+00	2,37E-03	2,06E-03	1,32E-05	1,05E+00	9,78E-04	8,50E-04	5,43E-06
T5	1,22E+00	3,30E-03	3,82E-03	6,26E-03	1,90E+00	5,12E-03	5,93E-03	2,85E-05	5,02E-01	1,35E-03	1,57E-03	7,54E-06
L1.G	5,86E-02	1,47E-03	2,54E-03	1,33E-02	2,18E-01	5,49E-03	9,47E-03	5,64E-05	4,05E-02	1,02E-03	1,76E-03	1,05E-05
L1.R	5,88E-02	1,98E-03	3,41E-03	2,67E-02	2,18E-01	7,31E-03	1,26E-02	1,13E-04	4,06E-02	1,36E-03	2,35E-03	2,11E-05
L1.M	5,92E-02	1,22E-03	2,10E-03	1,14E-02	2,18E-01	4,49E-03	7,74E-03	4,85E-05	4,09E-02	8,40E-04	1,45E-03	9,08E-06
L2.G	1,19E-01	4,81E-04	5,35E-03	1,50E-02	3,16E-01	8,22E-03	1,42E-02	6,51E-05	5,42E-02	5,17E-04	2,43E-03	1,12E-05
L2.R	1,20E-01	4,31E-04	4,80E-03	1,60E-02	3,16E-01	7,37E-03	1,27E-02	6,97E-05	5,44E-02	4,63E-04	2,19E-03	1,20E-05
L2.M	1,20E-01	3,15E-03	5,43E-03	1,83E-02	3,18E-01	8,33E-03	1,44E-02	7,95E-05	5,48E-02	1,43E-03	2,47E-03	1,37E-05
L3	3,51E-02	5,42E-04	9,03E-04	2,81E-02	2,99E-01	4,61E-03	7,68E-03	1,22E-04	2,48E-02	3,82E-04	6,37E-04	1,02E-05
L4	1,05E-01	3,56E-03	4,21E-03	5,67E-02	2,67E-01	9,07E-03	1,07E-02	2,45E-04	4,75E-02	1,62E-03	1,91E-03	4,37E-05

L5	2,27E-01	5,74E-03	9,57E-03	5,18E-02	5,01E-01	1,26E-02	2,11E-02	2,25E-04	9,88E-02	2,50E-03	4,16E-03	4,45E-05
L6	2,53E-01	6,51E-03	1,10E-02	6,79E-02	5,44E-01	1,40E-02	2,36E-02	2,95E-04	1,10E-01	2,81E-03	4,75E-03	5,95E-05
L7	2,49E-01	4,64E-03	1,09E-02	6,67E-02	5,53E-01	1,03E-02	2,41E-02	2,90E-04	1,09E-01	2,02E-03	4,74E-03	5,70E-05
S1	2,41E-01	1,07E-02	1,25E-02	1,38E-01	7,01E-01	3,13E-02	3,63E-02	5,96E-04	1,13E-01	5,03E-03	5,84E-03	9,58E-05
S2	7,36E-02	7,61E-03	1,01E-02	4,48E-01	3,59E-01	3,70E-02	4,94E-02	1,97E-03	6,07E-02	6,28E-03	8,37E-03	3,33E-04
S3	1,47E-01	4,59E-03	5,20E-03	2,58E-01	6,73E-01	2,11E-02	2,39E-02	1,12E-03	1,23E-01	3,85E-03	4,36E-03	2,04E-04
C1	2,43E-01	4,33E-03	6,68E-03	2,88E-02	5,01E-01	8,92E-03	1,37E-02	1,25E-04	1,04E-01	1,86E-03	2,86E-03	2,61E-05
B1	1,50E-01	3,41E-03	1,24E-03	7,84E-03	4,66E-01	1,06E-02	3,85E-03	3,43E-05	1,21E-01	2,76E-03	9,98E-04	8,89E-06
B2	3,31E-01	6,25E-03	2,24E-03	3,32E-02	8,75E-01	1,65E-02	5,92E-03	1,43E-04	2,67E-01	5,04E-03	1,81E-03	4,35E-05
R1	7,02E-02	4,04E-03	4,81E-03	2,23E-01	3,19E-01	1,84E-02	2,19E-02	9,66E-04	5,90E-02	3,40E-03	4,05E-03	1,79E-04
R2	1,47E-01	2,91E-03	3,52E-03	1,62E-01	6,73E-01	1,34E-02	1,62E-02	7,03E-04	1,23E-01	2,44E-03	2,96E-03	1,28E-04
P1	1,63E-01	2,17E-03	1,94E-03	7,27E-02	7,47E-01	9,97E-03	8,89E-03	3,16E-04	1,36E-01	1,82E-03	1,62E-03	5,77E-05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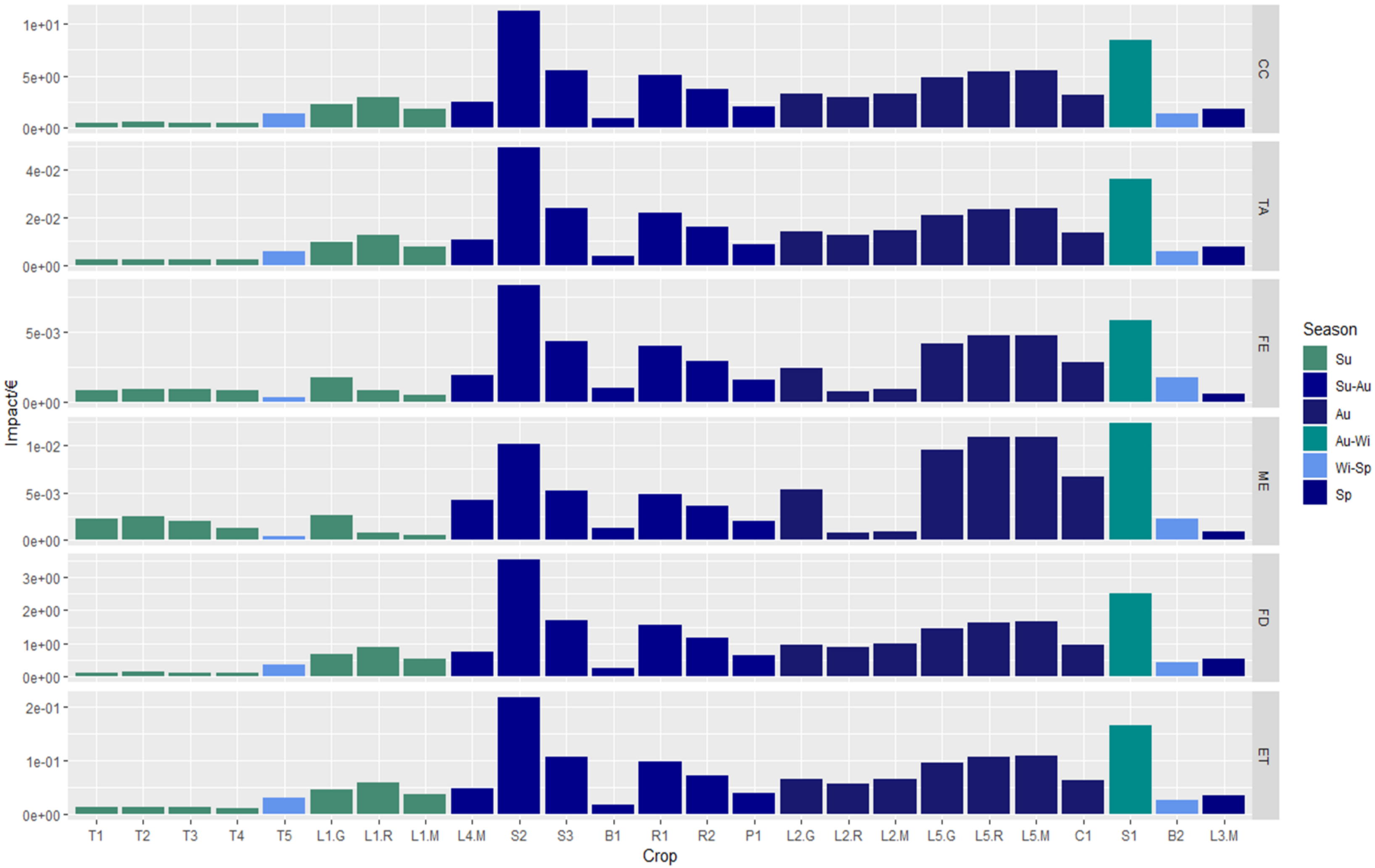
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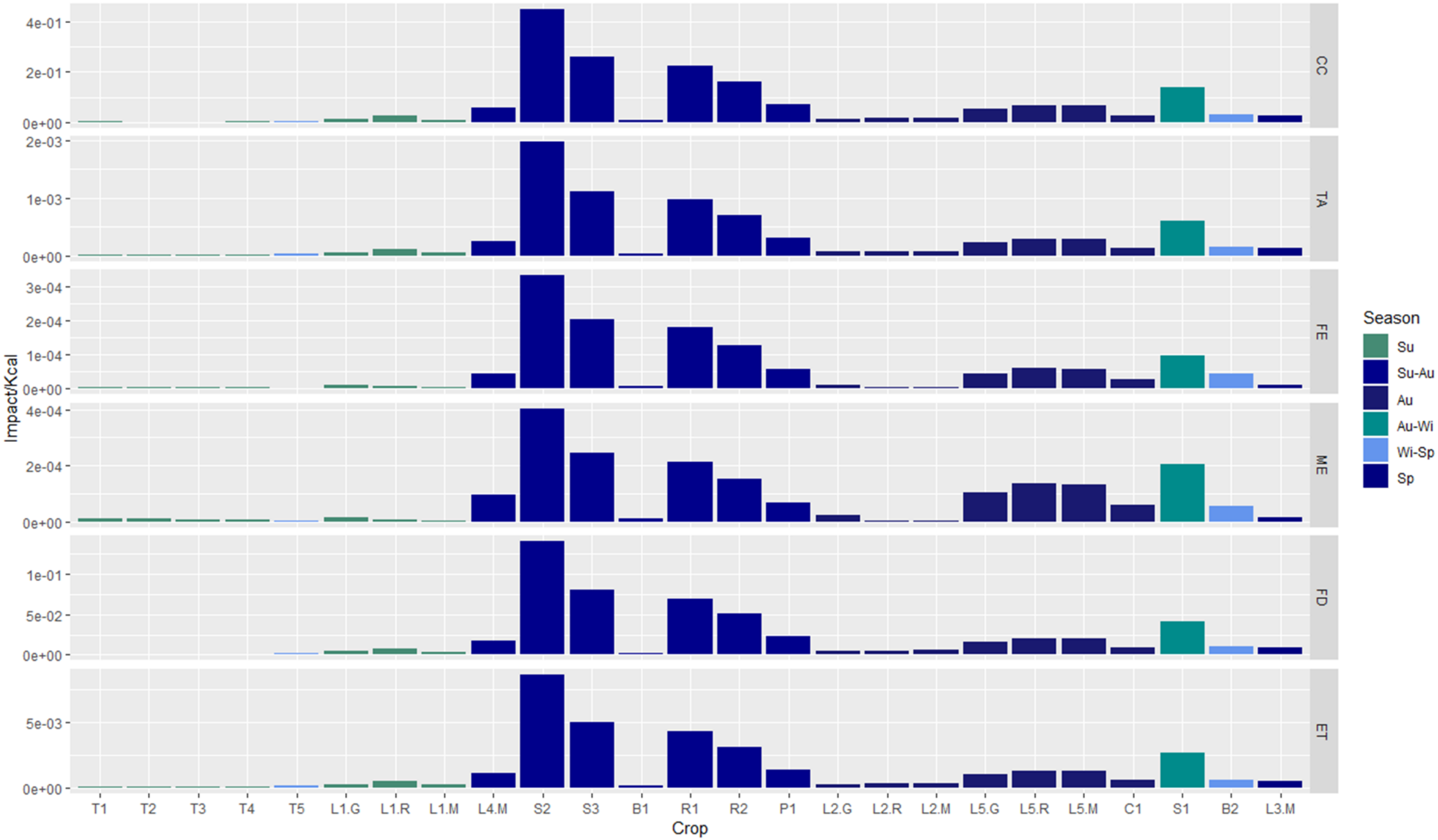
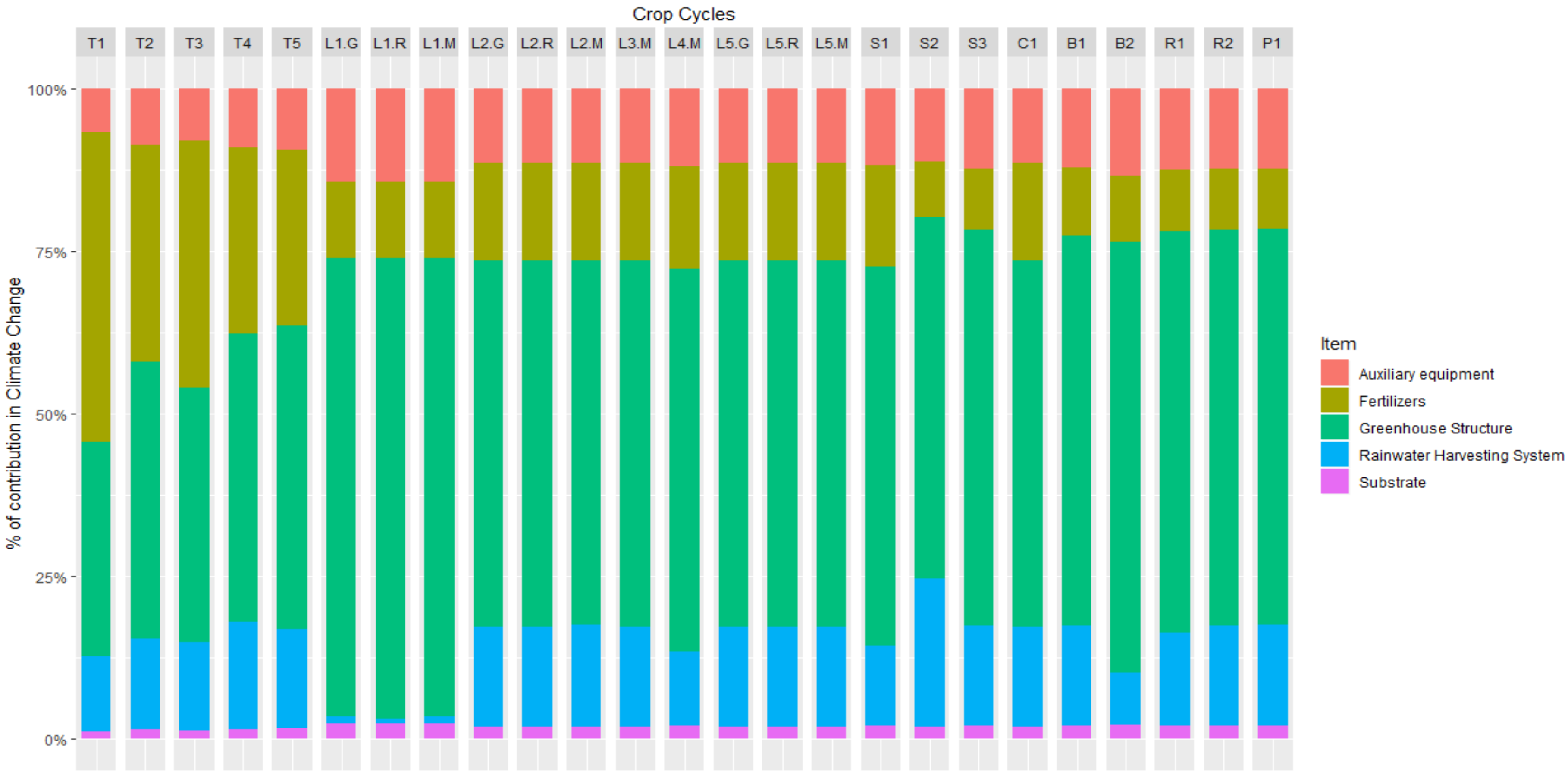


4e-01
2e-01
0e+00
CC
2e-03
1e-03
0e+00
TA
3e-04
2e-04
1e-04
0e+00
FE
4e-04
2e-04
0e+00
ME
1e-01
5e-02
0e+00
FD
5e-03
0e+00
ET
Impact/Kcal
T1
T2
T3
T4
T5
L1.G
L1.R
L1.M
L4.M
S2
S3
B1
R1
R2
P1
L2.G
L2.R
L2.M
L5.G
L5.R
L5.M
C1
S1
B2
L3.M
Crop
Season
Su
Su-Au
Au
Au-Wi
Wi-Sp
Sp



Crop Cycles
T1
T2
T3
T4
T5
L1.G
L1.R
L1.M
L2.G
L2.R
L2.M
L3.M
L4.M
L5.G
L5.R
L5.M
S1
S2
S3
C1
B1
B2
R1
R2
P1
100%
75%
50%
25%
0%
% of contribution in Climate Change
Item
Auxiliary equipment
Fertilizers
Greenhouse Structure
Rainwater Harvesting System
Substrate

Appendix 1.7. Detailed eco-efficiency analysis

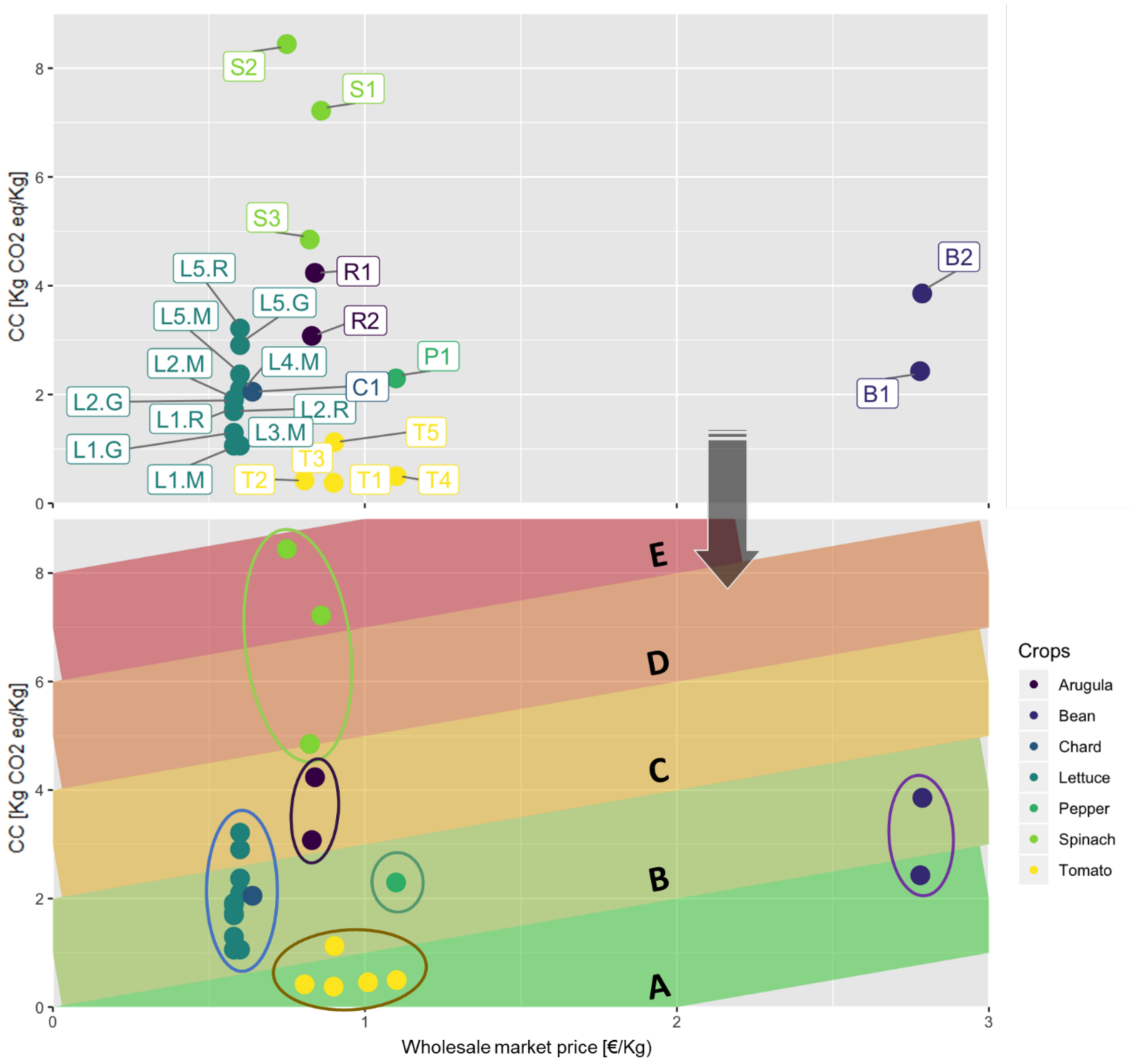
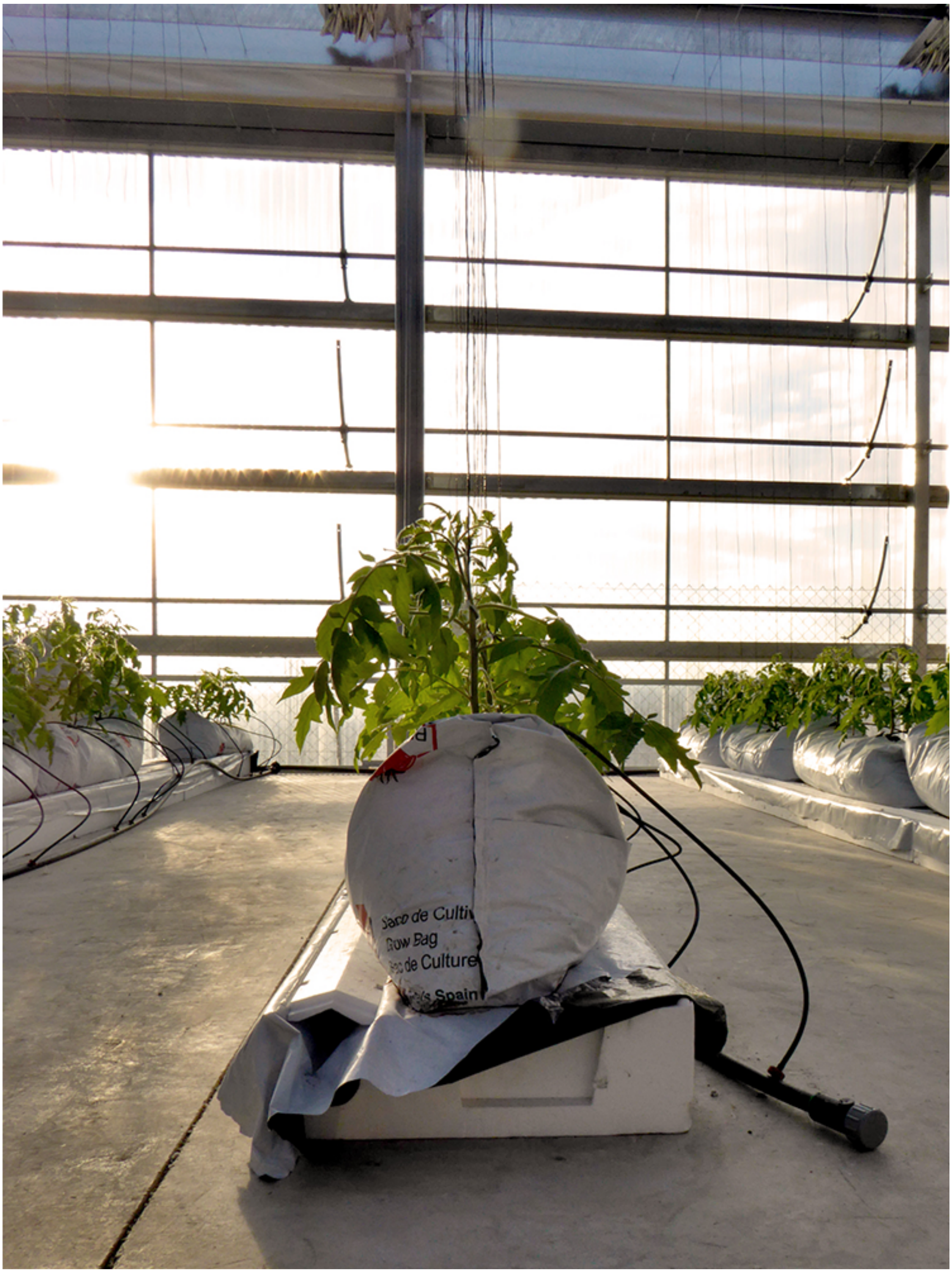


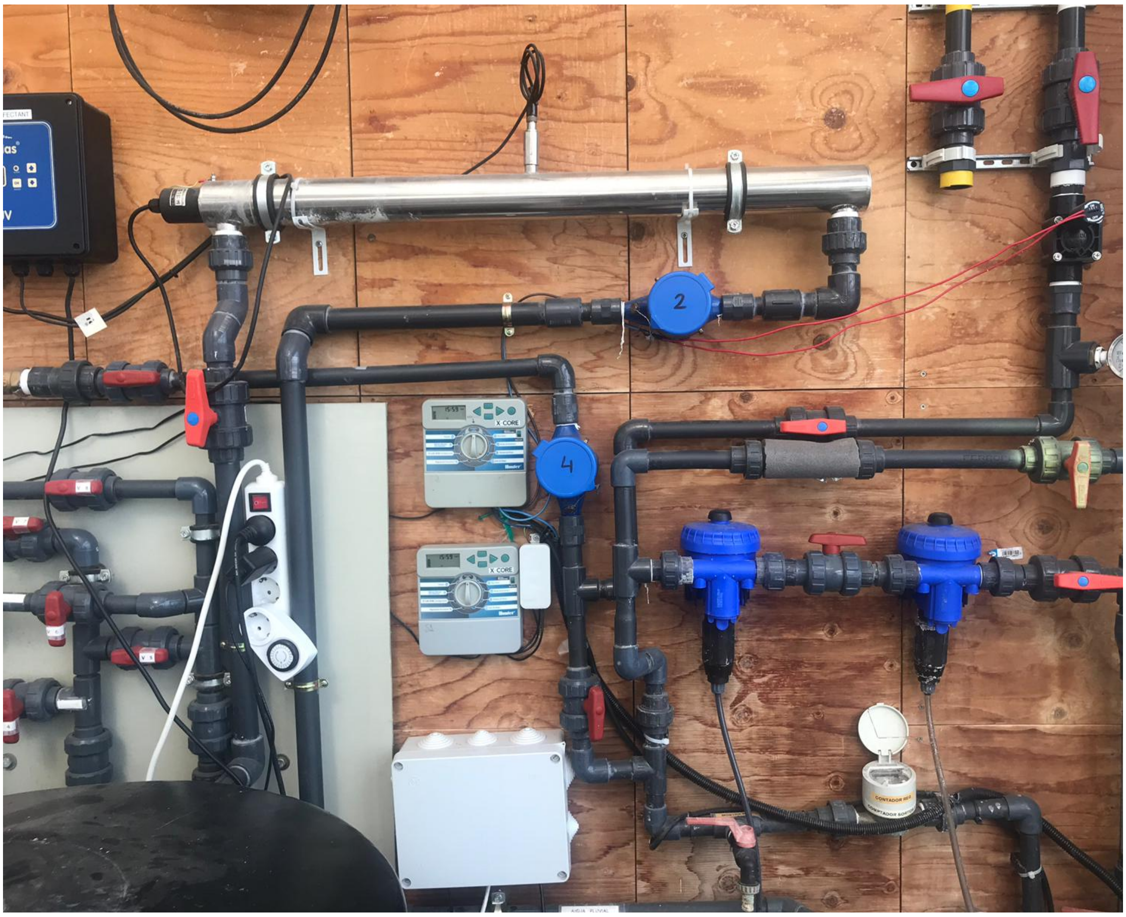
Figure S4. *Eco-efficiency of i-RTG crop cycles for climate change (CC) against the price of the crops in the market. T – Tomato; L – Lettuce; .G – Green oak lettuce; .R – Red oak lettuce; .M – Maravilla lettuce; B – Green bean; S – Spinach; C – Chard; R – Arugula; P - green pepper.*

Part of the supporting data related to Chapter 3 is in the form of spreadsheets. It can be found in the CD attached to the hard copy of this thesis under the name Appendix 1.8 or under request to the author.

Appendix 2. Supporting data related to Chapter 4

Appendix 2.1 Images of the system under study


Grow Bag

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Appendix 2.2. Detailed information of the different nutrient compositions supplied to the crop

Nutrient solutions	1st	2nd	3rd	4th	5th	6th
	11/1	19/1	17/2	28/2	24/3	03/5
Potassium dihydrogen phosphate, KH_2PO_4	136.00	136.00	136.00	136.00	136.00	136.00
Potassium nitrate, KNO_3	101.00	101.00	151.50	101.00	202.00	151.50
Potassium sulphate, K_2SO_4	217.50	435.00	435.00	435.00	435.00	435.00
Calcium Nitrate, $Ca(NO_3)_2$	246.00	369.00	369.00	533.00	574.00	492.00
Calcium Chloride, $CaCl_2$	111.00	83.25	111.00	111.00	138.75	166.50
Magnesium nitrate, $Mg(NO_3)_2$	74.15	148.30	148.30	74.15	74.15	74.15
Hortrilon ®	10.00	10.00	10.00	10.00	10.00	10.00
Sequestrene ®	10.00	10.00	10.00	10.00	10.00	10.00

Appendix 2.3 Inventory for the three recovery alternatives evaluated: nutrient recirculation, chemical precipitation and membrane filtration.

Energy consumption

The electricity considered for the crystallizator was assumed as 13.8 kWh to produce 1 kg of struvite (Yuan and Kim, 2017). Based on this energy consumption, a recovery of 1 kg of struvite from 100 m^3 of wastewater was considered (Munch and Barr, 2001; van Dijk and Braakensiek, 1985), resulting in 2.811 kWh for the total leachate volume produced.

For membrane filtration, 2.5 kWh was assumed to recover 1 m^3 of treated water (Hancock et al., 2012), including intake pumping and membrane treatment.

Table C1. Inventory for the nutrient recirculation in the i-RTG greenhouse rooftop

Element	Classification	Material	Quantity	Units	Lifespan	Ecoinvent designation
Leachate tank (200 L)	Materials	Polyethylene	8.0	kg	10	Polyethylene, high density, granulate {GLO}| market for | APOS, S
Sand filter	Materials	Sand	5.0	kg	5	Sand {GLO}| market for | APOS, S
	Materials	Polyvinyl chloride (PVC)	8.0	kg	20	Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S
Pump	Materials	Cast iron	8.8	kg	10	Cast iron {GLO}| market for | APOS, S
	Materials	Steel	1.0	kg	10	Steel, low-alloyed {GLO}| market for | APOS, S
UV disinfection lamp	Materials	Steel	0.75	kg	10	Steel, low-alloyed {GLO}| market for | APOS, S
PROCESSES						
Electricity	Electricity	Pump	0.674	kWh	-	Electricity, low voltage {ES}| market for | APOS, S
	Electricity	UV disinfection	0.108	kWh	-	
Transport (Chemicals + Auxiliary Equipment)	Transport	Lorry 3.5-7.5 metric ton	0.0584	tkm	-	Transport, lorry 3.5-7.5t, EURO3/RER S

Table C2. Inventory for the chemical precipitation alternative in the i-RTG greenhouse rooftop

Element	Classification	Material	Quantity	Units	Lifespan	Ecoinvent designation
Nutrients for molar ratio adjustment	Chemicals	Ammonium ($NH4^+$)	0.260	kg	-	Ammonium nitrate, as N {GLO}| market for | APOS, S
	Chemicals	Magnesium (Mg^{2+})	0	kg	-	Magnesium oxide {GLO}| market for | Alloc Def, S
Leachate tank (200 L)	Materials	Polyethylene	8.0	kg	10	Polyethylene, high density, granulate {GLO}| market for | APOS, S
Pump	Materials	Cast iron	8.8	kg	10	Cast iron {GLO}| market for | APOS, S
	Materials	Steel	1.0	kg	10	Steel, low-alloyed {GLO}| market for | APOS, S
Crystallizator (Struvite and Cap)	Materials	Sand	5.0	kg	5	Sand {GLO}| market for | APOS, S
	Materials	Steel	10.0	kg	10	Oxygen, liquid {RER}| market for | APOS, S
Air stripping device	Materials	O_2 cylinder tank	10.0	kg	10	Oxygen, liquid {RER}| market for | APOS, S
	Materials	O2 liquid	5.0	kg		Oxygen, liquid {RER}| market for | APOS, S
	Materials	Cylindrical glass tube	7.0	kg	10	Glass tube, borosilicate {GLO}| market for | APOS, S
	Materials	Air pump	5.0	kg	10	Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S
PROCESSES						
Electricity	Electricity	Crystallactor	14.6	kWh	-	Electricity, low voltage {ES}| market for | APOS, S
	Electricity	Air stripping device	5.0	kWh	-	
	Electricity	Pump	0,674	kWh	-	
Transport (chemicals and auxiliary materials)	Transport	Lorry 3.5-7.5 metric ton	0.102	tkm	50	Transport, lorry 3.5-7.5t, EURO3/RER S

Transport (crystallizator)	Transport	Lorry 3.5-7.5 metric ton	1.55	tkm	50	Transport, lorry 3.5-7.5t, EURO3/RER S

Table C3. Inventory for the membrane filtration alternative in the i-RTG greenhouse rooftop

Element	Classification	Material	Quantity	Units	Lifespan	Ecoinvent designation
Alkaline membrane cleaner	Chemicals	EDTA	0.028	kg	10	EDTA, ethylenediaminetetraacetic acid {RER}| EDTA production | APOS, S
Microfiltration + Reverse Osmosis Membrane	Materials	Polyvinyl chloride (PVC)	0.0053	kg	5	Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S
	Materials	Polyamide	0.00143	kg	5	Polyamide 6.6 fibres (PA 6.6), from adipic acid and hexamethylene diamine (HMDA), prod. mix, EU-27 S
	Materials	Polyethylene (PE)	0.0019	kg	5	Polyethylene, low density, granulate {GLO}| market for | APOS, S
	Materials	Fiberglass	0.0013	kg	5	Glass fibre {GLO}| market for | APOS, S
Leachate tank (200 L)	Materials	Polyethylene	8.0	kg	10	Polyethylene, low density, granulate {GLO}| market for | APOS, S
Pump	Materials	Cast iron	8.8	kg	10	Cast iron {GLO}| market for | APOS, S
	Materials	Steel	1.0	kg	10	Steel, low-alloyed {GLO}| market for | APOS, S
Concetrated wáter tank (200 L)	Materials	Polyethylene (PE)	8.00	kg	10	Polyethylene, low density, granulate {GLO}| market for | APOS, S
Permeate Water tank (300 L)	Materials	Polyethylene (PE)	15.00	kg	10	Polyethylene, low density, granulate {GLO}| market for | APOS, S
PROCESSES						
Electricity	Electricity	Membrane treatment	68.75	kWh	-	Electricity, low voltage {ES}| market for | APOS, S
	Electricity	Pump	0,674	kWh	-	

Transport (Chemicals and auxiliary materials)	Transport	Lorry 3.5-7.5 metric ton	0.0342	tkm	-	Transport, lorry 3.5-7.5t, EURO3/RER S
Transport (Membranes)	Transport	Lorry 3.5-7.5 metric ton	0.00155	tkm	-	Transport, lorry 3.5-7.5t, EURO3/RER S

Appendix 2.4 monitoring results

Nutrient Analysis		Concentration of nutrients (mg/L)								Nutrients mass (g)							
		Applied				Drained off				Applied				Drained off			
Sample	**Month**	**P**	**K**	**Ca**	**Mg**	**P**	**K**	**Ca**	**Mg**	**P**	**K**	**Ca**	**Mg**	**P**	**K**	**Ca**	**Mg**
001	January	106.18	357.86	158.92	36.84	43.61	253.47	123.31	41.16	44.17	148.87	66.11	15.32	11.50	66.87	32.53	10.86
002		61.69	316.90	141.67	35.38	54.05	281.64	119.19	37.49	12.52	64.33	28.76	7.18	7.92	41.26	17.46	5.49
003		40.39	316.19	142.80	33.07	56.15	326.21	119.19	35.33	9.25	72.41	32.70	7.57	8.73	50.70	18.52	5.49
004	February	26.92	196.78	133.65	30.77	46.85	386.29	136.39	42.15	7.32	53.52	36.35	8.37	4.93	40.68	14.36	4.44
005		24.57	175.10	131.86	36.16	23.65	253.82	119.77	38.70	14.15	100.86	75.95	20.83	7.97	85.55	40.37	13.04
006		21.23	173.55	123.80	35.82	11.32	205.31	95.49	34.88	6.79	55.54	39.62	11.46	1.38	25.06	11.66	4.26
007		21.23	186.63	127.93	33.89	5.01	166.76	90.89	34.43	31.14	273.79	187.67	49.72	2.58	85.93	46.84	17.74
008	March	30.44	294.39	160.81	12.53	9.24	218.25	103.76	23.31	37.93	366.81	200.36	15.61	4.67	110.30	52.44	11.78
009		28.37	259.06	148.58	10.72	7.22	297.86	99.62	10.03	45.48	415.28	238.18	17.19	3.98	164.26	54.94	5.53
010		28.04	251.75	151.98	10.73	4.03	409.42	140.01	9.31	53.06	476.31	287.55	20.31	2.14	217.58	74.41	4.95
011		30.17	245.51	158.18	10.31	4.94	367.04	136.04	6.23	36.35	295.84	190.61	12.43	2.34	173.65	64.36	2.95
012	April	27.01	319.29	180.93	12.11	2.91	406.31	154.26	8.45	81.63	964.90	546.77	36.60	4.08	570.88	216.74	11.87
013		32.52	341.07	188.20	11.68	5.48	495.37	224.39	12.30	85.46	896.34	494.59	30.68	5.27	476.06	215.64	11.82
014		28.63	335.41	187.04	11.61	16.49	393.65	219.16	12.89	73.66	863.01	481.26	29.88	16.86	402.39	224.02	13.17
015		32.46	317.78	193.62	11.44	12.84	441.68	249.04	14.83	109.52	1072.19	653.29	38.59	18.49	636.15	358.69	21.36
016	May	35.55	355.01	192.07	15.55	24.56	431.54	257.91	16.33	116.09	1159.46	627.29	50.80	42.53	747.41	446.68	28.28
017		32.36	320.75	189.47	10.68	18.00	485.48	289.06	18.16	55.04	545.59	322.29	18.17	11.84	319.34	190.14	11.94
018		29.88	292.25	185.33	12.61	8.04	567.71	356.81	24.85	78.30	765.70	485.56	33.04	8.33	588.08	369.61	25.74
019		24.66	240.80	139.65	9.05	11.20	441.68	296.92	20.76	77.49	756.60	438.78	28.45	14.09	555.46	373.41	26.10
020		22.53	239.42	119.11	12.43	7.71	427.99	248.80	16.67	75.82	805.90	400.91	41.83	8.93	495.51	288.05	19.30
021	June	27.15	273.83	140.48	8.78	12.40	333.79	182.51	10.44	103.18	1040.57	533.84	33.35	18.58	500.08	273.44	15.64

Nutrient Analysis		Concentration of nutrients (mg/L)								Nutrients mass (g)							
		Applied				Drained off				Applied				Drained off			
Sample	Month	P	K	Ca	Mg	P	K	Ca	Mg	P	K	Ca	Mg	P	K	Ca	Mg
022		29.17	290.93	152.52	9.32	14.61	433.62	239.06	14.84	78.45	782.32	410.14	25.07	13.76	408.39	225.16	13.98
023		28.28	304.36	140.83	8.88	25.18	590.36	327.68	19.58	133.99	1441.74	667.09	42.08	37.46	878.38	487.54	29.13
024		26.83	256.53	132.01	7.53	27.62	479.84	241.47	13.95	129.86	1241.61	638.95	36.46	57.49	998.76	502.60	29.04
025	July	29.01	303.10	143.56	8.08	38.81	627.86	311.37	17.22	93.16	973.26	460.98	25.94	59.35	960.07	476.12	26.32
026		24.73	259.45	139.56	9.52	28.28	401.78	209.26	12.78	103.28	1083.71	582.92	39.78	71.36	1013.97	528.10	32.26
027		27.75	278.29	154.66	12.35	16.20	343.48	164.99	14.86	102.48	1027.71	571.15	45.61	44.17	936.50	449.84	40.51

Date	pH		EC mS/cm		Date	pH		EC mS/cm		Date	pH		EC mS/cm	
	Irrigation	Leachate	Irrigation	Leachate		Irrigation	Leachate	Irrigation	Leachate		Irrigation	Leachate	Irrigation	Leachate
12-01-17	6.30	6.90	2.80	1.06	15-03-17	6.70	8.20	1.96	2.50	17-05-17	6.50	7.40	2.40	3.60
13-01-17	6.90	7.10	1.67	1.35	16-03-17	6.60	8.30	2.00	2.40	18-05-17	6.70	7.20	2.40	3.80
16-01-17	6.40	7.30	3.01	1.95	17-03-17	6.60	8.30	2.10	2.50	19-05-17	7.00	7.50	1.64	3.50
17-01-17	6.40	7.10	2.30	2.10	20-03-17	6.60	8.40	2.10	2.90	22-05-17	7.10	7.70	1.66	3.20
18-01-17	6.30	6.80	2.90	2.30	21-03-17	6.60	8.40	2.00	2.80	23-05-17	6.90	7.70	1.68	2.80
19-01-17	6.30	6.90	2.40	2.10	22-03-17	6.70	8.10	1.99	2.80	24-05-17	7.10	7.50	1.67	3.20
20-01-17	6.30	6.80	2.60	2.20	23-03-17	6.60	8.20	1.96	2.40	25-05-17	6.70	7.80	1.48	2.50
23-01-17	6.40	6.90	2.60	2.20	24-03-17	6.70	8.30	2.00	2.30	26-05-17	7.40	7.90	1.99	3.70
24-01-17	6.40	6.80	2.50	2.20	27-03-17	6.80	8.10	2.40	2.50	29-05-17	7.20	8.40	1.78	2.80
25-01-17	6.60	6.80	2.40	2.30	28-03-17	6.90	8.20	2.50	2.60	30-05-17	7.20	8.00	1.89	2.40
26-01-17	6.60	6.80	2.50	2.20	29-03-17	6.70	8.10	2.40	2.80	31-05-17	6.70	7.50	1.76	2.10
27-01-17	6.50	6.90	2.40	2.20	30-03-17	6.60	8.20	2.30	3.00	01-06-17	6.80	7.80	1.75	2.30
30-01-17	6.40	6.90	2.30	2.40	31-03-17	6.70	8.20	2.30	3.10	02-06-17	6.70	7.50	1.96	2.50
31-01-17	6.60	6.90	2.40	2.50	03-04-17	6.80	8.30	2.40	3.20	06-06-17	6.30	7.00	2.00	2.70
01-02-17	6.60	6.90	2.40	2.80	04-04-17	6.80	8.20	2.40	3.60	07-06-17	6.40	7.10	2.00	3.10
02-02-17	6.70	6.90	1.67	2.70	05-04-17	6.80	8.20	2.30	3.50	08-06-17	6.60	7.00	2.00	2.50
03-02-17	6.80	7.00	1.64	2.30	06-04-17	6.50	7.90	2.40	3.30	09-06-17	6.50	7.00	2.10	2.90
06-02-17	6.70	7.10	1.68	3.00	07-04-17	6.60	7.70	2.80	3.40	12-06-17	6.30	6.80	2.10	3.70
07-02-17	6.60	7.40	1.94	2.10	10-04-17	6.60	7.90	2.30	3.40	13-06-17	6.40	6.80	2.20	3.70
08-02-17	6.70	7.10	1.86	2.30	11-04-17	6.60	7.90	2.10	3.50	14-06-17	6.30	6.60	2.30	4.60
09-02-17	6.70	7.20	1.88	2.70	12-04-17	6.60	8.00	2.30	3.60	15-06-17	6.20	6.60	2.20	4.70
10-02-17	6.50	7.50	1.92	2.00	13-04-17	6.70	7.90	2.30	3.40	16-06-17	6.20	6.50	2.50	4.60
13-02-17	6.90	7.90	1.95	1.99	16-04-17	6.70	7.60	2.40	3.20	19-06-17	6.70	7.00	1.72	3.60

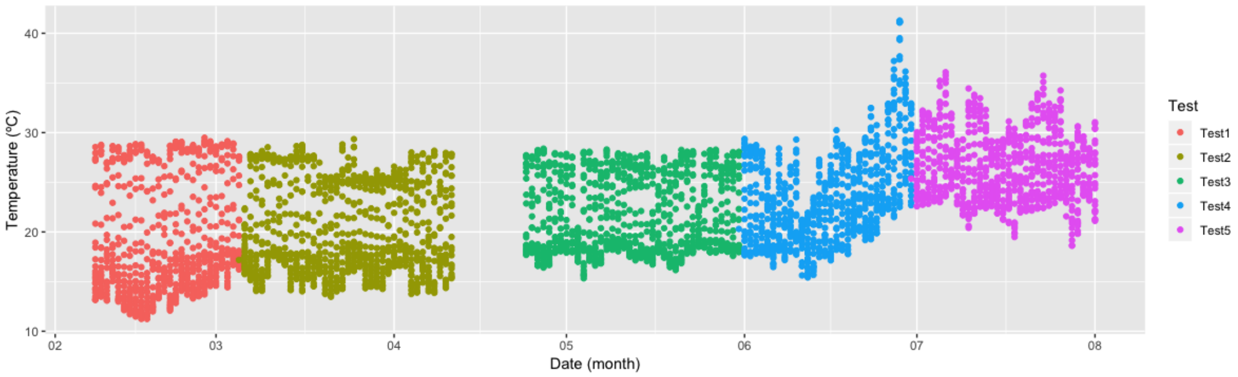
Date	pH		EC mS/cm		Date	pH		EC mS/cm		Date	pH		EC mS/cm	
	Irrigation	Leachate	Irrigation	Leachate		Irrigation	Leachate	Irrigation	Leachate		Irrigation	Leachate	Irrigation	Leachate
14-02-17	6.80	7.90	1.98	1.82	18-04-17	6.70	7.70	2.30	3.20	20-06-17	6.70	6.80	1.57	2.90
15-02-17	6.90	7.90	1.96	1.97	19-04-17	6.60	7.70	2.10	2.90	21-06-17	6.70	7.10	1.64	3.10
16-02-17	6.90	7.90	2.00	2.20	20-04-17	6.50	7.70	2.40	2.80	22-06-17	6.60	6.90	1.49	3.20
17-02-17	6.80	8.00	2.00	1.84	21-04-17	6.60	7.40	2.30	3.00	23-06-17	6.70	7.20	1.78	3.40
20-02-17	7.00	8.20	2.10	1.97	24-04-17	6.70	7.30	2.60	3.60	26-06-17	6.40	6.50	1.82	3.30
21-02-17	7.00	8.10	1.96	1.96	25-04-17	6.70	7.60	2.20	3.50	27-06-17	6.30	6.50	1.93	3.20
22-02-17	6.90	8.30	2.00	1.86	26-04-17	6.80	7.00	2.40	3.10	28-06-17	6.10	6.50	1.88	3.10
23-02-17	6.80	8.50	2.00	1.89	27-04-17	6.80	7.40	2.40	2.80	29-06-17	6.30	6.40	1.98	3.30
24-02-17	7.10	8.40	1.98	1.74	28-04-17	6.50	7.30	2.50	3.00	30-06-17	6.40	6.70	1.99	3.20
27-02-17	7.00	8.10	2.00	1.83	02-05-17	6.60	6.80	2.80	3.50	03-07-17	6.30	6.40	1.88	5.40
28-02-17	7.00	8.50	1.97	1.95	03-05-17	6.70	7.00	2.50	3.00	04-07-17	6.30	6.40	1.96	3.30
01-03-17	6.80	8.20	2.40	1.92	04-05-17	6.40	7.00	2.20	3.00	05-07-17	6.20	6.70	1.83	2.80
02-03-17	6.40	8.20	2.60	1.86	05-05-17	6.50	7.20	2.30	3.60	06-07-17	6.60	6.60	2.20	2.70
03-03-17	6.70	8.40	2.50	2.00	08-05-17	6.50	7.00	2.40	3.50	07-07-17	6.39	6.80	2.10	2.70
06-03-17	6.80	8.10	2.20	2.10	09-05-17	6.50	7.00	2.30	3.50	10-07-17	7.10	7.40	1.96	2.90
07-03-17	6.70	8.40	2.10	2.30	10-05-17	6.50	7.10	2.30	3.60	11-07-17	6.80	7.30	2.10	2.80
08-03-17	6.80	8.50	2.00	2.20	11-05-17	6.50	7.10	2.20	3.40	12-07-17	6.90	7.10	2.00	2.60
09-03-17	6.50	8.20	2.10	2.20	12-05-17	6.60	7.10	2.30	3.40	13-07-17	6.90	7.50	2.10	2.60
10-03-17	6.60	8.30	2.10	2.10	15-05-17	6.60	7.20	2.30	5.30	14-07-17	6.90	7.50	2.10	2.60
13-03-17	6.80	8.20	2.20	2.30	15-05-18	6.40	7.00	2.20	3.20	17-07-17	7.20	7.20	2.20	2.70
14-03-17	6.60	7.90	2.20	2.20	16-05-17	6.70	7.70	2.30	3.40	18-07-17	7.00	7.40	2.20	2.70

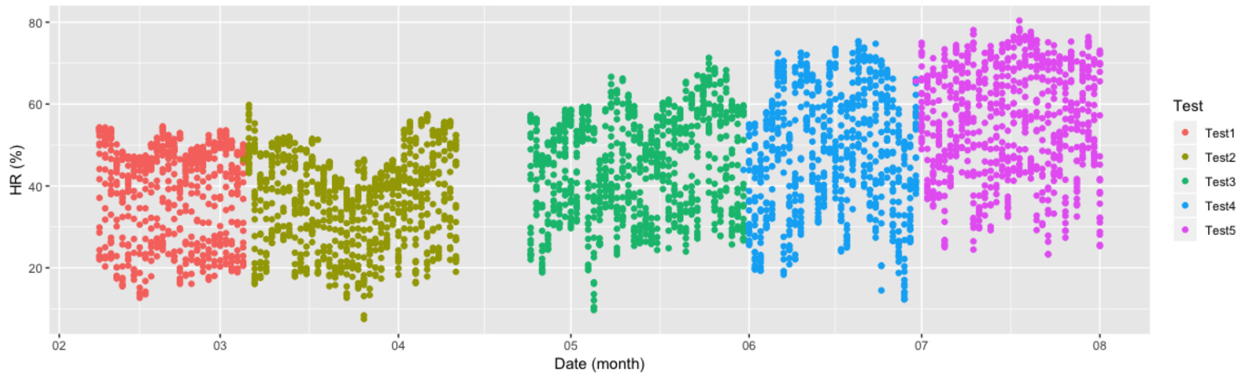
Appendix 3. Supporting data related to Chapter 5

Supporting data related to Chapter 5 is entirely in the form of spreadsheets. It can be found in the CD attached to the hard copy of this thesis under the names Appendix 3.1 and 3.2 (inventories) and Appendix 3.3 and 3.4 (results of the environmental asessment) or under request to the author.

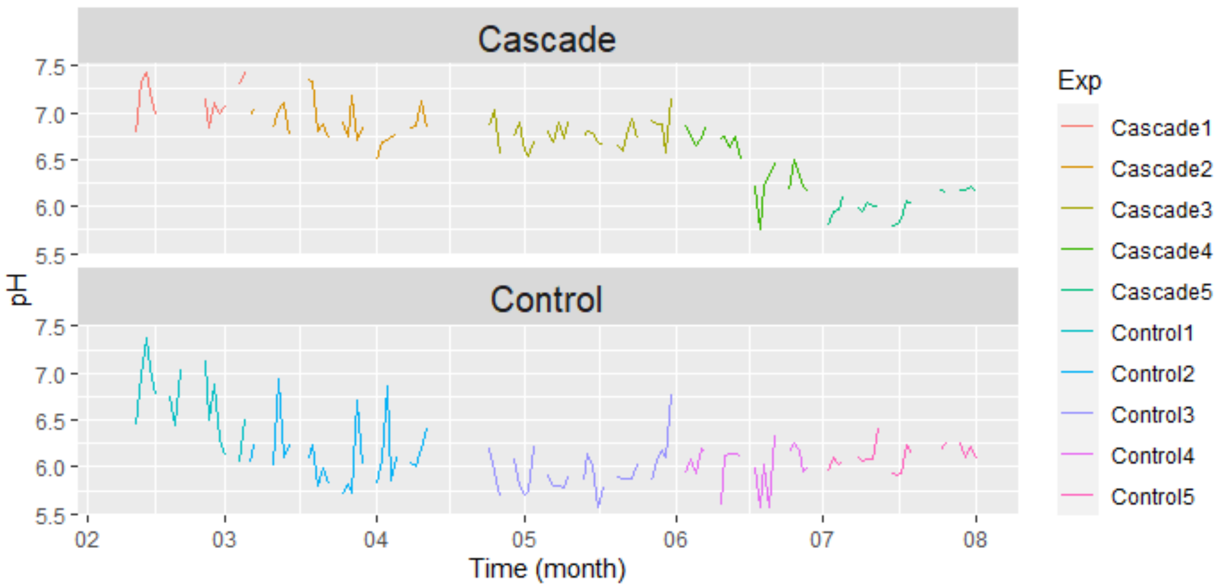
Appendix 4. Supporting data related to Chapter 6

Appendix 4.1 Hourly temperature and relative humidity values





Appendix 4.2 pH values



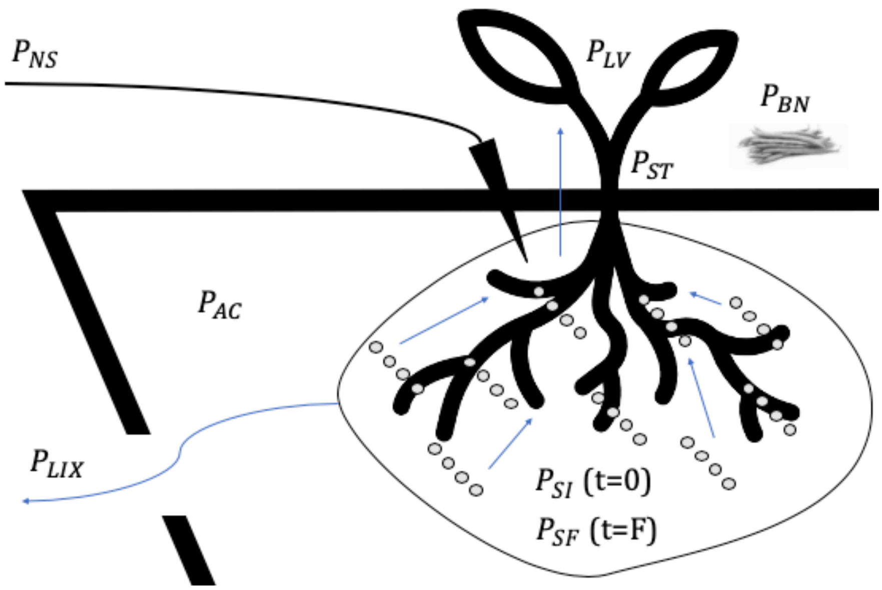
Appendix 4.3 Uptaken and irrigated nutrient per plant

Uptaken nutrients per plant (mg)								
Nutrients	T1 - Cas	T2 - Cas	T3 - Cas	T3 - Con	T4 - Cas	T4 - Con	T5 - Cas	T5 - Con
N	89.8	118.1	155.7	362.9	397.7	419.5	235.3	324.6
P	26.3	28.3	29.1	86.6	85.8	85.4	42.1	58.1
K	352.9	396.6	459.4	1233.7	1007.6	1026.4	541.3	755.2
Ca	70.8	53.1	53.6	134.6	145.4	143.8	69.4	110.3
Mg	13.2	11.0	12.2	27.1	30.6	27.3	18.1	23.6
S	10.4	12.4	13.1	34.8	30.5	32.5	17.4	23.5

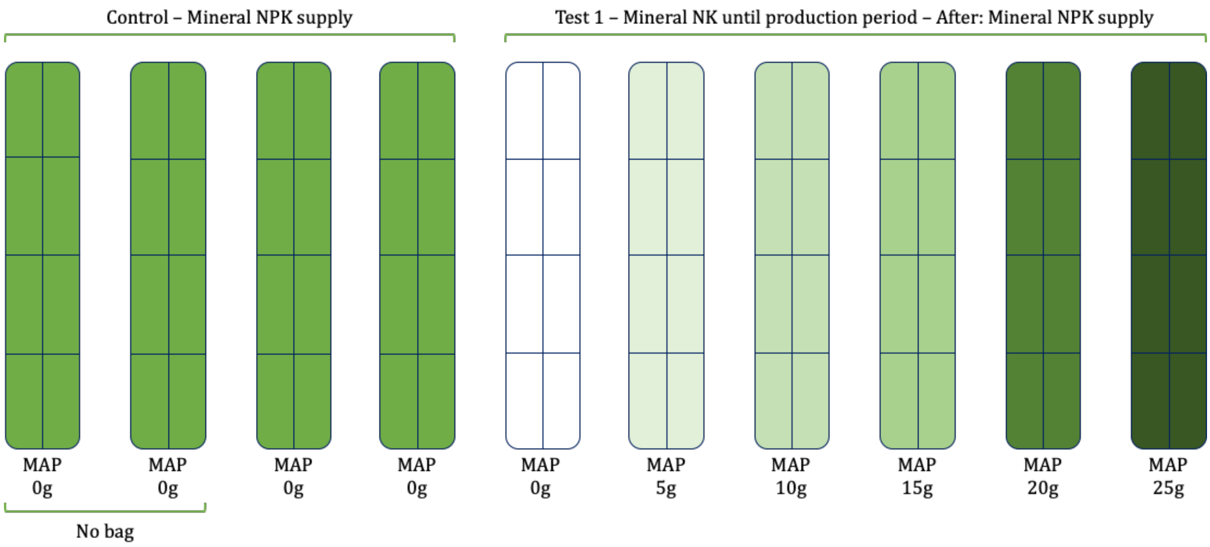
Irrigated nutrients per plant (mg)								
Nutrients	T1 - Cas	T2 - Cas	T3 - Cas	T3 - Con	T4 - Cas	T4 - Con	T5 - Cas	T5 - Con
N	62.4	101.9	361.4	2117.9	1708.0	2558.8	3599.4	1941.6
P	94.4	312.8	333.2	855.6	1341.0	1236.9	2245.9	1170.4
K	556.9	1628.5	2640.0	3874.4	7538.7	5190.2	10704.5	4731.8
Ca	299.1	771.5	997.0	2945.7	2876.8	3395.2	5022.7	2727.6
Mg	86.6	170.4	193.7	332.7	486.5	372.1	740.2	292.2
S	229.0	757.2	1157.2	1085.7	2338.4	1087.6	2889.4	1196.1

Appendix 5. Supporting data related to Chapter 7

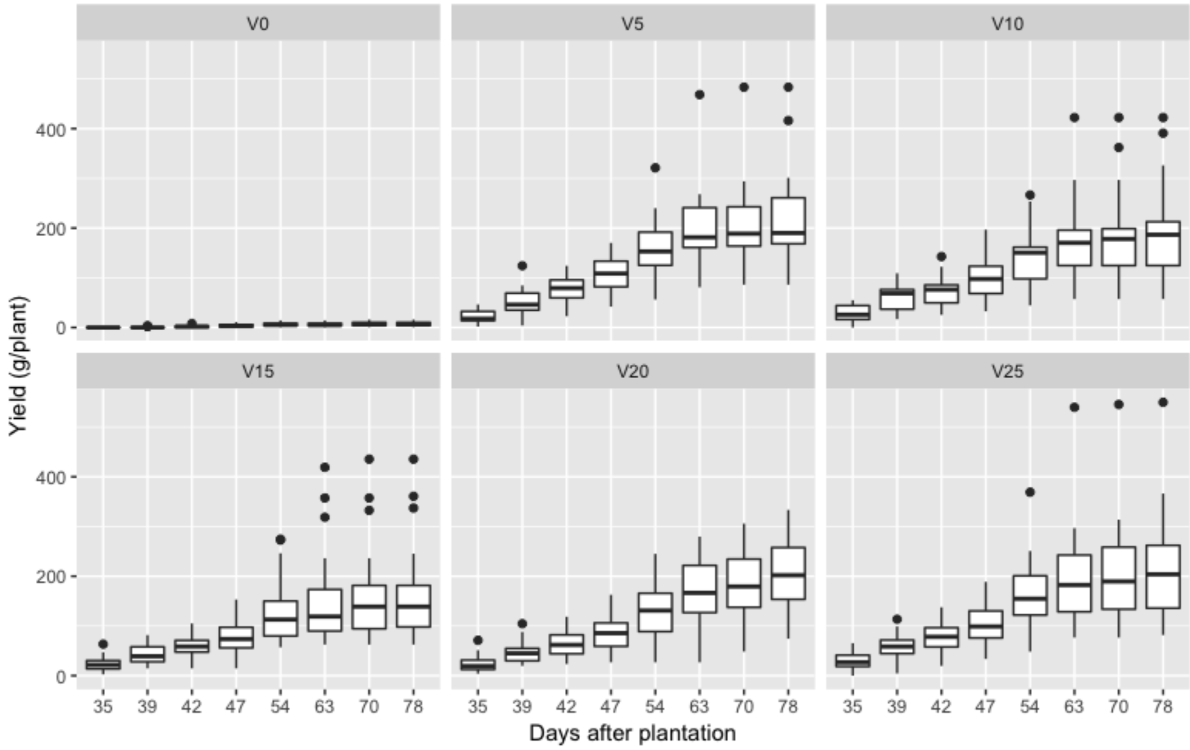
Appendix 5.1 Diagram of the perforated bag



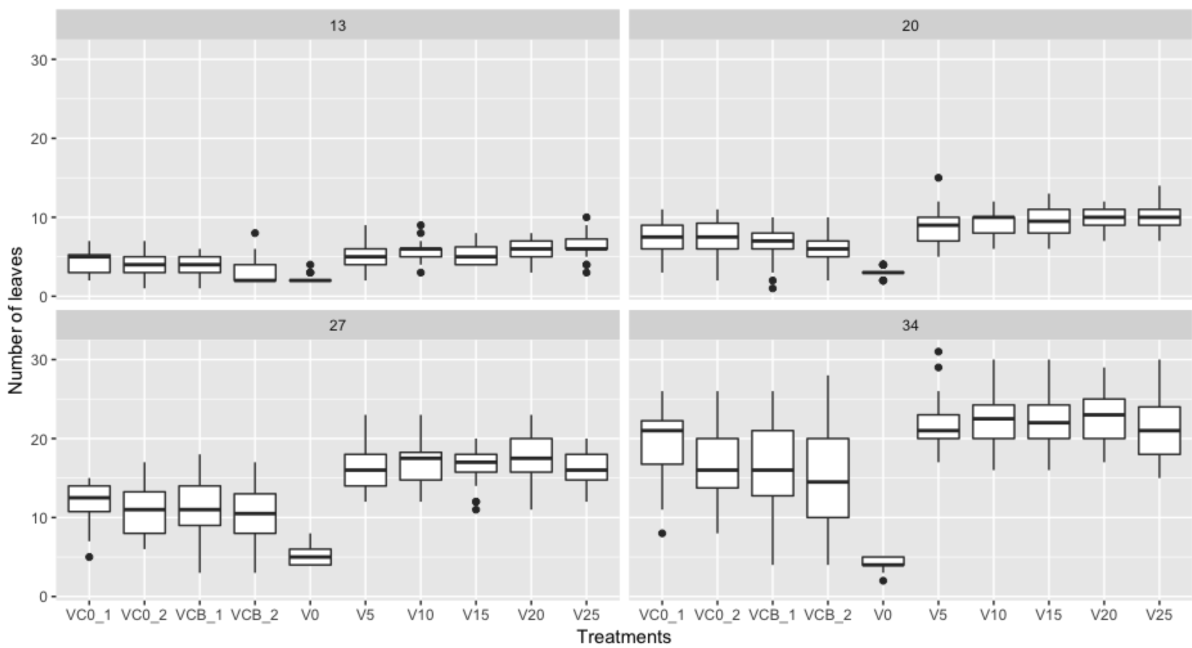
Appendix 5.2 Distribution of growing lines in the validation test



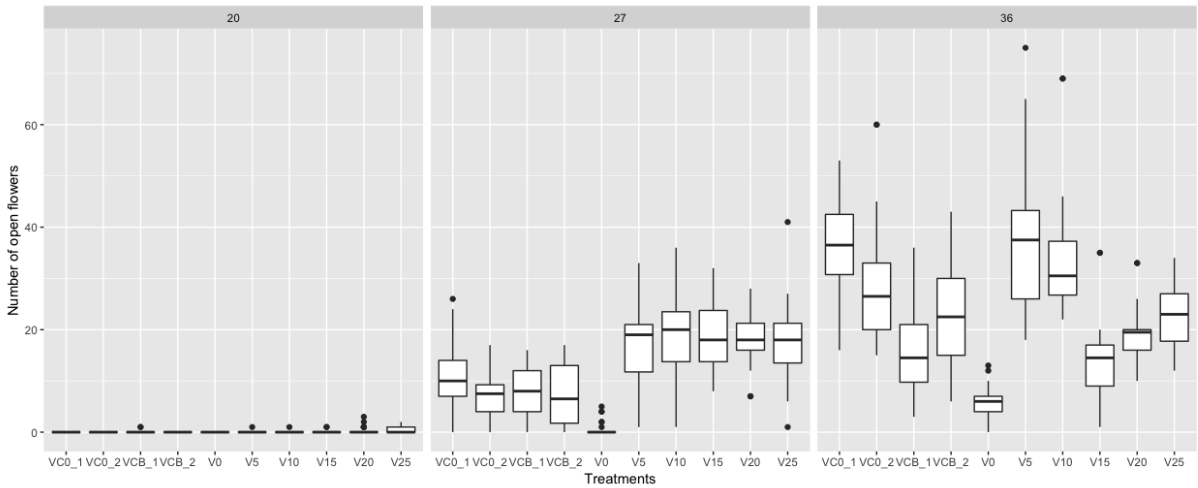
Appendix 5.3 Accumulated production of the struvite treatment in the validation test



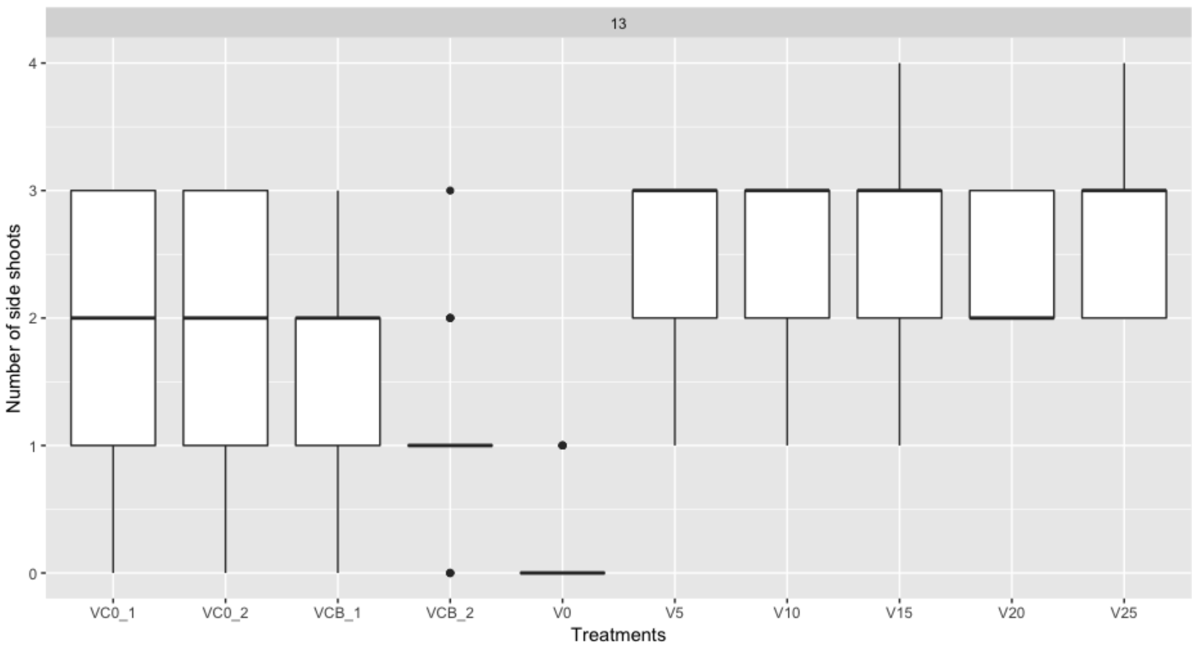
Appendix 5.4 Number of leaves per plant per treatment and Days after Transplanting (DAP) in the validation test.



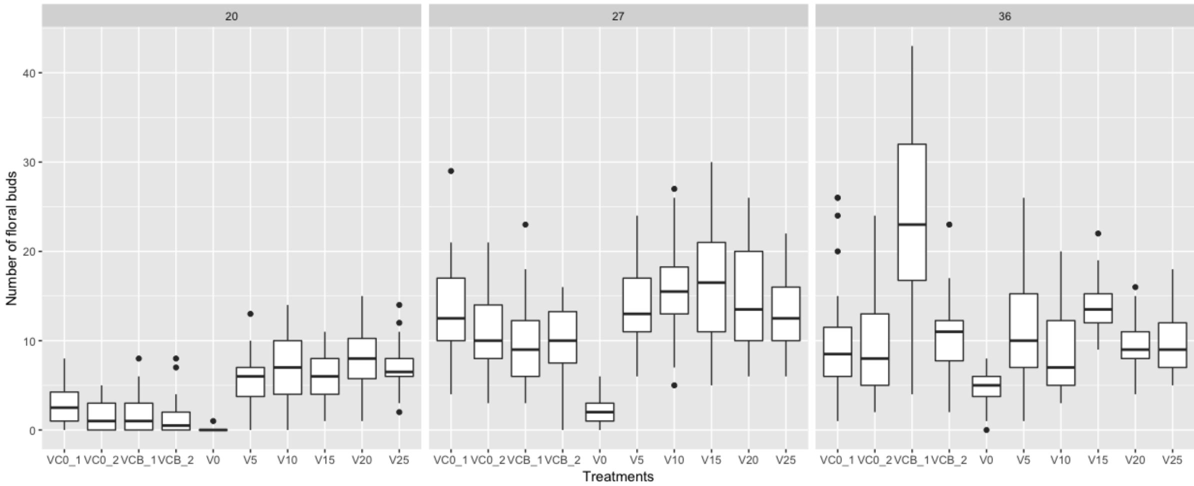
Appendix 5.5 Number of side shoots per plant per treatment and Days after Transplanting (DAP) in the validation test.



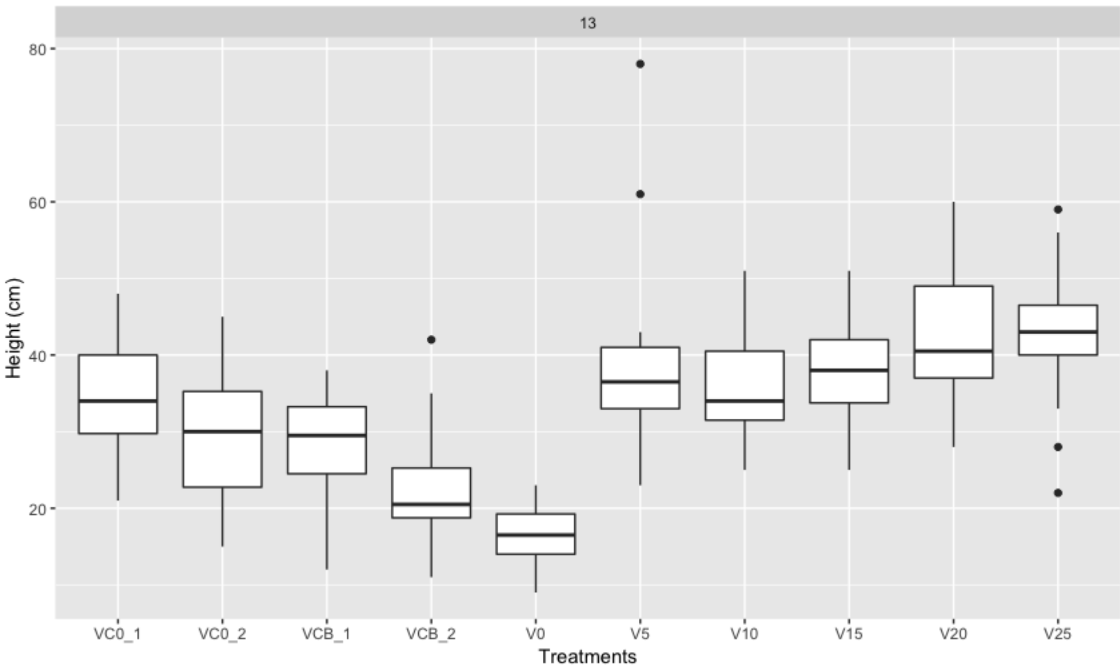
Appendix 5.6 Number of open flowers per plant per treatment and Days after Transplanting (DAP) in the validation test.



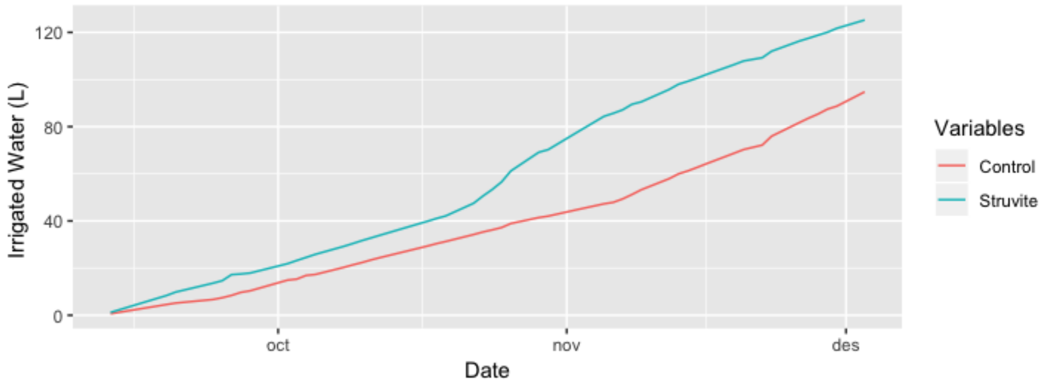
Appendix 5.7 Number of floral buttons per plant per treatment and Days after Transplanting (DAP) in the validation test.



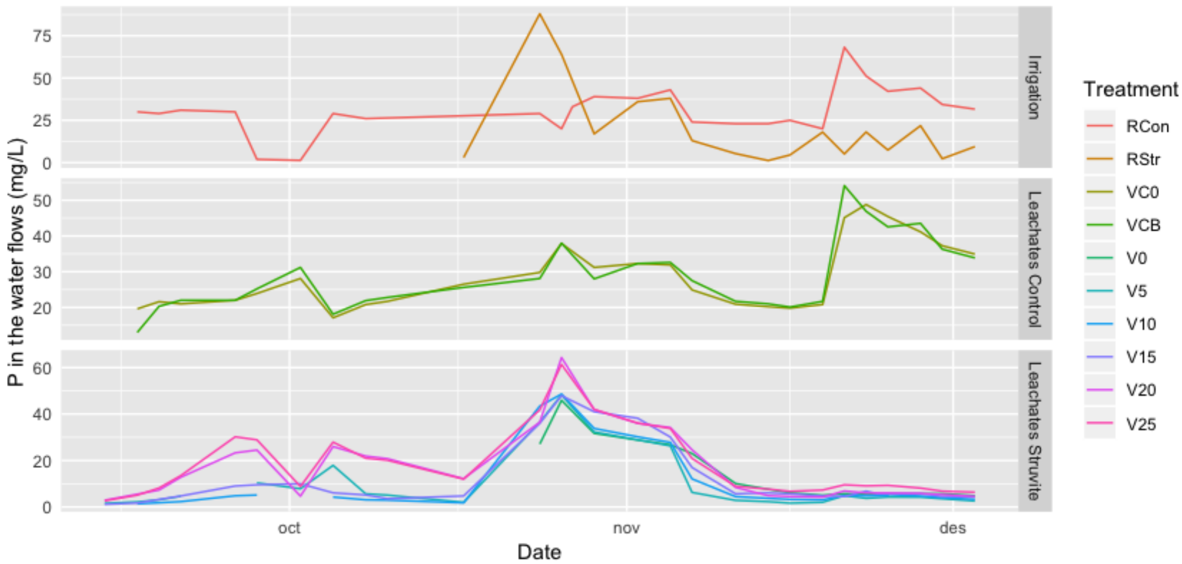
Appendix 5.8 Height (cm) plant per treatment and Days after Transplanting (DAP) in the validation test.



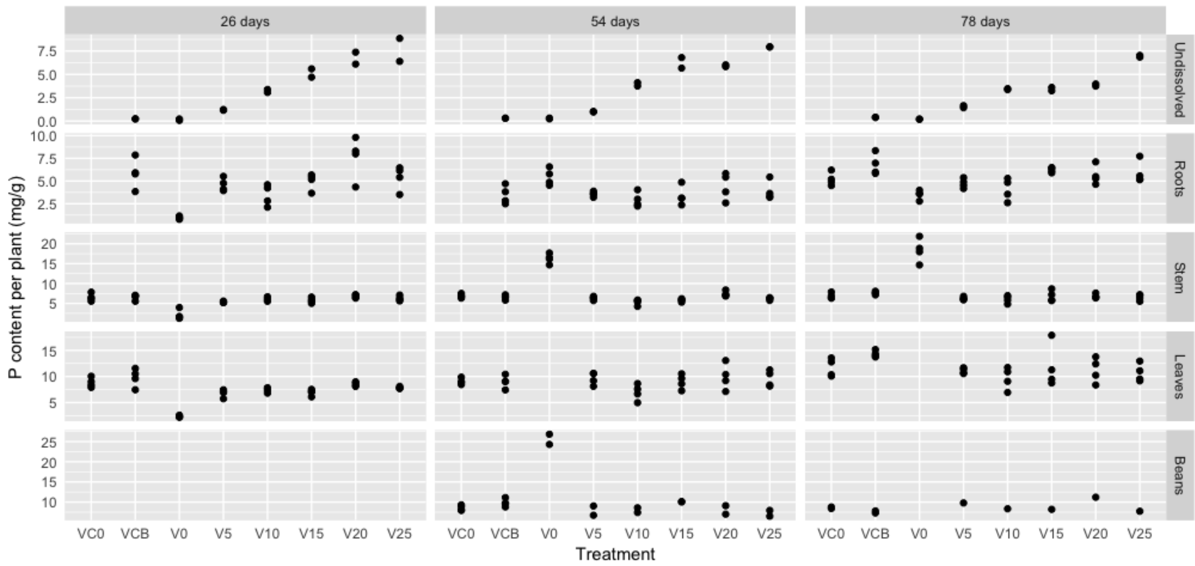
Appendix 5.9 Water irrigated per plant in the validation test



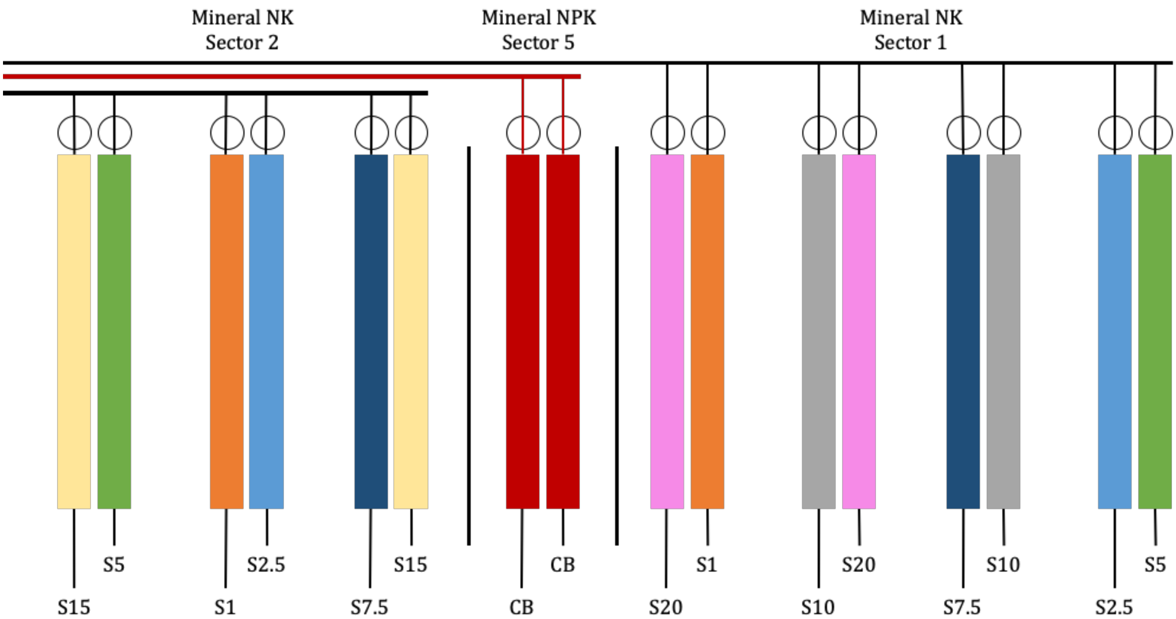
Appendix 5.10 Phosphorus concentrations in the multiple water streams in the validation test



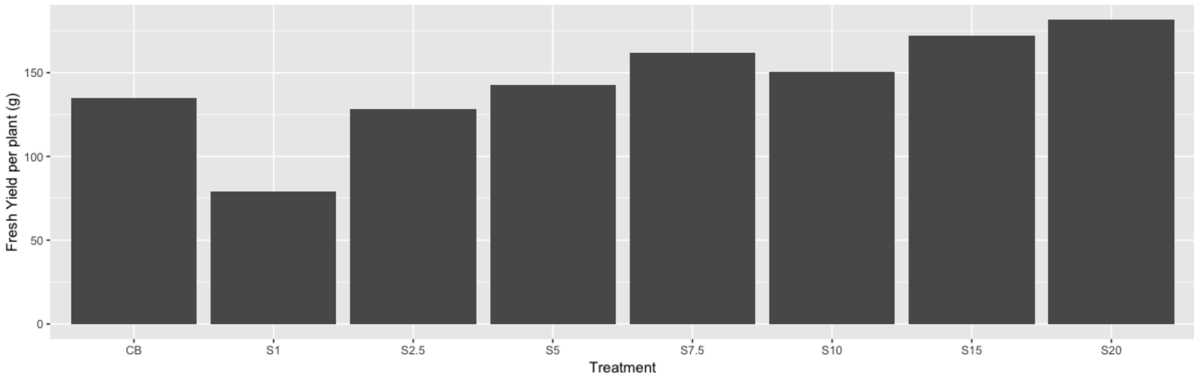
Appendix 5.11 P content per plant (mg/g) of the struvite treatment in the validation test



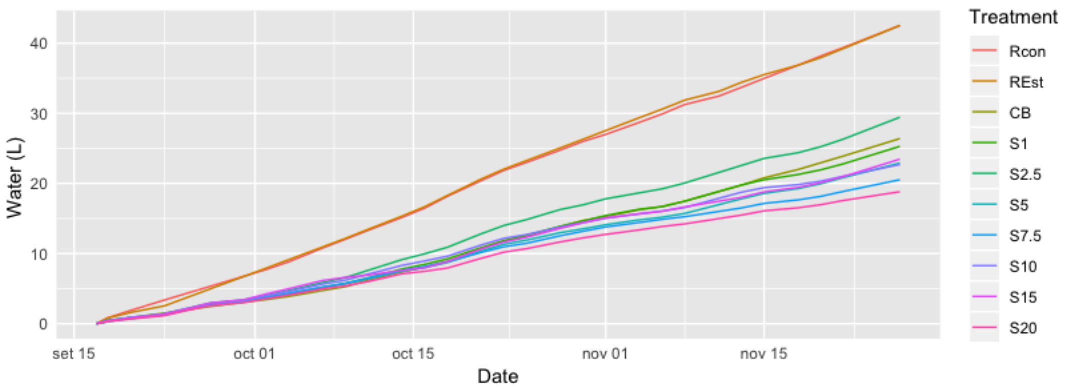
Appendix 5.12 Distribution of growing lines in the validation test



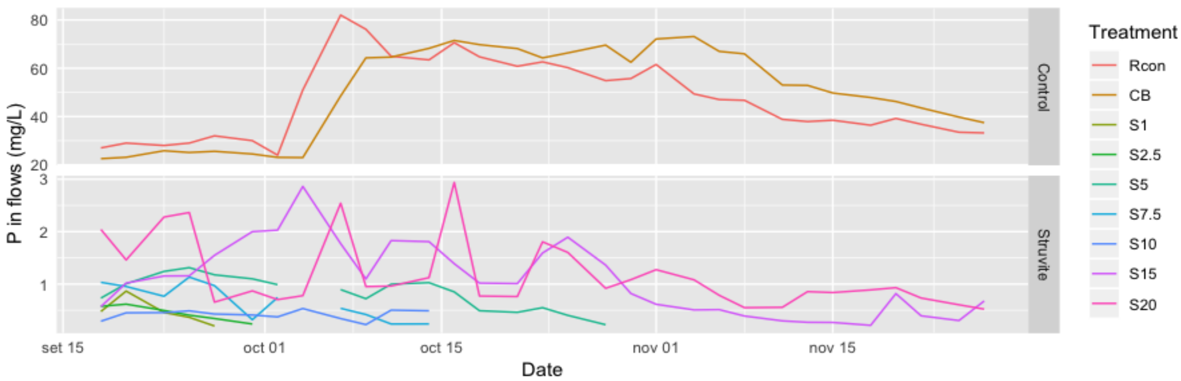
Appendix 5.13 Mean aggregated production per plant per treatment in the determination. test



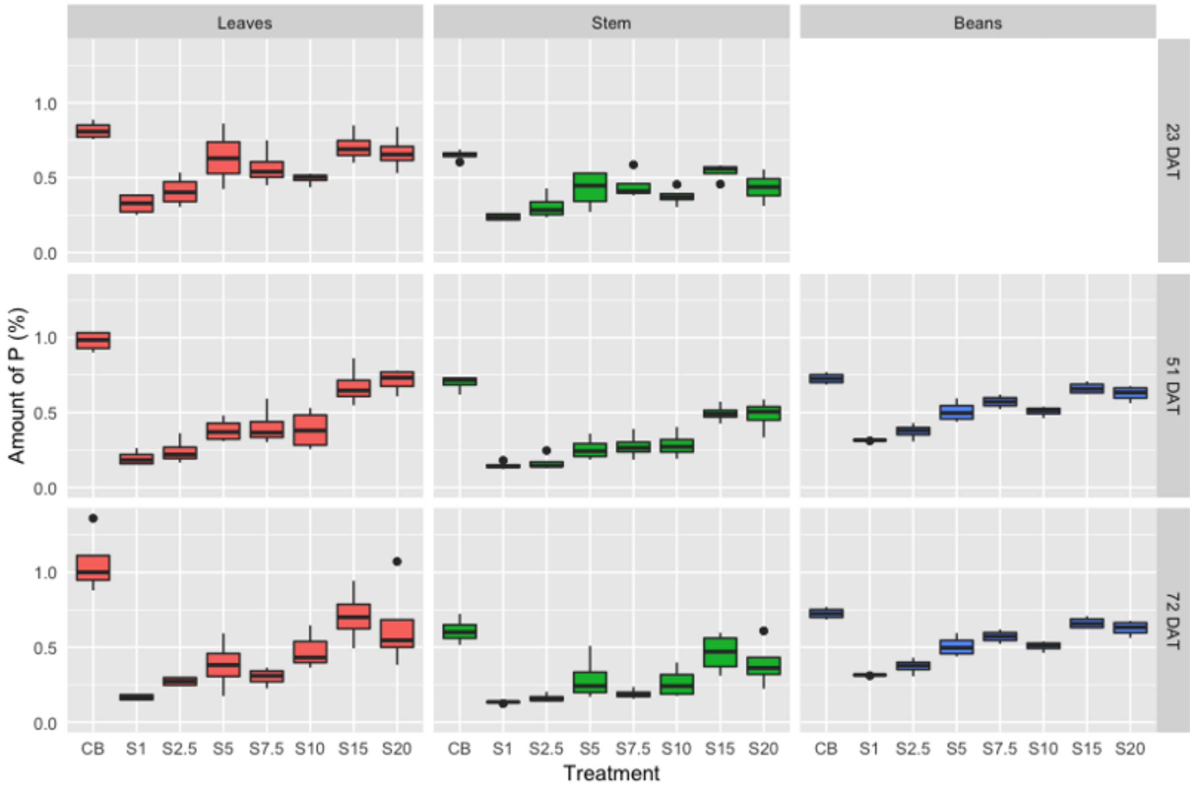
Appendix 5.14 Water irrigated and drained per plant in the different treatments in the determination test



Appendix 5.15 Phosphorus concentrations in the multiple water streams in the determination test

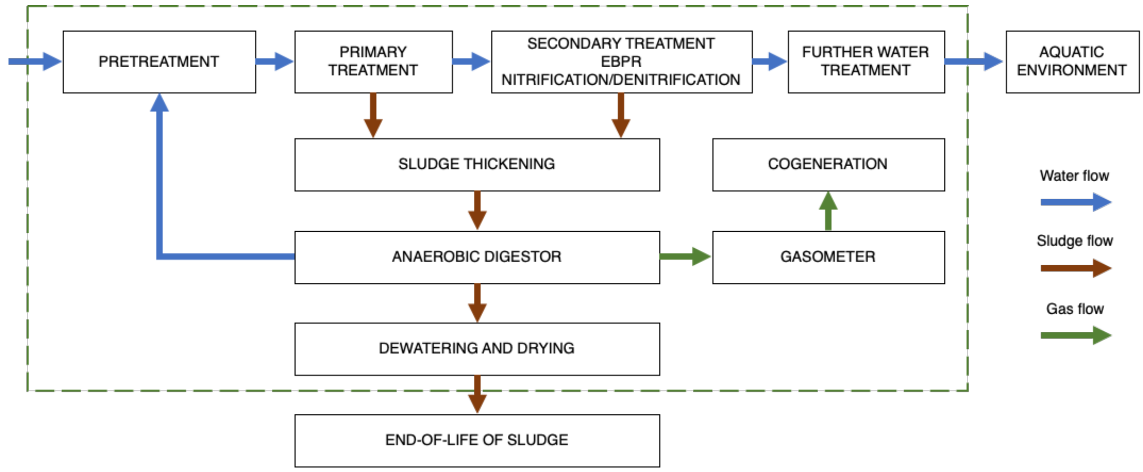


Appendix 5.16 Phosphorus concentrations in the different treatments, separated by plant organ and days after transplanting (DAT)

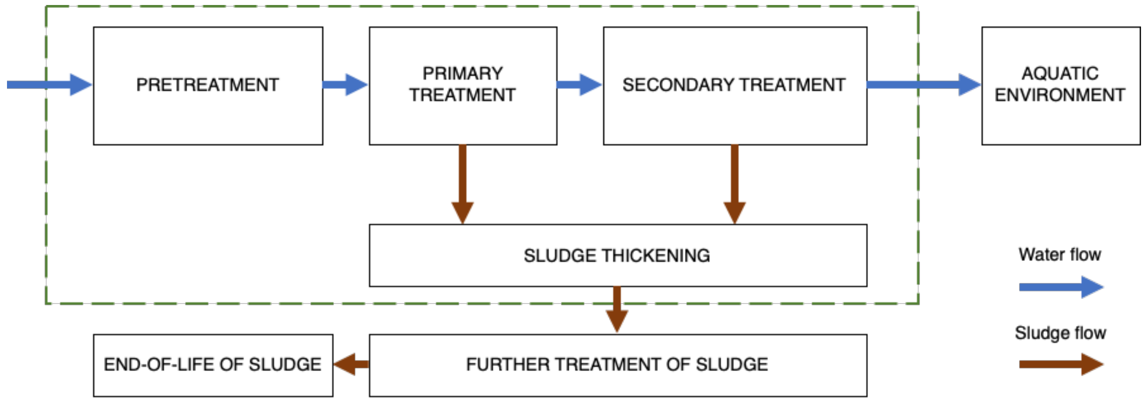


Appendix 6. Supporting data related to Chapter 8

Appendix 6.1 Operational scheme of the Llobregat WWTP



Appendix 6.2 Operational scheme of the Besós WWTP



Appendix 6.3 Total amount of wastewater treated in the Àrea Metropolitana de Barcelona in 2018 per WWTP

WWTP	m^3	%
Vallvidrera	333075	0,12%
Sant Feliu de Llobregat	21009842	7,56%
Montcada i Reixac	21009842	7,56%
Besòs	125457846	45,16%
Begues	415516	0,15%
El Prat de Llobregat	94347850	33,96%
Gavà-Viladecans	15218034	5,48%
SUM	277792005	100%

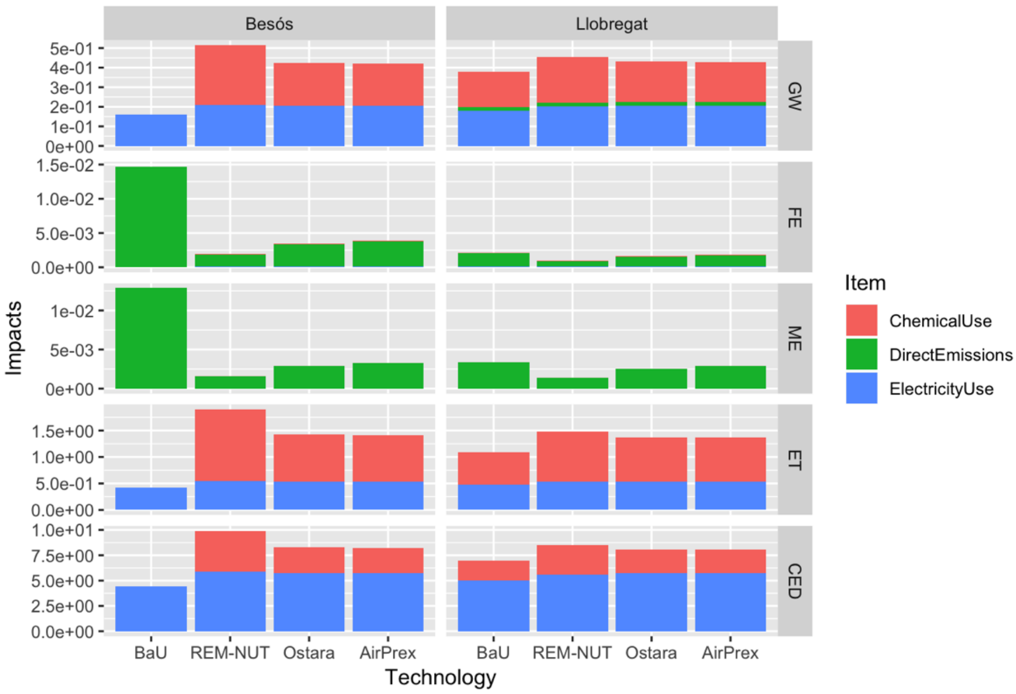
Appendix 6.4 Labels matching between Declaració Única Agrària (DUN) and Mercadé et al. (2010).

Labels matching between Declaració Única Agrària (DUN) and Mercadé et al. (2010). First column reference has information on the area of agricultural fields. Second column reference has information on the amount on the application of fertilizers	
DUN Labels	Mercadé et al (2010) Labels
Albercoquers	Fruita dolça
Albergínia	Horta
Alfàbrega	Flor i planta ornamental
Alfals no sie	Conreus farratgers
Alfals sie	Conreus farratgers
Altres Fruiters	Fruita dolça
Ametllers	Fruits secs
Anet	Flor i planta ornamental
Api	Horta
Avellaner	Fruits secs
Blat de moro	Conreus industrials
Blat tou	Conreus farratgers
Bleda	Horta
Boixac o calèndula	Flor i planta ornamental
Cànyem	Horta
Caqui	Fruita dolça
Carabassa	Horta
Carbassó	Horta
Carxofa	Horta
Cebes, calçots, porros i alls	Horta
Cirerers	Fruita dolça
Civada	Conreus farratgers
Cogombre	Horta
Col i coliflor	Horta
Colza	Conreus industrials
Coriandre	Conreus farratgers
Créixens	Horta
Enciam	Horta
Endívia, escarola i xicoira	Horta
Espàrrecs	Horta

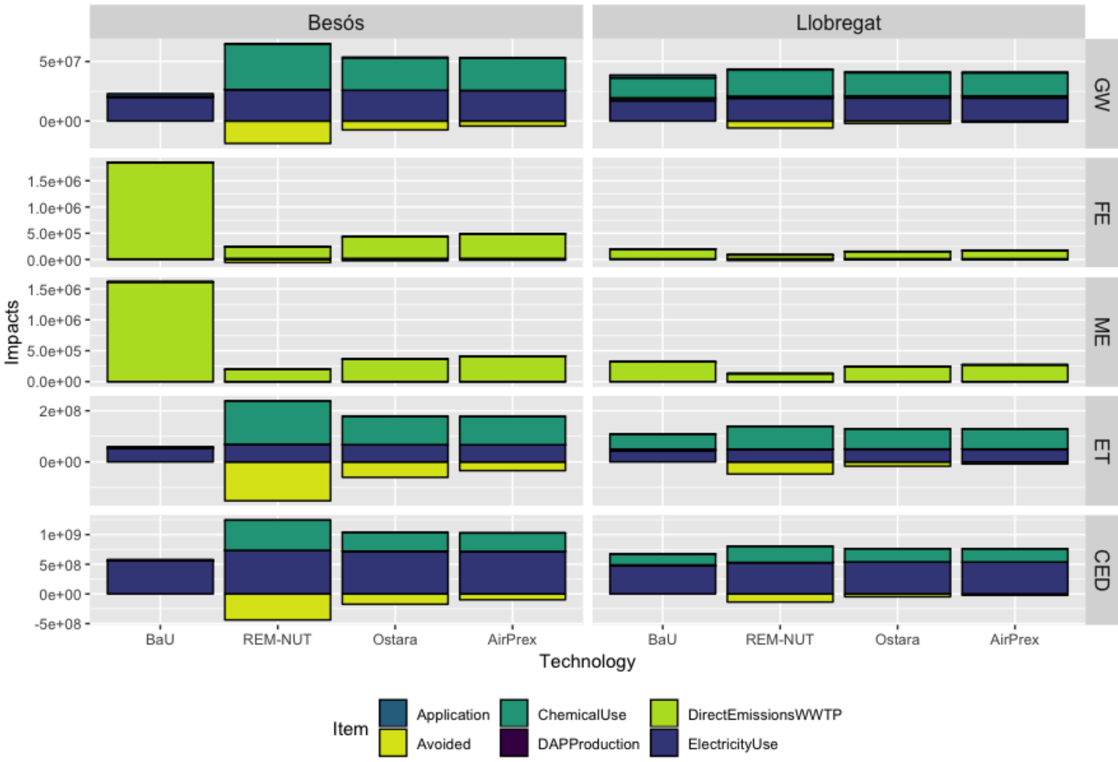
Espècies aromàtiques herbàcees	Flor i planta ornamental
Espècies aromàtiques llenyoses	Flor i planta ornamental
Espinacs	Horta
Fajol	Lleguminoses per a gra
Farigola o timó	Flor i planta ornamental
Faves i favons no sie	Horta
Faves i favons sie	Horta
Festuca	Conreus farratgers
Figuera	Fruita dolça
Flors i ornamentals	Flor i planta ornamental
Fonoll	Flor i planta ornamental
Fruiters varis	Fruita dolça
Garrofer	Lleguminoses per a gra
Guaret no sie/ sup. Lliure se*	Guarets i altres terres no ocupades
Guaret sie/ sup. Lliure sembra	Guarets i altres terres no ocupades
Horta	Horta
Julivert	Flor i planta ornamental
Kiwi	Fruita dolça
Llimoner	Cítrics
Maduixa	Horta
Magraner	Fruita dolça
Mandariner	Cítrics
Meló	Fruita dolça
Menta	Flor i planta ornamental
Mongeta no sie	Horta
Nap i col xinesa	Horta
Nectarins	Cítrics
Nesprer	Fruita dolça
Oliveres	Olivera
Ordi	Conreus farratgers
Pèsols no sie	Horta
Pastanaga	Patata
Patata	Patata
Pebrot	Horta
Pereres	Fruita dolça
Pereres/Pomeres	Fruita dolça
Pomeres	Fruita dolça
Presseguers	Fruita dolça
Presseguers/nectarins	Fruita dolça
Pruneres	Fruita dolça
Raím de taula	Fruita dolça
Rave	Horta
Ray-grass	Conreus farratgers
Remolatxa	Horta
Romaní	Flor i planta ornamental
Síndria	Fruita dolça
Sorgo	Cereals per a gra d'estiu
Taronger	Cítrics
Tomàquet	Horta
Trepadella no sie	Flor i planta ornamental

Trepadella sie	Flor i planta ornamental
Triticale	Cereals per a gra d'estiu
Vinya i civada no sie	Vinya
Vinyes	Vinya
Viver arbre i arbust	Flor i planta ornamental

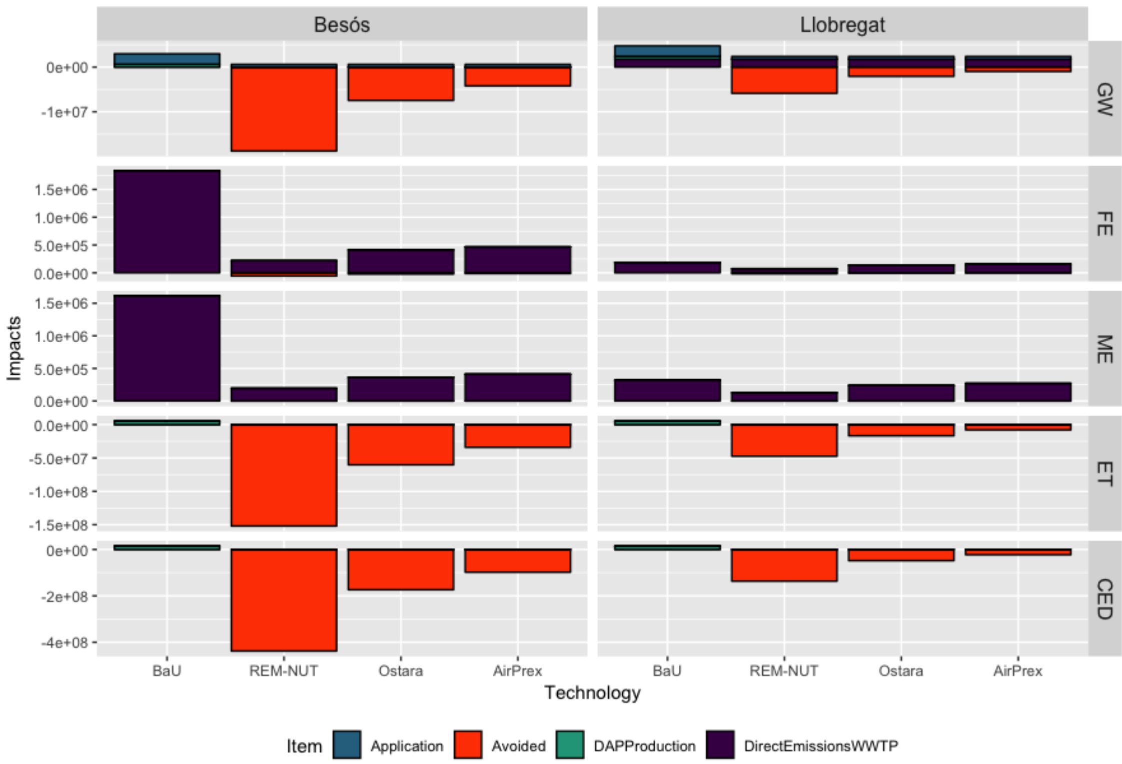
Appendix 6.5 Graph results for Table 8.3



Appendix 6.6 Impacts of a regional struvite recovery and reuse plan in the Àrea Metropolitana de Barcelona. GWP – Global Warming Potential (kg CO_2 eq); FE – Freshwater Eutrophication (kg P eq); ME – Marine Eutrophication (kg N eq); ET – Ecotoxicity (kg 1,4-DB eq); CED – Cumulative Energy Demand (MJ).



Appendix 6.7 Impacts of a regional struvite recovery and reuse plan in the Àrea Metropolitana de Barcelona, omitting impact from electricity use and chemical use. GWP – Global Warming Potential (kg CO_2 eq); FE – Freshwater Eutrophication (kg P eq); ME – Marine Eutrophication (kg N eq); ET – Ecotoxicity (kg 1,4-DB eq); CED – Cumulative Energy Demand (MJ).



Appendix 7. Supporting data related to Chapter 9

Appendix 7.1 References for the circular strategies

References for the circular strategies		
Strategy	Scenario	References
Struvite	S1	(Gell et al., 2011; Latifian et al., 2012; Y. Liu et al., 2011; Uysal et al., 2014; Yetilmezsoy et al., 2017)
	S2	
Compost	S3	(Dickson et al., 1991; Finck, 1988; Haghighi et al., 2016; Mazuela and Salas, 2005; Román et al., 2013; Sanjuan-Delmás et al., 2020; Urrestarazu et al., 2008)
	S4	
Water source	S5	(Martí Rufí-Salís et al., 2020b; Sanjuan-Delmás et al., 2018)
	S6	
Nutrient recirculation	S7	(Bouchaaba et al., 2015; M. Rufí-Salís et al., 2020; Martí Rufí-Salís et al., 2020c; Wernet et al., 2016; Zabaniotou et al., 2015)
	S8	(Incrocci et al., 2003; Muñoz et al., 2012)
Use of recycled materials	S9	Considering 100% use of recycled materials
	S10	(Briassoulis et al., 2013; Comission, 2008; EuRIC AISBL, 2015; La Vanguardia, 2019; UNEP, 2011; Wang et al., 2007)
Recyclability of materials	S11	Considered 100% of recycling materials
	S12	(Comission, 2008; Goonan, 2004; Scarascia-Mugnozza et al., 2012; Schmid, 2019; UNEP, 2011; Wang et al., 2007)
Combined	S13	Combined of some of the previous (specified in the manuscript)

Part of the supporting data related to Chapter 9 is in the form of spreadsheets. It can be found in the CD attached to the hard copy of this thesis under the name Appendix 7.2 or under request to the author.

Part of the supporting data related to Chapter 9 is in the form of a script from the R programing software. It can be found in the CD attached to the hard copy of this thesis under the name Appendix 7.3 or under request to the author.