Agro-urban sustainability through rooftop greenhouses, improving cities' sustainability. Economic viability and sustainable business models

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Doctoral thesis

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

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The present thesis entitled *Agro-urban sustainability through rooftop greenhouses, improving cities' sustainability. Economic viability and sustainable business models* by Alexandra Mario Pena has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB)

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“**П**ерфектната **П**одготовка **П**редотвратява **П**ровала на **П**редставлението.”

Bulgarian translation “Perfect preparation prevents the performance from failing”.

My dad golden rule calls “the 5P rule”

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Abbreviations, acronyms, and notations

ASR	Adopt a stewardship role
B	Boron
BEP	Break-even point
BM	Business model
BMC	Business Model Canvas
BoP	Base of the pyramid
$CaCl_2$	Calcium chloride
$Ca\ (NO3)_2$	Calcium nitrate
CO2	Carbon dioxide
CPS	Curtains and partitions system
Cu	Copper
CBA	Cost benefit analysis
CBM	Circular business model
CSA	Community supported agriculture
CityZen	Interreg Europe project: Enhancing scalable innovations and new business models based on urban farming ecosystem values
DFNO	Deliver functionality, not ownership
DSSS	Develop sustainable scale-up solutions
E-LCA	Environment life cycle assessment
EoL	End-of-life
ES	Encourage sufficiency
EPCS	External pest control specialist
FBWM	Final biomass waste management
Fe	Iron
FOOD-E	Food systems in European cities
FU	Functional unit
GROOF	Greenhouses to Reduce CO_2 on Roofs
GHGs	Greenhouse gases
ICTA	Institute of Environmental Science and Technology
i-RTG	Integrated rooftop greenhouse
IVC	Inclusive value creation
KH_2PO_4	Monopotassium phosphate
KNO_3	Potassium nitrate
LCA	Life cycle assessment
LCC	Life cycle cost

LCCA	Life cycle costing analysis
LCSA	Life cycle sustainability assessment
LCSA	Life cycle sustainability assessment
MFSRF	Marketplace for fresh, surplus, or rejected food
$Mg\ (NO_3)_2$	Magnesium nitrate
Mn	Manganese
Mo	Molybdenum
MRU	Maximise the resource use
NEWBIE	Horizon 2020 project: New Entrant netWork: Business models for innovation, entrepreneurship, and resilience in European agriculture
PBWC	Pruning biomass waste collection
PE	Polyethene plastic
PSS	Product-service system
PVC	Polyvinyl chloride
RF	Rooftop farming
RG	Rooftop garden
RSE	Repurpose for society and environment
RTG	Rooftop greenhouse
RWHS	Rainwater harvest system
SBM	Sustainable business model
SD	Sustainable development
SDG	Sustainable development goal
S	Sulfur
SI	Supplementary information
S-LCA	Social life cycle assesment
SM	Subscription model
SRNP	Substitute with renewable and natural processes
SS	System of sensors
TC	Total cost
TFC	Total fixed cost
TVC	Total variable cost
UA	Urban agriculture
UAB	Universitat Autònoma de Barcelona
UA-SBMs	Sustainable business models for urban agriculture
VAT	Value added tax
VF	Vertical farming
WLC	Whole life costing
WBSR	Waste-based solutions and reuse
Zn	Zinc

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Summary

Currently, more than half of the world population lives in urban areas and this tendency will reach 68% by 2050. Despite people are pulled towards the advantages of cities (e.g., health insurance, improved access to education, social services and cultural activities), negative outcomes are also expected such as exploitation of resources, pollution (air and water), poverty, reduction of agricultural land, fresh food problems due to the increased demand.

Deploying urban agriculture (UA) systems, especially integrated rooftop greenhouses (i-RTGs) as innovate UA forms might have the potential to mitigate these urbanization´s challenge, providing at the same time opportunities for sustainable city development in three dimensions: environmental, social and economic. In this regard, many studies have been focused on the analysis of the environmental aspects of UA by applying life cycle assessment (LCA) without paying enough attention to the economic ones through using life cycle cost analysis (LCCA) which application for economic assessment in different sectors (e.g., infrastructure, construction, building, agri-food) is constantly growing. Moreover, since previous research demonstrated that the high construction costs could be important barrier for future implementation of innovative UA system likes i-RTGs at large scale, the development of sustainable business models (SBMs) for UA can contribute to reducing them without increasing the impact on the environment and/or society. But overall, the research on SBMs for the agri-food sector is still limited, and particularly for UA systems is quite scarce.

To fill these research gaps, the general objective of this dissertation is to analyse the economic sustainability of UA, especially i-RTGs as innovative forms of UA for sustainable city development, from an LCC and SBM approach. To achieve the main objective, three specific objectives are established. The first is to analyse the evolution of the use of LCC in UA over a 22-year period. While the second is to analyse the economic viability of urban food production (tomato crop) from an i-RTG through applying LCC. Lastly, the third is to present a comprehensive categorisation and characterisation of SBM for UA and to provide recommendations for their selection and posterior application.

To do this, an innovative research approach is applied based on literature review and LCC methodologies, complemented by case study analysis, break-even point analysis (BEP), bibliometric analysis using software, and sustainable development goal (SDG) impact analysis.

The most relevant findings from analysing the evolution of the use of LCC in UA are that urban horticulture is the most studied UA practices and there is a scarce use of additional financial tools to complement the LCC analysis. Moreover, it is found that

frequently i) the four main LCC stage are not applied appropriately, and ii) essential costs like labour and infrastructure are excluded from the LCC calculations. Regarding the second specific objective, the results indicate that economic viability of the tomato crop from the i-RTG depends on the following four main costs (drivers) responsible for 61.8% of the total cost: i) labour (24.7%), (ii), rooftop greenhouse (RTG) structure (15%), iii) external pest control specialist (EPCS) (12.6%), (iv) and rainwater (9.5%). Therefore, their reduction is an important requirement to achieve economic viability. For instance, the labour cost can be minimised if volunteers and/or customers do the cultivation tasks, specially the most labour demanding harvest task. Concerning the RTG structure (initial investment) cost, it can be reduced by optimising its prototype, materials, and size since it is argued that high investment cost could be a possible barrier for implementing innovative UA systems at large scale. Regarding the third and fourth cost drivers, the EPCS could be minimised/avoided if staff training was provided and the rainwater cost could be decreased by optimising the rainwater tank size according to the productive area. Moreover, the results of applying an additional BEP demonstrated that a combination of high fixed costs (e.g., RTG structure) and low yields can impede the economic viability and profitability of i-RTG artisan production. Lastly, to complete with the third specific objective, a list of 11 archetypes is created including their relationship with the SDGs to be used for future analysis and development of SBMs for UA (UA-SBMs). However, four UA-SBMs archetypes are found to be particularly relevant to deploy sustainable UA system because of their major presence in the analysed cases and increased sustainable potential. Accordingly, one of the recommendations for the selection and posterior application of UA-SBMs archetypes is about using one of them or their combinations. Moreover, since it is discussed that the selection and future application of UA-SBMs archetypes depends on the particular UA case, the next recommendation is about performing an exhaustive previous study to verify if there some restrictions that can impede their implementation.

The novelty of the doctoral thesis for the research and practice on UA, LCC and SBMs can be consumed in three lines. It is first dissertation as far as its authors know that i) through a literature review on the use of LCC for UA context provides recommendations for improvement the LCC application in future research important to make balanced decision for sustainability; ii) analyse the LCC of tomato production in i-RTGs in detail by integrating essential labour and infrastructure costs, classifying fixed and variables costs and applying additional BEP analysis to find the optimal level of production to be sold and determinate the maximum level of fixed costs at different selling prices; and iii) presents a comprehensive categorisation and characterisation of UA-SBMs, including their relationship with the SDGs to facilitate the deployment of more resource efficient, socially responsible, economically viable and environmentally suitable food production systems in the urban areas.

Resum

Actualment, més de la meitat de la població mundial viu en àrees urbanes i aquesta tendència arribarà al 68% l'any 2050. Tot i que la gent es desplaça cap a les ciutats pels beneficis que ofereixen (per exemple, atenció médica, millor accés a l'educació, serveis socials, i activitats culturals), el procés d'urbanització a més comporta conseqüències negatives com l'explotació de recursos productius, la contaminació (aire i aigua), la pobresa, la reducció de les terres agrícoles i la manca d´aliments fresc a causa de l´alta demanda.

En aquesta relació, s'han demostrat que el desplegament de sistemes d'agricultura urbana (UA en anglès), i especialment les seves formes innovadores com a hivernacles integrats a les cobertes (i-RTG en anglès) tenen el potencial d'alleujar els problemes derivats de la urbanització, brindant simultàniamen oportunitats per al desenvolupament sostenible a les ciutats en tres dimensions: ambiental, social i econòmica. Tot i això, la majoria dels estudis anteriors s'han centrat en l'anàlisi dels aspectes ambientals de sostenibilitat de la UA mitjançant l'ús de l'anàlisi del cicle de vida (LCA en anglès) sense incidir als aspectes econòmics de sostenibilitat usant el anàlisi del cost del cicle de vida (LCCA en anglès) que és una aplicació per a l'avaluació econòmica en auge per a diferents sectors industrials. A més, atès que investigacions prèvies van revelar que els alts costos de construcció de formes innovadores d'UA com a i-RTG podrien ser una barrera important per a la seva futura implementació a la ciutat, el desenvolupament de models de negocis sostenibles (SBMs en anglès) per a UA sería una contribució valuosa per a la seva reducció sense augmentar l'impacte sobre el medi ambient i la societat. Però, en general, la investigació sobre SBMs per al sector agroalimentari encara és limitada i, en particular, per als sistemes d'UA és molt escassa.

Per abordar aquestes limitacions, l'objectiu general d´aquesta tesi doctoral és analitzar la sostenibilitat econòmica de la UA, particularment els i-RTG com les seves formes innovadores per al desenvolupament sostenible de la ciutat, des d´un enfocament de LCC i SBM. Per aconseguir l´objectiu principal, s´estableixen tres objectius específics. El primer objectiu és analitzar l´evolució de l´ús de LCC a la UA durant un període de 22 anys. Mentre que el segon objectiu és avaluar la viabilitat econòmica de la producció urbana d´aliments (cultiu de tomàquet) d´un i-RTG mitjançant l´aplicació de LCC. Finalment, el tercer objectiu és presentar una caracterització i categorització integral de SBMs per a UA i proporcionar recomanacions per a la seva selecció i posterior aplicació.

Aquest treball presenta un enfocament innovador que combina les metodologies i anàlisis següents: i) revisió de literatura, ii) LCC, iii) anàlisi d'estudi de cas, iv) anàlisi de punt d'equilibri (BEP en anglès), v) anàlisi bibliomètrica mitjançant l'ús de programari, i v) anàlisi d'impactes sobre els objectius de desenvolupament sostenible (SDGs en anglès).

Les troballes més rellevants de l'anàlisi de l'evolució de l'ús de LCC a UA són que i) l'horticultura urbana és la pràctica d'UA més estudiada entre els estudis que van fer servir LCC per a UA, i ii) l'ús d'eines financeres addicionals per complementar el LCC és molt escàs. A més, es troba que sovint i) les quatre etapes principals de LCC no s'apliquen adequadament, i ii) costos essencials com la mà d'obra i la infraestructura s'exclouen dels càlculs.

Pel que fa al segon objectiu específic, els resultats van indicar que la viabilitat econòmica del cultiu de tomàquet de l'i-RTG depèn dels quatre costos principals següents que contribueixen un 61,8% del cost total: i) mà d'obra (24,7%), (ii) infraestructura d'hivernacle a la coberta (en anglès RTG) (15%), iii) especialista extern en control de plagues (en anglès EPCS) (12,6%), i (iv) i aigua de pluja (9,5%). Per tant, la seva reducció és un requisit important per assolir la viabilitat econòmica. Per exemple, el cost de la mà d´obra es pot minimitzar si voluntaris o clients realitzen les tasques del cultiu, particularment durant la collita, que requereix més mà d´obra. Pel que fa al cost de la infraestructura de RTG (inversió inicial), es pot reduir mitjançant l'optimització del prototip, materials i mida, ja que aquest alt cost d'inversió podria ser una barrera significativa per implementar sistemes innovadors d'UA a gran escala. Pel que fa als costos d'EPCS i aigua de pluja, el primer es pot disminuir/evitar en proporcionar formació al personal dedicat al cultiu, mentre que el segon es pot reduir en optimitzar la mida del tanc d'aigua de pluja d'acord amb l'àrea productiva. Addicionalment, els resultats d'aplicar una anàlisi BEP addicional van indicar que la combinació d'alts costos fixos (per exemple, infraestructura de RTG) juntament amb rendiments productius baixos podrien ser un obstacle important per a la viabilitat econòmica i la rendibilitat de la producció hortícola d'un i -RTG.

Finalment, per assolir el tercer objectiu específic, es crea una llista d'11 arquetips incloent la seva relació amb els SDGs que servirà pel posterior anàlisi i desenvolupament de SBM per a UA (UA-SBM abreviatura en anglès). No obstant això, quatre arquetips d'UA-SBM resulten particularment rellevants per al desplegament de sistemes d'AU sostenibles a causa de la presència més gran en els casos analitzats i el potencial sostenible més gran. Per tant, una de les recomanacions per a la selecció i posterior aplicació dels arquetips és utilitzar-ne una o les combinacions. A més, ja que s'han discutit que la selecció i futura aplicació dels arquetips UA-SBMs depèn del cas particular d'UA, la següent recomanació és fer un estudi previ detallat per verificar si hi ha algunes restriccions que puguin impedir la implementació.

La novetat de la tesi doctoral per a la investigació i pràctica de UA, LCC i SBM es pot resumir en tres línies. És la primera dissertació que i) mitjançant una revisió de la literatura sobre l'ús de LCC per a UA ofereix recomanacions per millorar l'aplicació de LCC en investigacions futures per a la presa de decisions equilibrades de sostenibilitat; ii) analitza el LCC de la producció de tomàquet a i-RTG incloent costos essencials com a mà d'obra i infraestructura, classifica costos fixos i variables i aplica una anàlisi BEP addicional per trobar el nivell òptim de producció de venda i determinar el nivell màxim de costos fixos a diferents preus al públic; i iii) presenta una categorització i caracterització integral dels UA-SBM, inclosa la seva relació amb els SDGS per facilitar el desplegament de sistemes de producció d'aliments urbans més socialment responsables, econòmicament viables i ambientalment adequats a les àrees urbanes.

Resumen

Actualmente, más de la mitad de la población mundial vive en áreas urbanas y esta tendencia alcanzará el 68 % en el año 2050. Sin embargo, a pesar de que la gente se desplaza hacia las ciudades por los beneficios que ofrecen (por ejemplo, atención médica, mejor acceso a la educación, servicios sociales, y actividades culturales), el proceso urbanístico además conlleva consecuencias negativas tales como la explotación de recursos productivos, la contaminación (aire y agua), la pobreza, la reducción de las tierras agrícolas y la falta de alimentos fresco debido al alta demanda.

En esta relación, se han demostrado que el despliegue de sistemas de agricultura urbana (UA en inglés), y especialmente sus formas innovadoras como invernaderos integrados en las cubiertas (i-RTG en inglés) tienen el potencial de aliviar estos desafíos urbanísticos, brindando al mismo tiempo oportunidades para el desarrollo sostenible en las ciudades en tres dimensiones: ambiental, social y económica. Sin embargo, la mayoría de los estudios anteriores se han centrado en el análisis de los aspectos ambientales de sostenibilidad de la UA mediante el uso del análisis del ciclo de vida (LCA en inglés) sin prestar suficiente atención a sus aspectos económicos de sostenibilidad usando el análisis del coste del ciclo de vida (LCCA en inglés) cuya aplicación para la evaluación económica está en auge para diferentes sectores industriales. Además, dado que investigaciones previas revelaron que los altos costes de construcción de formas innovadoras de UA como i-RTG podrían ser una barrera importante para su futura implementación en la cuidades, el desarrollo de modelos de negocios sostenibles (SBMs en inglés) para UA sería una valiosa contribución para su reducción sin aumentar el impacto sobre el medio ambiente y/o la sociedad. Pero, en general, la investigación sobre SBMs para el sector agroalimentario es todavía limitada y, en particular, para los sistemas de UA es muy escasa.

Para abordar estas limitaciones, el objetivo general de esta tesis doctoral es analizar la sostenibilidad económica de la UA, particularmente los i-RTG como sus formas innovadoras para el desarrollo sostenible de la ciudad, desde un enfoque de LCC y SBM. Para lograr el objetivo principal, se establecen tres objetivos específicos. El primer objetivo es analizar la evolución del uso de LCC en UA durante un período de 22 años. Mientras que el segundo objetivo es evaluar la viabilidad económica de la producción urbana de alimentos (cultivo de tomate) de un i-RTG mediante la aplicación de LCC. Por último, el tercer objetivo es presentar una caracterización y categorización integral de SBMs para UA y proporcionar recomendaciones para su selección y posterior aplicación.

Para ello, se aplica un enfoque de investigación innovador que combina las siguientes metodologías y análisis: i) revisión de literatura, ii) LCC, iii) análisis de estudio de caso, iv) análisis de punto de equilibrio (BEP en inglés), v) análisis bibliométrico mediante el

uso de software, y v) análisis de impactos sobre los objetivos de desarrollo sostenible (SDGs en inglés).

Los hallazgos más relevantes del análisis de la evolución del uso de LCC en UA son que i) la horticultura urbana es la práctica de UA más estudiada entre los estudios que usaron LCC para UA, y ii) el uso de herramientas financieras adicionales para complementar el LCC es muy escaso. Además, se encuentra que con frecuencia i) las cuatro etapas principales de LCC no se aplican adecuadamente, y ii) costes esenciales como la mano de obra y la infraestructura se excluyen de los cálculos.

En cuanto al segundo objetivo específico, los resultados indicaron que la viabilidad económica del cultivo de tomate del i-RTG depende de los siguientes cuatro costes principales que contribuyen un 61,8% del coste total: i) mano de obra (24,7%), (ii) infraestructura de invernadero en la cubierta (en inglés RTG) (15%), iii) especialista externo en control de plagas (en inglés EPCS) (12,6%), y (iv) y agua de lluvia (9,5%). Por lo tanto, su reducción es un requisito importante para lograr la viabilidad económica. Por ejemplo, el coste de la mano de obra se puede minimizar si voluntarios y/o clientes realizan las tareas del cultivo, particularmente durante la cosecha que requiere más mano de obra. Respecto al coste de la infraestructura de RTG (inversión inicial), este se puede reducir mediante la optimización del prototipo, materiales y tamaño, ya que este alto coste de inversión podría ser una barrera significativa para implementar sistemas innovadores de UA a gran escala. En relación con los costes de EPCS y agua de lluvia, el primero se puede disminuir/evitar al proporcionar formación al personal dedicado al cultivo, mientas que es segundo se puede reducir al optimizar el tamaño del tanque de agua de lluvia de acuerdo con el área productiva. Adicionalmente, los resultados de aplicar un análisis BEP adicional indicaron que la combinación de altos costes fijos (por ejemplo, infraestructura de RTG) junto con bajos rendimientos productivos podrían ser un obstáculo importante para la viabilidad económica y la rentabilidad de la producción hortícola de un i-RTG.

Por último, para lograr el tercer objetivo específico, se crea una lista de 11 arquetipos incluyendo su relación con los SDGs que servirá para el futuro análisis y desarrollo de SBM para UA (UA-SBM abreviatura en inglés). Sin embargo, cuatro arquetipos de UA-SBM resultan particularmente relevantes para el despliegue de sistemas de AU sostenibles debido a su mayor presencia en los casos analizados y su mayor potencial sostenible. Por ende, una de las recomendaciones para la selección y posterior aplicación de los arquetipos es utilizar uno de ellos o sus combinaciones. Además, puesto que se han discutido que la selección y futura aplicación de los arquetipos UA-SBMs depende del caso particular de UA, la siguiente recomendación es realizar un estudio previo detallado para verificar si existen algunas restricciones que puedan impedir la implementación.

La novedad de la tesis doctoral para la investigación y práctica de UA, LCC y SBMs se puede resumir en tres líneas. Es la primera disertación hasta donde los autores sabes que i) a través de una revisión de la literatura sobre el uso de LCC para UA brinda recomendaciones para mejorar la aplicación de LCC en investigaciones futuras para la toma de decisiones equilibradas de sostenibilidad; ii) analiza el LCC de la producción de tomate en i-RTG incluyendo costes esenciales como mano de obra e infraestructura, clasifica costes fijos y variables y aplica un análisis BEP adicional para encontrar el nivel óptimo de producción de venta y determinar el nivel máximo de costes fijos a diferentes precios al público; y iii) presenta una caracterización y categorización integral de los UA-SBM, incluida su relación con los SDGS para facilitar el despliegue de sistemas de producción de alimentos urbanos más socialmente responsables, económicamente viables y ambientalmente adecuados en las áreas urbanas.

Dissemination and training

Part of this thesis is based on the following two published articles in peer-reviewed indexed journals from first quartile:

- Peña, Alexandra., Rovira-Val, M. Rosa., 2020. *A longitudinal literature review of life cycle costing applied to urban agriculture*. International Journal of Life Cycle Assessment 25, 1418–1435. https://doi.org/10.1007/s11367-020-01768-y
- Peña, Alexandra., Rovira-Val, M. Rosa., Joan Manuel F. Mendoza.,2022. *Life cycle cost analysis of tomato production in innovative urban agriculture systems*. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2022.133037

The PhD research project and some thesis results were presented at the following seminars:

- MdM Incubator, 2018. ICTA-UAB. Cerdanyola del Vallès, Barcelona.
  Oral communication: *Agro-urban sustainability through rooftop greenhouses, improving cities' sustainability. Economic benefits and business models.* Authors: Alexandra Peña, M. Rosa Rovira-Val
- FoodE Winter School. Sustainability Assessment of City-Region Food Systems. Online venue
  Oral communication: *A longitudinal literature review of LCC applied to urban agriculture.* Authors: Alexandra Peña, M. Rosa Rovira-Val

Additionally, some preliminary results of the dissertation were presented at the following international congresses and conferences as both oral and poster communication:

- 13th Conference of the International Society for Industrial Ecology (ISIE) - Socio-Economic Metabolism Section (May 13-15 , 2019).
  Oral communication: *LCC method for economic assessment of urban food production. Application in tomato production. Production of an integrated rooftop greenhouse (i-RTG) in Barcelona.*
  Poster communication: *A literature review of life cycle costing applied to the urban agriculture.*
- The 9th International Conference on Life Cycle Management 2019—Poznań, Poland, 1-4 September 2019.
  Oral communication: *LCC method for economic assessment of urban food production. Application in tomato production. Production of an integrated rooftop greenhouse (i-RTG) in Barcelona.*
  Poster communication: *A literature review of life cycle costing applied to the urban agriculture.*

Finally, the following training courses were taken to improve skills for the development of the PhD:

- *Training sessions:*

  i) December 2017: Mendeley (1.5h). UAB, Cerdanyola del Vallès.
  ii) April and May 2018: ISI Web of Knowledge (1.5h) and Scopus (2h). UAB, Cerdanyola del Vallès.
  iii) March 2019: Publish in open access (1.5h). UAB, Cerdanyola del Vallès.
- *Elevator Pitch Course (20h). UAB, Cerdanyola del Vallès. February 2019.*
- *Training workshops*
  i) October 2018. UAB, Cerdanyola del Vallès: a) Scientific Writing – The Why and How of Good Scientific Writing (16h), b) Core communication skills, time and project management (16h), and iii) Oral and Poster Presentations (18h)
  ii) October 2019. Introductory Course of R and R Studio. Statistical Programming with R (18h). UAB, Cerdanyola del Vallès
  iii) October 2021. Career development (4h). Online venue

Structure of the dissertation

This dissertation is composed of five main parts, seven chapters and an addendum to Chapter 4 as can be seen in Fig. X1.

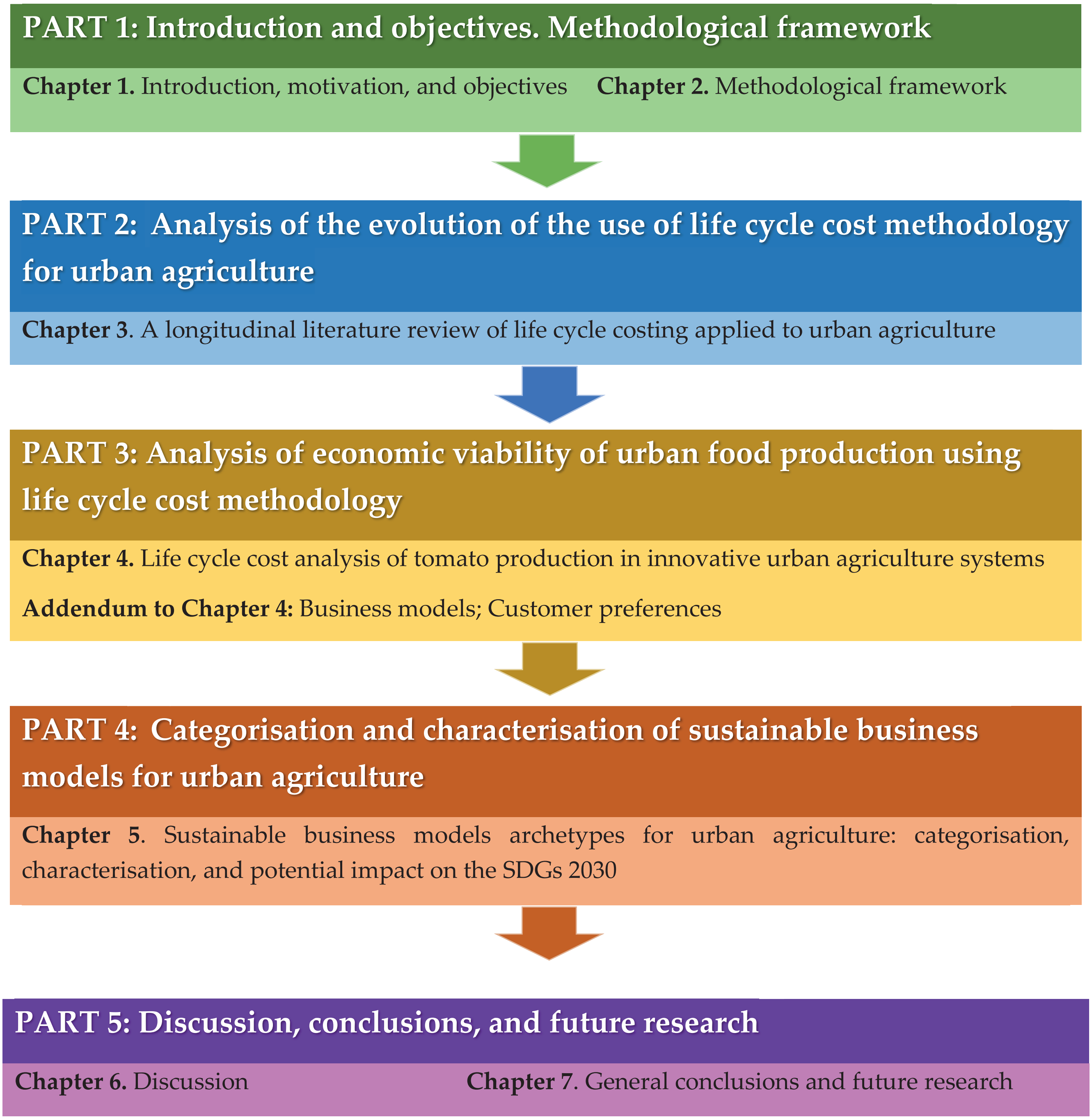

Fig X1. Structure of the dissertation

PART 1: INTRODUCTION AND OBJECTIVES. METHODOLOGICAL FRAMEWORK

Chapter 1

Introduction, motivation, and objectives

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Chapter 1. Introduction, motivation, and objectives

Firstly, this chapter highlights the importance to implement urban agriculture (UA) practices due to emerging problems in the cities. Secondly, the concept of life cycle cost (LCC) is introduced as a tool for evaluating the economic aspects of the sustainability of UA. Thirdly, the need to design sustainable business models for UA is justified. Lastly, the motivation and objectives of the dissertation are presented.

1.1. Emerging problems in the cities due to rapid urbanization

In 2007, it was estimated that for the first time in history, more people live in urban areas than rural areas (United Nations, 2007) and the urban population is forecasted to reach 68% (6.6 out of 9.7 billion people) in 2050 (UN DESA, 2018). As an example, in the European Union alone, 75% of the population lives in cities, and this tendency is expected to get to 83.7% by 2050. (UN DESA, 2019).

Despite people being pulled towards the advantages of cities such as improved access to education, health, social services, and cultural activities, negative consequences are as well expected. In this regard, unplanned urban growth can affect land, water, air, and wildlife due to the number of people, the number of buildings and construction, and the increased demands on resources. Moreover, waste accumulation (Adhikari et al. 2009), pollution (air and water), and limited water resources are the main environmental challenges that cities are facing (Uttara et al. 2012). Another critical challenge is related to the supply and distribution of food in the urban areas (Baud, 2000) due to the increased food demand (UNCCD, 2017) which is putting pressure on global food security (UNCCD, 2017). In this regard, it was estimated that 9.2 % of the world population (over 700 million people) experienced serious problems regarding food security in 2018 (Egal, 2019).

According to FAO, IFAD, UNICEF, WFP, and WHO (2019), currently, there are 820 million people hungry and malnourished albeit a third of all edible food (1.8 billion tonnes) continues to go uneaten (Ellen MacArthur Foundation, 2019) due to socio-economic problems (Ibarrola Rivas and Nonhebel, 2016).

For instance, the negative societal costs from producing food are considered to account for USD 5.7 trillion each year, as high as those of obesity, malnutrition, and other food consumption issues combined (Ellen MacArthur Foundation, 2019). This includes negative effects from farmers´ long-term exposure to low levels of pesticides, antimicrobial resistance, and air pollution. Likewise, pesticides and synthetic fertilizers used in conventional agriculture practices, including mismanagement of manure, can exacerbate air and soil pollution and leach chemicals into water supplies. Moreover, agriculture accounts for around 70% of global freshwater use and deforestation, being the agri-food industry the world's second-largest emitter of greenhouse emissions

(GHGs), with 25% of all human-caused emissions (FAO, 2017a).

Remarkably, a report by the Ellen MacArthur Foundation highlights that of 7.1 billion tons of food produced globally, approximately 40% is eaten in cities, where 2.8 billion tons of organic waste is produced. Moreover, it emphasizes that 80% of all food will be destined for consumption in the cities by 2050 and therefore they have huge potential to influence the way in which food is grown and eaten (Ellen MacArthur Foundation, 2019). Therefore, new agricultural practices for providing fresh food in the cities should be found to guarantee food security for the population at a lower cost within the framework of sustainable development (Nadal et al., 2015) and to be resilient to economic and sanitary crises such wars and pandemics (Barthel et al., 2019; Langemeyer et al., 2021).

1.2. Urban agriculture in the framework of sustainable development

The development of UA practices in the urban areas is a good example of combating the cities' fresh food problems, by providing relevant opportunities for sustainable urban development (Pearson et al., 2010; Thomaier et al., 2015). In this regard, Cerón-Palma et al., (2012) and Specht et al., (2014) highlighted the potential contribution of UA to improving the three dimensions of sustainability: environment, economy, and society.

Considering environmental sustainability, UA can increase biodiversity in cities (Van Tuijl et al., 2018) and contribute to the reduction of pollutant emissions, including GHGs, facilitating the adaptation and mitigation of climate change impacts (Bendt et al., 2013; Lwasa et al., 2015, 2014). Regarding social sustainability, UA can contribute to i) the target of the sustainable development goal (SDG) 2 by "feeding" the urban citizens with fresh food, and on the other hand, and ii) the community development by promoting social cohesion between different groups in the society to provide work opportunities and training for unemployed workers. Moreover, UA can be used for educational purposes through the organization of workshops, courses, and tours aiming to increase awareness among citizens regarding the origin and production of the food. Finally, UA can also has a valuable contribution to improving the economic sustainability in cities through (i) establishing new ways for income generation since there are several companies that use UA for commercial purposes (Lufa Farms, 2021; The Plant, 2021), (ii) offering recreational and tourist activities (Brooklyn Grange, 2022), and iii) encouraging research, innovation, and knowledge through the creation of R&D labs on-site in the urban farms or through collaboration with educational centers (Fertilecity, 2021; Harquitectes, 2015).

Overall, UA can be defined as "an industry located within (intra-urban) or on the fringe (peri-urban) of a town, city or metropolis, which grows or raises, processes and distributes a diversity of food and non-food products…" (Mougeot, 2000, p.11). It is a wide term that includes not only the cultivation of plants and animal rearing but also other associated activities such as the production and selling of agricultural inputs, marketing, post-harvesting, marketing, and commercialization (Orsini et al., 2013). There is a huge variety of different UA forms according to location, land ownership, use and technologies implemented (Nadal et al., 2015) however there is an emerging interest in the development of vertical farming (VF) or ZFarming forms of UA which includes rooftop gardens (RGs), indoor farms and rooftop greenhouses (RTGs). This is because of the deficient space in cities to support traditional ground agriculture and the lack of the main resources necessary for agricultural production such as water and energy (Specht et al., 2014; Thomaier et al., 2015). Amongst the VF forms of UA, RTGs and integrated rooftop greenhouses (i-RTGs) are getting more importance due to the increasing need for the development of new innovative food production spaces to promote food self-sufficiency in the urban areas (Sanyé-Mengual et al., 2015a).

1.3. Life cycle cost (LCC) to evaluate economic aspects of sustainability

Life cycle cost (LCC) also known as life cycle cost analysis (LCCA) commonly used method for economic assessment and analysis. It is framed within the life cycle sustainability assessment (LCSA), which includes different analyses for each of the three pillars of sustainability (environmental, economic, and social) (Swarr et al, 2011): (i) environmental life cycle assessment (E-LCA) or most known as life cycle assessment (LCA) for environmental measurement, (ii) LCC used for economic evaluation, and (iii) social life cycle assessment (S-LCA) to assessment of the social aspects of sustainability (UNEP, 2012) (Fig.1.1).

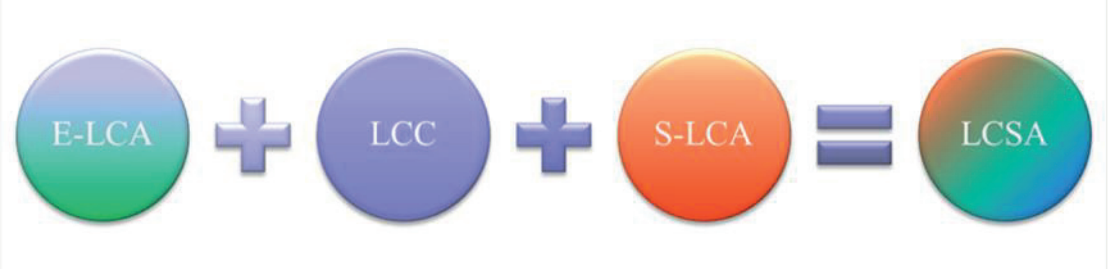


Fig. 1.1. Life cycle sustainability assessment (LCSA) and its composing analyses. Source: UNEP (2012)

LCC aims to quantify the total cost over the life cycle of a project to identify the cost-effectiveness of alternative projects for input into a decision-making or evaluation process (Norris 2001; ISO 2008). It is an economic evaluation technique that considers all costs and cash flows that emerge during the life cycle of a project, product, or service (Ammar et al., 2013) from the costs of design and acquisition through to operation, maintenance, and disposal (Wu and Longhurst, 2011; ISO 2008).

The interest in the use of LCC became popular in the mid-1960s, but 1996 may be considered the starting point because of the publication of the first official document containing a theoretical framework, the handbook entitled Life Cycle Costing Manual for the US Federal Management Program (Fuller and Petersen, 1996). Nowadays, LCC is distributed worldwide and is one of the most used procedures for economic assessment in different sectors such as infrastructure, construction, and building (Naves et al., 2018).

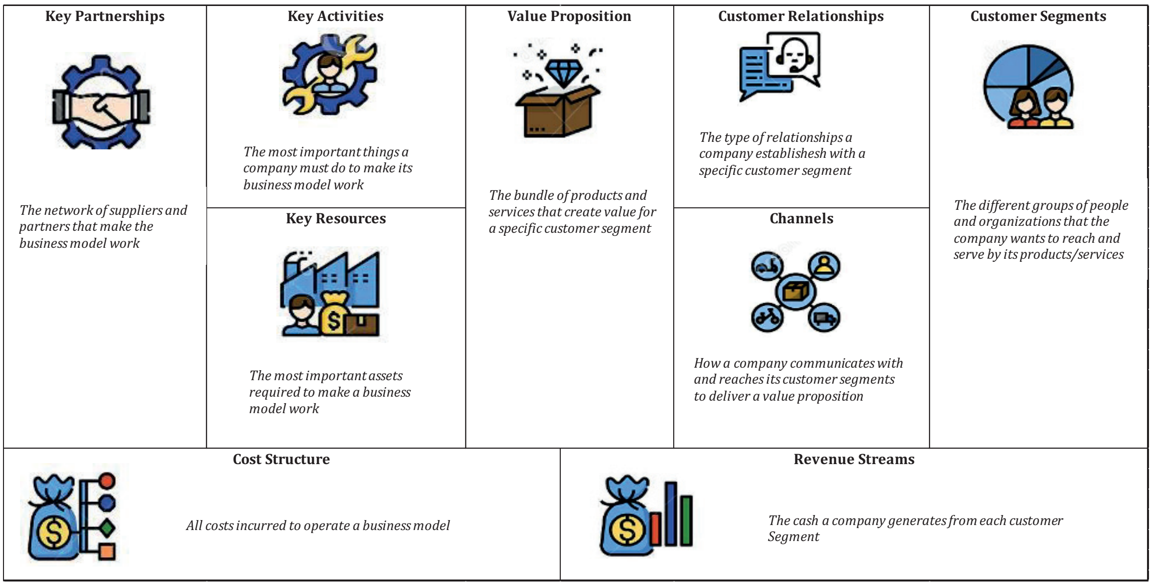
Applying LCC may be used for different purposes. For instance, as a tool for planning, optimisation, and hotspot identification within the LCSA, or for evaluating investment decisions (Rödger et al., 2018). However, the LCC differs from the traditional investment calculus since it has an expanded life cycle perspective, and therefore includes not only investment costs, but also operating costs during the lifetime of a product, process, or project (Gluch and Baumann, 2004). Exist other popular methods for assessing economic performance or such as cost-benefit analysis (CBA) (Carter and Keeler, 2008; Sanyé-Mengual et al., 2015a; Benis et al. 2018) and whole life costing (WLC) (ISO, 2008, Roebuck and Ashley, 2007). Nonetheless, the procedures and characteristics of CBA and WLC are very similar to those of LCC, and most of the time the authors refer to their methods as CBA or WLC while the methodology that they have used is LCC.

Concerning UA, LCA is the most extensively used life cycle methodology in many UA studies (Orsini et al., 2014; Goldstein et al., 2016; Sanjuan-Delmás et al., 2018a). While the environmental aspects of UA have been widely studied in the literature, the evaluation of its economic aspects (e.g., economic viability) through LCC is still insufficient (Sanye-Mengual et al., 2017a). Although, LCA is a suitable tool to assess environmental impacts, LCA outcomes are constrained for effective decision-making without the integration of economic data through LCC (Norris, 2001).

1.4. The need for design sustainable business models for UA

UA can be a driver for local economies that also contributes to the establishment of new business models (BMs) (Lynch et al., 2013). Moreover, appropriately designed BM for UA projects, can contribute to further key costs reduction, providing at the same time additional revenues and thus may improve the economic viability. For instance, by organising social and entertainment activities (e.g., education, events, therapeutic services, health care) along with the main production of food (Pölling et al., 2017).

A BM explains how an organization creates, delivers, and captures value (Osterwalder and Pigneur, 2010). This was illustrated by Osterwalder and Pigneur (2010) that created a business model canvas (BMC) which is a strategic management template that includes nine blocks representing the main components of each business: value propositions, customer segments, customer relationships, channels, key activities, key resources, key partnership, cost structure and revenue streams (Fig 2). In this regard, the LCC results provide valuable information for studying and developing BMs for UA, since the cost structure is an integral part of the business.



Key Partnerships
The network of suppliers and partners that make the business model work

Key Activities
The most important things a company must do to make its business model work

Key Resources
The most important assets required to make a business model work

Value Proposition
The bundle of products and services that create value for a specific customer segment

Customer Relationships
The type of relationships a company establishesh with a specific customer segment

Channels
How a company communicates with and reaches its customer segments to deliver a value proposition

Customer Segments
The different groups of people and organizations that the company wants to reach and serve by its products/services

Cost Structure
All costs incurred to operate a business model

Revenue Streams
The cash a company generates from each customer Segment

Figure 1.2: The Business Model Canvas, with brief explications of the nine main building blocks Source: Osterwalder and Pigneur (2010); icons: www.dreamstime.com

The most common business models of UA can be summarized as follows: *low-cost specialisation, differentiation, and diversification* (Van Der Schans, 2010; Pölling et al., 2017). The objective of the *low-cost specialisation* is to expand the business through specialisation and economies of scale (Van de Shans, 2010). *Differentiation* aims to create distinctions in marketing and production by integrating (parts of) the added-value chain on-farm. It is mainly associated with short supply chains with one or very few intermediaries (restaurant, canteens, another farm shop, etc), personal producer-consumer relationships, authenticity, and transparency (Pölling et al., 2017). Lastly, *diversification* in production as well as into services provides a wide variety of additional services connected or close to agricultural production such as (i) agro-tourism (recreation events, gastronomy, accommodation), (ii) social services (education, therapeutic services, health care), and (iii) other services of a public and private nature (maintenance, road cleaning in winter) (Heimlich and Barnard, 1992; Beauchesne and Bryant, 1999; Bailey et al., 2000; Zasada, 2011).

Within the three common BMs for UA, *diversification* is gaining more popularity in many studies (Pölling et al., 2017, Pölling and Mergenhaler, 2017; Recasens et al., 2016; Torquati et al., 2018) because of its major facility to be adapted to the urban conditions (Pölling et al., 2017a). Additionally, unlike low-cost specialisation, diversification is not only driven by economic purposes since creating environmental and social values are the main objectives as well (Recasens et al., 2016). For example, Social farming also named Green Care or Care Farming integrates agricultural production with healthcare or social services for people with special needs and is a common strategy of the diversified urban farms. In this regard, diversified BMs can lead to the development of a SBM aiming to provide a positive value for all stakeholders, including society and the environment (Hörisch et al., 2014). Moreover, developing SBMs for UA (UA-SBMs) can also contribute to overcoming the limitations associated with the higher production costs as additional value is offered and delivered to a wide number of stakeholders (Opitz et al., 2016; Sanyé-Mengual et al., 2017a; Specht et al., 2014).

SBMs are oriented to "create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organisation and its value-network create, deliver value and capture value (i.e., create economic value) or change their value propositions" (Bocken et al., 2014, p.44). Moreover, according to Kiron et al., (2013) and Schaltegger et al., (2015) focusing only on profitability, without paying attention to environmental and/or social aspects is an important obstacle to achieving a company´s economic goals.

SBMs group different typologies of BMs, such as product service systems (PSS) (Tukker, 2004), social enterprises (Grassl, 2012), and/or circular economy BMs (Lewandowski, 2016) which can contribute to sustainability in different ways. Nevertheless, categorisations, taxonomies, or archetypes are needed for future SBM development since they contribute to i) consolidating the existing knowledge by grouping SBMs with similar characteristics, and ii) identifying future research (Bocken et al., 2014).

Concerning UA, overall, the research on SBMs is very limited and mainly presented by studies describing specific BM cases with a sustainable potential such as an urban farm with social impact (Gittins & Morland, 2021), multifunctional edible landscapes (Robinson et al., 2017), and agro-tourism enterprise (Yang et al., 2010). However, neither of these studies have characterised or classified SBMs. The only exceptions are Schutzbank and Riseman (2013) and Senanayake et al., (2021) who made attempt to classify UA-SBMs, but those categorisations had some limitations.

Schutzbank and Riseman (2013) categorised SBMs for UA, but their classification comprehends the value delivery mechanism (e.g., sales and distribution mechanisms) and value capture system (costs and revenues), without explicitly addressing the value preposition and value creation BM building blocks. This is important constrain since the framework for categorising business model innovation (BMI) for sustainability in the agri-food sector should include the main four BM blocks (value propositions, value delivery, value creation, and value capture) to effectively explain the sustainability challenges addressed by them (Barth et al., 2017).

Recently, Senanayake et al., (2021) are also presented a SBM classification for the food industry that can also be used for UA system, but it was only focused on food waste (prevention, redistribution, recovery, and recycling) without including a social perspective which is as well important to impulse the sustainability of the food systems (Bocken et al., 2014).

Based on this, comprehensive categorisation and characterisation of UA-SBMs are needed to overcome the existing gaps regarding the limited SBMs classifications for UA systems and thus facilitate the implementation of more sustainable urban food systems.

1.5. Motivation

Cities have the potential to influence the food is grown since as mentioned above, 80 % of all food will be consumed in the cities by 2050, where currently 75% and 2.8 billion tons of organic wastes are generated (EMF, 2019). In this regard, the development of UA in urban and peri-urban areas can provide them with fresh food and contribute to sustainable city development (Van Tuijl et al., 2018).

Within the VF forms of UA that use the urban building to grow food, the RTG and i-RTGs are gaining more popularity because of their notable environmental, economic and social benefits, expressed in reduced food miles, improved community food security, and community outputs (Cerón-Palma et al., 2012; Specht et al., 2014). However, the last are expected to have further benefits compared to the RTGs since the i-RTGs take advantage of bidirectional resource flow exchange (building-greenhouse) such as rainwater, CO_2, and residual heat, which contribute to the reduction of the impact of the building and the food production system overall (Sanyé-Mengual et al., 2015a). Moreover, considering the elevated consumption of natural resources (75%) and energy (80%) in urban areas (EMF, 2019), i-RTGs that use renewable sources as production inputs (e.g., rainwater, CO_2, residual heat) can contribute to reducing the current trends).

Previous research on sustainability aspects of i- RTGs was focused on an analysis of the environmental assessment of their production through LCA (Sanjuan-Delmás et al., 2018a), recirculation of rainwater and nutrients (Rufí-Salís et al., 2020a, 2020b), use of biomass waste recovery (Manríquez-Altamirano et al., 2020), quantification of energy symbiosis (Muñoz-Liesa et al., 2020), study of different substrates options (Parada et al., 2021) or CO_2 capture and storage, among others (Fertilecity, 2016). However, the analysing of economic aspects through using LCC is still limited (Sanyé-Mengual et al., 2017a) which can impede the decisions making about balanced decisions for sustainability.

Moreover, the LCC results can be also used as a base (costs structure) for studying and developing BMs for UA/i-RTGs and thus contribute to the high demand on finding suitable business models for UA (BMs-UA) promoted from various projects such as (i) *Fertilecity I, II* (Fertilecity, 2021), (ii) *GROOF* (GROOF, 2022), iii) *FOOD-E* (FOOD-E, 2021), (iii) *NEWBIE* (NEWBIE, 2021), and (iv) *CityZen* (CityZen, 2021).

However, new BMs for UA must find to respond to the urban public needs by offering not agricultural production but also environmental, social, and ecological services (Recasens et al., 2016). On this matter, SBMs could be suitable for the UA conditions since they aim to deliver economic, social, and environmental value for a wide range of stakeholders, including society and environment (Bocken et al., 2013).

1.6. Objectives

To cover the research gaps detected in the previous sections, the overall objective of this dissertation is to analyse the economic sustainability of UA, especially i-RTGs as innovative forms of UA for sustainable city development, from an LCC and SBM approach. To achieve the main objective, the following specific objectives are established along the thesis:

a) To analyse the evolution of the use of LCC in UA to identify tendencies and common problems, and to propose recommendations for improvement.

b) To analyse the economic viability of urban food production from an i-RTG through LCC to (i) identify main cost drivers and propose different approaches to reduce them; and (ii) to examine production level output as an important variable affecting the economic viability and profitability.

c) To create a comprehensive categorisation and characterisation of sustainable business models for urban agriculture and to provide recommendations for their selection and posterior application to facilitate the deployment of more sustainable UA systems.

Chapter 2

Methodological framework

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Chapter 2. Methodological framework

This chapter describes in detail the methodologies and analyses performed to complete the objectives of this dissertation. The case study used in **Chapters 4, 5** where some of these methodologies/analyses are applied, is also presented.

2.1. General outlook

Table 2.1 present the methodologies and analyses applied in each chapter. In **Chapters 3 and 5**, the main methodology employed was *literature review* i) to examine the evolution of the use of life cycle cost (LCC) in a period of 22 years (Chapter 3) in urban agriculture (UA) context, and ii) to develop a pre-characterisation and pre-classification of sustainable business models for UA (UA-SBMs) (Chapter 5). While in the **Chapter 4** two methodologies were used**,** the LCC was applied to a relevant case study (Case study approach) to analyse the economic viability of urban food production (tomatoes type Coeur-de-boeuf) from an integrated rooftop greenhouse (i-RTG) complemented by an additional *break-even point* (BEP) analysis to determinate the optimum i) number of tomatoes to be produced and sold to cover the fixed costs, and ii) level of fixed cost at different selling prices for tomato Coeur-de-boeuf. Finally, **Chapter 5** included two additional analyses: i) *content analysis* thought using software for validation and creation of final list of UA-SBMs categories and configurations, and ii) *sustainable development goals (SDGs) impact assessment* to analyse the impacts (positives, negatives and neutrals) of the UA-SBMs archetypes on the SDGs and thus evaluate their sustainable potential. Finally, the same case study described in **Chapter 5** was applied to test the possible application of the UA-SBMs archetypes.

Table 2.1 Methodologies and analyses applied in each of the chapters

Chapter	Literature review	Case study	LCC	BEP analysis	Content analysis	SDGs impact assessment
C3	X					
C4		X	X	X		
C5	X	X			X	X

2.2. Literature review

The following five stages were considered to conduct the literature review in chapters 3 and 5 (Cooper, 1984):

- Formulation of the problem
- Data collection
- Data evaluation
- Analysis and interpretation
- Public presentation

More details about each of them are provided in the next subsections based on the guidelines provided by Cooper (1984) and Randolph (2009).

2.2.1. Formulation of the problem

This stage starts with the formulation of the questions that will give directions to the literature review. These questions should be based on the goal and focus of the review Then, the second step is to establish *criteria for inclusion/exclusion* to determine which references will be included in the review and which references will be excluded. For instance, in chapter 3, the criterion for selection of references was based on the condition that those must include combination the most popular keywords of LCC (e.g., LCC, life cycle cost, life cycle costing and life cycle cost analysis) and UA (e.g., urban agriculture, urban gardening, urban farming, rooftop greenhouse, etc) in the title, keyword list, abstract, or full text. While in chapter 5, the following two criteria for inclusion/exclusion to select useful journal papers were set: i) papers must explicitly address the topics of UA, BMs, or urban food systems; and ii) journal papers must include description of business cases including sustainable practices, or examples of factors and drivers that contribute to building UA-SBMs.

2.2.2. Data collection

The aim of this stage is to collect a semi-exhaustive, exhaustive, pivotal, or representative list of relevant references. This process frequently begins with electronic search of the Internet and the academic databases. In this regard, Web of Science and Scopus online academic databases were used to collect to collect the literature to review in both chapters 3 and 5. These online databases were selected since they are most widespread and are used by authors in the field of UA, LCC and SBMs, some examples are Petit-Boix et al., (2017); Scope et al., (2016); Bocken et al., (2014); Barth et al., (2017). Moreover, in chapter 5, it was necessary also include grey literature in order to collect reports and case studies from relevant online database of (i) European projects (CORDIS, 2021; Interreg Europe, 2021, Interreg Mediterranean, 2021, Interreg PROCEFA, 2021), (ii) institutions promoting sustainable development (Ellen MacArthur Foundation, 2021; Circle-lab, 2021a, SINTRA, 2021; European circular economy stakeholder platform, 2021a, Go Explorer, 2021; Circulator, 2021a; Circular X 2021a; State of Green, 2021a), and (iii) UA/agriculture (City Farmer, 2021, Agroecology info pool, 2021).

2.2.3. Data evaluation

This stage starts with the extraction and evaluation of the information provided from the selected literature references. The type of data to be extracted is defined by the focus and goal of each review. For instance, the objective of chapter 3 was to analyse the temporal and methodological evolution of LCC. Then, the extracted information was about distribution of publications by years and countries/regions as well as methodological characteristics such as Systems boundaries, functional unit, types of cost by cycle stage and other related. While in chapter 5, information about the main elements of a business model and sustainable benefits/trade-offs was selected since its objective was to categorise and characterisation of UA-SBMs. Moreover, if the focus of the review is integration or classification, the review should establish some system/criteria for this. In this regard, the criteria for classification of the selected references in chapter 3 were the similarity of the topic and type of study (empirical or literature review). Whereas in chapter 5, the selection criterion was the major innovation type., i.e., environmental, social, and economic. As the data are evaluated, the reviewer should document the process followed and the types of collected data. This information is mainly placed in the main text or as a supplementary information file.

2.2.4. Data analysis and interpretation

At this stage, the reviewer organises the collected information in order to allow its analysis and interpretation. It depends on the goal of the literature review which in many cases is to integrate and generalise the findings across outcomes, settings, units, and treatments; to conclude a debate within a field; or to bridge the language used across fields. For this purpose, the reviewer integrates the data by using quantitative, qualitative, or mixed methods, depending on the type of the extracted data. For instance, in chapters 3 and 5 qualitative methods (comparative and descriptive analysis) were used for the analysis and interpretation of data.

2.2.5. Public presentation

At this final stage, the review author must select which information is more important to be presented in the main text and which one is less important to be placed in the supplementary information file. The format in which the information is presented is also relevant: tables, graphs, diagrams, figures, etc.

2.2. Case study

A case study is an empiric method that “investigate a contemporary phenomenon (the “case”) in depth and within its real-world, especially when the boundaries between phenomenon and context may not be clearly evident” (Yin, 2017, pag. 15).

In other words, the reason to conduct a case study is due to the need for understanding a real-world case and suppose that such an understanding is probably to involve important contextual conditions (features) related to the analysed case (Yin and Davis, 2007).

The case study analysed in chapter 4 and chapter 5 corresponds to the i-RTG of a LEED-Gold certified building that hosts the Institute of Environmental Science and Technology (ICTA) in the main campus of the Universitat Autònoma de Barcelona (UAB) in Cerdanyola del Vallés, Barcelona (41° 29' 51.7'' N 2° 06' 31.8'' E) (Fig. 2.1).

Fig. 2.1. The i-RTG on the ICTA-UAB LEED-Gold certified building. Source: Fertilecity project. https://www.fertilecity.com/en/

Both the building and its greenhouse are innovative systems. On the one hand, the building was designed based on greenhouse model and with high sustainability criteria for rainwater collection and use, energy efficiency and reversibility to achieve the exigent LEED-Gold certificate. On the other hand, the rooftop used as greenhouse is an i-RTG because of the integration of rainwater, CO_2 and energy flow between the building and the greenhouse, which optimise the environmental performance of the system (Sanyé-Mengual et al., 2015a).

The building area is 8,237 m^2 divided into five floors (including rooftop) and two basements (Harquitectes, 2015). The rooftop floor has four i-RTG areas of 122.1 m^2 each (Fertilecity, 2015). Two of them were in fact used as greenhouses (also named i-RTG-Labs), one of them being exclusively for tomato production, and the other for short period vegetables, such as lettuces, chards, and green beans. The research work done in these two i-RTG-Labs was carried out by the project *Fertilecity II: Integrated rooftop greenhouses: a symbiosis of energy, water, and CO_2 emissions with the building – Towards urban food security in a circular economy* (CTM2016-75772-C3-1-R, AI/UE-Feder) aimed at using two-way greenhouse-building connections (exchange of flows) for more sustainable local food production. Many research issues were addressed such as recirculation of rainwater and nutrients for agriculture production (Rufí-Salís et al., 2020a, 2020b), use of the biomass waste recovery (Manríquez-Altamirano et al., 2020), quantification of energy symbiosis (Muñoz-Liesa et al., 2020), the study of different substrates options (Parada et al., 2021) or CO_2 capture and storage, among others (Fertilecity, 2016). Figure 2.2 illustrates those mentioned flows exchanges.

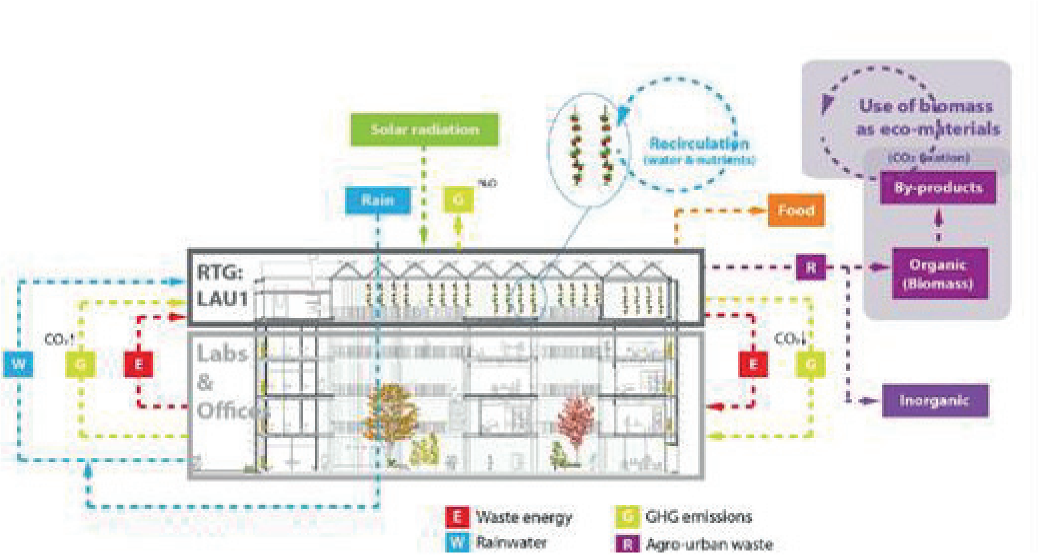


Fig. 2.2 Flow diagram of the ICTA-UAB building (adapted from Sostenipra, 2018). Acronyms: RTG-Rooftop greenhouse; LAU1: Laboratory of urban agriculture; GHG-Greenhouse gases.

The flow integration of the studied case is limited to the use of rainwater. Two consecutive tomato crops with the same characteristics and production cycles, were studied: years 2018 and 2019. However, only the LCC results for 2019 crop are presented and discussed. This is due to the problem that there was not a device for measuring labour hours, unlike other crop parameters quantified by electronic measurement tools (e.g., water consumption, solar radiation, etc.). This problem was observed in the crop 2018 and consequently in the crop 2019 a standard time for carry out each defined crop production task was established to have an accurate measure of labour time for crop production. Hence, the 2018 crop was considered as a trial version that allowed the development of refined data collection tools with the purpose of get more accurate results for the crop 2019.

The tomato variety cultivated was Coeur-de-boeuf (Lycopersicon esculentum var. Arawak) which stands out for the size of its pieces, which can reach up to 500g and it is mainly used for fresh salads. This variety is highly appreciated for its size and flavour, with an average price of 2.92 €/kg (OCU, 2018). The tomato was cultivated in a hydroponic system (Fig. 2.3), i.e., a soilless system that uses perlite volcanic stones as a substrate with 12 crop lines. The productive area (substrate area) was 84.3 m^2 from the total extension of the i-RTG- (122.1 m^2) and the period of study was the crop cycle: 7 months, from January to July.

Fig. 2.3 Coeur de boeuf tomatoes cultivated in a hydroponic system. Photos from the beginning of the crop and from the first harvest

2.3. Life cycle cost

LCC is an economic evaluation methodology that aims to quantify all costs and cash flows that emerge during the entire life cycle of a product, service, and project (Ammar et al., 2013). This methodology was applied to the studied case (see chapter 4) of artisan tomato production was performed following guidelines provided by Hunkeler et al. (2008), Swarr et al., (2011) and ISO (2008), including four stages: i) Definition of goal(s), scope, and functional unit; ii) Life cycle inventory & aggregate costs by costs category; iii) Costs estimation; and iv) Results interpretation and presentation. Each of them is explained in detail below.

2.3.1. Goals, scope, and functional unit

The LCC begins with the definition of the goal(s). In this regard, the LCC's goal of the studied case was to quantify the total cost of artisan integrated rooftop greenhouse (i-RTG) tomato production, with the following specific objectives:

- To present the costs of tomato production by life cycle stage, by cost group, cost category, cost item, and by fixed and variable cost.
- To identify the main cost drivers and propose reduction alternatives
- To analyse the costs variation considering different sensitivity scenarios

Regarding the scope of LCC, this can indicate which costs are included in the system boundaries and which are out of them. There are three commonly used approach to delimit the system boundaries. (i) *cradle-to-grave*; (ii) *cradle-to-farm gate*; and (iii) *cradle-to-consumer*. In the scope of the studied case was, the scope of the study was from cradle-to-farm gate included two main stages: (i) infrastructure and (ii) production. The infrastructure stage covers initial investment costs of assets (tangible and intangible) needed for production, while the production stage includes input items costs and waste costs (classified as outputs). Costs related to the maintenance activities stage were not included due to the following reasons: (i) no reparation or replacement activities took place during the analysed period and (ii) if maintenance operations were to be required, the costs are negligible (e.g., change of small spare parts such as ball valves, PVC elbow, etc.). Moreover, costs at the end-of-life (EoL) stage, associated with the decommissioning of the greenhouse structure, the production system and the recycling of materials were not considered due to the uncertainty in waste management practices after the long lifespan of the infrastructure.

Then, the process continues with the definition of the functional unit since LCC is always carried out for a certain function that must be fulfilled by the analysed system. In this regard, the following functional unit was defined as "1 kg of tomatoes grown and harvested in a i-RTG over a 7-month production cycle in the Metropolitan Area of Barcelona (Spain)".

2.3.2. Elaboration of life cycle cost inventory

This stage consisted in the elaboration of the cost inventory. For example, LCC can include four main life cycle stages: (i) construction(initial) stage, where initial investments costs are included; (ii) operation stage, covering all production inputs costs; (iii) maintenance stage, comprising repair and replacement costs, and (iv) end-of-life (EoL)/waste management stage, including disposal, recycling, demolition, decommission/dismantling costs ISO (2008). At this stage, the aggregated costs by cost category are also presented or other way for classifying the life cycle costs according to the goals established.

The life cycle cost inventory is presented as follow (chapter 4) based on the objectives established in 2.2.1: (i) *Life cycle stage*; (ii) *Cost group*. The Spanish general accounting plan (ICAC, 2007) was used to classify the infrastructure items into (a) intangible assets: computer software and (b) tangible assets: buildings, technical installations, machinery, equipment, furniture, and information technology equipment; (iii) *Cost category*. In this regard, four technical installations were identified: (a) system of sensors; (b) irrigation system; (c) curtains and partitions system and (d) production supporting system, and (iv) *Fixed or variable cost,* v) *Cost item* (e.g., labour, electrical energy, rainwater, etc).

2.3.3. Costs calculation

The main indicator of LCC is the total cost, calculated as a sum of the costs at the life cycle stage (s) included in the scope of each study. Has mentioned in 2.3.1., the scope of the studied case included two stages: infrastructure and production and the total LCC was calculated, the total LCC was calculated as follows (Equation 1)

$$LCC\ (€/kg) = CI + CP \qquad (1)$$

Where CI =infrastructure costs and CP=production costs

For the infrastructure costs, initial capital investments needed for production (greenhouse structure and other asset categories (i.e., the assets that last more than one crop cycle), it was necessary to estimate the years of lifespan to apply the proportional amortization cost for the tomato crop period (7 months). The amortization cost was computed using the Equation 2:

$$\text{Amortization cost} = (\text{Initial cost})/(\text{Lifespan (years)})\times(7\ \text{month})/12 \qquad (2)$$

Regarding the production cost, consumed items (consumables), in the 7-month production cycle, these were calculated as in Equation (3)

$$\text{Cost (consumable item)} = \text{Consumption unit cost €)} \qquad (3)$$

2.3.4. Results presentation

The LCC results are presented in chapter 4 as follows (i) contribution by life cycle stage and cost category; (ii) variable and fixed costs; and (iii) main cost drivers responsible for more than 60 % of the total cost.

2.4. Break-even point analysis

The break-even point (BEP) is the level of production to be sold that completely covers the total fixed cost. At this level the company has no losses. From this level, every additional unit sold contributes to generate profit. BEP is very useful in knowing the number of units to be sold so as not to have losses from the production activity (Gutierrez and Dalsted, 2012).

$$Break\ even\ point\ (in\ units) = \frac{(Fixed\ costs)}{(SP-VC)} \quad (2)$$

Where SP=selling price per unit, VC= variable cost per unit

This analysis was firstly applied to find the optimum number of tomatoes to be produced and sold to cover the fixed costs. For this purpose, the average used market price was between 3.0 €-4.0 € for 1 kg of tomatoes Coeur de boeuf with value added tax (VAT) included (4% in Spain). Moreover, the analysis assumes that 1 kg consists of 5 tomatoes (number of physical units) which was the average for two consecutive crops (2018 and 2019) and that all produced tomatoes would be commercialized without discriminating their size.

Then, the BEP formula was also used to determine the maximum level of fixed cost for a specific production area size, which includes the production output, and specific unitary variable cost. In this regard, the maximum level of fixed cost was calculated at selling price between 3.0 €-5.0 € to find how much the fixed costs must decrease in order to establish selling prices below 5.0 €. For the studied case the data used were a productive area of 84.3 m^2 with an average production output of 5,415 units (for two consecutive years), and variable unitary cost of 0.49 €.

2.5. Content analysis

Content analysis is a method for studying the content of a variety of data, which can include texts of many formats, audio, video, or picture (Bryman, 2011). It allows the reduction of phenomena or events into defined categories for better analysis and interpretation (Harwood & Garry, 2003).

This analysis was performed in **Chapter 5** which aimed to present a comprehensive categorisation and characterisation of UA-SBMs. This was elaborated though reviewing 54 references selected by applied inclusion criteria as described in 2.2.1 to create a pre-characterisation and pre-categorisation of UA-SBMs and which was later validated by using the content analysis and text mining software Wordstate 9 (Provalis, 2021a). This software was also used to create a final list of UA-SBMs represented by 11 archetypes.

The 54 selected references were introduced in the software to search for keywords that can describe the base archetypes (See Appendix 2.3). Additionally, the automatically obtained software results of frequent words and phrases (containing more than 2 words) also analysed to get additional information to create final classification of UA-SBMs.

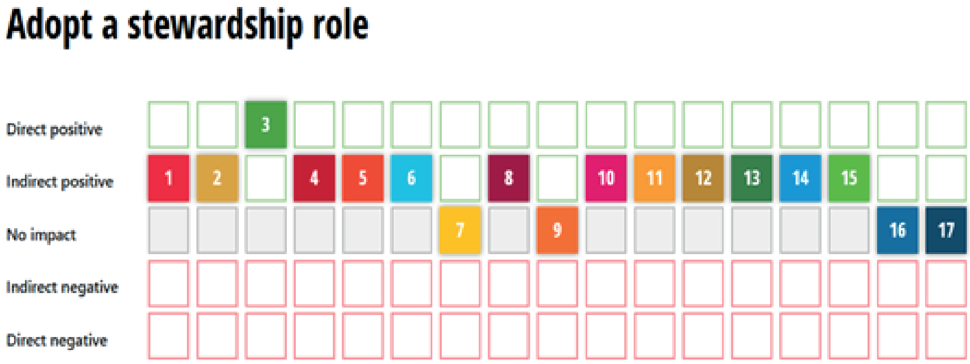
Then, a categorisation dictionary in Wordstate 9 was created to organise into groups those keywords corresponding to the original and the newly created archetypes to create the final UA-SBMs list. The categorisation dictionary in Wordstate 9 is a hierarchical tree where words/phases are grouped in a folder that represents a category name (Provalis, 2021b). In this case, the category name was each archetype name written in an abbreviated form (e.g., Adopt a stewardship form=ASR) with its corresponding keywords (e.g., certified organic products, heritage preservation) classified in a folder. This was useful not only for visualising the results but also for providing valuable statistics to evaluate each archetype based on its major or minor presence in the 54 analysed references.

2.6. Sustainable development goals impact assessment

To study the relations of UA-SBMs archetypes with the SDG 2030 (UN, 2015) in **Chapter 5**, by using the Sustainable Impact Assessment Tool (Chalmers, 2019) to analyse their sustainable potential. This tool employs a self-assessment of the archetypes´ impacts on the 17 SDGs by classifying and visualising them graphically. An example can be seen in Fig. 2.4.

The impacts of each archetype on the SDGs were analysed and classified as follows: i) direct impact (positive or negative) having an immediate one-step effect on an SDG, ii) indirect impact (positive and negative), a secondary effect further down a chain of events, and iii) no impact-there is no relation between the archetype and the SDGs, or its impact is determined as not relevant (GMV, 2020). The motivation behind the classification of each impact was based on the archetype characteristics, the sustainable (environmetal, social and economic) benefits expected of their implementation and a report analysing the nature of interlinkages between the SDGs (Griggs et al., 2017).

Fig. 2.4. Impacts (positives, negatives, and neutral) of the sustainable business models archetypes for urban agriculture "Adopt a stewardship role" on the sustainable development goals.



Based on this, the impacts of the UA-SBMs archetypes on the SDGs 2030 (UN, 2015) were presented as follows: i) positive with +1 (both direct and indirect) that contributes to the implementation of the SDG implementation, ii) negative with -1 (both direct and indirect) that counteracts the SDG implementation, and iii) no impact if the impact is considered as negligible (0). The motivation behind the classification of each impact was based on the archetype results and a report analysing the nature of interlinkages between the SDGs (Griggs et al., 2017). In the cases, where there is both negative and positive impacts were found with some SDGs, these were presented with +1/-1.

Unfortunately, the software was not able to visualise both a positive and negative impact identified in some archetype-SDG relations, however, this can be seen in the assessment reports of the UA-SBMs archetypes in Appendix 2.4.

PART 2: ANALYSIS OF THE EVOLUTION OF THE USE OF LIFE CYCLE COST METHODOLOGY FOR URBAN AGRICULTURE

Chapter 3

A longitudinal literature review of life cycle costing applied to urban agriculture

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Chapter 3 A longitudinal literature review of life cycle costing applied to urban agriculture

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This chapter is based on the following published journal paper:

Peña, A., Rovira-Val, M.R. *A longitudinal literature review of life cycle costing applied to urban agriculture.* The International Journal of Life Cycle Assessment 25, 1418–1435 (2020). https://doi.org/10.1007/s11367-020-01768-y

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Abstract

Purpose

The aim of this research is to carry out a literature review of the use of life cycle costing (LCC) in the urban agriculture (UA) sector by analysing its evolution over a 22-year period from its beginning in 1996 to July 2018.

Methods

A total of 442 references were obtained from two principal databases, Scopus and Web of Science (WoS). After a long refining process, 20 (4.5%) references containing the keywords LCC and UA were selected for analysis. Then, we classified and organized the selected references in 4 groups. Qualitative methods were used for analysis and results on general characteristics of the 20 references and by each group were elaborated. Lastly, we discussed and concluded the most significant findings. Limitations and future research were also included.

Results and discussion

Our major findings were as follows: (i) urban horticulture was the most studied urban agriculture practice among studies that used LCC for UA; (ii) LCC plays a secondary role in its integration with LCA; (iii) only 4 of the10 papers in group 1 used additional financial tools; (iv) very few (3) papers appropriately applied the four main LCC stages; and on the other side, essential costs like infrastructure, labour, maintenance, and end-of-life were frequently not included.

Conclusions

Since we found that life cycle assessment (LCA) was the predominant methodology, we suggest that future research apply both LCA and LCC analyses at the same level. The LCC analysis was quite incomplete in terms of the costs included in each LCC stage. We recommend that the costs at the initial or construction stage be considered a necessity in future studies in order to implement these new systems on a large scale. Due to the limited use of labour cost at the operation stage, we also suggest that labour be included as an essential part of the urban production process. Finally, for more complete LCC analysis for UA, we recommend (i) that all LCC stages be considered and (ii) that additional financial tools, such as net present value (NPV), internal rate of return (IRR) and payback period (PBP), be used to complement the LCC analysis.

Keywords:
LCC, Life cycle cost, Life cycle costing, Life cycle cost analysis, Life cycle sustainability assessment (LCSA), Urban agriculture, Literature review, Economic sustainability

3.1. Introduction

Nowadays, more than half of the world's population lives in urban areas, and this tendency is expected to increase to 68% by 2050 (UN DESA, 2018). For example, in the European Union alone, 75% of the population lives in cities, and this number is estimated to reach 80% by 2020.

As a result, rapid urbanization can bring an extensive range of undesirable consequences, such as a reduction in fertile lands, deforestation, water and air pollution, reduced drainage of rainfall, poverty, and problems in the supply of fresh food (Baud 2000). In this sense, some experts are concerned about the capacity of the biosphere to provide enough food for the increased human population in urban areas (Gilland, 2006).

To find a solution to cities' fresh food problems, Nadal et al., (2015) suggested that new forms of agriculture should be found to guarantee food security for the population at a lower cost within the framework of sustainable development. Urban agriculture (UA) would be a good example of this.

In the literature, there are many definitions of UA, but in general, it can be defined as "an industry located within (intra- urban) or on the fringe (peri-urban) of a town, city, or metropolis, which grows or raises, processes, and distributes a diversity of food and non-food products…" (Mougeot, 2000, p.11). UA is a broad term and includes not only plant cultivation and animal rearing but also other related activities such as the production and selling of agricultural inputs, post-harvesting, marketing, and commercialization.

According to many authors, UA, which provides fresh food in urban settlements, may alleviate cities' food problems, and simultaneously contribute to their sustainability (Sanyé- Mengual et al., 2017a; Specht et al., 2014; Benis and Ferrão, 2018; Ackerman et al., 2014; Goldstein et al. 2016; Opitz et al. 2016). In this regard, various authors found a strong relationship between UA and the three pillars of sustainability: environment, economy, and society.

To assess the different levels of sustainability of UA, the use of an appropriate methodology is needed. Pieces of evidence from the scientific literature show that life cycle sustainability assessment (LCSA) is the main methodology used for this purpose in many studies (Sanyé-Mengual et al., 2015a; Liaros et al., 2016; Sanyé-Mengual et al. 2018a; Kim and Zhang, 2018; Dorr et al. 2017; Benis et al. 2018). Three distinct analyses are avail- able in the framework of LCSA: life cycle assessment (E-LCA or LCA), which is used for the evaluation of environmental aspects; life cycle costing (LCC), which is used for the evaluation of economic aspects and social life cycle assessment (S-LCA), which is used for the evaluation of the social aspects of sustainability (Kloepffer 2008; Swarr et al. 2011).

As far as we know, most UA studies focus mainly on the environmental aspects of UA by using LCA. In this sense, LCA is the most widely used life cycle methodology based on its implementation and the interpretation of its results (Orsini et al., 2014; Goldstein et al., 2016; Sanjuan-Delmás et al., 2018a). While the environmental aspects of UA are extensively studied in the literature, an evaluation of the economic aspects of UA through LCC is still missing (Sanyé- Mengual et al., 2017a). Some authors have used combined LCA and LCC analyses, but the results are not relevant because LCA and LCC can be correlated negatively and positively, i.e., financial feasibility does not always mean environmental viability and vice versa (European Commission, 2010).

The aim of LCC is to quantify the total cost over the life cycle of a project to identify the cost-effectiveness of alternative pro jects for input into a decision-making or evaluation process (Norris, 2001; ISO, 2008). LCC, also known as life cycle cost analysis (LCCA), is an economic evaluation technique that takes into consideration all costs and cash flows that appear during the life cycle of a project, product, or service (Ammar et al., 2013) from the costs of design and acquisition through to operation, maintenance, and disposal (Wu and Longhurst 2011; ISO, 2008). There are other popular methods for assessing the economic performance of a project or product, such as the cost-benefit analysis (CBA) (Carter and Keeler, 2008; Sanyé-Mengual et al., 2015a; Benis et al., 2018) and whole life costing (WLC) (ISO ,2008). The characteristics and procedures of CBA and WLC however are very similar to those of LCC and most of the time that authors refer to their methods as CBA or WLC while the methodology that they have used is LCC.

This methodology became popular in the mid-1960s, but 1996 is considered the starting point because in this year, the first official document describing the theoretical framework for LCC, the handbook entitled Life Cycle Costing Manual for the US Federal Management Program (Fuller and Petersen, 1996), was published. Currently, LCC is spread worldwide and is one of the most commonly used procedures for economic assessment in different industries. Evidence from the scientific literature shows the growing interest in this methodology in industry, infrastructure, construction and building sectors (Naves et al., 2018).

As far as we know, there is no evidence of a literature review on LCC applied to UA because the only LCC review papers that we found were for the aforementioned sectors. The purpose of this paper is to fill this gap by studying the evolution of LCC analysis in a UA context from 1996 to July 2018 by conducting a literature review.

This study is the first attempt to systematize the existing academic literature on the use of LCC for the growing UA sector. The results will be helpful in identifying common problems in LCC calculation, analysis, and interpretation. The findings will also serve as a guide for future researchers by promoting a greater application of LCC in the UA sector.

We have organized the paper as follows:

Part 1: Introduction,
Part 2: Methods,
Part 3: Results,
Part 4: Discussion, and
Part 5: Conclusions.

3.2. Methods

This study is a longitudinal analysis of a 22-year period, from 1996 to July 2018. The year 1996 is the starting point of our investigation because it is the year of the publication of the first official paper containing a theoretical framework for LCC (Fuller and Petersen, 1996.

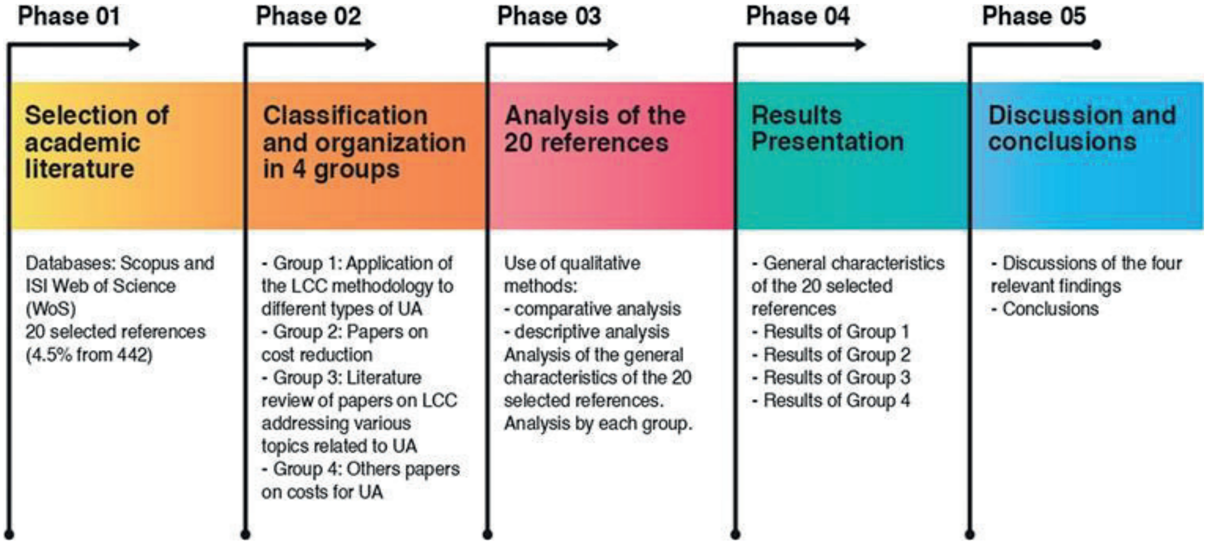

Fig. 3.1 Research methodology process

The first phase was to select the academic papers for our review. Therefore, we had to find the most appropriate keywords to successfully describe the relationship between LCC and UA. For LCC, we chose the 4 most popular words: LCC, life cycle cost, life cycle costing and life cycle cost analysis. As for UA, we found a greater number of different terms, but the most popular were urban agriculture (Orsini et al., 2013; Goldstein et al., 2016; Sanyé- Mengual et al., 2017a; Hamilton et al., 2014; Specht et al., 2014); urban gardening/gardens (Orsini et al., 2013; Grewal and Grewal, 2012); urban farming/farms (Orsini et al., 2013; Specht et al., 2014) and rooftop greenhouse garden/farms (Cerón-Palma et al., 2012; Orsini et al., 2014; Sanyé-Mengual et al., 2015b; Sanyé-Mengual et al., 2015c; Dorr et al., 2017; Sanyé-Mengual et al. 2017a; Zinia and McShane, 2018; Artmann and Sartison,, 2018).

To organize our database, we classified all the different words and terms regarding UA into five groups (see Table 3.1). After that, we created different combinations of the keywords for both LCC and UA.

Table 3.1 Database of different words and terms regarding UA

Urban agriculture (UA)	Urban farming/farms
	Urban gardening/gardens
	Urban food systems
Vertical agriculture	Vertical farming/vertical farms
	Vertical farm systems
	Zero-acreage farming (Zfarming)
	Vertical greenhouses
	Indoor farms
	Interior gardens
Urban horticulture	Urban horticultural systems
	Organoponics
	Soilless systems
	Hydroponics
Urban rooftop agriculture (URA)	Building-integrated agriculture
	Rooftop greenhouses
	Rooftop gardens
	Rooftop farming/farms
	Hydroponic rooftop gardening/gardens
Others	Community gardens
	Home gardens
	Agricultural gardens
	Allotments of urban land
	Urban Park

Scopus and ISI Web of Science (WoS) online databases were selected because they are the most widespread and are used by several authors in the field (Petit-Boix et al., 2017;

Ilg et al., 2017; Kambanou and Lindahl, 2016; Scope et al., 2016). As a result, we obtained 442 references, 223 were from WoS and 219 from Scopus, which then had to be refined. Given that the abbreviation LCC can be linked to other expressions and concepts, we had to remove the results which were not associated with LCC. Moreover, the focus of our research was on UA only; therefore, we also excluded papers on conventional agriculture from the analysis. Consequently, the remaining references included both LCC and UA. Finally, we removed all the repeated references. The final result was 20 references for analysis (4.5% of the initial 442) containing both terms LCC and UA.

Then, the second phase was to classify the selected references into 4 groups. The underlying criteria for classification were similarity of the topic and type of the study (empirical or literature review).

Group 1: Application of the LCC methodology to different types of UA consisted of 10 papers describing the use of LCC methodology in different types of UA, e.g., home gardens, rooftop greenhouses and aquaponics systems. In *Group 2: Papers on cost reduction* were made up of 3 papers on cost reduction. *Group 3: Literature review of papers on life cycle costs addressing various topics related to UA* included 4 literature reviews. *Group 4: Other papers on costs for UA* were composed of 3 research papers on costs of UA which did not specify the methodology used.

The third phase was to analyse both the characteristics of the set of 20 selected references as a whole and the distinctive aforementioned groups using qualitative methods (Saldaña, 2003; Ragazzi, 2017). We mainly used comparative analysis, but in some cases, a descriptive analysis was applied when it was not possible to compare. The next stage (phase 4) was to present the results on general characteristics of the 20 selected references and the results group by group.

The last step of the methodological process (phase 5) was to discuss and conclude the most relevant findings. Limitations and suggestions for future research were also presented.

3.3. Results

In this section, we present the results on the general characteristics of the 20 references in terms of the number of publications by year, type of paper and source, leading regions, and countries to show the evolution of the use of LCC for UA. After that, the results by groups are presented.

3.3.1. General characteristics

In this section, we present the general characteristics of the 20 papers selected.

We found that the first scientific paper on LCC applied to UA was published in 2008 (Nguyen and Weiss 2008) just after the publication of the first standard: ISO 15686-5

(2008) containing the theoretical basis of this methodology. Most of the papers (6 publications or 30%) were published in 2018, followed by 2015 (5 publications or 25%) and 2017, which had 3 publications or 15%. In 2014 and 2016, 2 papers were published for each year, while in 2008 and 2009, we only found one paper per year. During the next four years (2010-2011-2012-2013) we did not find any publication.

According to the results, the most important year was 2015 because of the substantial increase in the publications, e.g., from zero, one or two papers in the first seven years to 5 in 2015. In 2016, we noticed a small decrease, but over the next two years (2017 and 2018), the number of publications increased notably, e.g., in 2018, the growth was 15% compared with that of the previous year. From these results, we can conclude that the interest in using LCC for UA is increasing and that this tendency will probably continue in the coming years (Fig. 3.2).

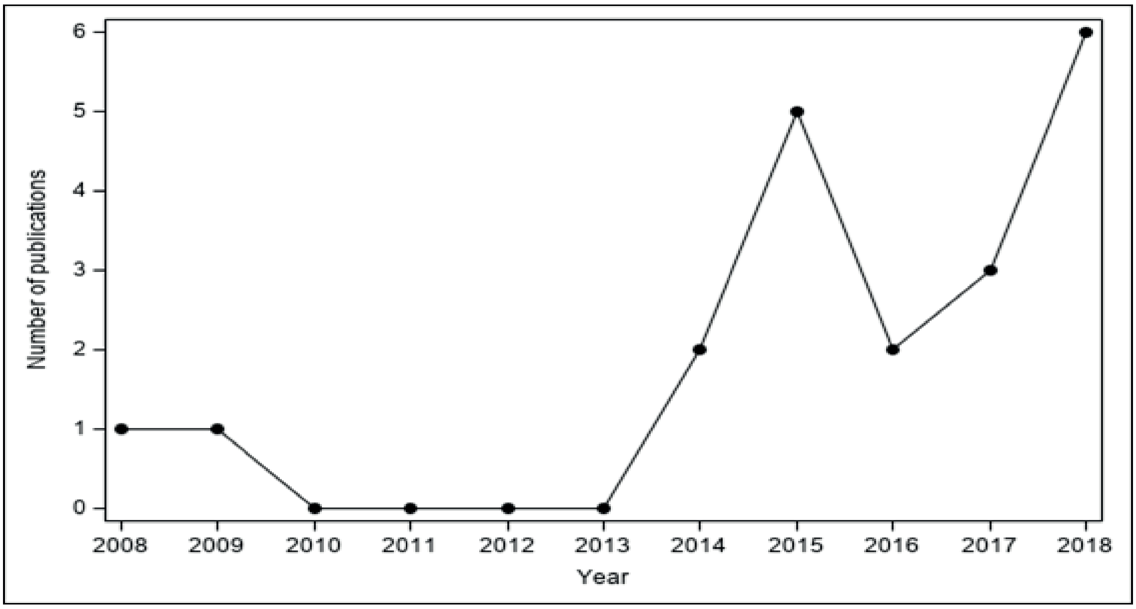

Fig. 3.2 Number of publications by year

Regarding the types of papers and their sources, we found that all the references were articles. Of the articles, 16 or 80% were original papers and 4 or 20% were review papers. Peer-reviewed journals were the main source, accounting for 85% of the total number of references, while the remaining 15% were conference proceedings (Fig. 3.3).

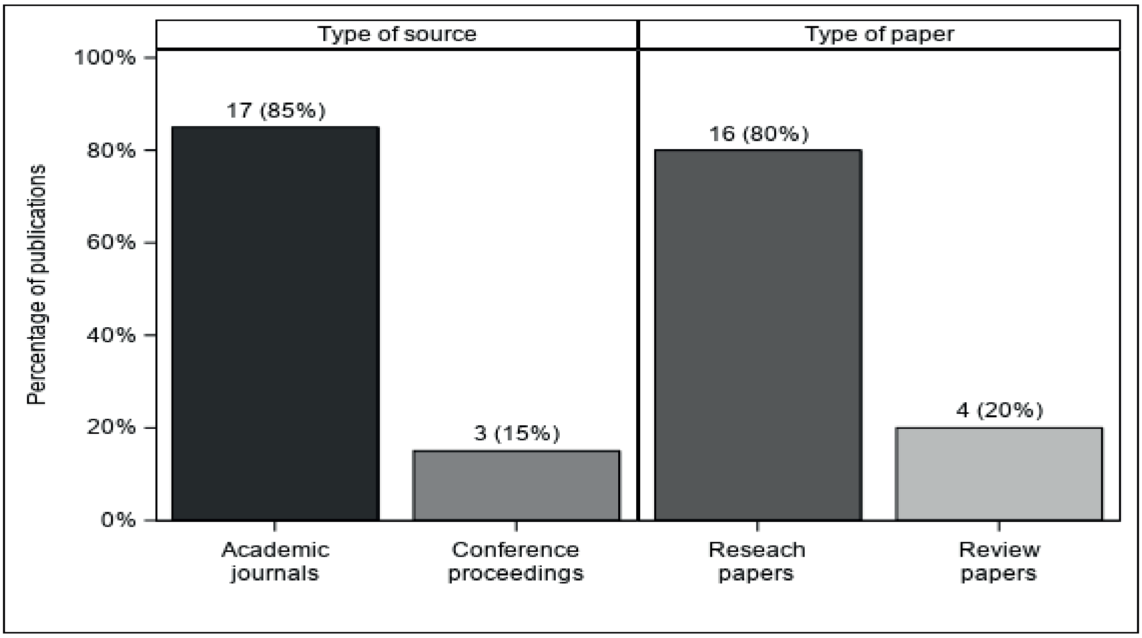

Fig. 3.3 Type of source and type of paper

By regions, Europe was the leading region with 11 articles or 55% of the total, followed by North America (Canada and USA) with 5 publications or 25%. Asia had 3 papers (15%), while the Middle East (Israel) had only one (Fig. 3.4).

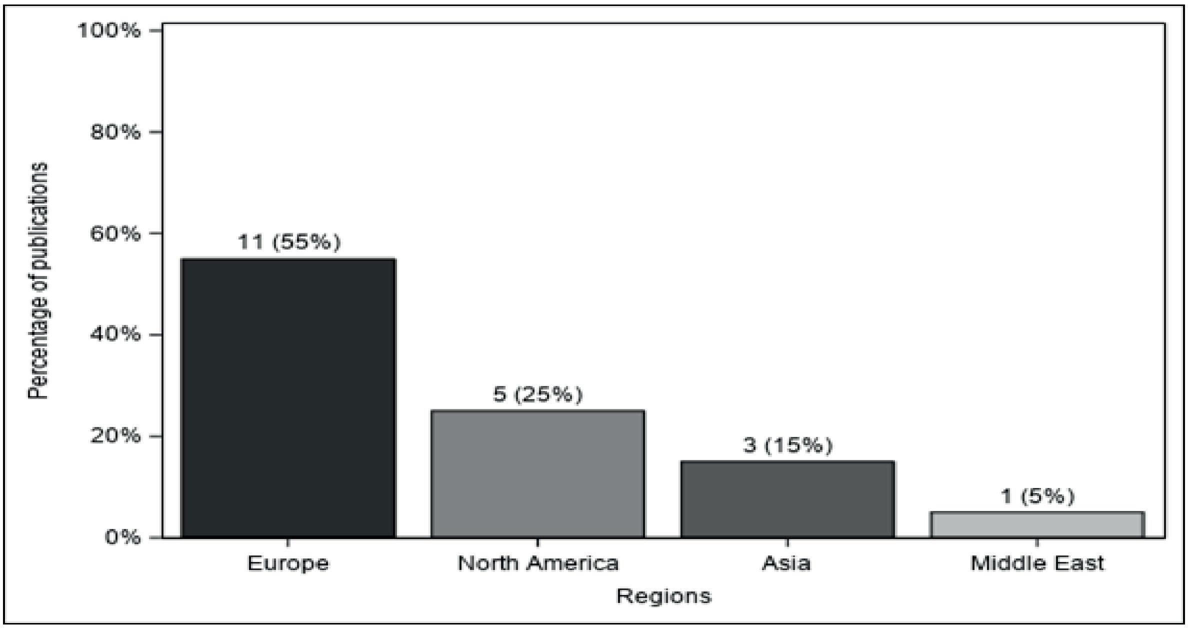

Fig. 3.4 LCC for UA papers by regions

Within the European region, Spain with 4 publications and Italy with 2 had a preeminent position over the rest of the countries which had only 1 publication (Fig. 3.5).

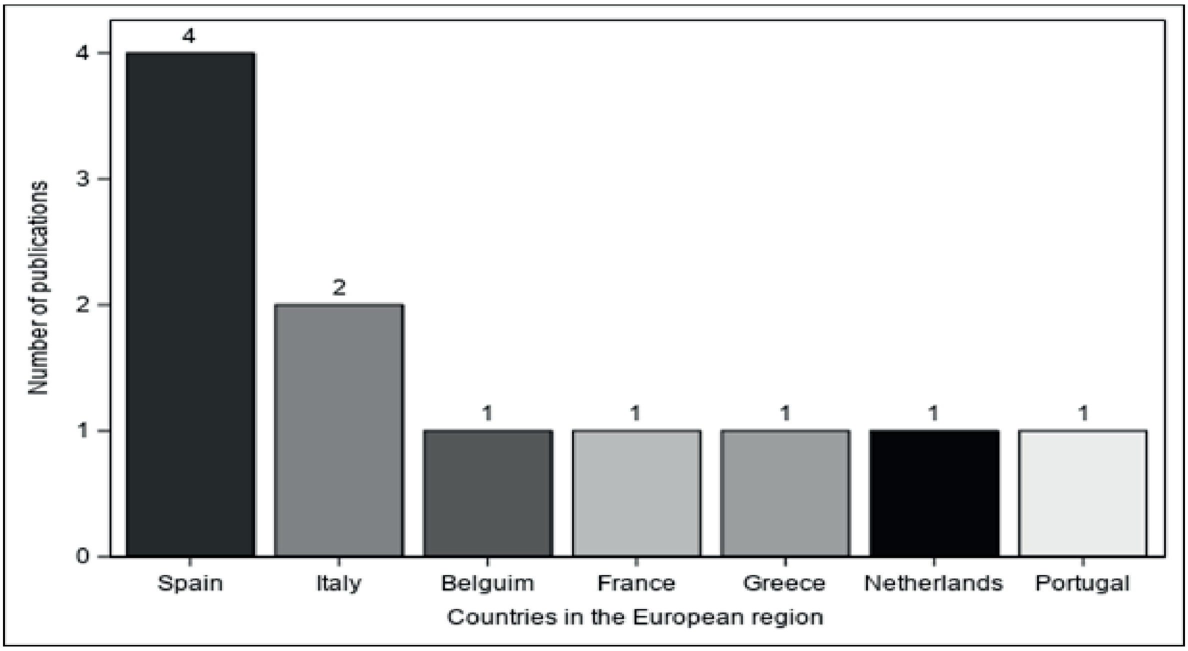

Fig.3.5 LCC for UA papers in the European region

3.3.2. Group 1: application of the LCC methodology to different types of UA

This first group included 10 papers (50% of total selected) describing the application of LCC to different types of UA, e.g., home gardens, rooftop greenhouses and aquaponics systems. We analysed the papers in relation to 10 different comparison criteria that we grouped into three parts: (i) type of urban agricultural practice, research topic; LCC integration with LCA or S-LCA and LCC guidelines followed; (ii) system boundaries, functional unit, use of financial tools and additional analyses for assessment; (iii) type of LCC (conventional, environmental and societal) and costs used according to the life cycle stage.

3.3.2.1. Type of urban agricultural practice, research topic, LCC integration with LCA/S-LCA and LCC guidelines followed

Table 3.2 presents a summary of the results by type of urban agricultural practice, research topic, LCC integration with LCA/S-LCA and LCC guidelines followed.

Table 3.2. Results by type of urban agricultural practice, research topic, LCC integration with LCA/S-LCA and LCC guidelines followed

Reference	Type of urban agriculture practice	Research topic	Integration with LCA or S-LCA	LCC guidelines
Kim and Zhang (2018)	Aquaculture	solar water heaters	YES	ISO 15686-5(2017)
Forchino et al. (2018)	Aquaponics	Indoor aquaponics system		Ciroth and Franze (2009)
Dorr et al.(2017)	Urban horticulture	Rooftop gardening practices		ISO 15686-5 (2008)
Llorach-Massana et al.(2016)		Phase-change materials (PCM) for a solar storage system		
Sanyé-Mengual et al. (2015a)		Rooftop greenhouse		
Sanyé-Mengual et al.(2015c)		Cultivation techniques and crops		
Sanyé-Mengual et al. (2018a)		Home gardening		ISO 14040 (2006)
Opher et al. (2018)		Water reuse approaches		UNEP/SETAC (2011)
Liaros et al. (2016)		Urban indoor plant factory	No	Kishk et al. (2003)
Benis et al. (2018)		Productive uses of rooftops		No described

In the literature, there are several basic urban agricultural practices: horticulture, aquaculture, livestock raising, forestry and other farming activities (Baumgartner and Belevi, 2001).

Urban horticulture related to the growth of vegetables or fruits was the most studied urban agricultural practice in 8 of the 10 papers in this group, while Kim and Zhang, (2018) studied aquaculture (fish production), and Forchino et al., (2018) analysed an aquaponics system (fish and plants co-production). Figure 3.6 displays these findings graphically.

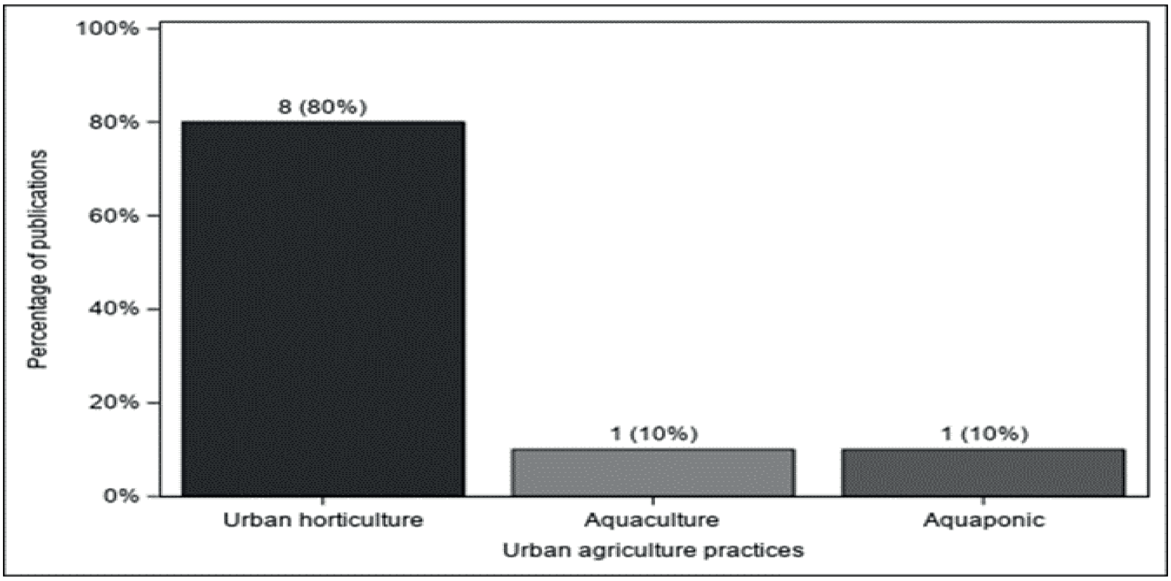

Fig.3.6 Type of Urban agricultural practices

To better illustrate these results, we classified the urban horticulture papers into two subgroups. In the first subgroup, 3 papers on traditional forms of UA, such as home gardens (Opher et al., 2018; Sanyé-Mengual et al., 2018a) and multichannel greenhouses (Llorach-Massana et al., 2016), were included. The second subgroup comprised 5 papers on some innovative forms of UA, such as indoor farms (Liaros et al., 2016), rooftop greenhouses for open-air production (Benis et al., 2018), rooftop greenhouses (Sanyé-Mengual et al., 2015a) and rooftop gardens (Dorr et al., 2017; Sanyé- Mengual et al., 2015c). All of these innovative forms are part of the building-integrated forms of UA, such as vertical farming or ZFarming and urban rooftop agriculture (URA). We placed 5 of the urban horticulture papers in the second group, while the remaining 3 were included in the first group. Figure 3.7 shows the proportion between papers on traditional forms and innovative forms of UA.

From this, we can state that the focus of the authors using LCC for UA in the studied period of 22 years (1996–2018) was mainly on the building-integrated forms of UA (indoor farms, rooftop greenhouses, rooftop gardens) rather than on the traditional ones (home gardens and multichannel greenhouses).

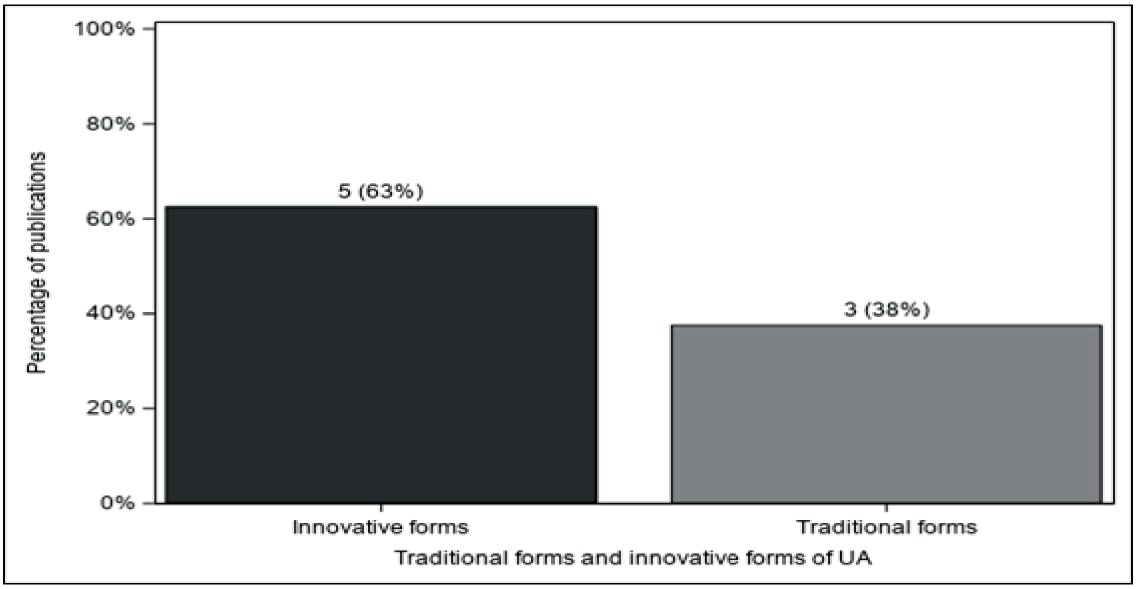

Fig. 3.7 Proportion between papers on the traditional forms and innovative forms of UA

We found different research topics in the 10 papers of group 1. From the 8 papers on urban horticulture practice, Liaros et al., (2016) evaluated the economic efficiency of urban indoor plant factories with artificial lighting as a business model, while Benis et al., (2018) compared two of the main uses of rooftops: urban food production and energy generation. Llorach-Massana et al., (2016) analysed the environmental and economic performance of the use of phase-change materials for a solar energy storage system used in a root zone to replace conventional root zone systems that depend on gas, oil or biomass. More specifically, they studied its application for improving the productivity of a multi-channel greenhouse. Opher et al., (2018) assessed the sustainability of four water reuse approaches for toilet flushing and garden irrigation in urban dwellings. The commonality among the 4 remaining papers was the analysis of the economic sustainability of urban food production (Sanyé-Mengual et al., 2018a; Dorr et al., 2017; Sanyé-Mengual et al., 2015a,c). Sanyé-Mengual et al., (2018a) investigated the environmental impacts and the economic costs of vegetables produced in a home garden in Padua (Italy), while Dorr et al., (2017) assessed the environmental and economic impacts of rooftop gardening practices on crop and substrate selection. Sanyé-Mengual et al., (2015a) estimated the environmental and economic performance of a rooftop greenhouse (RTG) in Barcelona in comparison with a multi-channel greenhouse in Almeria. Finally, Sanyé-Mengual et al., (2015c) compared different cultivation techniques and crops. Regarding the papers on fish production, Kim and Zhang, (2018) investigated solar water heaters for the improvement of fish production (aquaculture), whereas Forchino et al., (2018) quantified the environmental and economic impacts of the design of an indoor aquaponics system.

On the other hand, we noted that, of the 10 papers that formed the first group, only Liaros et al., (2016) and Benis et al., (2018) applied LCC in isolation from the other life cycle analyses. This means in general the authors preferred to combine the LCC analysis with LCA or S-LCA. The reason for this was perhaps that they wanted to illustrate the full picture of sustainability including the environment, economy and society. LCA and LCC analyses must be executed in the same way, e.g., the same system boundaries, functional units and allocation methods (Hunkeler et al. 2008). However, LCA and LCC can be correlated negatively or positively, i.e., financial feasibility does not mean environmental viability and vice versa (European Commission, 2010).

With reference to the LCC guidelines followed, ISO (2008) was the most commonly used in 5 of the 10 papers (Dorr et al., 2017; Llorach-Massana et al., 2016; Sanyé-Mengual et al., 2015a and 2015c; Sanyé-Mengual et al., 2018a), and the updated version, ISO (2017), was found in the publication by Kim and Zhang (2018). Other LCC guidelines, such as those by Ciroth and Franze (2009), were applied in the study by Forchino et al. (2018), while Liaros et al. (2016) used the following paper for this purpose: Whole life costing in construction: a state-of-the-art review (Kishk et al., 2003). Finally, only the guideline ISO (2006) was used for both LCA and LCC analyses in Sanyé-Mengual et al., (2018).

3.3.2.2. System boundaries, functional unit, financial tools and additional analyses for assessment

Table 3.3 shows a summary of the findings by system boundaries and functional unit.

We found three different approaches for assessment in relation to the system boundaries: cradle-to-grave, cradle-to-farm gate and cradle-to-consumer. Only Sanyé-Mengual et al., (2015a) applied all three assessment approaches. For example, they used a cradle-to-grave approach to estimate the cost of a greenhouse structure, while a cradle-to-farm gate analysis was carried out at the production stage, and finally, they applied a cradle-to-consumer approach at the consumption point. For example, they used a cradle-to-grave approach to estimate the cost of a greenhouse structure, while a cradle-to-farm gate analysis was carried out at the production stage, and finally, they applied a cradle-to-consumer approach at the consumption point. According to our results, the most widely procedure was a cradle-to-farm gate, which was found in five of the papers (Dorr et al., 2017; Forchino et al., 2018; Llorach- Massana et al., 2016; Sanyé-Mengual et al., 2015a and 2015c). In contrast, Sanyé-Mengual et al., (2018a) used a cradle-to-consumer or cradle-to-fork approach, and Kim and Zhang (2018) applied a cradle-to-grave approach. The only exceptions were the publications by Liaros et al., (2016), Benis et al., (2018) and Opher et al., (2018), in which the system boundaries were not described but were considered to be a cradle-to-consumer approach.

Table 3.3 System boundaries and functional unit

Reference	System boundaries approach	Functional unit
Kim and Zhang (2018)	cradle-to-grave	An additional 1000 kg of fish production
Sanyé-Mengual et al., (2015a)		1m² of a greenhouse structure
Forchino et al., (2018)	cradle-to-farm gate	1 kg of lettuce and fish considered as a co-product
Dorr et al., (2017)		1 kg of tomatoes and lettuce
Llorach-Massana et al., (2016)		1 kg of tomatoes
Sanyé-Mengual et al., (2015a)		
Sanyé-Mengual et al., (2015c)		1 kg of lettuce, tomatoes, chili peppers, eggplants, melons, and watermelons
Sanyé-Mengual et al., (2018a)	cradle-to-consumer	1 kg of lefty and fruit vegetables
Sanyé-Mengual et al., (2015a)		1 kg of tomatoes
Benis et al., (2018)	Not described but a cradle-to-consumer approach could be considered	1m² of rooftop
Opher et al., (2018)		Annual supply, reclamation, and reuse of water
Liaros et al., (2016)		1 kg of sweet basil

Regarding the functional unit in urban horticulture papers, the most commonly used was 1 kg, which was applied to harvested vegetables such as sweet basil (Liaros et al., 2016); leafy vegetables and fruits (Sanyé-Mengual et al., 2018a); tomatoes (Llorach-Massana et al., 2016; Sanyé-Mengual et al., 2015a); tomatoes and lettuce (Dorr et al., 2017) and lettuce, tomatoes, chilli peppers, eggplants, melons and watermelons (Sanyé-Mengual et al., 2015c). In aquaculture, the functional unit in the study of Kim and Zhang (2018, p.47) is a special case expressed as an additional 1000 kg fish production (as a result of using hot water) per year over the course of 10 years. While in aquaponics, Forchino et al. (2018) used as a functional unit, 1 kg of produced lettuce and fish (tilapia) considered as a co-product. We also found functional units not related to vegetables or fish production. For example, in Benis et al., (2018), the functional unit was 1 m² of rooftop used for food production or energy generation, whereas in Opher et al., (2018), it was the annual supply, reclamation and reuse of water consumed by a hypothetical city.

Various authors recommend the use of different financial tools to complement LCC analysis, such as net present value (NPV) (ISO 2008, Kim et al., 2015; Assad et al., 2015; Carter and Keeler, 2008, Ammar et al. 2013; Vargas-Parra et al. 2014), internal rate of return (IRR) or return on investment (ROI) (Wong et al., 2003, Fuller and Petersen, 1996), payback period (PBP) (Farreny et al., 2011; ISO, 2008; Koroneos and Nanaki, 2012), inflation rate (Wong et al. 2003; Fuller and Petersen, 1996), break-event point (BEP) (Jeong et al., 2015) and savings-to-investment ratio (SIR) (Jeong et al.2015; Wong et al., 2003; ISO, 2008). Because of its importance, in this section, we present some of the examples we detected for the use of financial tools. We found that 4 of 10 papers applied additional financial tools. Table 3.4 presents a summary of these results.

Table 3.4. Use of financial tools

Reference	Financial tools
Benis et al., (2018)	• Net present value (NPV)
Liaros et al., (2016)	• Internal rate of return (IRR)/Return on investment (ROI)
	• Simple payback period (SPBP)
Benis et al., (2018)	• Interest/discount rate (%)
Kim and Zhang (2018)	
Benis et al., (2018)	• Inflation rate (%)
Llorach-Massana et al., (2016)	
Kim and Zhang (2018)	• Escalation rate (%)
Liaros et al., (2016)	• Complete payback period (CPBP)
	• Simple net present value (sNPV)
	• Benefit-to-cost ratio (BCR)

For example, Liaros et al., (2016) used the following financial tools: simple payback period (SPBP), complete payback period (CPBP), NPV, simple net present value (sNPV), benefit-to-cost ratio (BCR) and return on investment (ROI). Benis et al., (2018) estimated a 50-year discounted cash flow (DCF) for rooftop systems through NPV, IRR and PBP. Discount rate (%) and annual inflation (%) were also included in their analysis. The inflation rate was also considered in Llorach-Massana et al., (2016). Finally, Kim and Zhang (2018) analysed the economic feasibility of solar heating. The financial tools used for this purpose were escalation rate (e) and interest/discount rate (i).

In many LCC studies, a sensitivity analysis was applied as an additional analysis for assessment (Carter and Keeler, 2008; Assad et al., 2015, European Commission, 2010). Its main purpose of this analysis is to show the effects of changing key assumptions in order to consider different possible results as a way of reducing uncertainty (ISO, 2008). A sensitivity analysis was also used in 6 of the 10 examined papers (Kim and Zhang, 2018; Liaros et al., 2016, Sanyé-Mengual et al., 2015a, c; Llorach-Massana et al., 2016, Dorr et al., 2017). For example, in the study by Kim and Zhang (2018), a sensitivity analysis was used to evaluate various inputs, such as electricity costs, the cost of thermal solar collectors, collector efficiency, retail fish price, number of initial fish stocks and choice of species. Liaros et al., (2016) used this analysis to identify which economic factors affected the performance of a plant factory as an investment option. Sensitivity analysis was also applied in the work of Sanyé-Mengual et al., (2015a) to illustrate how their results depended on crop yield and distance, while Llorach- Massana et al., (2016) and Dorr et al., (2017) used this analysis to assess the type of scenario analysed. Finally, Sanyé-Mengual et al., (2015c) assessed the availability of re-used elements and the use intensity of a rooftop garden through sensitivity analysis.

Other types of additional analyses for assessment were found in the publication by Sanyé-Mengual et al., (2018a). They applied an eco-efficiency analysis to study the relationship between environmental impact and economic costs.

3.3.2.3. Type of LCC and type of costs used by life cycle stage

Three different types of LCC analyses exist: conventional, environmental, and social (Hunkeler et al., 2008; UNEP/SETAC, 2011). Conventional LCC covers all costs internal to the organization, while external costs are included in both environmental and societal LCC. Environmental LCC addresses external environmental costs that are likely to be internalized for decisions in the near future (e.g., through carbon prices or taxes). Finally, societal LCC includes all further external costs related to specific scenarios on a societal level (Skovgaard et al., 2007) to examine welfare losses and gains associated with the re-allocation of re- sources (Møller et al., 2014). Our results indicated that only Benis et al., (2018) applied all three types of LCC.

Since LCC takes into consideration the costs and cash flows arising from design and acquisition from operation and maintenance through to disposal (ISO, 2008, Wu and Longhurst, 2011), four main stages should be included in the LCC analysis (Fuller and Petersen, 1996, Jeong et al., 2015, Kim et al., 2015, Koroneos and Nanaki, 2012, Sanyé-Mengual et al., 2015a, Vargas-Parra et al., 2014).

- Initial or construction stage, where initial investment costs are included
- Operation stage, involving all costs accrued during the usage of the asset
- Maintenance stage, which consists of the costs of repair and replacement and
- End-of-life (EoL) stage, comprising the decommissioning/ dismantling, demolition, disposal and recycling costs

Table 3.5 shows the results of type costs used by each life cycle stage. This table also shows (in the last column) those costs that were not included in the LCC analysis:

- Initial or construction stage: rooftop garden installation
- Operation stage: labour costs
- Maintenance stage: infrastructure maintenance, replacement costs
- End-of-life (EoL) stage: recycling costs

These results are especially significant because for the first time they reveal that essential costs, like labour or the initial investment, are frequently not included. As we discuss later (see “Discussion” section), this is a weakness on the LCC application to UA.

Table 3.5 Type of costs used by life cycle stage

Reference	**Costs included by life cycle stage**				**Costs not included**
	Construction	**Operation**	**Maintenance**	**End-of-Life**	
Kim and Zhang (2018)	-Technical installations: solar water heating system	-Annual operation and maintenance costs (solar water heating system) -Maintenance costs (auxiliary electric water heater)		-	-Recycling cost (end-of-life) -Replacement costs (maintenance)
Forchino et al., (2018)	-Infrastructure: building cost -Technical installations: aquaponics production system	-Production Inputs: plants, water, energy, fish feeds	_	-	- Labour cost (operation)
Benis et al., (2018)	-Infrastructure: greenhouse structure	-Production inputs: plants, water, energy, organic fertilizer, labour	-Replacement costs of materials and equipment	-Dismantling costs	_
Opher et al., (2018)	-Technical installations: water reuse system	-Electricity -Seawater desalination costs		_	_
Sanyé-Mengual et al., (2018)	-Technical installations: cultivation and irrigation system	-Production inputs -Distribution transport -Gardener transport (purchase of materials)	_	-Transportation to the recycling plant	-Labour cost (operation)
Dorr et al., (2017)		-Tap water	_	-Recycling costs of water and materials	-Rooftop garden installation (Construction) -Infrastructure (maintenance) -Labour cost
Liaros et al., (2016)	-Building refurbishment -Technical installations: e.g., artificial lighting system -Equipment: e.g., office furniture, carts, servers etc.	-Production inputs: energy, labour, seeds, water, etc.	-Maintenance costs (building and technical installations)	-Dismantling costs of building installations	-

Llorach-Massana et al., (2016)	-Technical installations: e.g., solar energy storage system with PCM	-Fuel consumption	-Replacement costs of technical installations -Labour for basic maintenance	-	-End-of-life costs
Sanyé-Mengual et al., (2015a)	-Infrastructure: greenhouse structure -Technical installations: cultivation and irrigation system	-Production inputs: water, energy, fertilizers, pesticides, and labour	-Maintenance costs (infrastructure)	-Transportation to recycling plant (infrastructure)	-
Sanyé-Mengual et al., (2015c)	-Technical installations: cultivation and irrigation system	-Crop inputs: tap water, electricity, fertilizers, substrate	--	-Transportation to recycling plant (materials)	-Labour cost

3.3.3. Group 2: papers on cost reduction

In this section, we present the results from 3 other research papers that have optimized costs. They also used LCC for this purpose (Table 3.6).

Table 3.6 Papers on costs reduction

Reference	Costs to be optimized
Zidar et al., (2017)	
Zhao and Meng (2014)	Operation and maintenance costs
Halwatura and Jayasigne (2009)	Initial capital cost

The objective of Zidar et al., (2017) was to present a decision-support tool for green infrastructure (GI) systems to improve urban ecosystem services in Camden, USA. The authors analysed the possibility for expansion of UA through community gardens. They examined the possibility of life cycle cost reduction by looking for new funding sources for the vacant lots located at the intersection of Vine and Willard in North Camden, USA. The authors confirmed that local people involved in various green garden programmes could reduce the operation and maintenance life cycle costs.

Zhao and Meng (2014) analysed the operation costs, including the running maintenance costs, of the construction of agricultural water-saving facilities in Tianjin, China. Based on the life cycle cost theory, they found that designing innovation is the key to controlling the complex operation costs. Additionally, they investigated the effect of the investment and financing model on the design innovation process because, on the one hand, the manner of investment and financing can help to solve the construction-funding gap, whereas on the other hand, it will alter water-saving costs.

The last paper in this group, Halwatura and Jayasigne (2009), aimed to determine the ways in which an insulated roof slab could affect the energy needs for air conditioning in Sri Lanka and considered its influence on the life cycle costs. Despite the fact that this paper was related more to the construction and building sector, it was strongly connected with UA because of the opportunity for the creation of rooftop gardens to minimize the initial capital cost of the insulated roof slabs. The insulated roof slabs were expected to have additional benefits in comparison with those of a conventional roofing system, such as better cyclone resistance, low maintenance and the ability to create a greener environment with a rooftop garden. According to the authors, there was a significant reduction in the slab top temperature, with the presence of rooftop vegetation leading to energy savings, which was considered in the life cycle analysis.

3.3.4. Group 3: literature review of papers on LCC addressing various topic related to UA

In this section, we analysed 4 other papers that were literature reviews addressing various topics related to UA, including life cycle costs (Benis and Ferrão, 2018; Nguyen and Weiss, 2008; Sanyé-Mengual et al., 2017a; Sanyé-Mengual et al., 2015 b) (Table 3.7).

Table 3.7. Literature review papers on LCC analysis/ life cycle costs

Reference	Type of urban horticulture	Findings related to the LCC analysis/life cycle costs
Benis and Ferrão (2018)	commercial farming	• High construction costs of the urban commercial farms in comparison with conventional and rural farms • Elevated operation costs due to the lack of subsidies (e.g., water, energy)
Nguyen and Weiss (2008)	vertical farms	• Construction and operation costs depend on location, market, season, demand, supply, energy costs and many other factors • The construction time and overall costs could be minimised by reducing the waste in construction and reasonable use of resources • An appropriate design for the end-life stage would lead to construction techniques for decreasing whole life-cycle costs
Sanyé-Mengual et al., (2015 b)	urban rooftop agriculture (URA)	• Open-air rooftop gardens have lower economic costs than rooftop greenhouses
Sanyé-Mengual et al., (2017a)		
		• Decisions in the design phase of URA (cultivation technique, crop choice and management) are important for improving its economic sustainability

The first paper aimed to analyse the environmental, economic, and social aspects of urban commercial farming as a part of urban horticulture based on case studies in northern Europe (Benis and Ferrão, 2018). The authors examined two main points regarding the economic aspects of urban commercial farming: the level of investment and operation costs versus productivity. They confirmed that the capital expenditures of commercial farms are higher in comparison with those of conventional and rural farms and that the existence of prohibitive rents and high construction costs also reflect these results. According to the authors, the reason for the elevated operating costs was their high-energy needs and the lack of municipal subsidies (e.g., energy and water subsidies). Despite the higher costs, they demonstrated that the benefits of urban commercial farms could be found in the shortened supply chain where the logistics costs were reduced, and the added value of the fresher product may have justified a higher selling price.

Nguyen and Weiss (2008) analysed vertical urban farms' systems considering life cycle costs, design, construction, operation and infrastructure integration for environmental management and residences. The authors explained that construction and operation costs and revenues varied tremendously depending on location, market, season, demand, supply, energy costs and many other factors. According to the authors, waste reduction in construction and rationalized use of construction resources can decrease the construction time and thus decrease the overall costs. The selection of an appropriate design for the end-of-life stage could also lead to construction techniques for reducing the whole life cycle costs.

The literature review of Sanyé-Mengual et al., (2017a) was based on an updated version of their previous work presented during the 7th International Aesop Sustainable Food Planning Conference in Torino, Italy (Sanyé-Mengual et al., 2015b). Sanyé-Mengual et al. (2017a) used an interdisciplinary approach to evaluate different topics related to the sustainability of URA, including its environmental impacts and economic costs. The environmental impacts were evaluated by LCA, and the economic costs were evaluated through LCC. They analysed three case studies for this purpose: a rooftop greenhouse (RTG) in Bellaterra, Spain; a community rooftop garden (CRG) in Bologna, Italy and a private rooftop garden (PRG) in Barcelona, Spain. In comparison with the rooftop greenhouses, for open-air rooftop gardens, they found lower environmental impacts and economic costs. As for the design phase of URA, the LCC and LCA results accentuated the possible contribution of URA products in improving both economic and environmental sustainability. The LCA and LCC results also highlighted the importance of the decisions made in the design phase in relation to the cultivation technique, crop choice and management.

3.3.5. Group 4: other papers on costs for UA

The last group is formed of 3 research papers that calculated costs for UA without specification of the methodology used. Table 3.8 presents a summary of the results by type of urban agricultural practice, limitations and costs included.

Table 3.8 Other papers on costs for UA

Reference	Urban agricultural practice	Limitations	Costs included
Love et al. (2015)	aquaponics	• The infrastructure/capital cost and the labour cost were not included	Production/operation costs: energy, water, fish feed
Algert et al., (2014)	urban horticulture: community gardens		Production/operation costs: plants, seed, fertilizers, tools, and soil amendment
CoDyre et al., (2015)	urban horticulture: home gardens	• Only one city was investigated • Drought and above-average temperatures, which affected the productivity	• Capital cost • Operation costs: land and labour

In the first paper, Love et al., (2015) analysed a small-scale raft aquaponics system in Baltimore (USA) to explain the operating conditions as production inputs (energy, water, and fish feed) and outputs (edible crops and fish) and their relationship. The main limitation of the study was that the authors did not consider the infrastructure/capital and the labour costs for the analysis. Other operation/production costs, such as the costs of energy, water, and fish feed, were included. The results show that raising fish created a net loss, while crop cultivation presented a net gain when comparing market prices to energy costs. Accordingly, the authors suggested that new approaches for minimizing heating for fish should be found or that new species able to survive at lower water temperatures should be used.

Algert et al., (2014) investigated the capacity of community gardens to affect food affordability in an urban setting by documenting the vegetable outputs and cost savings of com- munity gardens in the city of San Jose, California (US). The system boundaries were limited to the production stage, excluding labour and infrastructure/capital costs. The authors calculated the economic cost by quantifying the following inputs needed for production: seeds, fertilizers, tools, and soil amendments. The results of the study revealed that the vertical growth of high-yield, higher-value vegetables such as tomatoes, cucumbers, and peppers, can provide greater cost savings relative to the cost of purchasing the same amount of vegetables in a retail setting.

Finally, in the last paper, CoDyre et al., (2015) presented the results of a preliminary survey aimed at evaluating the productivity of urban gardens in the medium-sized Canadian city of Guelph. All gardens analysed were home gardens in private yards that included backyard plots and community garden spaces. The main limitation of the study was that only one city was investigated. Moreover, the analysed gardening season was subject to drought and above-average temperatures, which affected productivity. The survey aimed to assess the productivity of urban gardens in terms of land, labour and capital. Different policy outcomes were also evaluated to promote the potential of urban gardening. The results showed that, on average, tomatoes represented 37% of all harvests, followed by potatoes at 12% and squash at 7%. The authors found that the level of production and input costs varied widely across gardeners and that there was great potential in urban self-provisioning. They suggested two main methods for improving self-provisioning among the gardeners: putting more land into production and improving the gardener's skills.

3.4. Discussion

In this section, we discuss the 4 most relevant findings from the "Results" section: (i) type of urban agriculture practice from group 1 and group 3; (ii) LCC integration with LCA/S- LCA from group 1; (iii) use of financial tools from group 1 and (iv) type of costs used at each life cycle stage from group 1, group 2 and group 4. We considered these findings the most important for the following reasons: (i) all of them are part of group 1, the major group consisting of 10 papers or 50% of 20 selected references; (ii) the most studied type of urban agriculture practice (horticulture) is important because it provides information for future directions of research of LCC in UA and finally, (iii) the life cycle stages are a fundamental part of the LCC methodology (ISO 2008); in this respect, the discussion on the type of costs used by life cycle stage is relevant.

Taking into account the importance of these findings, we present a discussion of each of them as follows:

- Type of urban agriculture practice
- LCC integration with LCA/S-LCA
- Use of financial tools
- Type of costs used by life cycle stage

3.4.1. Type of urban agricultural practice

The results of "3.2.1. Type of urban agricultural practice, research topic, LCC integration with LCA/S-LCA and LCC guidelines followed" (group 1) indicated that the most studied urban agricultural practice related to LCC was urban horticulture in 8 of the 10 papers. Urban horticulture was also analysed by all the authors in "Group 3: literature review papers on life cycle cost addressing various topics related to UA" (see Table 3.7). This result was not surprising because Parece et al., (2016) stated that, among plant and animals used for food, the plant production represented by urban horticulture was predominant.

Within urban horticulture studies, the building-integrated forms of UA such as vertical farming or zero-acreage farming (ZFarming), including indoor farms, rooftop greenhouses, rooftop gardens and further innovative forms, are becoming more popular. The main reason for this is the insufficient space for traditional ground agriculture in many urban cities and the lack of resources needed for production, such as water and energy (Specht et al., 2014; Thomaier et al., 2015). We found clear examples of some innovative forms of UA that use advanced technology for resource optimization in Sanyé- Mengual et al., (2015a) and Benis et al., (2018). For example, Sanyé-Mengual et al., (2015a) analysed the environmental and economic performances of a rooftop greenhouse (RTG) that took advantage of its integration into a sustainable building for optimizing water and energy consumption. Benis et al., (2018) evaluated the economic sustainability of high-tech rooftop greenhouse (RG) farms. Based on these results, we expect that the growing interest in innovative building-integrated forms of UA will continue in the future since the urbanization process is unavoidable (UN DESA, 2004). In light of this, we determined that more use and LCC research for UA is needed to evaluate the economic sustainability of these increasing building-integrated forms of UA.

3.4.2. LCC integration with LCA/S-LCA

One of the major findings of our study is the secondary role of LCC in its integration with LCA. Our results show that 9 of the 10 analysed papers in group 1 included both LCA and LCC analyses.

In all cases, LCA was the principal methodology, with LCC clearly playing just a secondary role. This was based on 4 of 10 studies (Forchino et al., 2018; Sanyé- Mengual et al. 2018a; Dorr et al., 2017; Sanyé-Mengual et al., 2015c) where the environmental impact through LCA was extensively studied through LCA but the economic evaluation by LCC was incomplete. One possible explication for the insufficient LCC analysis was the fact that the authors' main background was in environmental sciences, meaning that they had relatively less expertise in cost accounting. Since we found that the proportion of the three analyses (LCA, LCC and S-LCA) comprising LCSA was not equivalent, special attention should be paid to the use of LCC within the LCSA framework. Therefore, we strongly recommend that future works apply the three types of assessments equally, i.e., LCA, LCC and S-LCA methods should have the same or similar weight (e.g., 33% for each type of analysis) to make more balanced decisions for the improvement of sustainability in the UA context. It is also worth mentioning that only 1 of the 10 papers, Benis et al., (2018) applied LCC analysis at each level (conventional, environmental and societal).

3.4.3. Use of financial tools

Many authors have suggested the use of financial tools to complement LCC analyses such as NPV (ISO 2008; Kim et al., 2015; Assad et al., 2015; Vargas-Parra et al., 2014), IRR (Wong et al., 2003; Fuller and Petersen, 1996) and PBP (Farreny et al., 2011; ISO, 2008;

Koroneos and Nanaki, 2012). Since we found that only 4 of 10 analysed papers in group 1 used these additional financial tools, we strongly recommend the use of financial tools in future research.

3.4.4. Type of costs used by life cycle stage

The life cycle sustainability framework is based on the assessment of environmental, economic and social impacts of a product, project or service in all life cycle stages. From our thorough review of the literature from the last decade (before 2008 we did not find any publication using LCC for UA), we can state that there is very poor use of life cycle stages when calculating the cost of UA. It was a difficult task to identify how the authors classified costs in each of the LCC stages, especially at the construction and operation stages. The main reason for this is that some authors used their own classification when referring to the life cycle stages for both LCA and LCC. It seems that little attention has been paid to this part of LCC analysis until now. In our opinion, the lack of classification of costs in the life cycle stages is not irrelevant because it impedes the comparison between similar studies of UA. Our results show that only Benis et al., (2018); Liaros et al., (2016) and Sanyé-Mengual et al., (2015a) included all four LCC stages: construction, operation, maintenance and end-of-life. Although ISO (2008) does not require all stages to be included, we consider that, for the progress of UA and its contribution to the sustainability of cities, it is necessary to know the complete cost, that is, including all four stages, when using LCC analysis; otherwise, the information generated will not be sufficient for decision-making.

Despite the difficulty in identifying each LCC stage in the analysed literature, following our argument on the relevance of the stages, we present a discussion of the type of costs used by life cycle stage (construction, operation, maintenance and end-of-life) based on the results derived from 16 papers from group 1, group 2 and group 4.

3.4.4.1. Initial or construction stage

The initial or construction stage of LCC includes the initial investment costs (Jeong and Lee, 2009; Kim et al., 2015; Wu and Longhurst, 2011; ISO, 2008). These costs could be the costs of infrastructure, project design or taxes on construction goods or services, among many others (ISO, 2008). Some authors also used the term capital cost when referring to these costs (Halwatura and Jayasigne, 2009; Love et al., 2015).

In the case of UA, the initial investment costs are (i) the infrastructure, e.g., the greenhouse structure (Benis et al., 2018; Sanyé-Mengual et al., 2015a); (ii) the technical installations ;e.g. the aquaponic production system (Forchino et al., 2018), cultivation system and irrigation system (Dorr et al., 2017; Sanyé-Mengual et al., 2018a; Sanyé-Mengual et al. 2015a, c), solar water heating system (Kim and Zhang, 2018) and artificial lighting system (Liaros et al., 2016) and (iii) other equipment, such as office furniture, carts and servers (Liaros et al., 2016).

From the 16 papers analysed in groups 1, 2 and 4, we identified 4 papers (25% of the total analysed) that did not contain them or some important costs such cost of infrastructure were not included. This was because some authors such Love et al., (2015) did not disclose the available information about the initial costs, or the cost of the infrastructure (rooftop garden) was not considered due to study constraints as in Dorr et al., (2017).

Based on this result, in our opinion, not including costs at the construction stage, especially the cost of infrastructure, is a big hurdle in the use of LCC analysis for UA. As we mentioned, we assume that the growing interest in innovative building-integrated forms of UA will continue in the next few years, so information about initial investment costs is very important in making decisions for implementing or not implementing these new systems on a large scale.

3.4.4.2. Operation stage

The operation stage of LCC comprises all operation costs accrued during the usage of the asset (ISO, 2008, Jeong et al., 2015; Jeong and Lee, 2009; Wu and Longhurst, 2011). Regarding UA, we identified the following operation costs: rent (Liaros et al., 2016); production inputs or crop inputs such plants or seeds (Forchino et al., 2018; Benis et al., 2018; Sanyé- Mengual et al., 2018a; Dorr et al. 2017; Sanyé-Mengual et al. 2015a), water and energy (Kim and Zhang 2018; Forchino et al., 2018; Benis et al., 2018; Opher et al., 2018; Sanyé- Mengual et al., 2018a; Dorr et al., 2017; Liaros et al., 2016, Sanyé-Mengual et al., 2015a; Love et al., 2015; Llorach- Massana et al., 2016), labour (Benis et al. 2018; Liaros et al., 2016; Llorach-Massana et al., 2016; Sanyé-Mengual et al., 2015a) and finally distribution and gardener transport (Sanyé-Mengual et al., 2018a).

A surprising finding within the operation stage was that only 5 or 31% of the 16 analysed papers (groups 1, 2 and 4) included the labour costs. The main reasons authors did not account for them were as follows: (i) it was not considered relevant; (ii) there was a lack of information (Love et al., 2015) and (iii) there was concern about the increase in the total cost when labour was included (Algert et al., 2014).

However, some authors strongly recommended the inclusion of labour costs at the operation stage. For example, Woodward (1997) classified labour as the main operation cost, while Lu et al., (2017) stated that labour costs were an important factor and that its exclusion was the main reason for the incomplete LCC analyses in some studies. Finally, Sanyé-Mengual et al., (2015a) also demonstrated that labour was the most significant operation cost when analysing the economic performance of a rooftop greenhouse (RTG) in Barcelona.

We also agree that labour costs should be considered in the use of LCC for UA. We think that this condition is necessary for improving the LCC analysis in the UA context. The main argument is that labour is an important production factor in addition to raw materials and utilities (i.e., energy and water) (Baumgartner and Belevi, 2001). The principal objective of UA is to produce and provide plants and animals for food; in this respect, labour is an essential part of this production process.

3.4.4.3.Maintenance and end-of-life stages

Repair and replacement costs are included at the maintenance stage, while the end-of-life (EoL) stage consists of decommissioning/dismantling, demolition, disposal and recycling costs (Fuller and Petersen, 1996; ISO, 2008; Jeong et al., 2015).

Replacement or repair costs of construction materials and installations at the maintenance stage were considered in 8 of the 16 papers (Kim and Zhang, 2018; Benis et al., 2018; Opher et al., 2018; Liaros et al., 2016; Llorach-Massana et al., 2016; Sanyé-Mengual et al., 2015a; Zidar et al., 2017; Zhao and Meng, 2014). Regarding the EoL stage, 7 of the 16 papers included or studied these costs. For example, dismantling costs of greenhouse structures were included in Benis et al., (2018), while Liaros et al., (2016) included these costs for building installations necessary for an urban indoor farm. In Sanyé-Mengual et al., (2015a), the cost of transport of infrastructure waste (rooftop greenhouse) to a recycling plant was considered, while Sanyé-Mengual et al., (2015c) included this cost for cultivation materials. Finally, Dorr et al., (2017) considered the recycling costs of water and materials.

The two main reasons authors did not account for the maintenance and end-of-life costs were (i) the lack of information about them (Llorach-Massana et al., 2016) and (ii) that they do not consider them relevant because these costs were times lower than initial/construction or operation costs (Opher et al., 2018).

Given that the lack of information is a recurrent reason for not including costs, we suggest future research to consider both maintenance and end-of-life costs for more complete LCC for UA. This is primarily because Lu et al., (2017) explained that disposal and demolition costs, as well as labour costs, are important factors and that their not inclusion is the main reason for insufficient LCC analysis. As for the maintenance costs, we presume that the importance of these costs will increase in the future because of their dependency on construction costs. In this regard, including maintenance costs should also be a requirement in future research.

3.5. Conclusions

The aim of this research was a literature review of the use of LCC methodology for the UA sector and its evolution over a period of 22 years beginning in 1996 and ending in July 2018. For this purpose, we accurately reviewed 20 selected references.

This paper is a significant contribution to the field because it is the first literature review ever performed on the use of LCC in the UA context. We think that it can contribute to the advancement of the balance of the application of LCC within the life cycle sustainability assessment framework.

The scope of this research was limited to papers related to urban food production (edible plants and animal rearing), while other agricultural activities, such as the production and sale of agricultural inputs, post-harvesting, marketing and commercialization of agricultural production, were excluded from the analysis. On the basis of this constraint, future research could attempt to investigate other UA activities.

The main finding of this research was the complementary role of LCC in its integration with LCA. The key analysis was always LCA, with LCC being secondary. Our results also show that LCC analysis was quite incomplete regarding the costs considered in each life cycle stage. We found that 25% of 16 analysed papers (groups 1, 2 and 4) did not include costs at the initial/construction stage nor some important costs such cost of infrastructure were not considered. At the operation stage, labour cost, the principal cost of operations, was mainly ignored in 11, or 69%, of the 16 papers from groups 1, 2 and 4. As well as this, the costs at the maintenance and end-of-life stages were also generally excluded by authors. Only three authors accurately classified the costs by LCC stage (Benis et al. 2018; Liaros et al., 2016; Sanyé-Mengual et al. 2015a), which we consider the basic characteristic of LCC analysis. Additionally, since we found that only Benis et al. (2018) applied all three types of LCC (conventional, environmental and societal), we can conclude that the use of LCC analysis for UA is still in its early stages.

On the basis of these deficiencies, firstly, we strongly recommended future works to apply both LCA and LCC analyses at the same level. To accomplish this, LCC should be performed by people with relatively more expertise in cost accounting. Secondly, the inclusion of costs at the initial or construction stage is a necessary condition in order to improve the current use of LCC for UA and to evaluate its economic sustainability. Special attention needs to be paid to the labour costs at the operation stage, as it is an essential part of the production process. To this effect, lack of information should not be a pretext for not including essential costs.

Finally, all four main LCC stages should be considered in future research for more complete LCC analyses for UA. The use of additional financial tools, such as net present value (NPV), internal rate of return (IRR) and payback period (PBP), would be advisable to complement LCC analysis.

PART 3:ANALYSIS OF ECONOMIC VAIBILITY OF URBAN FOOD PRODUCTION USING LIFE CYCLE COST METHODOLOGY

Chapter 4

Life cycle cost analysis of tomato production in innovative urban agriculture systems

Pictures representing the tomato´s 7-month cultivation cycle and the remains of the crop. Source: Sostenipra

Chapter 4 Life cycle costing of artisan tomato production in building-integrated rooftop greenhouses

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This chapter is based on the following published journal paper:

Peña, A., Rovira-Val, M. R., & Mendoza, J. M. F., (2022). *Life cycle cost analysis of tomato production in innovative urban agriculture system*s. Journal of Cleaner Production, 133037. https://doi.org/10.1016/j.jclepro.2022.133037

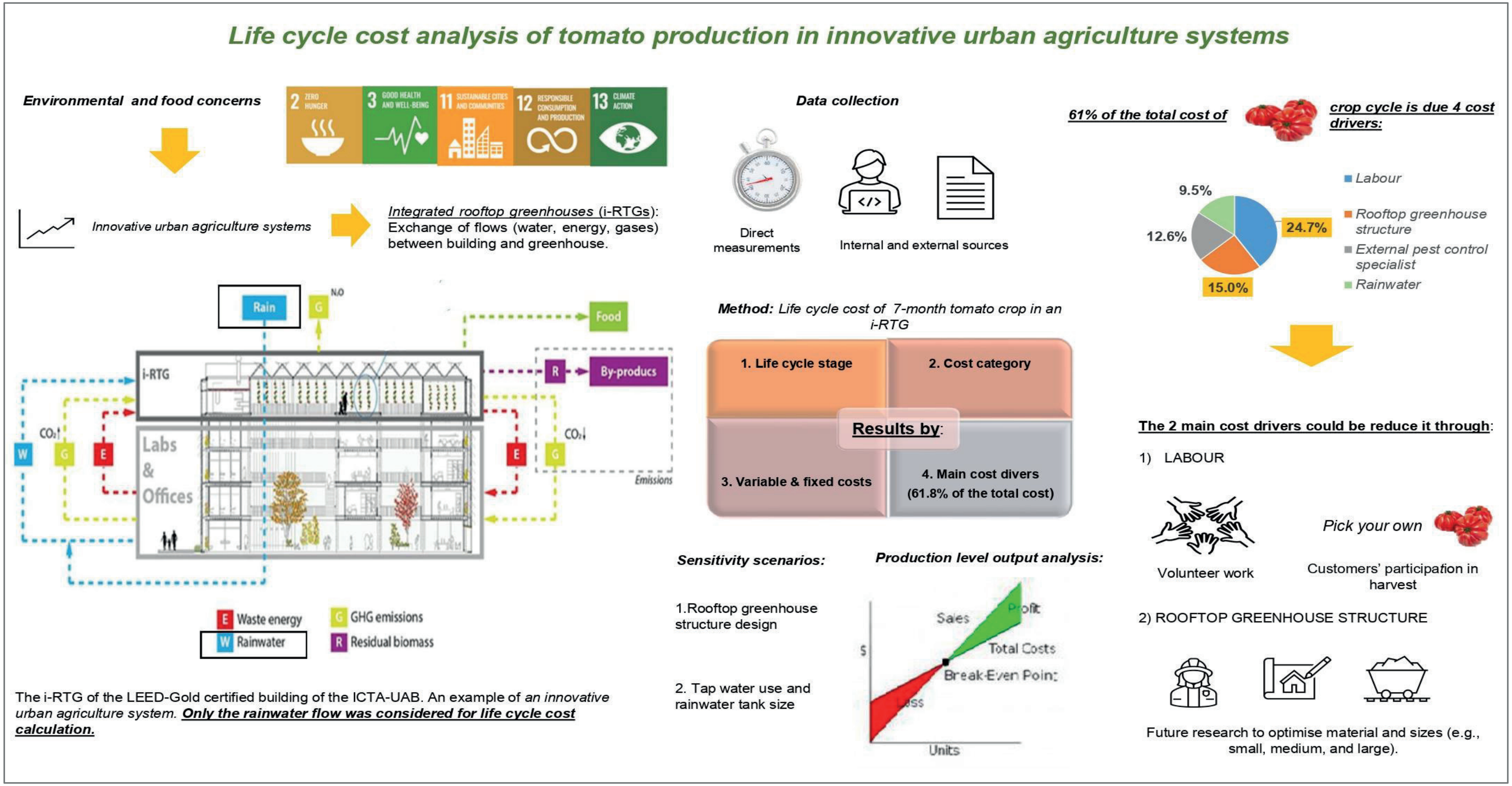
Data have been updated by Addendum to Chapter 4:

- Business models
- Customer preferences

Abstract

The construction of innovative urban agriculture systems in cities has increased due to food and environmental concerns. While the environmental performance of urban agriculture has been extensively studied, research on the life cycle costs urban agriculture systems is still limited, which constraints sustainability-oriented decision-making processes. This paper analyses the economic viability of tomato production cycle in an innovative building with an integrated urban agriculture system in rooftop by applying the life cycle cost methodology. The data was collected from direct measurements and internal and external sources. To calculate labour costs, a customised data collection sheet was created. The results are presented by life cycle stage, cost category and type of cost (fixed & variable). Results indicate that the main cost drivers for tomato production are labour (24.7%), the rooftop greenhouse structure (15%), the external pest control (12.6%), and rainwater consumption (9.5%), accounting altogether for 61.8% of the total costs. Accordingly, cost reduction solutions are evaluated through the development of sensitivity scenarios (rooftop greenhouse structure design, tap water use and rainwater tank size), including the consideration of another relevant aspect, such as the role of the production level output, as it can greatly influence the economic viability and profitability. Finally, the main environmental and social aspects of these urban production systems are also included.

Keywords:
Economic viability, Food security, LCC, Sustainable cities, Urban agriculture, Urban food production



Life cycle cost analysis of tomato production in innovative urban agriculture systems

Environmental and food concerns

Innovative urban agriculture systems

Integrated rooftop greenhouses (i-RTGs): Exchange of flows (water, energy, gases) between building and greenhouse.

The i-RTG of the LEED-Gold certified building of the ICTA-UAB. An example of *an innovative urban agriculture system.* ***Only the rainwater flow was considered for life cycle cost calculation.***

Data collection

Direct measurements

Internal and external sources

Method: *Life cycle cost of 7-month tomato crop in an i-RTG*

1. Life cycle stage

2. Cost category

Results by:

3. Variable & fixed costs

4. Main cost divers (61.8% of the total cost)

Sensitivity scenarios:

1. Rooftop greenhouse structure design

2. Tap water use and rainwater tank size

Production level output analysis:

61% of the total cost of ***crop cycle is due 4 cost drivers:***

The 2 main cost drivers could be reduce it through:

1) LABOUR

Volunteer work

Pick your own

Customers' participation in harvest

2) ROOFTOP GREENHOUSE STRUCTURE

Future research to optimise material and sizes (e.g., small, medium, and large).

Fig. 4.1. Graphical abstract

4.1. Introduction

The world population is estimated to increase from 7.7 billion in 2019 to 9.7 billion (+26%) in 2050 (UN DESA, 2019). Currently, more than half of the world population lives in urban areas and this tendency is projected to reach 68% in 2050 (UN DESA, 2018). Therefore, population growth and rapid urbanization is putting pressure on global food security due to the increased demand on food (UNCCD, 2017). For instance, it was estimated that 9.2 % of the world population (over 700 million people) experienced serious problems regarding food security in 2018 (Egal, 2019). Nowadays, a third of all edible food (1.8 billion tonnes) is wasted (EMF, 2019), even though there are currently more than 820 million hungry and malnourished people (FAO, IFAD, UNICEF, WFP and WHO, 2019). This is due to existing differences in land and water availability between developed and underdeveloped countries (Ibarrola Rivas and Nonhebel, 2016).

Additionally, agriculture is responsible for 70% of global freshwater use and deforestation, making the agri-food industry the world's second largest emitter of greenhouse gas emissions (GHGs), accounting for 25% of all human-caused emissions (FAO, 2017a; EMF, 2019). Interestingly, the Ellen MacArthur Foundation (EMF) has estimated that from the 7.1 billion tons of food produced globally, approximately 40% is eaten in cities, where 2.8 billion tons of organic waste is produced (EMF, 2019). Likewise, it is estimated that 80% of all food will be destined for consumption in the cities by 2050 and therefore they have huge potential to influence the way in which food is produced and eaten, and how food waste is managed.

In the context of sustainable city development, the implementation of urban agriculture (UA) can provide relevant opportunities for efficient food production (Pearson et al., 2010; Thomaier et al., 2015), helping achieve the 2030 sustainable development goals (SDGs) (UN, 2015). UA can likewise increase biodiversity in cities (Van Tuijl et al., 2018) and help to reduce pollutant emissions, facilitating the adaptation and mitigation of the impact of climate change (SDG 13) (Bendt et al., 2013; Lwasa et al., 2014). UA may contribute in at least three ways on a social level: i) it is an important element of food security strategies to 'feed citizens', and to fight chronic hunger (SDG 2) in developing countries, ii) it an also contribute to community development, e.g., through activities to increase social cohesion (SDG 10) between different groups in society to provide work opportunities for unemployed workers, and iii) it can be used for educational purposes (SDG 4) to increase awareness among citizens regarding food production, e.g. by organizing workshops, courses and tours. Finally, it can as well contribute to improving economic sustainability in cities (SDG 8) by (i) generating new income (SDG8) since there are several companies that use UA for commercial purposes., e.g. Lufa Farms in Montreal (Canada), Panasonic Factory Solutions Asia Pacific (Singapore), The Plant in Chicago (USA), (ii) promoting innovation, research, and knowledge (SDG9) through the creation of R&D labs on-site in the urban farms or collaboration with educational institutes (e.g., Science Barge, Sky Green, Urban Farmers AG); and finally, (iii) offering recreational and tourist activities (e.g. Brooklyn Grange in New York (USA), Xiedao Green Resort in Beijing (China) (Van Tuijl et al., 2018).

UA can be defined as "an industry located within (intra-urban) or on the fringe (peri-urban) of a town, city or metropolis, which grows or raises, processes and distributes a diversity of food and non-food products" (Mougeot, 2000, p.11) and it comprises of a huge variety of different forms such as community gardens, vertical farming (VF), or urban farms among many (Van Tuijl et al., 2018). However, there is a growing interest in the development of VF or ZFarming forms of UA such as indoor farms, rooftop greenhouses (RTGs), or rooftop gardens (RGs) due to the insufficient space available in cities to support traditional ground agriculture and the lack of resources needed for agricultural production, such as water and energy (Specht et al., 2014; Thomaier et al., 2015). Among the VF forms of UA, RTGs are gaining popularity due to the increasing interest in the development of innovative food production spaces and promotion of food self-sufficiency in urban areas (Sanyé-Mengual et al., 2015).

RTGs can have notable environmental, economic and social benefits, such as reduced food miles, improved community food security, and community outputs (Cerón-Palma et al., 2012; Specht et al., 2014). Going one step further, additional benefits could be expected through the construction of integrated rooftop greenhouses (i-RTGs). This innovative option has the particularity that resource flow such as rainwater, CO_2 and heat, can be integrated in a bidirectional way building-rooftop greenhouse. This integration will contribute to the reduction of the environmental impact of the building and the food production system overall (Sanyé-Mengual et al., 2015a).

The life cycle environmental performance of UA has been extensively analysed in the literature by means of life cycle assessment (LCA), however the use of life cycle cost (LCC) for the evaluation of the economic viability is still very limited (Sanye-Mengual et al., 2017a). This was also supported by a previous literature review study based on 20 references analysing the use of LCC in UA over the last two decades (Peña and Rovira-Val, 2020). The results of that study identified problems in the application of LCC methodology in UA such as the frequent not inclusion of essential costs such as operational labour and infrastructure intro the cost calculation. According to Lu et al., (2017), the exclusion of the labour identified as the most significant operation cost (Sanyé-Mengual et al., 2015a) and an important production factor (Baumgartner and Belevi, 2001) was the main reason for the incomplete LCC analysis in many UA studies (Lu et al., 2017). Regarding, the infrastructure cost (e.g., greenhouse structure), its inclusion in the LCC is crucial for future development of UA in cities, especially for boost the implementation of innovative environmentally friendly UA systems on a large scale. Moreover, the results of that literature review also releveled that the LCC was frequently integrated with LCA, but they were not applied at same level since the principal analysis was always LCA, while LCC played just a very secondary role. This is an important constraint since although LCA is a relevant tool to analyse environmental impacts, LCA findings are limited for effective decision-making without the integration of complete economic data with LCC (Norris, 2001).

Hence, the overall objective of this paper is to analyse the economic viability of artisan tomato production to provide recommendations to promote the UA in rooftop greenhouses in cities. To achieve the main objective, the following specific objectives were established:

(i) To identify main cost drivers and propose reduction alternatives.
(ii) To analyse the potential variability in the results based on changes in main cost drivers.
(iii) To analyse the role of production level output as important variable affecting the economic viability and profitability.

The tomato crop was selected for analysis since (i) tomatoes are the most consumed vegetable worldwide after potatoes (20.8 kg/capita in 2017) (FAO, 2020) and (ii) they are typically used in greenhouse production (Hochmuth and Hochmuth, 2018) because it is relatively easy to grow in comparison to cucumbers and lettuce, and yields can be high. Likewise, tomatoes were the second most sold vegetable in Mercabarna (the food distribution centre of Barcelona) at 87,100 tonnes sold or 14,31% of the total of sold vegetables in 2019 (MercaBarna, 2019).

As far as the authors are aware, this study is the first to analyse the LCC of tomato production in i-RTGs well made for better decision-making by (i) including infrastructure and labour costs; (ii) classifying fixed and variable costs, and (iii) applying additional break-even point (BEP) analysis to find the optimal level of production to be sold and determinate the maximum level of fixed costs at different selling prices. The study is also complementary to the previous research of Sanjuan-Delmás et al., (2018a) where the LCA was performed to quantify the environmental impacts of tomato production in the same case study.

4.2. Methodology

This section explains how the LCC was performed to determine the economic viability of artisan i-RTG tomato production. First, the case study is presented. Secondly, the application of the LCC methodology is explained. Primary data was gathered through novel data collection protocols developed for this purpose (e.g., registry of the hours worked on the crop and consumption of materials) and secondary data from internal and external sources.

4.2.1. Description of the case study

The case study is the integrated rooftop greenhouse of the LEED-Gold certified building that hosts the Institute of Environmental Science and Technology (ICTA-UAB) in the main campus of the Universitat Autònoma de Barcelona (UAB) in Barcelona province (See Appendix 1.1). Both, the building, and its greenhouse, are innovative systems. On one side, the building's LEED-Gold certificate recognizes its high level of Leadership in Energy and Environmental Design. On the other, the greenhouse in the rooftop is also innovative because of the integration of several flows between the building and the greenhouse (rainwater, CO_2 and energy), which optimise the environmental performance of the system (Pou et al. 2015).

The flow integration of the studied case is limited to the use of rainwater. Two consecutive tomato crops with the same characteristics and production cycles, were studied: years 2018 and 2019. However, only the LCC results for 2019 crop are presented and discussed. This is due to the problem that there was not a device for measuring labour hours, unlike other crop parameters quantified by electronic measurement tools (e.g., water consumption, solar radiation, etc.). This problem was observed in the crop 2018 and consequently in the crop 2019 a standard time for carry out each defined crop production task was established in order to have an accurate measure of labour time for crop production. Hence, the 2018 crop was considered as a trial version that allowed the development of refined data collection tools with the purpose of get more accurate results for the crop 2019.

The tomato variety cultivated was Coeur-de-boeuf (Lycopersicon esculentum var. Arawak) which stands out for the size of its pieces, which can reach up to 500 g and it is mainly used for fresh salads. This variety is highly appreciated for its size and flavour, with an average price of 2.92 €/kg (OCU, 2018).

The tomato was cultivated in a hydroponic system, a soilless system that uses perlite volcanic stones as a substrate (See Appendix 1.2), containing 171 plants in total. The productive area (substrate area) was 84.3 m^2 from the total extension of the i-RTG (122.1 m^2) and the period of study was the crop cycle: 7 months, from January to July.

4.2.2. Life cycle costing (LCC)

LCC is an economic evaluation technique that aims to quantify all costs and cash flows that emerge during the entire life cycle of a product, service, and project (Ammar et al., 2013). The LCC of artisan tomato production followed the guidelines provided by Hunkeler et al. (2008), Swarr et al., (2011) and ISO (2008), as described below.

4.2.2.1. Goals, scope and functional unit

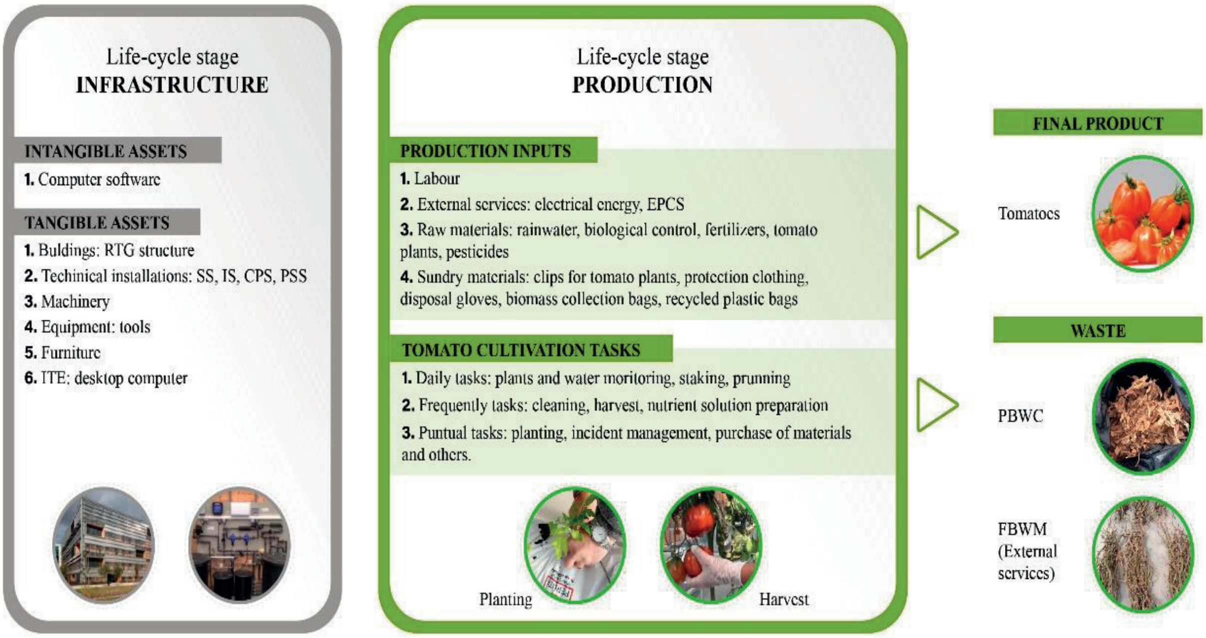
The aim of the applied LCC was to quantify the total cost of artisan i-RTG tomato production, with the following specific objectives:

(i) To present the costs of tomato production by life cycle stage, by cost category and by fixed and variables.

(ii) To identify the main cost drivers and propose reduction alternatives

(iii) To analyse the costs variation considering different sensitivity scenarios

The scope of the study was from cradle to gate, covering two main stages: (i) infrastructure and (ii) production. The infrastructure stage includes initial investment costs of assets (tangible and intangible) needed for production, all of them are fixed cost. The production stage includes input item costs and waste costs (classified as outputs), these costs are mainly variable and those specific items that are not variable by unit were calculated as a proportional part during the analysis period. Fig. 4.2 illustrates the scope of the study, whereas Table 4.1 provides detailed information of all considered costs.



FU=1 kg of tomatoes grown and harvested in a i-RTG over a 7-month production cycle cycle in the Metropolitan Area of Barcelona (Spain)

Figure 4.2 Scope of the study. Acronyms: RTG structure=Rooftop greenhouse structure; SS=System of sensors; IS=Irrigation system; CPS= Curtains and partitions system; PSS= Production supporting system; ITE: Information technology equipment; EPCS=External pest control specialist; PBWC= Pruning biomass waste collection; FBWC=Final biomass waste collection

Costs related to the maintenance activities stage were not considered due to the following reasons: (i) no reparation or replacement activities took place during the analysed period and (ii) if maintenance operations were to be required, the costs are negligible (e.g., change of small spare parts such as ball valves, PVC elbow, etc.). Thus, the exclusion of maintenance costs is not considered to affect the results. Finally, costs at the end-of-life (EoL) stage, the costs related to decommissioning of the greenhouse structure, the production system and the recycling of materials were not included due to the uncertainty in waste management practices after the long lifespan of the infrastructure, which for buildings is typically considered 50 years.

The functional unit (FU) used in the calculations was defined as "1 kg of tomatoes grown and harvested in a i-RTG over a 7-month production cycle in the Metropolitan Area of Barcelona (Spain)". This is the typical FU (1 kg of product) considered in most UA studies (Peña and Rovira-Val, 2020).

4.2.2.2. Life cycle cost calculation

The total LCC cost of the 2019 crop was calculated as described in Equation (1)

$$LCC\ (€/kg) = C_I + C_P \qquad (1)$$

Where C_I =infrastructure costs and C_P=production costs

For the infrastructure costs, initial capital investments needed for production (greenhouse structure and other asset categories (i.e., the assets that last more than one crop cycle), the economic depreciation cost (also named amortisation) of such assets was calculated applying the 2nd Accounting Standard Property, plant, and equipment of the Spanish general accounting plan (ICAC, 2007). Specifically, section 2. Subsequent measurement, 2.1. Depreciation, which provides the depreciation definition:

Property, plant, and equipment shall be depreciated on a systematic and rational basis over the useful life of the assets, considering their residual value and based on impairment normally incurred due to operational wear and tear, and considering potential technical or commercial obsolescence.

No residual value was considered feasible for any of the assets. Regarding their useful life, this was defined as years of operational use and the depreciation period associated to each asset element (see complete list in Table 1) was estimated according to the greenhouse technicians' opinion:

- Computer software (for sensors data): 10 years.
- Building or construction cost is separated from Land cost. According to financial accounting standards, depreciation is only applied to the construction cost. For building, the usual criterion was applied: 50 years.
- Technical installations: 10 years, except for the Production supporting system (bags of substrate: perlite volcanic stones) that need to be renewed every 3 years.
- Machinery: 5 years.

- Equipment: 5 years. This estimation could be 3 or 5 years. The last was selected because we estimated that these small tools could be used during more time than just one single research project (in Spain 3 years).

After estimating the years of lifespan, the proportional amortisation cost for one tomato crop period (7 months) was calculated using the following equation:

$$Amortisation\ cost\ = \frac{Initial\ cost}{Lifespan\ (years)} \times \frac{7\ month}{12} \qquad (2)$$

Regarding the production cost, consumed items (consumables), in the 7-month production cycle, these were calculated as in Equation (3)

$$Cost\ (consumable\ item) = Consumption \times unit\ cost\ €) \qquad (3)$$

4.2.2.3. Life cycle inventory

Table 4.1 presents the life cycle inventory of all considered costs of artisan i-RTG tomato production. The costs are presented by (i) *Life cycle stage*; (ii) *Cost group*. The Spanish general accounting plan (ICAC, 2007) was used to classify the infrastructure items into (a) intangible assets: computer software and (b) tangible assets: buildings, technical installations, machinery, equipment, furniture, and information technology equipment; (iii) *Cost category*. In this regard, four technical installations were identified: (i) system of sensors; (ii) irrigation system; (iii) curtains and partitions system and (iv) production supporting system. Detailed information about the composing elements of each technical installation can be found in the Appendix 1.3 and (iv) *Cost item*.

It is worth mentioning that labour and transport costs were included in all costs at the infrastructure stage. This was because the elements of this stage, such as rooftop greenhouse structure and building installations, were part of the ICTA-UAB building constructed in 2014 and detailed information about the number of working hours spent on construction and transportation was not available. As was the case with the cost of machinery and tools. At the production stage, transport costs were also integrated in the cost of all items since the transportation cost was unknown because they were not specified in the invoices of raw and consumable materials.

Table 4.1 Life cycle cost inventory of integrated rooftop greenhouse (i-RTG) tomato production in 2019

Life cycle stage	Costs group	Cost category	Fixed or Variable Cost	Cost item	Lifespan (years)	Quantity		Cost (€) [b]	
						Cycle [a] (1,068 kg)	1 kg	Cycle [a] (1,068 kg)	1 kg
INFRASTRUCTURE	*INTANGIBLE ASSETS*	*Computer software*	*Fixed*	Computer software for sensors data	10	5.83E-02	5.46E-05	35.9	0.03
				Subtotal				***35.9***	***0.03***
		Buildings	*Fixed*	Rooftop greenhouse structure (122.14 m ^{2})	50	1.17E-02	1.09E-05	813.3	0.76
				Subtotal Computer software				***813.3***	***0.76***
		Technical installations	*Fixed*	System of sensors	10	5.83E-02	5.46E-05	260.7	0.24
				Irrigation system	10	5.83E-02	5.46E-05	236.6	0.22
				Curtains and partitions system	10	5.83E-02	5.46E-05	139.9	0.131
				Production supporting system	3	1.94E-01	1.82E-04	45.1	0.04
				Subtotal Technical installations				***682.3***	***0.6***
		Machinery	*Fixed*	Balance; maximum: 6.5 kg	5	1.17E-01	1.09E- 04	28.6	0.027
				Balance; maximum: 60 kg	5	1.17E-01	1.09E- 04	77.8	0.073
				Conductivity tester	5	1.17E-01	1.09E- 04	8.8	0.008
				Ph tester	5	1.17E-01	1.09E- 04	8.8	0.008
				Backpack Sprayer, capacity 12L	5	1.17E-01	1.09E- 04	5.5	0.005
				Backpack Sprayer, capacity 1L	5	1.17E-01	1.09E- 04	1.3	0.001

	TANGIBLE ASSETS			High pressure cleaner	5	1.17E-01	1.09E- 04	9.6	0.009
				Hand pallet truck up to 300 kg	5	1.17E-01	1.09E- 04	47.5	0.044
				Security camera	5	1.17E-01	1.09E- 04	135.2	0.127
				Subtotal Machinery				***323.1***	***0.3***
		Equipment	*Fixed*	Hose,25 meter	5	1.17E-01	1.09E-04	5.12 €	0.0048
				Hose holder	5	1.17E-01	1.09E-04	6.45 €	0.0060
				Broom	5	2.33E-01	2.18E-04	0.39 €	0.0004
				Dustpan	5	1.17E-01	1.09E-04	1.47 €	0.0014
				Nylon working gloves	5	4.67E-01	4.37E-04	0.40 €	0.0004
				Goatskin working gloves	5	1.17E-01	1.09E-04	0.92 €	0.0009
				Pruning scissors	5	3.50E-01	3.28E-04	6.37 €	0.0060
				Belt (pruning scissors)	5	1.17E-01	1.09E-04	0.73 €	0.0007
				Cover for pruning scissor	5	2.33E-01	2.18E-04	0.62 €	0.0006
				Drill, 710W	5	1.17E-01	1.09E-04	6.56 €	0.0061
				Protective glasses	5	1.17E-01	1.09E-04	1.39 €	0.0013
				Protective mask	5	1.17E-01	1.09E-04	3.93 €	0.0037
				Tool case	5	1.17E-01	1.09E-04	4.25 €	0.0040
				Pliers	5	3.50E-01	3.28E-04	9.06 €	0.0085
				Blade cutter	5	1.17E-01	1.09E-04	0.57 €	0.0005
				Screwdriver	5	4.67E-01	4.37E-04	1.62 €	0.0015
				Flexometer, 5m	5	1.17E-01	1.09E-04	0.57 €	0.0005

				Wrenches	5	2.33E-01	2.18E-04	4.33 €	0.0041
				Hammer	5	1.17E-01	1.09E-04	1.40 €	0.0013
				Handsaw	5	1.17E-01	1.09E-04	0.75 €	0.0007
				Flange tension gun	5	1.17E-01	1.09E-04	1.75 €	0.0016
				Polyethylene shovels,	5	4.67E-01	4.37E-04	0.66 €	0.0006
				Electrician scissors	5	1.17E-01	1.09E-04	0.92 €	0.0009
				Subtotal Equipment				***60.2***	***0.056***
		Furniture	***Fixed***	Wooden wardrobe	5	1.17E-01	1.09E-04	4.8	0.0045
				Wooden table	5	1.17E-01	1.09E-04	4.8	0.0045
				Aluminium ladder,	5	1.17E-01	1.09E-04	8.7	0.0081
				PVC rolling stool	5	1.17E-01	1.09E-04	2.8	0.0026
				Plastic bin	5	1.17E-01	1.09E-04	3.6	0.0034
				Subtotal				***24.6***	***0.023***
		Information technology equipment	***Fixed***	Desktop computer	10	5.83E-02	5.46E-05	20.9	0.020
				Subtotal Infor. technology equipment				***20.9***	***0.020***
				Total Infrastructure stage (I)				**1,960.3**	**1.8**
PRODUCTION		***Direct labour***	***Variable***	Labour (hrs)		239	2,21E-01	1,339.7	1.3
				Subtotal Direct labour				***1,339.7***	***1.3***
		External services	***Fixed***	External pest control specialist (€)		cycle proportion [c]		682.2	0.6
				Pruning biomass waste collection (unit)		1	9.36E-04	142.8	0.13
			Variable	Electrical energy (kWh)		1,903	1.78E+00	189.3	0.18

	INPUTS & OUTPUTS			Final biomass waste management (unit)		1	9.36E-04	169.4	0.20
				Subtotal External services				***1,183.7***	***1.1***
		Raw materials	***Variable***	Rainwater [d]		59.5	5.57E-02	517.4	0.5
				Biological control		0.7	6.6E-04	167.3	0.16
				Fertilizers [e]		89.5	8.4E-02	92.2	0.09
				Tomatoes plants		171	1.60E-01	68.2	0.064
				Pesticides [f]		0.932	4.7E-04	27.2	0.0254
				Subtotal Raw materials				***872.3***	***0.84***
		Sundry materials	***Variable***	Clips for tomato plants		2,565	2.40E+00	27.2	0.025
				Protection clothing		16	1.50E-02	23.2	0.022
				Disposable gloves		50	4.68E-02	3.2	0.003
				Biomass collection bags		30	2.81E-02	11.2	0.010
				Recyclable plastic bags		4	3.75E-03	1.0	0.001
				Subtotal Sundry materials				***65.8***	***0.062***
				Total Production stage (II)				**3,461.5**	**3.3**
				TOTAL FIXED COST (TFC)				***2,785.3***	***2.6***
				TOTAL VARIABLE COST (TVC)				***2,636.5***	***2.5***
				TOTAL COST (I+II)				**5,421.8**	**5.1**

[a] Based on 7-month crop consumption in physical units

[b] VAT % excluded

[c] Calculated as 2/3 of the total invoice of annual service contract for pest control monitoring

[d] Rainwater cost was calculated as 7-month amortization of the available Rainwater harvest system

[e] KH_2PO_4, KNO_3, $CaCl_2$, Mg $(NO_3)_2$, K_2SO_4, Ca $(NO_3)_2$, Sequestrene (Fe), Hortrilon (Fe, Mn, Zn, Cu, B, Mo)

[f] Pesticides included: Sulfur (S), Heliosufre (sulfur 72%), Insecticidal soap and Neemazal (natural insecticide)

4.2.3. Data collection and monetarization

This section explains how consumption and monetarization data was collected and calculated. The information is presented following the two stages included in the case study: infrastructure and production. The percentage of the value added tax (VAT) was not included in costs due to the research-oriented nature of the building of the case study.

4.2.3.1.Infrastructure costs

The costs of the infrastructure stage are presented in Table 4.1 and Figure 4.3 (in the Results section). Secondary data such as invoices and other similar documents provided mainly by the internal accounting system was used. When the data was not complete, external sources were consulted such as suppliers, online shops, and experts. In the case that a cost element was no longer available on the market, similar products were used to obtain the approximated cost.

It was not possible to separate the specific structure cost of the rooftop greenhouse from the total building cost. For that reason the structure cost was calculated as un average cost based on (i) the real construction cost for 1m^2 of the building, which is high since it includes all technical installations, materials and elements used for the different activities of all floors; (ii) the cost for 1m^2 of rooftop based on a budget, excluding electrical installations; and (iii) the cost for 1m^2 of the rooftop greenhouse structure estimated in Sanyé-Mengual et al., (2015a) without considering electrical installations as well.

Finally, to estimate the lifespan needed for the calculation of economic amortisation of the intangible and tangible assets, experts (architects, civil engineers, and agricultural engineers) and references in the literature (e.g., Sanjuan-Delmás et al., 2018a) were consulted.

4.2.3.2. Production costs

The cost of the production stage (see Table 4.1 and Figure 4.3) includes the costs of all inputs items as well as two outputs (biomass waste). They were classified in four cost categories: direct labour, external services, raw materials, and sundry materials.

Regarding direct labour, this cost category involved the labour of people who directly participated in the tomato production process. Unlike other crop parameters measured using technical devices (e.g., water consumption, solar radiation, etc.), a device to quantify for working hours was not available. A daily register of working hours of cultivation tasks was designed and implemented (e.g., plant monitoring, water monitoring, nutrient solution preparation, pruning, staking, harvesting). The template used for this purpose can be seen in the Appendix 1.4. A tested standard time for each task was established to secure an accurate measurement of labour time consumed. The unitary cost per working hour for a basic agriculture worker was obtained from the database of the Ministry of Agriculture, Livestock, Fisheries and Food of the Government of Catalonia (Government of Catalonia, 2016).

The next group, external services, included the following four costs items: external pest control specialist (EPCS), electrical energy, pruning biomass waste collection (PBWC) and final biomass waste management (FBWM). The cost of the EPCS was calculated based on the annual service contract for monitoring the crops for signs of insects, rodents, and other pests. It was estimated that the service for the tomato production was 2/3 of the total invoice. For electrical energy cost, units consumed were taken from a previously created register (Excel file) and the energy price was provided by an expert involved in the project. Regarding PBWC cost, the service of urban waste collection was used (municipality of Cerdanyola del Vallès) and its cost was gathered from the Barcelona Metropolitan area's website. Finally, the cost of the FBWM was estimated based on a carrier budget and included the recollection of the final biomass waste and its transportation to the treatment plant in the nearest municipality.

Raw material costs included five cost items: rainwater, biological control, fertilizers, tomato plants and pesticides. The rainwater consumed came from the rainwater harvest system (RWHS) which is part of the ICTA-UAB building and supplies rainwater to the toilets of the building, ornamental plants, and all crops. Hence, only the proportional amount of the amortization cost of the RWHS parts was included. Data about consumed biological control, fertilizers, tomato plants and pesticides were obtained from the daily register of the research group Sostenipra running the Fertilecity project, while their unitary prices were collected from invoices or delivery notes.

Finally, data about consumed sundry consumable materials (e.g., clips for tomato plants, protection clothing, disposable gloves) was gathered from the afore mentioned Excel file, while unitary prices were collected from invoices and websites (online shops, products databases).

4.3. Results and discussion

In this section the results and discussion are presented in four parts. The first part presents the LCC results of artisan i-RTG tomato production as follows: (i) contribution by life cycle stage and cost category; (ii) variable and fixed costs; (iii) the four main cost items (cost drivers) responsible for 61.8 % of the total cost are discussed: labour, rooftop greenhouse structure, EPCS, and rainwater. The second part presents the results of the sensitivity assessment to determine the potential variability in the results according to changes in: rooftop greenhouse structure and rainwater. The sensitivity assessment was omitted from labour cost since no significant difference between the working hours spent on tomato production in the studied case and conventional greenhouses was found. Sensitivity scenarios were not established for the EPCS either due to uncertainty about the time spent (hrs) on tomato production. In the third part, the role of the production level output as an important element affecting the economic viability and profitability is presented. Moreover, environmental and social aspects of the i-RTGs are addressed.

4.3.1. LCC of 2019 of artisan i-RTG tomato production

4.3.1.1. Contribution by life cycle stage and cost category

Total tomato production in 2019 was 1,068 kg at a total cost of 5,421.8 € (VAT % excluded), which is equivalent to 5.1 €/kg (see Table 4.1). The production stage had the largest contribution with 63.8%, followed by the infrastructure stage with 36.2%.

By cost category, the following five are responsible for 90.2% of the total cost as follows: (i) direct labour with 24.7%, (ii) external services with 21.8%, (iii) raw materials with 16.1%, (iv) buildings with 15.0% and (v) technical installations with 12.6% (Fig. 4.3).

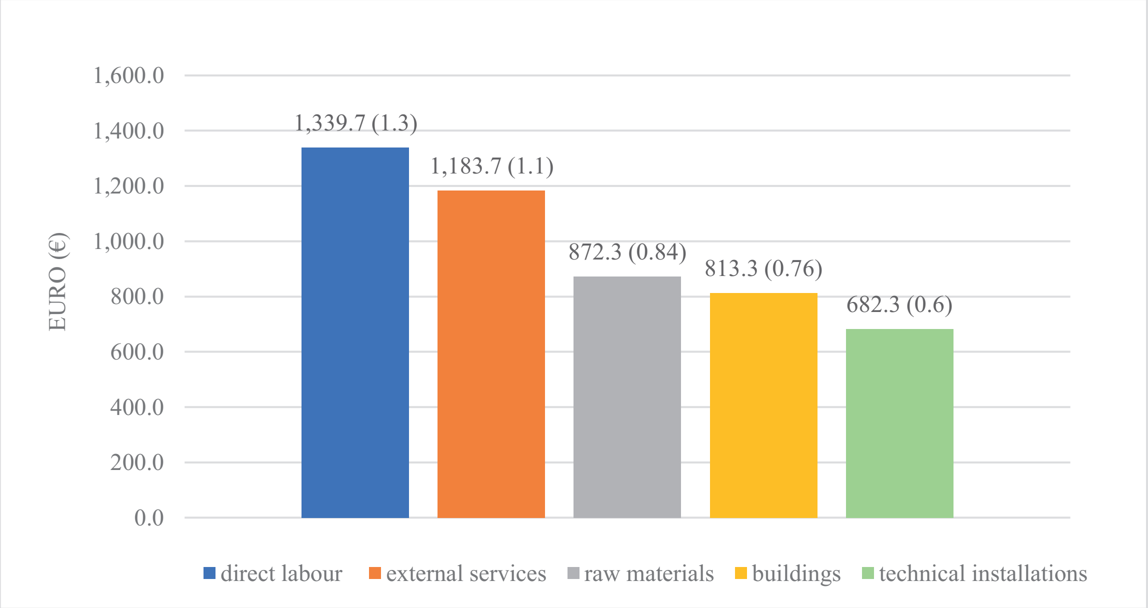


Fig. 4.3 Five main cost categories responsible for 90.2% of the total cost. Presented in €/cycle and €/kg (in parentheses)

From these five cost categories, the four main cost items (cost drivers), responsible for 61.8 % of the total cost, are discussed later: labour from direct labour, i-RTG structure from buildings, EPCS from external services, and rainwater from raw materials.

4.3.1.2. Variable and fixed costs

As mentioned in section *4.2.2.1.*, by life cycle stage all infrastructure stage costs are fixed and in the production stage almost all costs are variable with exception of two specific items: (i) the EPCS, and (ii) the PBWC. In this regard, the TFC accounts for 51.4% (2,785.3 €/2.6 €/kg) and the TVC for 48.6% (2,636.5 €; 2.5 €/kg).

From the production stage the EPCS is a fixed cost because it is a fixed annual amount for the service contract for pest control monitoring on several crops and the proportion for tomato crop was estimated at 2/3 of the total invoice. The PBWC cost is a similar case since it is the amount of the annual fee for the urban waste collection service in Cerdanyola del Vallès municipality. Nevertheless, these costs would be avoided in the future if other options were available, that is: (i) if their own staff had pest control expertise and (ii) if the pruning waste were used for compost. Regarding the fixed costs, the following six cost items are identified as having important contributions (81.7%) to the TFC: (i) i-RTG structure with 29.2%; (ii) EPCS with 24.5%; (iii) system of sensors (SS) with 9.4%; (iv) irrigation system (IS) with 8.5%, (v) PBWC with 5.1%, (vi) curtains and partitions system (CPS) with 5% (Fig. 4.4). Concerning variable costs, five cost items contribute to 90.4% of the TVC: (i) labour with 50.8%, (ii) rainwater with 19.6%, (iii) electrical energy with 7.2%, (iv) FBWM with 6.4% and (v) biological control with 6.3%. The amount as €/cycle and €/kg can be seen in Fig. 4.4.

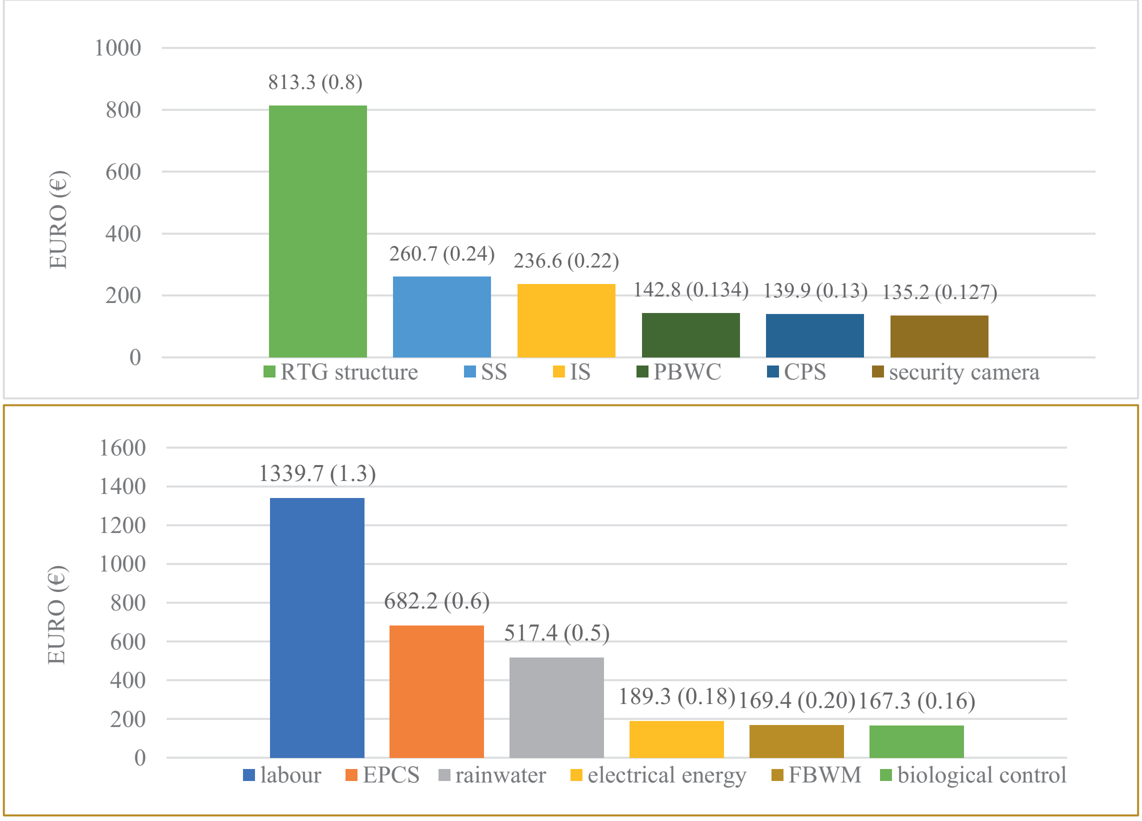


Fig. 4.4. Main variable (above) and fixed (below) cost items presented in €/cycle and €/kg (in parentheses). Acronyms: RTG (rooftop greenhouse), SS (system of sensors), IS (irrigation system), PBWC (pruning biomass waste collection), CPS (curtains and partitions system), EPCS (external pest control specialist).

4.3.1.3. Characterization of main cost drivers

The following four cost items have a key role in the TC: (i) labour; (ii) rooftop greenhouse structure; (iii) EPCS; and (iv) rainwater. Each one contributes over 9% to the TC, while their sum contribution accounts for 61.8% (Fig. 4.5). Therefore, the reduction of these costs is essential in achieving economic viability since they are the main drivers of the TC. The next sections analyse each of them in-depth and propose alternatives for cost reduction.

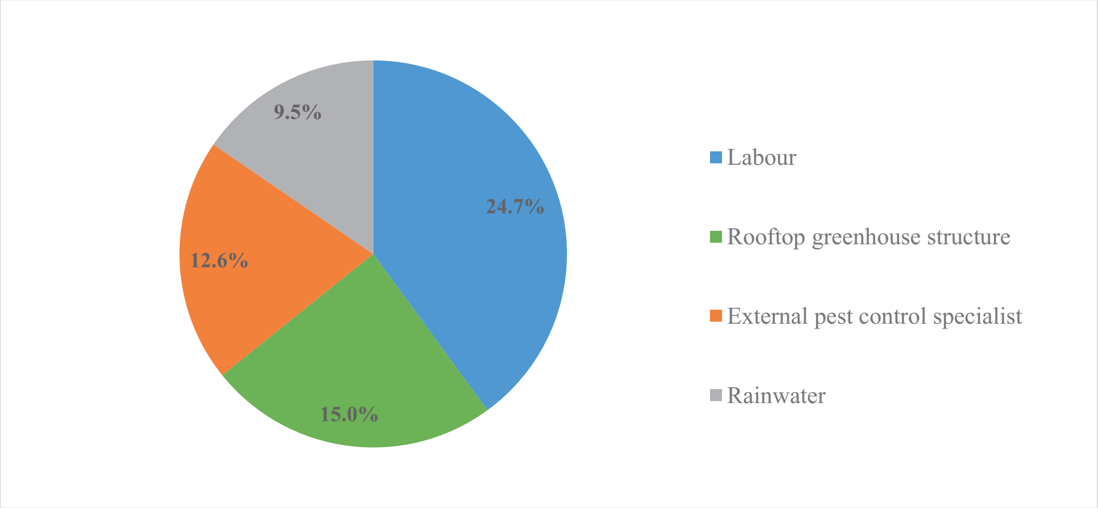


Fig. 4.5 Contribution of the four cost drivers to 61.8% of the total cost. Acronyms: RTG (rooftop greenhouse), EPCS (external pest control specialist).

I) Labour cost

Labour was the core cost driver, accounting for 50.8% of the TVC and 24.7% of the total cost. Previous research on the topic demonstrated that labour contributed to 30-45% of the total tomato production cost.

In the case studied, it was difficult to calculate the working hours as it was necessary to separate the time spent on production from the time devoted to other experimental tasks with the same tomato crop, such as nutrients recovering in Rufí-Salís et al., (2020a).

The results are consistent with other studies in the literature highlighting that labour is the main cost driver in tomato production (Çetin and Vardar, 2008; Keskin et al., 2010; Barrett et al., 2012; Taki et al., 2013; Testa et al., 2014; Sanyé-Mengual et al., 2015a; Albaladejo-García et al., 2018; Cáceres Hernández et al., 2018). The reason is that tomatoes are one of the highest labour demanding crops since it is mainly harvested by hand, probably due to the availability of cheap labour (Çetin and Vardar, 2008). This happens, for instance, in Turkey, China, and India who are among the top 10-tomato producers worldwide (Çetin and Vardar, 2008) and also applies in Spain and The Netherland, the biggest European tomato producers (Ibarrola-Rivas et al., 2020).

On the other hand, the labour cost strongly depends on the working hours required. In this regard, the working hours spent per m^2 for tomato cultivation in conventional greenhouses for industrial production in Almeria is 2.83 h/m^2 per crop (based on 1840 working hours and 650 m^2) (Cámara-Zapata et al., 2019), which is the same efficiency ratio as the artisan tomato production in the i-RTG (based on 239 working hours and 84.3 m^2). This is an important finding that makes a valuable contribution of this study to the literature on innovative rooftop greenhouse tomato production. It demonstrates that the efficiency level is the same (i) in two different tomato production systems (industrial conventional greenhouses versus innovative i-RTG) and (ii) in two different sized productions (large versus small).

There are several examples in the literature about labour reduction costs by using non-paid working hours. For instance, the use of volunteer work is one of the most commonly applied in UA projects (Liu, 2015). Another way is through the "self-pick" strategy. This strategy also called "you-pick"/"pick-your-own" is a direct marketing approach where customers do the harvest task themselves and this is a way to decrease the labour cost since harvesting consumes many working hours. (Ernst and Woods, 2014; Liu, 2015).

II) Rooftop greenhouse structure

The rooftop greenhouse structure was the second most important cost driver for artisan tomato production, contributing to 29.2% of the TFC and 15.0% of the TC. In the case studied, the i-RTG structure is an integral part of the building (Sanjuan-Delmás et al., 2018b) which is high-tech and composed of steel (0.836 kg/m^2), concrete (0.212 kg/m^2), polycarbonate (0.032 kg/m^2), low-density polyethylene (0.006 kg/m^2), polyester (0.0008 kg/m^2) and aluminium (0.0008 kg/m^2) (Sanyé-Mengual et al., 2015a).

Estimating the usual 50-year lifespan for economic amortisation of buildings, its cost was calculated to be 11.4 €/m^2/year, which was 22.6% higher than the average cost for a high-tech RTG of 9.3 €/m^2/year (calculated with the average of 329 €/m^2 and 600 €/m^2) (Ackerman, 2012 Milford et al., 2019). The higher cost in the case studied is because information on the specific rooftop greenhouse structure cost was not available, and its cost was calculated as an average cost (see 4.2.3.1). However, this cost could have been reduced if a study for optimization of construction materials had been carried out during the building design phase (Sanjuan-Delmás et al., 2018b). Moreover, the size of the studied case structure is small (artisan) with a production area of only 84.3 m^2, therefore there is a need for designing medium and large size i-RTGs to facilitate the RTG expansion in cities in the future.

Based on these considerations, future research should optimise the rooftop greenhouse structure (prototype, materials, and cost) by considering different sizes (e.g., small, medium, and large) helping to make decisions for implementing these innovative UA systems on a larger scale. Sanyé-Mengual et al., (2015a) discussed that this is a crucial condition since the rooftop greenhouse structure cost could be a possible barrier for future development.

III) External pest control specialist

The EPCS was the third main cost driver, contributing to 24.5% of the TFC and 12.6% of the TC. It was the service provided from an external specialist for monitoring the crops for signs of insects, rodents, and other pests. As mentioned in *4.2.3.2. Production costs*, this is an annual service contract with a closed price, classified as a fixed cost, and the cost assigned to the tomato crop was calculated as 2/3 of the total invoice.

This significant cost could be reduced or avoided in the future by providing specialized training on sustainable pest prevention and control to the personnel responsible for the tomato production.

IV) Rainwater cost

Rainwater was the fourth largest cost, accounting for 19.6% of the TVC and 9.5% of the total cost of the crop in 2019, where 59.5 m^3 of rainwater was consumed, that is 0.056 m^3/Kg (56 litres/Kg). As mentioned in *4.2.3.2. Production costs*, this cost was calculated as the economic amortization of the RWHS (pipes, water tank, materials). For the crop period of 7 months, it was 517.4 €, i.e., 1 m^3 of rainwater costs 8.7€. This cost is more than three-times higher than the cost of tap water, estimated at 2.5 €/m^3 based on 150.9€/cycle (Aigües de Barcelona, 2020). This large cost is due to the great capacity of the RWHS (water tank, materials used) which was designed to supply rainwater to the toilets, ornamental plants of the building and all crops in the rooftop greenhouses (Sanjuan-Delmás et al., 2018b).

In this regard, previous studies that analysed the economic performance of the rainwater harvesting installations concluded to be financially non-viable (Christian Amos et al., 2016; Gao et al., 2017; Ishida et al., 2011; Roebuck et al., 2011, 2012). However negative financial viability does not necessarily mean negative economic viability since the LCC results give economic measures, not economic decisions (Amos et al., 2018). Therefore, the economic evaluation should include wider considerations such as the definition of need, and indirect benefits shown in improved health through water, sanitation, and hygiene (Alexander et al., 2014), which have a socio-economic impact that is often complex to measure in financial terms. Benefits for the whole society may have more value than simply economic costs (Domenech and Saurí, 2011; Beatty and McLindin, 2012). For instance, these technical installations have a great potential to alleviate the increased water demand caused by urbanization (Barthwal et al., 2014) and improve the water security in urban areas (Amos et al., 2018). Hence, the rainwater capturing, and use may help to reduce both tap water consumption and the energy for water treatment and pumping, which contribute to sustainability.

Unlike tap water with which scarcity is one of the main environmental concerns (EC, 2010), rainwater is a relatively clean and abundant renewable resource, especially in the Mediterranean area. For instance, it has been forecasted that on average in 2051, tap water availability for the region of Catalonia will decrease by 17.8% and in Southern Catalonia, the decrease could be higher, 70-75% (Duran et al., 2017). Furthermore, there is an uncertainty with the price of the tap water since a report from the Catalan Water Agency indicated that in the period 2005-2015, the price of water increased by 50% (5% annual) and this tendency will continue in the following years (Vargas-Parra et al., 2019).

A previous case study explained that in a Mediterranean climate with low and variable precipitations, the use of RWHSs covered most of the water need for flushing toilets and 60% of the demand for landscape irrigation (Domènech and Saurí, 2011). Similarly, Fragkou et al., (2016) demonstrated the high potential of the Mediterranean region to supply its water needs from rainwater runoff, taking into account all urbanized areas as collectors, where the water self-sufficiency potential varies from 8% to 500% with an overall average above 100% for the regional system.

4.3.1. Sensitivity analysis

4.3.1.1. Rooftop greenhouse structure

The potential variability in the results was analysed by comparing the structure of the case studied to three structural systems suitable to be placed on the roof (RF structure hereafter): (i) intensive green roof for open-air farming (Benis et al., 2018), (ii) medium-tech RTG (Proksch, 2017) and (ii) high-tech RTG (Proksch, 2017, Milford et al., 2019).

The intensive green roof is an uncovered structure for open-air agricultural production. The building cost per m^2 is around 130 euro/m^2 over a lifespan of 40 years or 3.3 euro/m^2/year, including (i) a waterproofing membrane and a root barrier that divide the wet layers from the underlying building rooftop; (ii) a drainage layer that facilitates the removal of excess water; (iii) a filter fabric that avoids the drainage layer from clogging; and (iv) other layers: water retention, substrate and vegetation (Benis et al., 2018). The main difference between the medium-tech and high-tech RTGs is in the construction materials (Proksch, 2017). For instance, the medium-tech greenhouse support structure has a steel frame, and the covering materials are double PE or rigid plastic. While the high-tech support structure has a steel or aluminium frame and the covering materials are more durable such glass and polycarbonate, which is the case of the studied case.

The cost of a conventional medium-tech greenhouse varies from 26 to 88 €/m^2 ($30-100) depending on the used materials and the cost of high-tech greenhouses, both on the ground, are from 126 to 252 ($150-300) depending on materials, climate control, ventilation (Proksch, 2017). But placed on the roof, their costs can increase up to three times (Milford et al., 2019). Hence, the average cost of building medium-tech RTGs varies from 171€/m^2 to 378€/m^2, while for high-tech RTGs from 329 to 426 €/m^2 ($375–485). However, in 2019, it was estimated that a high-tech RTG covered by glass could reach 600 €/m^2. The lifespan was considered to be 50 years by Sanyé-Mengual et al., (2015a) and Benis et al., (2018) due to the concrete structure. Since the cost of greenhouse structures can vary across countries (Harada and Whitlow, 2020; Proksch, 2017), in the sensitivity analysis the average cost for a high-tech structure of 465 euro/m^2 or 9.3 €/m^2/year from a cost rank of 329 €/m^2 to 600 €/m^2 was used. In comparison, the cost of the studied i-RTG structure was 570 €/m^2. The cost of each mentioned rooftop farming (RF) structure can be seen in Appendix 1.5 and in Table 4.2 (here in €/m^2/year).

Table 4.2 presents the results of the sensitivity analysis from replacing the studied case structure cost (Scenario 0) with the cost of (i) an intensive roof for open-air cultivation (Scenario 1); (ii) a medium-tech RTG (Scenario 2) and (iii) an average high-tech RTG (Scenario 3). For Scenario 1 and Scenario 2, a lifespan of 40 years was considered since this structure is made of less resistant materials than the high-tech RTG.

Table 4.2 Life cycle cost variation by using alternative types of RF structure

Scenario	Lifespan	RF structure cost (€/m^2/year)	Tomato total cost (€/cycle)	Tomato cost per kg (€/kg)	Variation (Scenario $_{1,2,3}$ - Scenario $_0$)		
					Tomato total cost (€/cycle)	Tomato cost per kg (€/kg)	%
***Scenario 1:** Intensive roof for open-air cultivation*	40	3.3	4,843.6 €	4.5	-578.2	-0.54	-11.9
***Scenario 2:** Medium-tech RTG*	40	4.3	4,914.8 €	4.6	-506.9	-0.47	-10.9
***Scenario 3**: High-tech RTG*	50	9.3	5,271.1 €	4.9	-150.7	-0.14	-2.9
***Scenario 0**: Baseline*	50	11.4	5,421.8 €	5.1			

The results revealed that the most notable cost reductions in the total tomato cost and the tomato cost per kg were very similar for the two simplest structures with 11.9% in Scenario 1 (reduction of 578.2 €/cycle; 0.54 €/kg) and 10.9% (reduction of 506.9 €/cycle; 0.47 €/kg) in Scenario 2. While by comparing the case studied structure cost (Scenario 0) with the average cost of the same high-tech structure in Scenario 3, only a small decrease of 2.9 % (150.7€/cycle; 0.14 €/kg) in the total cost and the cost per kg was noticed. Hence, the sensitivity analysis supported that the structure of the case studied is high-tech RTG and supports the recommendation of Sanjuan-Delmás et al., (2018b) that the structure cost could be reduced in future research if an optimization study of construction materials were carried out during the building design phase.

4.3.1.2. Rainwater cost

As has been mentioned in *IV) Rainwater cost*, this cost was calculated as the economic amortization of the RWHS (ICTA-UAB). The rainwater tank had a considerable capacity of 100 m^3, used to supply toilets, ornamental plants, and all rooftop crops in the building (Sanjuan-Delmás et al., 2018b). The rainwater tank cost was 6,800€ which disproportionately increased the RWHS (ICTA-UAB) cost. Nevertheless, it was estimated that a 20 m^3 tank (this is a fifth part) would be enough for 90% of rainwater needed for the crop irrigation (Sanjuan-Delmás et al., 2018b).

Therefore, here the sensibility assessment (Table 4.3) was carried out to estimate the costs variations (total cost and cost per kg) by replacing: (i) the use of rainwater with tap water and (ii) the rainwater tank capacity with a smaller one, i.e., 20 m^3 instead of 100 m^3 as Sanjuan-Delmás et al., (2018b) proposed.

Table 4.3 Life cycle cost variation by using tap water and 20 m3 water tank

			Variation (Scenario $_{1,2}$ - Scenario 0)		
	Tomato total cost (€/cycle)	**Tomato cost per Kg (€/kg)**	**Tomato total cost (€/cycle)**	**Tomato cost per Kg (€/kg)**	**%**
Scenario 1: Tap water	5,055.3	4.7	-366.5	-0.3	-6.8
Scenario 2: Small rainwater tank (20 m^3)	5,372.0	5.0	-49.8	-0.1	-0.9
Scenario 0: Baseline rainwater & big water tank (100 m^3)	5,421.8	5.1			

Cost data from the Barcelona water supplier website (Aigües de Barcelona, 2020) and online supplier were used to estimate the tap water cost and the cost of the 20 m^3 water tank.

If tap water was used for irrigation, the cost would be 150.9 € or 70.8% less than using rainwater (517.4 €), while the reduction in the total tomato production cost is 366.5 € or 6.8% (Scenario 1). However, although the cost of consuming rainwater is higher in comparison to tap water, the use of rainwater can bring significant environmental, economic, and social benefits. Environmentally, rainwater harvesting on the roof can reduce the impact of storm water runoff in the area, which can otherwise damage creeks and other diversity of species. Additionally, it was demonstrated that the construction of RWHS combined with food production is associated with low environmental impacts (Toboso-Chavero et al., 2019). Economically, rainwater use can contribute to saving money on water bills by storing water in an economic way. For instance, in some areas, local councils have introduced cash-back refund plans for those who install a rainwater tank. In this regard, rainwater use for irrigation could be beneficial in the following years due to the uncertainty of the future price of supply water (Amos et al., 2018). Finally, there are expected social benefits related to health issues and personal preferences. For example, some people prefer to consume rainwater since there are no added chemicals that are used to treat mains water supply. Moreover, rainwater is a suitable option in some areas where water is salty and scarce, contains heavy metals or has an unpleasant odour (Rain Harvesting, 2021).

Regarding the size of the rainwater tank, if 20 m^3 were used, the cost of the rainwater tank would be reduced from 6,800 € (100 m^3) to 2,530 € (20 m^3) or 62.8% less which supposes a decrease of 49.8 € in the total tomato production cost or 0.9%. Therefore, the substitution with a smaller rainwater tank could be a viable option.

4.3.2. Production level output

The production level output is an important aspect affecting the economic viability and profitability of any economic activity. For this reason, has been calculated for the tomatoes production of the studied case by adding an additional BEP analysis. The BEP is the level of production to be sold that completely covers the TFC. At this level the company has no losses. From this level, every additional unit sold contributes to generate profit. The BEP is very useful in knowing the number of units to be sold so as not to have losses from the production activity (Gutierrez and Dalsted, 2012). A BEP analysis is performed in this section (Equation 4).

$$Break\ even\ point\ (in\ units) = \frac{(Fixed\ costs)}{(SP - VC)} \quad (4)$$

Where SP=selling price per unit, VC= variable cost per unit

The current average market price is between 3.0 €-4.0 € for 1 kg of tomatoes Coeur de boeuf with VAT included (4% in Spain). The analysis assumes that 1 kg consists of 5 tomatoes (number of physical units) which was the average for two consecutive crops (2018 and 2019) and that all produced tomatoes would be commercialized without discriminating their size.

The complete table of results of the BEP analysis can be seen in Appendix 1.6. Prices between 3.0 € and 5.0 € are not suitable for the studied case because the BEP is above the i-RTG productive capacity (the production average was 5,415 units in 2018 and 2019 crops). Hence, price range to be used it 5.1 € to 5.5 € for the productive area of 84.3 m^2 with a total fixed cost of 2,785.3 € and variable cost per unit of 0.49 €. But in the authors' opinion, this range of prices would be too high for the local market. The reasons for the high selling prices of 1 kg of tomatoes are the elevated fixed costs (rooftop greenhouse structure) and the small cultivation area (84.3 m^2) which limits the productive capacity.

The BEP equation can be applied here to determine the maximum level of fixed cost for a specific production area size, which includes the production output, and specific unitary variable cost. In this regard, the maximum level of fixed cost is calculated at selling between 3.0 €-5.0 € to find how much the fixed costs have to decrease in order to establish selling prices below 5.0 €. For the studied case: a productive area of 84.3 m2 with an average production output of 5,415 units (for two consecutive years), and variable unitary cost of 0.49 €.

The complete table of results can be seen in Appendix 1.7. Selling prices between 3.00 € and 3.6€ are discarded since their average fixed costs would be 920.6 € meaning that they must decrease by 1,864.7€ or 66.9% comparing with the current fixed cost of 2,785.3 €, which is hard to achieve. At selling prices between 3.7 € - 4.3 €, the average fixed cost would be 1,678.7 €, hence a large reduction of 39.7% on average must be made to achieve it. Finally, at the selling price range from 4.4 € to 5.0 €, the average fixed costs would be 2,436.8 € and must decrease by 12.5% on average, which seems feasible with the optimization of the rooftop greenhouse structure and the technical installations in future research. For instance, this can be possible by using reduced, recycled, or less costly materials.

Lastly, previous studies that analysed the economic potential of the RTGs through LCC demonstrated that for some agriculture practices such as hydroponics, the unitary economic cost strongly depended on the yield size (Sanyé-Mengual et al. 2015a; Benis et al., 2018; Weidner et al., 2019). For instance, Sanyé-Mengual et al. (2015a) found that local tomatoes grown in small yield RTGs have higher unitary economic costs than those produced via conventional large-scale production. In contrast, tomatoes grown in local RTGs with high crop yield size >25 kg/m^2 have not only a lower unitary economic cost but also at the same time have better environmental characteristics. In this regard, it was estimated that to achieve higher economic and environmental performance, the i-RTGs require an annual tomato crop yield of 55 kg/m^2 (Sanyé-Mengual et al., 2015a). While in Benis et al., (2018), the recommended yield size for this purpose was calculated to be approximately 70 kg/m^2. In the case of the 2019 i-RTG tomato crop, the yield was 12.66 kg/m^2, considerably lower than required.

For a specific production size, based on the BEP analysis and the previous research, it could be concluded that it is crucial to optimize fixed costs, otherwise it would be necessary to sell the products at a high price that allows to cover all these costs. For instance, it might be possible by using reduced, recycled, or less costly materials of the rooftop greenhouse structure.

4.3.3. Environmental and social aspect of i-RTGs

Unlike the non-integrated RTGs and conventional greenhouses on the ground, i-RTGs have demonstrated better environmental (Sanyé-Mengual et al., 2018b; Sanjuan-Delmás et al., 2018a). For instance, Sanyé-Mengual et al., (2018b) demonstrated that i-RTGs environmental savings were 2.1 times for avoided CO_2 emissions and 1.8 for energy consumption by comparing the differences between non-integrated RTGs and i-RTGs in retail parks. In comparison with conventional greenhouses, i-RTGs have between a 50 and 75% lower impact on five of six impact categories. Specifically, the environmental savings of i-RTG artisan tomato production were 0.58 kg of CO_2 equivalent per kg versus 1.7 kg of CO_2 from conventional greenhouses (Sanjuan-Delmás et al., 2018a).

Moreover, the role of i-RTGs to improve energy efficiency in buildings was analysed in Nadal et al., (2017). They found that i-RTGs could recycle 43.78 MWh of thermal energy (or 341.93 kWh/m2/yr) from buildings and that compared to the conventional greenhouse, heated with oil, gas, or biomass systems, i-RTGs can also achieve greater annual carbon and economic savings as follows: (i) 113.8 kg CO_2(eq)/m^2/yr and 19.63 €/m^2/yr compared to oil heated; (ii) 82.4 kg CO2(eq)/m^2/yr and 15.88 €/m^2/yr compared to gas heated, and (iii) 5.5 kg CO_2(eq)/m2/yr and 17.33 €/m^2/yr compared to biomass heated.

Later, Muñoz-Liesa et al., (2020) quantified the bi-directional energy exchange between greenhouses and buildings. Together with Nadal et al., (2017), they demonstrated that 98 kWh/m2/year of heating energy is passively recovered (84% during night-time) by i-RTGs from building waste heat. As well as that, the energy savings of the building are 35 kWh/m^2/year (equal to 4% of the building's annual electricity needs) thanks to the insulating capacity of i-RTGs. This results in an overall 128 kWh/m^2 of annual net energy savings equivalent to 45.6 kg CO_2 eq/m^2, considering 5 kWh/m^2/year are required to operate the building climate system that enables the bi-directional (greenhouse-building) thermal exchange.

Regarding social sustainability, UA activity has been demonstrated to have positive contributions in different aspects: (i) better food and nutrition security, (ii) health improvement, (iii) establishment of jobs for the urban poor; and (iv) inclusion of disadvantaged people or social (Orsini et al., 2013). However, the construction of building-based UA forms such as rooftop farms (open-air) and rooftop greenhouses can be associated with additional social benefits such as improved customer awareness about the origin of the food (Specht et al., 2014; Sanyé-Mengual et al., 2016), improved community building (Sanyé-Mengual et al., 2016), educational benefits (Kortright & Wakefield, 2010; Specht et al., 2015), transparency and creation of new experimental spaces (Specht et al., 2014).

If integrating greenhouses into buildings for UA would have positive impacts as foment food self-sufficiency policies or energy/water-saving policies in the short term (Cerón-Palma et al., 2012), special attention needs to be devoted to the great opportunity for environmental education of building-based UA because of its possible effects in the longer run.

Nowadays the interest in analysing social aspects of UA in rooftop greenhouses, as a necessary component of this activity is growing. In this regard, it is worth to mention the ongoing project GROOF-Greenhouses to reduce CO2 on rooftops, aimed to define the state of the art of the building integrated greenhouse for a more resilient built environment, which includes the analysis of their social performance, but results are not available yet (GROOF, 2022).

Finally, UA products are mostly associated with positive customer perceptions (Ercilla-Montserrat et al., 2019; Grebitus et al., 2020) but the high price is a big barrier for posterior purchase intentions (Grebitus et al., 2017). Nonetheless, customers tend to pay a premium price for locally grown products (Willis et al., 2016, Boys et al., 2014) since they assume that they are fresher, of higher quality and better tasting. Additionally, local production can also benefit de local community enhancing the local economy and benefit the environment at the same time (McGarry-Wolf et al., 2005; Zepeda and Leviten-Reid, 2004) (See Addendum A to Chapter 4).

4.4. Conclusions

This paper analysed the economic viability of an artisan tomato production in the rooftop of an innovative building with an integrated urban agriculture system. LCC was applied to quantify its total cost by life cycle stage, by cost category and by fixed and variable cost, identifying the main cost drivers, proposing cost reduction alternatives, using sensitivity scenarios, and including the production level output calculations, as a relevant factor for the economic viability and profitability. As far as the authors are aware, this is the first study analysing the life cycle economic viability of tomato production in i-RTGs including essential costs such as labour and infrastructure, which tend to be missing in research on UA. The results are valuable for public administrations or investors with ability to promote policies or funding for the implementation of economically and environmentally sustainable food production in cities. It also contributes to the UA literature by improving academic knowledge on the economic performance of alternative production systems for further sustainability-oriented research on the topic.

The results indicated that the production stage had a major contribution to the TC and five cost categories (direct labour, external services, raw materials, buildings, and technical installations) account for 90.2% of it. The main cost drivers are labour, rooftop greenhouse structure, EPCS and rainwater, determining nearly 62% of the TC. Thus, the reduction of these costs is an essential requirement to achieve economic viability.

An important finding that makes a valuable contribution to the literature on innovative rooftop greenhouse tomato production is that there was the same efficiency in the main cost driver, labour (hours spent per m^2) both (i) in two different tomato production systems (conventional greenhouses versus innovative i-RTG) and (ii) in two different size productions (large versus small).

The managerial implications derived from findings to facilitate the economic viability and contribute to the implementation of i-RTG production are derived from (i) the reduction strategies of cost drivers and (ii) to stablish the adequate production level output. Respecting the reduction of cost drivers (labour, rooftop greenhouse structure, EPCS and rainwater cost), labour and rooftop greenhouse structure are crucial. As the core cost driver (50.8% of TVC and 24.7% of TC) considered strategies for labour cost reduction were: (i) use of volunteer work and (ii) customers' participation in harvest task. In regard to the second cost driver, the rooftop greenhouse structure, that could be a possible barrier for implementing these innovative UA systems on a large scale (Sanyé-Mengual et al., 2015a) it is a key condition to reduce its cost optimising prototypes, materials, and sizes (e.g., small, medium and large) to allow making decisions for this initial investment. Regarding the third and fourth cost drivers, the EPCS could be reduced or avoided if staff training was provided, and the rainwater cost could be decreased by optimising the rainwater tank size according to the productive area. Last, the size of production area is relevant for the role of production level output. As break-even point demonstrated, high fixed costs and low yields is a combination that impede the economic viability and profitability of i-RTG artisan production.

This study has several constraints: (i) the costs at EoL stage were not included; (ii) it was carried out in a Mediterranean climatic zone with a mild and hot climate and no abundant rains; and (iii) the economic costs of additional innovative technical installations (e.g., water recycling system), used to reduce environmental impacts, which could increase the total costs were not considered since they were still in construction during the analysed period.

Based on these restrictions, future research should: (i) perform more complete LCC by including costs at the maintenance stage, if they were significant, and at the EoL stage with the cost of decommissioning the greenhouse structure; (ii) optimise the rooftop greenhouse structure and the rainwater harvesting systems (design, materials and cost) for different sizes (e.g., small, medium and large); (iii) consider cold climatic zones for analysis since some costs such as energy for heating to guarantee an adequate temperature for plants could be bigger; and (iv) include the economic costs of innovative technical installations (e.g., water recycling system and other future systems) used to reduce impacts on environment. Furthermore, for a fuller LCC, the external environmental cost should also be considered in future research.

Overall, future research should develop sustainable business models for the rooftop greenhouse food production, boosting the integration between building and rooftop greenhouse which should contribute to economic cost reductions and improved environmental and social impacts. For instance, this could be done by selecting appropriate business models to reduce main cost drivers and environmental impacts by providing complementary services which provide notable social benefits (e.g., recreation events, gastronomy, education, therapeutic services, health care, etc.) and contribute at the same time to obtain additional revenues (See Addendum B to Chapter 4).

Finally, rooftop greenhouse food production could also be analysed from another perspective different from a profitable activity for trade. The promotion of food production in rooftop greenhouses could be convenient for self-sufficiency in urban areas, in line with the promotion that energy production for the self-sufficiency is being strongly encouraged by all levels of public administrations. In this regard, research on the social aspects of UA in rooftop greenhouses could contribute to its development.

Addendum to Chapter 4

A: Customer preferences

B: Business models

This Addendum is based on Appendix A of the Supplementary data of the published document:

Peña, A., Rovira-Val, M. R., & Mendoza, J. M. F., (2022). *Life cycle cost analysis of tomato production in innovative urban agriculture systems*. Journal of Cleaner Production, 133037. https://doi.org/10.1016/j.jclepro.2022.133037

A. Customer preferences

The customer preferences towards organic or local food products have been notably increasing in the last decade (Jefferson-Moore et al., 2014), due to environmental and health concerns such pollution (air and water) and unsustainable use of nutrients and pesticides (Grebitus et al., 2020). In this regard, UA has a strong potential to provide them with local and nutritious food. On the other hand, there are many examples where UA initiatives were started with the aim to reduce the impact on the environment, for instance the re-use of nutrients (Rufí-Salís et al., 2020a, 2020b).

Traditionally, customer preferences for food have been based on two factors: price and quality (Pardillo Baez et al., 2020) but recently, other factors associated with perceived public benefits such as sustainability have been increasingly influencing purchasing decisions (Gracia et al., 2012). This is mainly due to growing awareness of environmental, ethical and social problems as a consequence of unsustainable production and consumption practices (Sidali et al., 2016; Verain et al. 2015; Reisch et al. 2013). As a result, customers´ preferences for local, organic, and seasonal food have increased (Feldmann and Hamm, 2015; Gracia et al.,2012; Levidow and Psarikidou, 2011), based on social welfare such as environmental quality improvement, public health, social efficiency and reduction in food miles (Berg and Preston, 2017). Hence, local food is highly promoted (Horst et al., 2016). In this regard, UA offers direct access to local food (Grebitus et al., 2017), contributing in this way to the creation of sustainable food systems (Ackerman et al., 2014).

UA products are mostly associated with positive customer perceptions (Ercilla-Montserrat et al., 2019; Grebitus et al., 2020) but the high price is an big barrier for posterior purchase intentions (Grebitus et al., 2020). Nonetheless, customers tend to pay a premium price for locally grown products (Willis et al., 2016, Boys et al., 2014) since they assume that they are fresher, of higher quality and better tasting. Additionally, local production can also enhance the local economy and benefit the environment (McGarry-Wolf et al., 2005; Zepeda and Leviten-Reid, 2004).

The willingness to pay a higher price for the tomatoes produced in the i-RTG (ICTA-UAB) was also demonstrated by Ercilla-Montserrat et al., (2019), where the tomatoes were perceived to be more environmentally friendly than those available on the market. This variety of tomato, Coeur-de-bouef, stands out because of the size of its pieces, which can reach up to 500 g (OCU, 2018). The selling price per kg on conventional markets is between 3.0€/kg - 4.0€/kg VAT included (La botiga, 2020) with 2.95 €/kg (OCU, 2018) being the average. However, the results of this research indicated that the cost per kg is 5.1€ VAT excluded, which is notably higher. This may impede preferences towards purchase since previous research reveals that customers tend to pay a small premium price for sustainable UA products (Onozaka and Mcfadden, 2011). Nonetheless, as indicated in sections 3.1.3.2. and 3.1.3.4., the tomato production cost could be reduced by optimizing the cost of the infrastructure (fixed costs) and the cost of the consumed rainwater (variable costs).

On the other side, urban air pollution and unsustainable use of nutrients are also key factors that negatively influence customer preferences towards sustainable UA products (Grebitus et al., 2020). Two important studies on air quality and recycling nutrients (sustainable use) were carried out for the i-RTG (ICTA-UAB), contributing to the alleviation of these problems. The first study concluded that the air in Barcelona city was not a source of contamination for urban crops since the concentration of heavy metals was low (Ercilla-Montserrat et al., 2018). While the results of the second study showed that by applying closed-loop systems in an i-RTG, 40% of irrigation water and between 35 and 54% of nutrients can be saved daily (Rufí-Salís et al., 2020b). Unfortunately, the cost of recycling water and nutrients was not included in the LCC calculation as during the analysed crop period (the year 2019), this experimental system was under construction. For future studies, we recommend including the economic cost of this recycling system as well as the costs of other future systems used to reduce environmental impacts. This would be essential to analyse the full potential of the i-RTG to produce organic, sustainable, and clean production.

Based on the mentioned studies, it can be concluded that the i-RTGs have the great potential to satisfy the customers' expectations for sustainable food which includes their willingness to pay a premium price.

This Addendum is based on Appendix A of the Supplementary data of the published document:

Peña, A., Rovira-Val, M. R., & Mendoza, J. M. F., (2022). *Life cycle cost analysis of tomato production in innovative urban agriculture systems*. Journal of Cleaner Production, 133037. https://doi.org/10.1016/j.jclepro.2022.133037

B. Business models

BMIs refers to the process of inventing and conceiving new forms of making business which goes beyond simple re-design and single optimization of products, technologies, processes, and existing practices (Chesbrough, 2007). In this regard, the BMIs are associated with the implementation of new mechanisms for offering, creating, delivering, and capturing value that can be used as a vehicle to re-conceptualize the purpose of the organization and improve its performance (Osterwalder and Pigneur, 2010). In fact, BMIs can deliver up to four times greater benefits than product or process improvements, including more sustainable returns over time (Lindgardt et al., 2009). Hence, a growing number of companies are taking advantage of the BMIs as a source of competitive advantage and a driver for corporate transformation and renewal (Amit and Zott. 2012).

According to Lynch et al. (2013), UA can be a driver for local economies and also contributes to the establishment of new business models, understood as the process by which a company puts a strategy into practice (Zott et al., 2010; Osterwalder and Pigneur, 2010).

The most common business models of UA can be summarized in three categories: i) low-cost specialisation, ii) differentiation and iii) diversification (Van der Schans, 2010; Pölling et al., 2017). Low-cost specialisation aims to expand the business through specialisation and economies of scale (Van der Shans, 2010). Differentiation is based on creating distinctions in production and marketing by integrating (parts of) the added-value chain on-farm. It is mainly associated with short supply chains with one or very few intermediaries (restaurants, other farm shops, canteens, etc), personal producer-consumer relationships, transparency, and authenticity (Pölling et al., 2017). Lastly, diversification in production as well as in services offers a wide variety of additional services related or close to agricultural production such as (i) agro-tourism (recreational events, gastronomy, accommodation); (ii) social services (education, therapeutic services, healthcare) and (iii) other services of a public and private nature (maintenance, road cleaning in winter) (Heimlich and Barnard 1992; Beauchesne and Bryant 1999; Bailey et al., 2000; Zasada 2011).

Within the three typical business models for UA, diversification is gaining more popularity (Pölling and Mergenthaler, 2017; Torquati et al., 2018; Pölling et al., 2017;

Recasens et al., 2016) because it’s easily adapted to urban conditions (Pölling et al., 2017). Moreover, compared to low-cost specialisation, diversification is not only driven by economic purposes since it also creates environmental and social values (Recasens et al., 2016). For instance, Social farming also named Green Care or Care Farming that integrates agricultural production with healthcare or social services for people with special needs is a common strategy of the diversified urban farms (Pölling et al., 2016). In this regard, diversified business models can lead to the development of SBMs where positive value for all stakeholders, including the society and the environment, is pursued (Evans et al., 2017).

Because of the transformative potential of UA to enhance the sustainability of urban food systems and cities, the development of SBMs for UA can contribute to overcoming the limitations related to higher production costs as additional value is offered and delivered to a wide number of stakeholders (Opitz et al., 2016; Sanyé-Mengual et al., 2017; Specht et al., 2014).

Since the balance between expenditure and profits is a key element of each business model (Osterwalder and Pigneur, 2010), the development of SBMs for UA can contribute to cost reductions without increasing the impact on the environment and/or society. For instance, by using renewable sources (low environmental impact), the reduction of large variable costs such as heating and electricity can be expected (Yang et al., 2010). Other examples are: (i) resource sharing for different activities (e.g., agricultural production, leisure activities, education, etc.) that leads to the decrease of fixed costs (Van der Schans, 2016) and labour costs; and (ii) offering training packages on sustainable production and consumption which have a positive social impact and economic profit (Food from the sky, 2021). In this way, future research should develop SBM for the studied case. For instance, this could be done by selecting the most suitable SBM archetype based on the classification of Bocken et al., (2014).

PART 4: CHARACTERISATION AND CATEGORISATION OF SUSTAINABLE BUSNESS MODELS FOR URBAN AGRICULTURE

Chapter 5

Sustainable business models archetypes for urban agriculture: characterisation categorisation, characterisation, and potential impact on the SDGs 2030.

Picture: Sustainable development goal. Source: Adobe Stock, copyright free

Chapter 5 Sustainable business models archetypes for urban agriculture: categorisation, characterisation, and potential impact on the SDGs 2030

Abstract

The implementation of urban agriculture (UA) practices is acknowledged as an instrumental strategy for alleviating fresh food security challenges due to urban growth. Nevertheless, the high investment costs for some urban agriculture systems (e.g., urban agri-food roofs) limit their current implementation in the cities. The development of sustainable business models (SBMs) for UA can help to overcome implementation cost limitations by delivering value to a wider number of stakeholders. However, categorizations, taxonomies or archetypes are required to support decision-making processes in the design, implementation and upscaling of UA-SBMs, which is a topic that has been poorly analysed in the available literature. Building upon a systematic analysis of academic and grey literature, this paper provides aa categorisation of 11 UA-SBMs. Each UA-SBM is characterised according to their value proposition, value creation and delivery and value capture. Possible limitations/negative-side effects are also included in the result section. Likewise, each UA-SBM is analysed against the Sustainable Development Goal to determine the potential (positive and/or negative) sustainability impacts. Finally, the UA-SBM categorisation system is validated through its application to a real-life case study (building-integrated rooftop greenhouse system).

Building upon the findings four main conclusions and recommendations for future research can be drawn: i) four archetypes (“Waste-based solution & reuse”, “Maximise the resource use”, “Adopt a stewardship role”, and “Repurpose for society and environment”) should be necessarily considered for future analysis and development of UA-SBMs since their major presence in the analysed cases (57% from the total 54 analysed references) and increased sustainable potential; ii) the selection and application of UA-SBM archetypes depends on each individual case however a previous exhaustive study should be carry out to evaluate more exactly the selection; iii) combining different UA-SBM archetypes can reinforce their sustainable potential and can help overcoming the limitations of the implementation of each individual archetypes; and iv) future research should focus on the quantification and validation of the sustainable benefits associated with each UA-SBM to reinforce the results of this study.

Moreover, these archetypes can contribute to building up innovative UA-SBMs to be useful not only to attract local government investors to make decisions about the implementation of sustainable UA systems at large scale but also to motivate change towards the UA restrictions in some cities.

Keywords:
Bioeconomy, Food, Self-sufficiency, Sustainable cities, Urban food production, Vertical farming.

5.1. Introduction

Today over half of the global population lives in urban areas (UNFPA, 2007) and this share is expected to reach 68% by 2050 (UN DESA, 2018). However, unplanned urban growth can lead to negative consequences, such as waste accumulation, atmospheric pollution, reduction in agricultural lands, and high exploitation of energy and water resources (Adhikari et al. 2009; Uttara et al., 2012). Moreover, cities are facing serious fresh food security challenges due to increased demand which compromise the production capacity of agricultural lands (FAO, 2017b). According to EMF (2019), about 80% of global food production will be consumed in urban areas by 2050.

Consequently, new agricultural practices for the production and delivery of fresh and sustainable food should be pursued to ensure urban food security within the framework of the SDGs 2030 (Nadal et al., 2015). In this regard, the implementation of urban agriculture (UA) practices, mostly related to plant cultivation, is acknowledged as an instrumental strategy for combating fresh food security challenges in urban and peri-urban areas (Maxwell et al., 1998; Orsini et al., 2013), while contributing to sustainable city development(Thomaier et al., 2015; Zasada, 2020).

Concerning urban environmental sustainability, UA can help to increase biodiversity (SDG 15), reduce water, energy and land requirements for food production (SDG12) and reduce atmospheric pollution and GHG emissions, contributing to climate change mitigation (SDG 13) (Masi et al., 2014; Van Tuijl et al., 2018). With regard to social sustainability, aside from providing fresh food, UA systems can facilitate social empowerment, drive local community development (SDG 10) and serve as vehicle for educational purposes (SDG 4) (Ehrenberg, 2008; Cockrall-King, 2012; Masi et al., 2014; Müller, 2012). Lastly, UA can improve economic sustainability (Van Tuijl et al., 2018) by (i) generating new sources of income (SDG8) (Lufa Farms, 2021), (ii) supporting innovation, research, and knowledge development (SDG9) (Harquitectes, 2015; Fertilecity, 2021), and (iii) offering recreational activities (Brooklyn Grange, 2021) (SDG3).

Despite the potential sustainability benefits provided by UA systems, the high investment costs for some alternatives (e.g., rooftop farming) due to infrastructure and life cycle management requirements, could limit their implementation in cities (Zambrano-Prado et al., 2021). Accordingly, the design and implementation of appropriate business models (BMs) is crucial to drive the deployment of cost-efficient and sustainable UA systems (Koop, 2020).

A BM represents the logic of how a company puts a strategy into practice by creating, delivering, and capturing value (Osterwalder et al., 2005). Accordingly, low-cost specialisation, differentiation, and diversification (Van der Schans, 2010) have been identified as suitable BMs to ensure the long-term profitability of UA systems under challenging urban conditions, such as increased fresh food demand, pollution, and overcrowding (Pölling et al., 2017). Among these BMs for UA, diversification is the most implemented so far (Pölling and Mergenthaler, 2017; Pölling et al., 2017) because of its higher capacity for adaption to urban conditions (Pölling et al., 2017).

Moreover, compared to low-cost specialisation, diversification BMs are not only driven by economic purposes since they combine agricultural production with social activities (e.g., assisting people with special needs) and/or environmental services (e.g., environmental protection) (Pölling et al., 2016, Recasens et al., 2016). Accordingly, diversification BMs can convey to the development of sustainable business models (SBMs) oriented to "create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organisation and its value-network create, deliver value, and capture value (i.e., create economic value) or change their value propositions" (Bocken et al., 2014, p.44). Indeed, some authors suggest that a narrow focus on profitability without paying attention to environmental and/or social aspects can limit the company's ability to achieve its economic goals (Kiron et al. 2013; Schaltegger et al. 2015). This is crucial for UA systems since developing well-designed sustainable business models (SBMs) for UA (UA-SBMs) can contribute to overcoming the high implementation costs by delivering value to a wider number of stakeholders (Opitz et al., 2016; Sanyé-Mengual et al., 2017b).

However, a common language is needed to unify the existing SBM concepts, such as product-service system (Tukker, 2004), social enterprises (Grassl, 2012) and/or circular economy BMs (Lewandowski, 2016, Heyes et al. 2018). Categorisations, taxonomies, or archetypes describing groups and configurations of SBMs have been proved successful for consolidating the current knowledge on SBMs to support BM experimentation, and ii) identifying future research gaps (Bocken et al., 2014).

Various SBMs archetypes can be found in the literature, e.g., Bocken et al. (2014), Clinton and Whisnant (2014), Lüdeke-Freund et al., (2018), Takacs et al., (2020). However, most of these archetypes have been developed to drive sustainable innovation in the manufacturing industry (e.g., Bocken et al. 2014) or the service sector (Yip and Bocken 2018). Accordingly, little attention has been placed on the development and analysis of SBM archetypes for food production and consumption (Barth et al., 2017, 2021), and particularly, for UA systems.

Despite the existence of some studies analysing SBMs for food production, such as food and beverage (Dressler & Paunović, 2019; Belyaeva et al., 2020) and agri-food (Ulvenblad et al., 2019; Barth et al., 2021), very few studies used specific categorisations to describe the corresponding SBMs (Franceschelli et al., 2018; Ulvenblad et al., 2019; Barth et al., 2021) and they are focused on specific cases, such as restaurants (Franceschelli et al., 2018) or a national food systems (Ulvenblad et al., 2019; Barth et al., 2021). This limitation also applies to UA systems, where the available on SBMs is even more scarce and mainly focused on describing urban farms with social impact (Gittins & Morland, 2021), multifunctional edible landscapes (Robinson et al., 2017), or agro-tourism enterprises (Yang et al., 2010). However, neither of these studies have categorised and/or characterised UA-SBMs. The only exceptions are the works from Schutzbank and Riseman (2013) and Senanayake et al., (2021).

Whereas Schutzbank and Riseman (2013) have categorised five UA-SBMs, their approach is limited as the authors only characterise the value delivery (e.g., sales and distribution mechanisms), and value capture mechanisms (costs and revenues), without explicitly addressing the value proposition (i.e., products/services offered) and value creation processes (e.g., key activities, resources).

Likewise, Senanayake et al., (2021) recently presented a SBM classification for the food industry that can be also applied for UA systems. However, their SBM framework is only focused on food waste management (prevention, redistribution, recovery, and recycling) without analysing other sustainability practices, including social aspects; the latter being key as social involvement is crucial to support the deployment and upscaling of SBMs (Bocken et al., 2014).

In an attempt to overcome the existing research gaps in the literature, this paper presents a comprehensive categorisation and characterisation of UA-SBMs, including their relationship with the SDGs 2030, to facilitate the deployment of more resource efficient, socially responsible, economically viable and environmentally suitable food production systems in cities. Accordingly, a list and analysis of UA-SBMs is presented in sections 5.3.1-5.3.2, followed by an analysis of their sustainable potential (sustainable benefits and relation with the SDGs) in section 5.3.3. The application of the UA-SBM categorisation as a tool to deploy UA-SBMs in cities is illustrated in section 5.3.4 with a real-life case. Finally, key conclusions and recommendations for future research are provided in sections 5.4 and 5.4, respectively.

5.2. Methodology

The research methodology applied to identify, categorise and characterise UA-SBMs archetypes comprised six major steps (Figure 5.1), including

i) Systematic literature review of the academic, grey literature, and additional databases to collect data for analysis;
ii) Data analysis to create a pre-characterisation and pre-classification of UA-SBMs;
iii) Comparison with existing SBMs categorisations (base archetypes) to verify if the pre-characterised and pre-categorised UA-SBM archetypes can fit them or if new archetypes have to be created;
iv) Content analysis for validation and creation of final list of UA-SBMs categories and configurations;
v) Analysis of the impacts of the UA-SBMs on the SDGs 2030 to evaluate their sustainable potential; and
vi) Evaluation of the application of the UA-SBMs archetypes in a real case study.

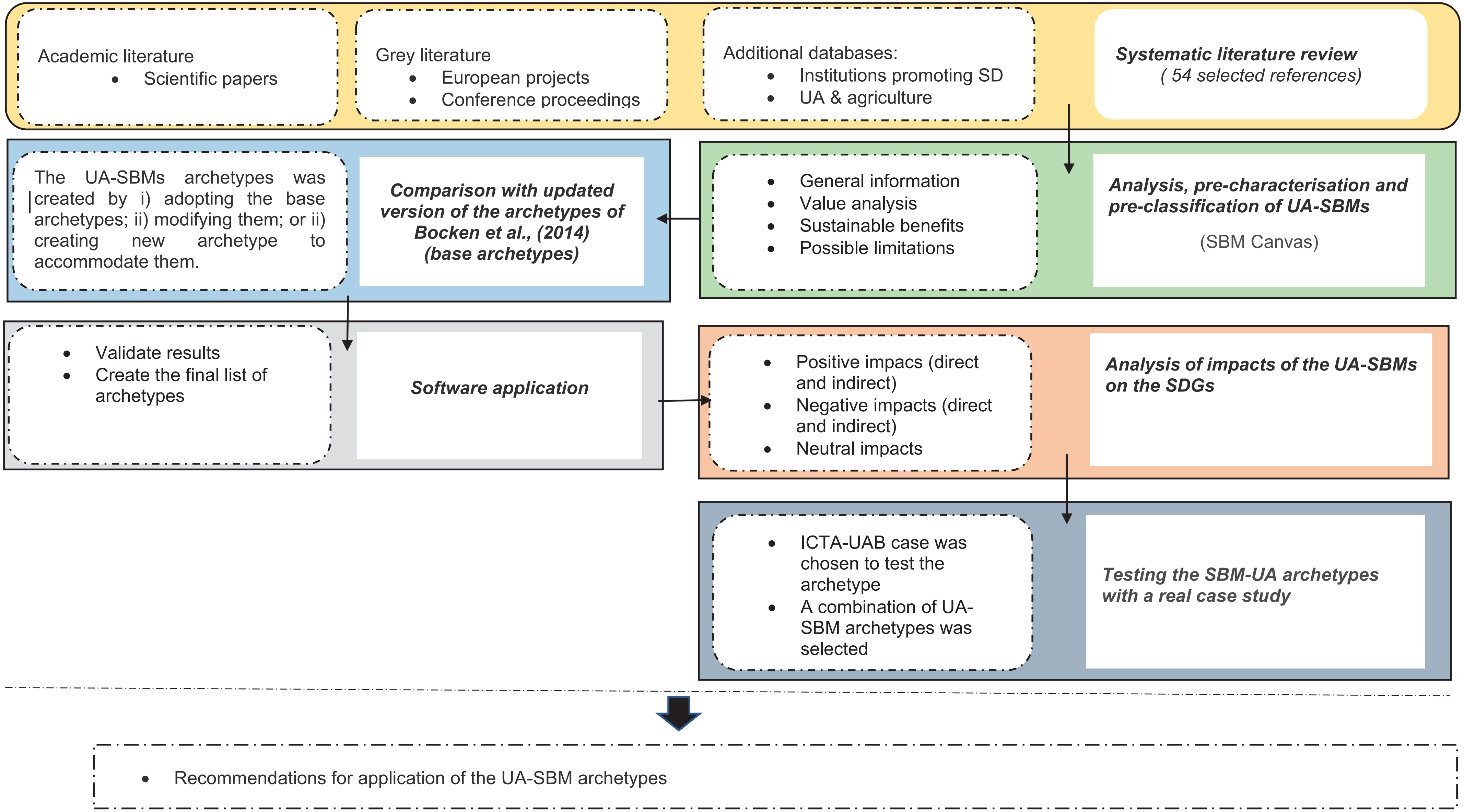


Fig. 5.1 The six-stage methodological process. Acronyms: .SD- sustainable development; UA-urban agriculture; UA-SBM-sustainable business models for urban agriculture; SDG-sustainable development goal

5.2.1. Systematic literature review on UA-SBMs

Relevant data for analysis was collected by systematically reviewing i) academic literature; ii) grey literature, and iii) databases including business cases on UA systems. As a result, 54 references containing 132 case studies of UA-SBMs were obtained from the three document searchers to categorise and characterise UA-SBMs, as illustrated in Figure 5.2. A list and a brief description of the analysed case studies is presented in Appendix 2.1, while more details are given in the next sections.

5.2.1.1. Revision of academic literature on UA-SBMs

The Scopus and Web of Science (WoS) search engines were used to identify relevant publications on UA-SBMs up to December 22, 2021, without applying any time and/or geographical restrictions. Only journal papers written in English were considered.

Three literature searches were performed by using different combinations of keywords: 1) synonyms of UA systems and BMs; 2) synonyms of UA systems and SBMs; and 3) synonyms of UA systems, BMs, and sustainability or sustainable development, as shown in Appendix 2.2.

After the elimination of duplicates and out-of-scope papers by reading the title, keywords and abstract, the number of hits obtained was 247. However, to select those useful journal papers for analysis the following inclusion criteria were set: i) papers must explicitly address the topics of UA, BMs, or urban food systems; and ii) journal papers must include description of business cases including sustainable practices, or examples of factors and drivers that contribute to building UA-SBMs. This resulted in 20 journal papers for comprehensive analysis.

The same selection criteria were also used to select additional references on UA-SBMs from the grey literature and examples of novel UA-SBMs from databases including UA/agriculture cases.

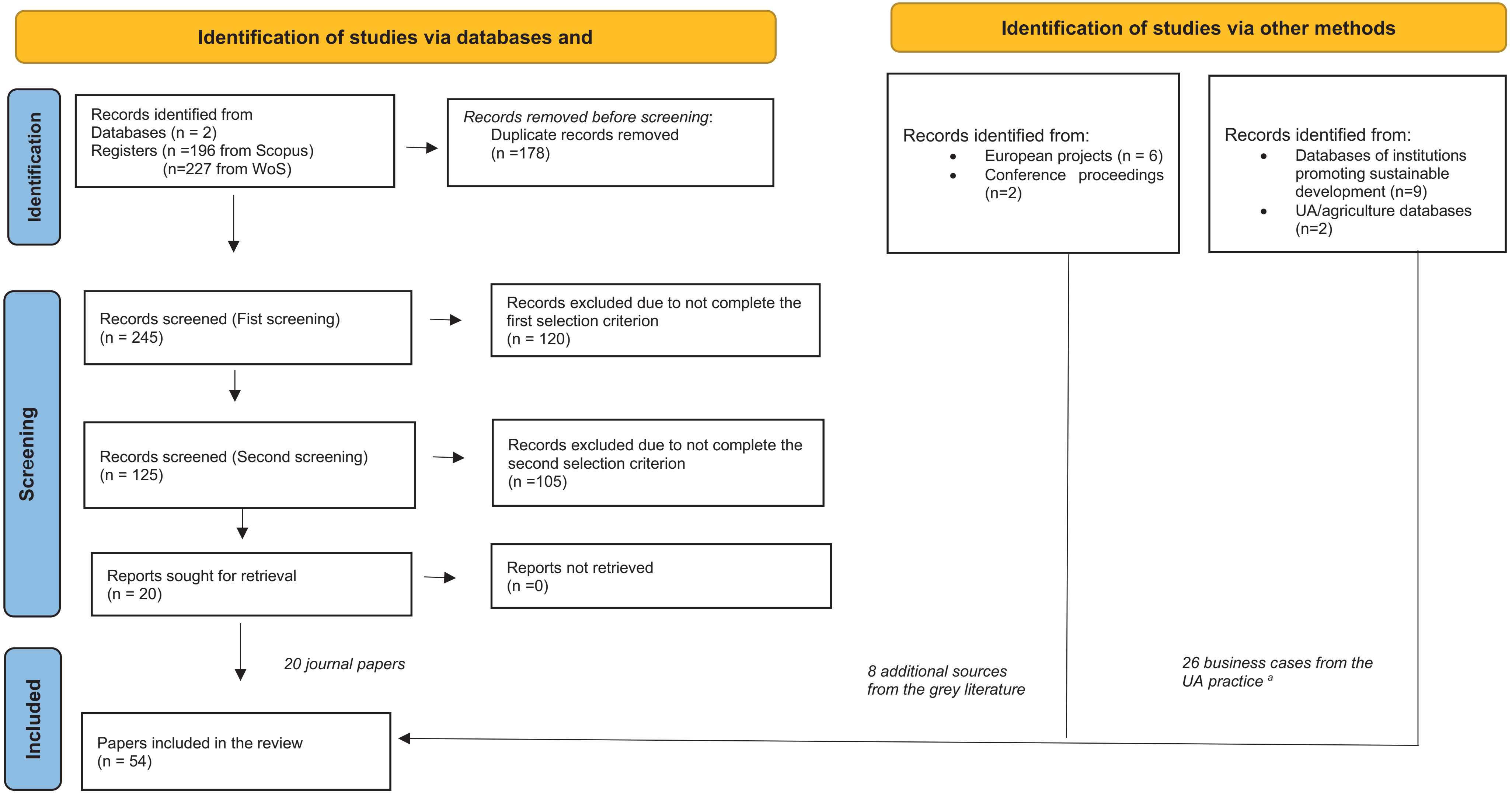


Figure 5.2 Systematic literature process and outcomes based on the PRISMA flow diagram of Page et al., (2021).

[a] Note: Some business cases were complemented with information from their company websites

5.2.1.2. Revision of grey literature on UA-SBMs

Two major sources of grey literature were revised:

(i) European projects (CORDIS, 2021; Interreg Europe, 2021, Interreg Mediterranean, 2021, Interreg PROCEFA, 2021).
(ii) Conference proceedings papers (Sanyé-Mengual et al., 2017b; Gehani, 2014).

As result, 8 additional references including 6 European projects and 2 conference proceeding papers were collected from the grey literature.

5.2.1.3 Revision of additional databases including business cases from the UA practice

Two databases were revised to collect data on novel UA-SBMs:

i) Institutions promoting SD (Ellen MacArthur Foundation, 2021; Circle-lab, 2021a, SINTRA, 2021; European circular economy stakeholder platform, 2021a, European circular economy stakeholder platform 2021a, Go Explorer, 2021; Circulator, 2021a; Circular X 2021a; State of Green, 2021a),
ii) Databases including UA and agriculture cases (City Farmer, 2021, Agroecology info pool, 2021).

From them 26 business cases containing examples of novel UA-SBMs were collected.

5.2.2. Analysis, pre-characterisation and pre-classification of UA-SBMs

The resulting 54 documents were analysed to create a pre-characterisation and pre-classification of UA-SBMs using an Excel-based template integrating four blocks:

I) General information of each analysed case: country/geographical region, type of organisation (for-profit/non-for profit), description and objective/mission
II) SBM building blocks based on Osterwalder et al., (2005) and Richardson (2008) including value proposition (product/services, customer segments and relationships), value creation & delivery (key resources, channels, partners and technology), value capture (costs & revenues)
III) Sustainable screening, involving potential environmental (planet), social (people), and economic (profit) benefits.
IV) Possible limitations to implement the UA-SBMs.

5.2.3. Comparison with existing SBMs categorisations

The results from section 2.2 were compared to the updated version of the SBMs archetypes of Bocken et al., (2014) further developed by Bocken et al., (2016) and Lüdeke-Freund et al., (2016) (further called base SBM archetypes) was used for comparison considering (i) it is one of the most completed SBM classifications, including technological, social, and organisational innovations that can contribute to building SBMs; and (ii) it was applied to categorise SBMs in various sectors (Lüdeke-Freund et al., 2018), including the agri-food industry (Ulvenblad et al., 2019).

The aim of this comparison was to check if the pre-characterisation and pre-classification of UA-SBMs can fit the base SBM archetypes or new archetypes have to be created.

Accordingly, a classification and characterisation of UA-SBMs was elaborated by i) adopting the base archetypes, ii) modifying them, or iii) establishing new archetypes based on the literature review outcomes. Regarding the new established archetypes, they were created by consulting other SBM classifications describing those classified UA-SBMs which could not meet the base archetypes. For example, the UA-SBM archetype *Subscription model* was developed by using the classifications of Takacs et al., (2020) and Lüdeke-Freund et al., (2018) which included this UA-SBM archetype.

The resulting UA-SBM archetypes were organised in three groups according to Boons & Lüdeke-Freund, (2013): i) environmental, ii) social; and iii) economic, based on the primary aim of the SBMs. For instance, the environmental UA-SBMs archetype is driven by environmental purpose, while the delivery of economic and social benefits is a secondary consequence derived from the implemented environmental innovations.

Accordingly, the environmental UA-SBMs included archetypes with the primary goal to deliver environmental benefits, frequently supported and driven by technological innovations (e.g., hydroponic system, rainwater harvest system, smart technology, food waste recycling system) (State of green, 2021b; Circle-lab, 2021c; AgFunder, 2016). The social UA-SBMs group comprised archetypes with the main goal to deliver social benefits, often in support of and motivated by social innovation addressing behaviour change. Lastly, the economic UA-SBM archetypes integrated SBMs with a focus on economic sustainability through organisational innovation, such as social enterprise, and not-for-profit organisations (Go Explorer, 2020; Rooftop Republic, 2021).

5.2.4. Content analysis for validation of the final UA-SBMs categorisation

The mining and content analysis software Wordstate 9 (Provalis Research, 2021a) was used to validate the results of the previous sections and create a final list of UA-SBMs.

The 54 selected references were introduced in the software to search for keywords that can describe the base archetypes (Appendix 2.3). Moreover, the automatically obtained software results of frequent words and phrases (containing more than 2 words) also analysed to get additional information to create final classification of UA-SBMs.

Then, a categorisation dictionary function in Wordstate 9 was used to organise into groups those keywords corresponding to the base and the newly created archetypes to create the final UA-SBMs list. The categorisation dictionary in Wordstate 9 is a hierarchical tree where words/phases are grouped in a folder that represents a category name (Provalis Research, 2021b). In this particular case, the category names corresponded to each archetype name (e.g., Adopt a stewardship form=ASR) with its associated keywords (e.g., certified organic products, heritage preservation) classified in a folder. This was useful not only for visualising the results but also for providing valuable statistics to evaluate each archetype based on its coverage in the 54 analysed references.

5.2.5. Analysis of impacts of the UA-SBMs on the SDGs 2030

The links and relationships of the resulting UA-SBMs archetypes with the SDGs 2030 (UN, 2015) were analysed by using the Sustainable Impact Assessment Tool (Chalmers, 2019) to analyse their sustainable potential. This tool employs a self-assessment of the potential impacts on the 17 SDGs and presents graphical visualization of the outputs. This tool was selected because it is free and easy to use for the identification and analysis of sustainability aspects of projects and products.

To evaluate the impact on an SDG, the relevant cause-effect relations need to be measured and described. Based on this, the relevant impact can be positive or negative and direct or indirect. However, in some cases there is not impact due to the lack of relevant cause-effect. A positive impact contributes to implement the SDG a negative impact can neutralise its implementation. Regarding the direct impact (positive or negative), this has an immediate one-step effect on a SDG. While the indirect impact (positive and negative) is a secondary effect further down a chain of events. Moreover, in some cases where there are not relevant cause-effect relations, it might be said that there is not impact (GMV, 2020).

Based on this, the impacts of the UA-SBMs archetypes on the SDGs 2030 (UN, 2015) were presented as follows: i) positive with +1 (both direct and indirect) that contributes to the implementation of the SDG implementation, ii) negative with -1 (both direct and indirect) that counteracts the SDG implementation, and iii) no impact if the impact is considered as negligible (0). The motivation behind the classification of each impact was based on the archetype results and a report analysing the nature of interlinkages between the SDGs (Griggs et al., 2017). In the cases, where there is both negative and positive impacts were found with some SDGs, these were presented with +1/-1.

The tool was not able to visualize graphically the existence of both positive and negative impacts identified in some archetype-SDG relations. However, the reasons behind them can be seen in the assessment reports of UA-SBM archetypes. An example can be seen in Appendix 2.4.

5.2.6. Testing of the UA-SBMs archetypes with a real case study

The application of the categorisation of UA-SBM archetypes was tested with a real case study to explore the type of UA-SBM more suitable for implementation.

An integrated rooftop greenhouse (i-RTG) located on a LEED-Gold certified building that hosts the Institute of Environmental Science and Technology (ICTA) at campus of the Universitat Autònoma de Barcelona (UAB) in Cerdanyola del Vallés, Barcelona (41° 29' 51.7" N 2° 06' 31.8" E) (Fertilecity, 2021), was used as case study.

This i-RTG UA system differs from the conventional greenhouses on the roofs since it has the particularity that resource flow such as rainwater, CO_2, and heat, can be integrated in a bidirectional way building-rooftop greenhouse. Therefore, this integration can contribute to the reduction of the environmental impact of the building and the food production system overall (Sanyé-Mengual et al., 2015). The exchange of flows (water, energy, gases) can be seen in Figure 5.3.

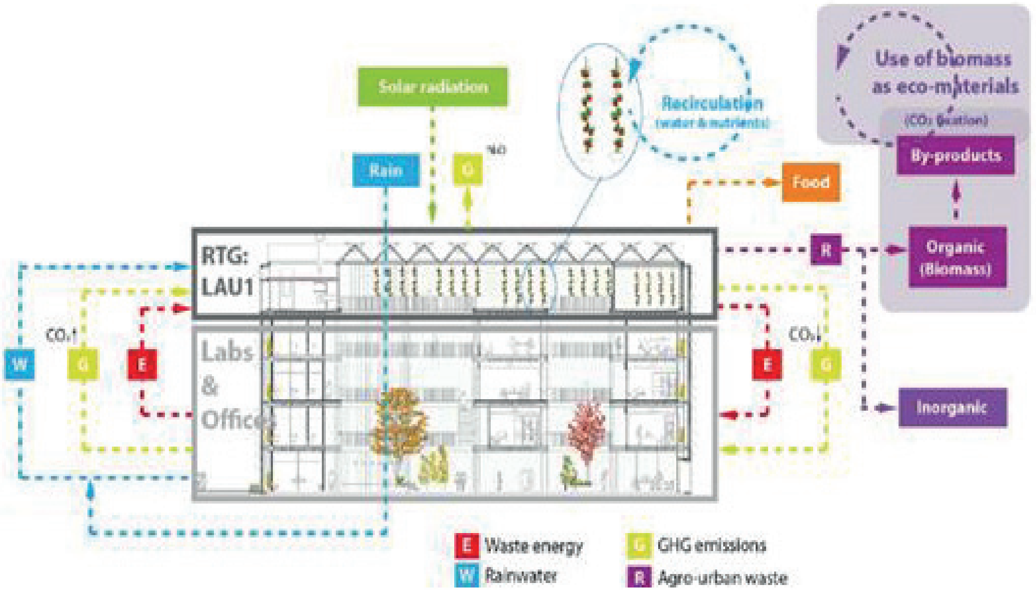


Fig 5.3 Flow diagram of the ICTA-ICP building (adapted from Sostenipra, 2018). Acronyms: RTG-Rooftop greenhouse; LAU1: Laboratory of urban agriculture; GHG-Greenhouse gases.

The building´s rooftop has two greenhouses of 122.1 m² each (Fertilecity, 2015), destinated for different agricultural production and purposes. The first is used being exclusively for tomato production cultivated in a hydroponic system (i.e., a soilless system), while the second for short period vegetables, such as lettuces, chards, and green beans.

Currently, the agriculture production is designated for self-consumption, distributed among the people of the building. The greenhouse disposes of a recirculation system for reusing water and nutrients for plant growth. (Rufí-Salís et al., 2020a, 2020b) and LED lamps to accelerate the plant growth. Moreover, the potential applications of using residual biomass for substates and as a raw material for other products (e.g., fences/trellises, packaging, boards, panels, and blocs) were analysed in Manríquez-Altamirano et al., (2020) and Manríquez-Altamirano et al., (2021). Moreover, the area of the rooftop near the greenhouse is also used for hosting a different kind of events (e.g., parties, seminars, concurs).

An automatic irrigation system is implemented for plant irrigation using mainly rainwater. Regarding the use of materials, fungible materials such as clips for tomato plants, and bags for collection biomass are mainly reused. However, the production costs are high due to the following three key costs: i) labour, ii) rooftop greenhouse structure, and iii) rainwater. In this regard, it was discussed the need for developing SBMs for the i-RTG (ICTA-UAB) case to improve the integration between building and rooftop greenhouse which should contribute to economic cost reductions and improved environmental and social impacts (Peña et al., 2022).

5.3. Results

First, the resulting list of 11 UA-SBMs together with the software results analysing their coverage in the literature are presented. Then, each UA-SBMs archetype is characterised according to the value propositions, value creation and delivery, and value capture. Subsequently, the sustainable potential of the UA-SBMs archetypes is evaluated. Finally, the results from testing the possible application of the UA-SBMs for the case of ICTA-UAB are provided.

5.3.1. Categorisation of UA-SBMs

5.3.1.1. UA-SBM archetypes

Table 5.1 presents the 11 resulting UA-SBMs, including: 1) Maximise the resource use (MRU), 2) Waste-based solutions and reuse (WBSR); 3) SRNP (Substitute with renewable and natural processes), 4) Deliver functionality, not ownership (DFNO), 5) Adopt a stewardship role (ASR), 6) Encourage sufficiency (ES), 7) Marketplace for fresh, surplus, or rejected food (MFSRF), 8) Repurpose for society and environment (RSE), 9) Inclusive value creation (IVC), 10) Develop sustainable scale-up solutions (DSSS), and 11) Subscription model (SM).

Seven of them correspond to the updated categorisation of Bocken et al., (2014), two are concrete modifications (WBSR and MRU) and the rest two are new (SM and MFSRF) (See Table 5.1).

Table 5.1 The sustainable business model archetypes for urban agriculture; Acronyms: MRU=Maximise the resource use; WBSR=Waste-based solutions and reuse; SRNP=Substitute with renewable and natural processes; DNFO=Deliver functionality not ownership; ASR= Adopt a stewardship role; ES= Encourage sufficiency; MFSRF= Marketplace for fresh, surplus, and rejected food; RSE= Repurpose for society and environment; IVC= Inclusive value creation; DSSS= Develop sustainable scale-up solution; SM=Subscription model.

GROUP	**ARCHETYPE**	**DESCRIPTION**	**EXAMPLES**
Environmental	MRU (modified)	Do more with fewer resources (e.g., water, energy, space, labour), generating less waste, emissions, and pollution (Bocken et al., 2014).	• *Advanced robotics for UA*: Floating Farm in Rotterdam (Netherlands) is the world's first floating farm that uses advanced robotics to optimise labour to a minimum for urban farming by using three robots instead of humans (Circle-lab, 2021b, Atlas Obscura, 2021). • *LED energy-saving lamps for UA:* Many indoor UA farms (e.g., Urban Farmers, Plant Lab, Badia Farm) use LED grow light to shorten cultivation cycle (Armanda et al., 2019) and to optimise the energy use.
	WBSR(modified)	Reuse materials and products. Turn waste into feedstocks for other products/ processes. Production of energy and/or compost from waste.	• *Aquaponic urban farm*: The ECF farm produces vegetables and fish using aquaponic system based on industrial symbiosis strategy or co-product recovery where residual/ secondary outputs from aquaculture system (fish production) become inputs (fertiliser) for hydroponic system (vegetable production) (R2π, 2019). • *Upcycled products in UA*: Permafungi recycles coffee ground waste to create biodegradable lamps based on myco material (European Circular Economy Europe, 2021b; PermaFungi, 2021). • *Reused growing materials (e.g., plastic containers, substrates):* The vertical farming enterprise Aerofarms uses patented reusable cloth substrates for plant growing (Armanda et al., 2017).
	SRNP	Reduce environmental impacts by addressing resource constraints associated with non-renewable sources and made-man artificial production systems (Bocken et al., 2014).	• *Rainwater* instead of tap water for irrigation (Lufa Farms, 2021) and for animals to drink (Circle-Lab, 2021b; Atlas Obscura, 2021) • Using *bikes* (European Circular Economy Europe, 2021b; PermaFungi; 2021; Instagreen; 2021; InstaGreen; 2016) or *electric vehicles* (Lufa Farms, 2021) to deliver urban greens instead of using fossil fuel vehicles to reduce carbon emissions.

Social	DFNO	Provide services that satisfy users' needs without their having to own physical products (Bocken et al., 2014).	• *Rent-of-field:* renting small parcels from UA farm to interested city dweller. The renters are responsible for the further cultivation and harvest work, while the farmers offer the exchange of knowledge, tools, and water in return (Polling et al., 2017). • *Growing as a service or Farming as a service*: The enterprise Hollbium (Circular X., 2021b) offers hydroponics growing system as a service including watering, organic nutrients, plants, and general maintenance.
	ASR	Proactively engaging with all stakeholders to ensure their long-term health and well-being (Bocken et al., 2014).	• *Cultural development and promotion*: The agro-tourism Xiedao Green Resort incorporates activities in its business model such testing local cuisine, festival celebration and the experience of farming operations provide various societal benefits related to the protection of the traditional culture and heritage (Yang et al., 2010). • *Organically certified UA products*: Silmusalaatti produces salad sprouts that are naturally produced and organically certified (without fertilisers, pesticides, or preservatives) which serves as a guarantee of its commitment to customers (health issues) and the environment (SINTRA, 2017a).
	ES	Offer UA solutions that actively seek to reduce consumption and production (Bocken et al., 2014).	• Hollbium offers *modular hydroponic system made from resistant material with high endurance, for durability and reusability* (Circular X, 2021b) to prolong the product lifetime and thus reduce consumption
	MFSRUP (new)	Using a physical or online place to facilitate interactions between multiple interdependent groups of customers (Takacs et al., 2020).	• *Virtual marketplace*: Jinghe online farm serves as an online platform when consumers select products to buy, and Jinghe sends these orders to the producers, who then harvest it, or get it out of their storage and ensure it is sent to Jinghe, who does the packaging in a box and sends it to the customers (Oudwater et al., 2013). • *Farmers' markets*: These differ from the traditional food markets, since are dedicated to offer local UA to consumers at a reasonable price without any intermediary so that farmers' profit (MADRE, 2018);

Economical	RSE	Prioritising delivery of social and environmental benefits rather than economic profits (i.e., stakeholder value) maximisation, The traditional business model where the customer is the primary beneficiary may shift (Bocken et al., 2014).	• *social enterprises driven by a social mission*, e.g., in Harvest of Hope which social mission is to "improve income and household food security and indirectly empower disadvantaged households by building their confidence and capacities in farming"(Oudwater et al., 2013) • *non-profit organisations* aim to deliver similar benefits as the social enterprises but the profit-making is not their priority, e.g., in Menjadors Ecològics with the social mission to "introduce more healthy, educational and sustainable models in school canteens"(MADRE; 2018). • *hybrid businesses, co-existence of two businesses*, e.g., in The Plant, a collaborative community of food production interconnected businesses between the for-profit owner/developer Bubbly Dynamics, the educational non-profit Plant Chicago, and the dynamic community of food businesses co-located together. The social mission of The Plant is "to cultivate local circular economies".(The Plant, 2021).
	IVC	Sharing resources, knowledge, ownership, and wealth creation. Inclusive value generation (Bocken et al., 2014 ; Lüdeke-Freund et al., 2016 ; Ritala et al., 2018).	• *Public-private partnership/model-* An example for shared ownership implemented in many UA enterprises, e.g., The Buobai co-composting plant; Cesspit emptiers, Waste Concern (Cofie et al., 2013), Baix Lobregat Agrarian Park; Le Serre dei Giardini Margherita (MADRE, 2018) • *Jobs for the urban poor*: Waste Concern which main activity is the production of compost, also provides jobs as well for the urban poor (Cofie et al., 2013).
	DSSS	Provision of sustainable UA solutions at a large scale to maximise benefits for society and the environment (Bocken et al., 2014).	• *Incubator/hub for business*: The Plant and Mercadis act as incubators for business to support sustainable UA entrepreneurship thought education/training, connection with possible investors, funding, etc (MADRE, 2018; The Plant, 2021). • *Franchising*: The business model of DeCo! Sustainable Farming is franchising type where newly delegated plant managers take management and compost technology training for quicker

			scaling-up efforts and promoting local entrepreneurship (Oudwater et al., 2013).
	SM (new)	Provide fresh UA products and/or services obtained through paying a predefined (mainly fixed) fee/tax/price via subscription or membership (Takacs et al., 2020).	• *Subscription-based mode for produce:* BrightFarms provides its customers with long-term, fixed-price purchase agreements to ensure them a steady supply and pricing as well as year-round access to fresh produce (AgFunder, 2016; Circle-lab, 2021c). • *Community supported agriculture model*: Many UA farms have implemented this model, e.g., Local Food Noods (Go Explorer, 2018a and Local Food Noods, 2021), Harvest of Hope (Oudwater et al., 2013). It consists of supporting the farm operations through providing physical labour from subscribed community members that in return receive deliveries (vegetable boxes) directly from the farm at frequent intervals (Krul & Ho, 2017).

5.3.1.2. More frequent UA-SBM archetypes addressed in the revised literature

According to the software results (see section 2.4), four UA-SBMs archetypes are the most frequently covered in the revised literature (ASR, WBSR, MRU, RSE), whereas ES, DSSS, and DFNO, are the least addressed so far (Figure 2).

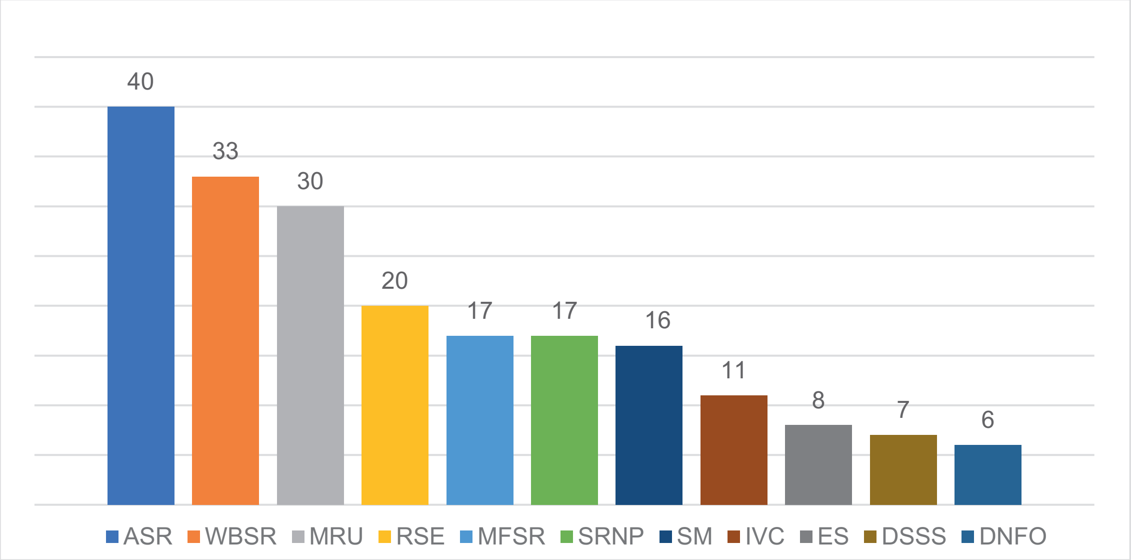


Figure 5.3 UA-SBMs addressed in the revised literature(54 documents).Acronyms: WBSR (Waste-based solutions and reuse), ASR (Adopt a stewardship role), SM (Subscription model), MRU (Maximise resource use), RSE (Repurpose for society/environment, MFSRF (Marketplace for fresh, surplus, and rejected food), DFNO (Develop functionality not ownership). SRNP (Substitute with renewable and natural processes), ES (Encourage efficiency), IVC (Inclusive value creation), DSSS (Develop sustainable scale-up solutions).

The keywords associated with ASR, WBSR, MRU, RSE archetypes are found approximately in 57 % of the total 54 references analysed. (See Appendices 2.5-2-8). While, the keywords related to ES, DSSS and DNFO archetypes can be found only in 13 % of this total (See Appendices 2.9-2.11).

Keywords related to the rest of the UA-SBMs can be seen in Appendices 2.13-2.16 as follows: i) MFSRF (Appendix 2.12), ii) SRNP (Appendix 2.13), iii) SM (Appendix 2.14), and iv) IVC (Appendix 2.15).

5.3.2. Characterisation of UA-SBMs

5.3.2.1. Environmental UA-SBM archetypes

This groups includes three UA-SBM archetypes: i) Waste-based solutions and reuse (WBSR), ii) Maximise the resource use (MRU), and (iii) Substitute with renewable and natural (SRNP). The complete value analysis (i.e., value propositions, value creation & delivery, and value capture) can be seen in Appendix 2.16.

- Value propositions

Both MRU and WBSR aim to reduce waste and optimise resources, however, the second seeks to reduce waste to a minimum (Bocken et al., 2014). To do that, many urban farms applied the MRU offer fresh vegetables cultivated with fewer resources such as water, energy, nutrients, and space (AgFunder 2016; SINTRA 2017a, Armanda et al., 2018; Lufa Farms, 2021; Silmusalatti, 2021). Moreover, this archetype also provides customers with innovative UA growing solutions seeking to optimise not only the use of energy (Armanda et al., 2019) and materials (State of Green, 2021b) but also labour. For instance, Artemis has developed special software (an intelligent platform for urban farming) that tracks and analyses all farm data in one place, enabling growers to optimise plant performance and thus reduce operational labour (Go Explorer, 2018b).

Regarding the WBSR, the waste output is lessened at a minimum by providing waste-based products such as biodegradable lamps (Circular Economy Europe, 2021b; PermaFungi 2021), soaps (Circulator, 2021b), energy (Cofie et al., 2013), and compost (Lufa Farm, 2021). Also typical for this archetype is using waste as production input for other processes, such as aquaponic production which is very frequent example in many urban farms such as ECF Farms (R2π, 2019); The Plant (The Plant, 2021), Fresh Guru (ORHI, 2019), Ecco Jäger Farm (Sanyé-Mengual et al., 2017b).

Finally, the UA farms implementing the SRNP mainly offer two types of products: i) UA fresh products cultivated with renewable sources/energies instead of conventional ones (e.g., rainwater instead of tap water) (Lufa Farms, 2021), and ii) UA growing solutions using renewable sources/energies, e.g., urban farms in shipping containers powered by renewable energy (Go Explorer, 2019; Agricool, 2021).

Concerning customer segments, there are mainly two types of customers for the three UA-SBMS: i) business clients, such as other urban farmers, retailers, restaurants, wholesalers, food producers, manufacturing industries, and ii) local end-consumers/end users. The relation with the business clients is mainly based on close direct contacts, while the relationship with end-consumers is more often unipersonal (e.g., online ordering or store purchase) (Senanayake et al., 2021).

- Value creation &delivery

The main activity for the three UA-SBM archetypes is the production and selling of UA fresh products and food growing solutions. However, the WBSR and SRNP comprise some additional activities.

For instance, the WBSR entails i) sourcing and collecting of waste (The Plant 2021; Circle lab, 2018b; Robert-Jab Vos, 2018; Circle-lab, 2020; Circle-lab, 2021b; Atlas Obscura, 2021; SINTRA, 2017b and 2017c); ii) recycling waste for the production of upcycling products (e.g., biodegradable lamps) (European circular economy stakeholder platform, 2021b;

PermaFungi, 2021), compost/fertiliser (Lufa Farms, 2021; Circle-lab, 2021b, Atlas Obscura, 2021) and energy (Cofie et al., 2013); (iii) using waste as production input for plant/growing (e.g., coffee waste grounds as a substrates) (SINTRA 2017b, Helseni, 2021; Circulator, 2021b), insect farming (SINTRA, 2017c) or feeding animals (Circle-lab, 2021b; Atlas Obscura, 2021); and iv) reusing material/products, e.g., patented reusable cloth medium for plant growing (Armanda et al., 2018).

Regarding the SRNP, this archetype includes also as main activity the distribution of UA fresh products by using low emission means of transportation, such bikes and electrical vehicles (Lufa Farms, 2021; Instagreen 2016 and 2021).

Since these UA-SBM archetypes are based on technological innovations with the primary aim to reduce environmental impacts (Boons & Lüdeke-Freund, 2013), resources and technology are crucial for their implementation.

Typical examples of key enabling technologies implemented by many urban farms are: i) aquaponic technology and digesters for compost/ biogas in the case of the WBSR (R2π, 2019; Cofie et al., 2013), ii) drip irrigation technology, energy saving LED lamps (Armanda et al., 2019), automatisation of the production process concerning the MRU (Circle-Lab, 2021b; Atlas Obscura, 2021; Go Explorer, 2018b), and iii) rainwater harvest systems for collecting rainwater (Lufa Farms, 2021) or solar panels (MADRE, 2018) with regard to the SRNP. Another key resource is the use of qualified human labour (e.g., engineers, architects) necessary for research and development of new environmental technologies (Armanda et al., 2019).

This archetype group is characterised with diverse distribution channels such as direct sales (on farm), online shops, local retailers, restaurants, social media, fairs, and events (Circle-lab, 2018a; Square roots, 2021; The Plant, 2021; SINTRA, 2017a; Silmusalaatti, 2021; Go Explorer, 2019; Agricool, 2021; Circle-lab, 2021c; AgFunder, 2016; Circulator, 2021b; Infarm, 2018 and 2021; ORHI, 2021). An interesting example of distribution scheme is the case of Lufa Farms which distributes its urban greens though the local community (Lufa Farms, 2021).

Regarding key partners, since the MRU seeks to reduce the consumption of production resources, collaborations with technological I+D centres for research, universities are necessary to develop new technologies (Armanda et al., 2019). While, for the WBSR, typical are the partnerships with cafés, restaurants, hotels, food/meat industries for being main providers of waste inputs for plant/mushrooms growing or producing other waste-based materials (The Plant, 2021; Rotterzwan, 2021; Circle-lab, 2020; Grocycle, 2021; European circular economy stakeholder platform, 2021b; PermaFungi, 2021). Regarding, the SRNP, providers of technological innovations aiming to minimise the use of non-finite resources and/or energy are examples for successful partnerships (ORHI, 2021).

- Value capture (costs and revenues)

Qualified engineers, architects, or other university graduated persons, represent the most important costs since people with university degrees tend to receive higher salaries than those without any university degree (Clarke, 2007). Other relevant costs are annual amortisation of assets (technology), labour for periodical maintenance of technology implemented and costs for its installation.

Regarding revenues structure, among the three archetypes, more additional revenues can be obtained from the WBSR archetype. This is because the UA enterprises that have implemented this archetype have a diversified BM. In this regard, aside from selling UA fresh produce and products made from waste (e.g., substrates, energy, compost), these enterprises also offer waste as inputs for other industries, e.g., crop residues for bioplastic, biomass (ORHI, 2019).

- Limitations for the implementation of environmental UA-SBM

The following two negative side effects can be expected from implementing the WBSR: i) it may convey to fast sale cycles and more use of materials; and ii) it may require waste streams to be sustained for creating value and this contradict to its objective to eliminate waste at minimum (Bocken et al.,2014; 2016; Lüdeke-Freund et al., 2016; Ritala et al., 2017).

Regarding the MRU, the automatisation of the production and/or implementation of advanced technology such as robots in Floating Farm (Circle-lab, 2021b; Atlas Obscura, 2021) to reduce labour at minim may lead to job losses.

Regarding SRNP, the lack or complex of recyclability for some technological solutions, e.g., solar panels; and the footprint related to the production of renewable energy technologies (e.g., solar panels) (Vlaanderen Circular, 2022), can lead to environmental burden shifting or rebound effects.

5.3.2.2. Social UA-SBM archetypes

The four archetypes included in this category are i) Adopt a stewardship role (ASR), ii) Marketplace for fresh, surplus and rejected food (MFSRF), iii) Encourage sufficiency (ES), and iv) Deliver functionality not ownership (DFNO). Appendix 2.17 presents the complete value analysis

- Value propositions

Both MFSRF and ASR archetype provide UA food but with some differences. For instance, the MFSRF aside from fresh food, also offers surplus and rejected food due to the aesthetic reasons to prevent waste (Senanayake et al., 2019).
Since the social purpose of the ASR is to impact positively to the human health (Bocken et al., 2014), the UA food offer is mainly fresh or organic (SINTRA, 2017a). Moreover, the

ASR also provides services aiming to improve the well-being/health of the local community such as an education courses (Circulator, 2021b), leisure/cultural events (Yang et al., 2010), and diets programs (MADRE, 2018).

Regarding ES and DFNO archetypes, their offers do not include urban food. ES offers UA growing solutions such a modular hydroponic system made from resistant materials (Circular X, 2021b) to prevent planned obsolescence and prolong the product lifetime (Takacs et al.,2020) and hence reduce consumption. On the other hand, DNFO provides services instead of production to satisfy the customers' needs without having their own products (Bocken et al., 2014) which can be described as "experience" in the "rent-of-field" concept.

Focusing on customers, direct contacts with the consumers are important, especially for ASR because its aim is to engage them with the full story of production/supply chain to establish relationship based on transparency and trust. Also, DFNO looks for motivating the shift away from ownership (Bocken et al., 2014). Regarding customer segments for all the archetypes included in this group, business clients (e.g., other urban farmers, local restaurants, retailers, grocery stores) are typical (Oudwater et al.,2013; Cofie et al., 2013; MADRE, 2018). Following by end-user interested in the case of the ASR, MFSRF, and DFNO archetypes (MADRE, 2018). While, in the case of the DFNO governmental clients such urban planners are common (Circular X, 2021b; Hollbuim, 2021).

- Value creation & delivery

Focusing on ASR, the production and selling of UA fresh products and/or provision of services aiming to ensure the long-term health (e.g., organic farming without using synthetic nutrients and pesticides) (SINTRA, 2017a; Silmusalaatti, 2021; Oudwater et al., 2013; MADRE, 2018) and wellbeing (e.g., leisure and education activities) (The Plant, 2021; Yang et al., 2010) of all stakeholders (including society and the environment) determine the types of activities developed. Direct sales and/or distribution of fresh, surplus, or rejected (due to aesthetic reasons) UA products (Oudwater et al., 2013; MADRE, 2018) are typical activities addressed by MFSRF.

Concerning the ES, the main activities are the design, rent, and sale of UA growing solutions having long-lasting design (Circular X, 2021b; Hollbuim, 2021). While regarding the DFNO, typical activities are the rent/leasing of UA growing solutions (Martin & Bustamante, 2021) or urban land for growing food (Polling et al.,2017).

Human resources are common key resource for all four archetypes included in this group. Oher key resources for the ASR are certifications of quality to bring trust and transparency and innovative technology such as blockchain for greater transparency, food safety, and identification (Davies & Garrett, 2018), e.g., organically certified production (SINTRA, 2017a), QR code (blockchain technology) on the packaging of urban greens which customers to know how the food is produced (Circle-lab, 2018a; Square roots, 2021).

Regarding MFSRF, for the correct functionality of the online marketplace for urban food products, resources such the possession of website, online databases, and facilities for storing products/packaging are need, which is the case of Jinghe online farm in China (Oudwater et al., 2013). While for running physical marketplaces, aside from human resources, other key resources are space and bank credit (MADRE, 2018). While ES and DFNO archetypes use as main resource a specialised software for monitoring and detecting incidents (Davies & Garrett, 2018; Circular X, 2021).

Regarding key channels, they are mainly short without intermediaries or very few intermediaries, especially for the MFSRF since it aims to facilitate the interactions between multiple interdependent groups of customers (Takacs et al., 2020) using a physical or digital/online place (Oudwater et al., 2013; MADRE, 2018).

Concerning key partners, basic condition for the functionality of the ASR is to establish close partnership between the UA organisation, local authorities (e.g., local government; citizens) and other local farmers (Bocken et al., 2014). While collaborations with different stakeholders' groups (investors, sponsors, logistic companies, customers cooperatives, local municipalities, local farmers) are important for successful implementation of MFSRF (MADRE, 2018). Regarding ES, partnerships with grocery stores, retailers, and local authorities are typical (Circular X, 2021b). Lastly, for the correct functionality of the DFNO archetype, collaborations with providers of growing inputs, and software solutions could be needed (Balcarová et al., 2016; Martin & Bustamante, 2021).

- Value capture (costs and revenues)

Regarding key costs, these are related to the key resources such as i) salaries, ii) rent and bank charges in the case of MFSRF, and iii) maintenance of digital platforms in the case of ASR and MFSRF (Oudwater et al., 2013).

Revenues are obtained mainly from selling of products/services with exceptions of the MFSRF and DFNO. For instance, the main resource of revenues in the case of the MFSRF are membership taxes (Oudwater et al., 2013). While regarding the DFNO, leasing and renting are typical for the urban farms that offer UA growing solutions as a service (Martin & Bustamante, 2021). However, more revenues can be expected from the ASR since it has a diversified BM the urban food production is combined with wide variety of complementary services, e.g., education courses, training programs, diets programs, etc.

- Limitations for the implementation of social UA-SBM

Regarding ASR, although the positive effects of this archetype to ensure the long-term well-being of society (e.g., health) and long-term viability of the value network, if is not combined with efficiency improvements, the positive impact on the environment would be minimal (Lüdeke-Freund et., 2016). Moreover, according to Bocken et al., (2014), the ASR would take advantage of other archetypes such as waste-based one. This is also supported by the results of this study since it was found that the ASR was mainly combined with the archetype WBSR and RSE.

Concerning MFSRF, using physical spaces (e.g., farmer markets) for selling of UA products may have seasonal character which can obstruct the year-round supply since favourable climatic conditions are needed to set up outside marketplaces.

Moreover, the UA growing solutions provided from the ES tend to be expensive and there is possibility to remain niche since go against the growing principle (Vlaanderen Circular, 2022). However, combining it with other archetypes such as the SM can improve the access to such UA solutions. For instance, Hollbium offers its modular hydroponic system as well via subscription (Circular X, 2021b).

Finally, the DFNO improves the access to previously expensive UA food and growing solutions through offering rent or lease at reasonable price. Nevertheless, the increased accessibility may lead to increased consumption which can contradict to the aim to the archetype ES that seek to reduce the excessive consumption.

5.3.2.3. Economical UA-SBM archetypes

This group contains the following four UA-SBM archetypes: i) Repurpose for society & environment (RSE), ii) Inclusive value creation (IVC); iii) Subscription model (SM), and iv) Develop sustainable scale-up solutions (DSSS). The full value analysis can be seen in Appendix 2.18.

- Value propositions

The RSE and the DSSS have similar value propositions since both aim to maximise the benefits for the environment and society (Bocken et al., 2014) however there is difference regarding organisational structure and key customers.

For instance, the RSE uses the following organisational structures: (i) social enterprises driven by a social mission (Oudwater et al., 2013), (ii) non-profit organisations aim to deliver similar benefits as the social enterprises but the profit-making is not their priority (MADRE; 2018), (iii) hybrid businesses, co-existence of two businesses (for-profit business and not-for-profit organisation), where the for-profit enterprise use part of the profit to finance the non-for-profit organisation (The Plant, 2021), and (iv) alternative ownership: cooperative, mutual (farmers), collectives (MADRE; 2018). While the key customers associated with this archetype are mainly two types: i) local people, mainly those in not favourable situations such as people with mental health issues, immigrants, low-skilled persons (e.g., in Gittins & Morland, 2021; Oudwater et al., 2013), and ii) business clients such as local restaurants and retailers (e.g., in The Plant, 2021; Rooftop Republic, 2021; Go Explorer, 2020).

In contrast to RSE, the DSSS includes organisational structures such a franchising scheme, incubators for businesses and crowdfunding (Bocken et al., 2014) to support the scale-up of early-stage UA entrepreneurs, small business; home-based businesses or others interested in implementing sustainable practices in their businesses (key customers) by providing resources, education and/or funding (The Plant, 2021, Circular Economy Europe, 2021a; MADRE, 2018; Oudwater et al., 2013; Cofie et al., 2013).

Regarding the archetypes SM and IVC, the first offers UA products/services on subscription/ membership basis (Circle-lab, 2021c; AgFunder, 2016; Oudwater et al., 2013; Krul & Ho, 2017), while the second seeks to create inclusive value through joint initiatives where resources, ownership, and/ or knowledge is shared or previously neglected social groups (e.g., poor people) are included as value-creating partners (i.e., as employees, suppliers, or distributors) instead of customers (Bocken et al., 2014; Lüdeke-Freund et al., 2016; Ritala et al., 2018). Subscribed members are the main customers of the SM, being two types: i) business clients-urban farms, restaurants, retailers (Circular X., 2021b; AgFunder, 2016); ii) local end-consumers interested to consume fresh local products at reasonable prices or as a compensation to participate in the harvest (Krul & Ho, 2017). While the IVC aims reach a wide range of customers without discriminating any (Lüdeke-Freund et al., 2016).

Regarding customer relations, all archetypes need to establish direct relations with the customers to complete their aims (Oudwater et al., 2013; MADRE; 2018).

- Value creation & delivery

Since the aim of the RSE is to prioritise the delivery of social and environmental benefits rather than economic profit) maximisation and this can be done through the implementation of programs aiming to promote UA to increase food supply, create livelihoods (Go Explorer, 2020, Rooftop Republic, 2021), alleviate poverty and protect environment (Circle-lab, 2021d; Oudwater et al., 2013). While for the SM archetype the two main activities are: i) Selling or distributing UA fresh products (AgFunder, 2016; Krul & Ho, 2017; Infarm 2018 and 2021); and 2) Selling or renting/leasing services (Circular X., 2021b). In both cases, the focus is on the predefined fee/tax/prices (mainly fixed) paid via subscription (Takacs et al., 2020). Concerning the IVC, this archetype is presented by UA activities (e.g., production, selling, distribution, organising events on UA) that share resources (materials and human) and ownership (e.g., public- private) (MADRE, 2018), or knowledge (The Plant, 2021). Lastly, the DSSS includes activities that aiming to stimulate and support sustainable UA entrepreneurship such as education/training, connection with possible investors, funding (The Plant, 2021; MADRE, 2018; European Circular Economy Stakeholder platform, 2021b; Cofie et al., 2013; Oudwater et al., 2013; Vitiello et al., 2014; Vieira et al., 2019)

Regarding key resources, human resources are common for all of them. However, the IVC mainly use as a principal human power previously neglected social group (e.g., poor people, low-skilled persons) by providing them with employment opportunities and/or including them as key partners, e.g., jobs for the urban poor (Cofie et al., 2013). While voluntaries are necessary for the correct operation of the RSE (Gittins & Morland, 2021). In relation to the SM, the subscribed customers can be key human resources and key partners as well since they can do the harvest by themselves and supporting the farm operations which is typical for CSA model (Krul & Ho, 2017). Other important resources are digital/online platforms used in the SM (Go Explorer, 2018a; Local Food Nodes, 2021; Oudwater et al., 2013) and the DSSS. (The Plant, 2021; Circular Economy Europe, 2021a).

Regarding key channels, this archetype group characterises with short supply channels with very few intermediaries (MADRE, 2018). While regarding key partners, there is a need for close cooperation between the company and the local authorities and other stakeholder group to complete the archetypes goals (Bocken et al., 2014). In this regard, the RSE might require non-traditional business partnership (e.g., non-governmental organisation, etc) which is the case of the social enterprise Harvest of Hope (Oudwater et al., 2013) that partners with the non-governmental organisation Abalimi Bezekhaya to achieve its social mission (Cape Town Online Magazine, 2021; Circle-lab, 2021d).

- Value capture (cost & revenues structure)

Regarding cost structure, the main costs are associated with the key resources, for instance labour, maintenance of digital/online platforms.

Concerning revenues streams, they are obtained mainly through selling of UA products and services in the case of the RSE and IVC. While the main revenues streams from applying the SM and the DSSS come from a paying a predefined fee/tax/prices. In the case, this is mainly fixed (e.g., in Circle-lab, 2021c; AgFunder, 2016), while in the second can be both a variable (e.g., franchising, licensing) (Cofie et al., 2013; Oudwater et al., 2013) or fixed (e.g., participation in programs for incubating sustainable businesses) (The Plant, 2021; European circular economy stakeholder platform 2021a; MADRE, 2018).

- Limitations for the implementation of economical UA-SBM

Despite the positive contribution of the economical group UA-SBM archetypes, if they are not including efficiency improvements, their contribution to the environmental sustainability may be minimal (Vlaanderen Circular, 2022). Hence, these archetypes should be combined with some of the environmental (MRU, WBSR and SRNP) ones to overcome this limitation. There are many successful examples of UA enterprises combining economical with environmental UA-SBM, e.g., Permafungi (Circular Economy Europe, 2021b; PermaFungi, 2021), Rotterzwan (Circulator, 2021b), The Plant

(The Plant, 2021), DeCo!! (Cofie et al., 2013), Hollbium (Circular X, 2021b), and Harvest to hope (Oudwater et al., 2013).

Moreover, the RSE and SM have other important weak points. For instance, since in most of the case RSE depends on external funding (e.g., donors, sponsors), this may endanger the economic viability at long turn (Gittins & Morland, 2021). While, regarding the DSSS, sometimes the focus on scale might detract from sustainability purposes and there is possible risk of unproven radical innovation (Lüdeke-Freund et al., 2016).

5.3.3. Sustainable potential of the UA-SBMs

Appendices 2.19-2.21 show the sustainable benefits expected from the 11 UA-SBMs, while Appendix 2.22 their relationship with the SDGs.

5.3.3.1. Environmental UA-SBMs archetypes: sustainable benefits and relationships with the SDGs

Waste-based solution & reuse (WBSR) and Maximise the reuse use (MRU) archetypes are identified to impact directly and positively more SDGs (4 of 12) in comparison with the Substitute with renewables and natural processes (SRNP) which contributes directly only to the achievement of the SDG 7. Regarding indirect positive contributions, all the three archetypes are related to SDG 13 and SDG 14 since they help the waste reduction and marine pollution from UA land-based activities which also help for mitigating climate change impacts (UN, 2015). Concerning negative contributions, the SRNP is found to be related negatively (indirectly) to SDG 1. While both positive and negative indirect impact is identified in the following archetypes-SDG relationships: i) WBSR with the SDG 2 and SDG 3, and ii) SRNP with the SDG 6. Finally, regarding neutral contributions or no impact, those are identified with the SDGs 1 (WBSR and MRU), 4 (only MRU), 5 (all), 9 (only WBSR), 10 (WBSR and MRU), and 16 (all). The reason for this is because they did not meet the archetypes aims.

The reasons behind these impacts in their integration with the expected sustainable benefits (environmental, social, and economic) from their implementation are explained below.

- Environmental benefits

Since WBSR and MRU archetypes aim to reduce waste and improve resource use (e.g., water, energy) through the implementation of technological innovations (Bocken et al., 2014) they impact directly and positively the SDGs 6, 7, 9, and 12 associated with the optimisation of resources (SDG 6 and SDG 7), the advance of the technologies (SDG 9), and responsible production and consumption (SDG 12). While the SRNP directly contributes to the advance of SDG 7, especially the target 7.2 aims to increase substantially the share of renewable energy which completely meets the archetype objective. Moreover, the SRNP through including technological innovations that seek to substitute the use of conventional sources with renewable ones (e.g., rainwater instead of tap water use) might have a positive indirect contribution to SDG 6, particularly the target 6.4 which aims to substantially increase water-use efficiency across (UN, 2015). Both contributions to SDG 6 and SDG 7 can help for conservation of resources such as fresh water and electrical energy by minimising their consumption or substituting them with renewable ones (Go Explorer, 2019; Agricool, 2021; Lufa farms, 2021). However, the SRNP is also found to be connected negatively (indirectly) with SDG 6 (Target 6.1 and 6.4) because the increased utilization of unconventional water supply options to satisfy growing demands for safe, affordable freshwater supplies could constrain renewable energy deployment if those options (e.g., desalination) are highly energy-intensive (Griggs et al., 2017).

The reduction of the emissions associated with burning fossil fuels is a purpose shared by WBSR and SRNP though the production of energy from waste and from natural sources (e.g., sun) (Circle-lab, 2021b; Atlas Obscura, 2021) or using bike or electric vehicles to deliver UA fresh products (SRNP) (Lufa Farms, 2021; InstaGreen, 2016 and 2021) can impact positively the SDG 11 (Target 11.6) and SDG 13 (Overall).

Moreover, through reusing growing materials, such as cultivation substrates , which is the case of Aerofarms (Armanda et al., 2019), the virgin material use can decrease (Bocken et al., 2014) which is positive direct contribution to the target to the SDG 15, particularly the Target 15.1 ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services (UN, 2015).

- Social benefits

Regarding society, positive impacts related indirectly to the SDG 8 and SDG 11 also can be presumed such i) jobs opportunities for people for qualified people (e.g., engineers, architect) and those working on the maintenance of the environmental technologies and ii) reduced carbon emissions in the cities. Moreover, the WBSR can help for the increased awareness on sustainability, composting, and home gardening (Senanayake et al., 2021) and to contribute for development of the UA in the cities (indirect impact on SDG 4). While the SRNP can contribute to the reduction of stress on the city's infrastructure and hence to impact indirectly the SDG 11 because of intercepting and using rain and meltwater water instead of directing it and wasting it in the sewers (Lufa Farms, 2021).

However, the SRNP might impede the achievement of social goals since is found to be connected negatively (indirectly) with SDG 1 (Target 1.4) since renewable technology (e.g., rainwater harvest system) are mainly highly priced (Peña et al., 2022) and this might be obstacle for their implemented in poor countries.

Special is the case of the WBSR since both positive and negative indirect relations exist with the following socially-oriented SDGs: i) SDG 2 since without environmentally sound management of chemicals and all wastes throughout their life cycle is impossible to ensure sustainable food production systems and implement resilient agricultural practices (SDG 2, target 2.4) but there might be a possible competition (indirect negative impact) of crops for producing food or bioenergy; and ii) SDG 3 because it can contribute to a substantial reduction of the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination through ensuring environmentally sound management of chemicals and all wastes throughout their life cycle (Griggs et al., 2017) but a negative impact can also be possible if there is no control regarding the used wastewater to prevent illness transmitted via water (target 3.9) (Griggs et al., 2017).

- Economic benefits

Great costs saving, and thus increased profit are possible thanks to i) reduced consumption of production inputs (MRU) (SDG 12), ii) using waste as raw material and reusing materials instead of buying them (WBSR) (SDG 15), and iii) using renewable sources and/or energies instead of non-finite sources (e.g., tap water) (SDG 7) and conventional energy (Bocken et al., 2014).

However, the greatest economic benefits can be expected by implementing the WBSR. This is expressed in the greatest cost savings and new sources for generating revenues and thus profit. For instance, using waste streams and wastewater in the production process can reduce significatively the costs of raw materials (Cofie et al., 2013; Plant, 2021). Additionally, producing energy from waste can also significantly reduce energy expenditure. In this regard, it was calculated that using waste-based energy can decrease the energy costs to operate an agro-tourism in China by RMB 4000 or 561€ per day (Yang et al., 2010).

Regarding new sources for obtaining revenues and thus profit, aside from offering urban agriculture products, the waste can be used to produce and sell waste-based materials/products such as biodegradable lamps (PermaFungi, 2021), compost (Cofie et al., 2013), coffee waste-based soap/beer (Circulator, 2021b). Moreover, the waste streams also can be sold as a raw material for other uses (e.g., bioplastics, heat) (ORHI, 2019).

5.3.3.2. Social UA-SBMs archetypes. Sustainable benefits and relationships with the SDGs

Within this group, the Adopt of the stewardship (ASR) is identified to contribute to the achievement of more SDGs (5 of 12) directly and positively in comparison to the rest of the archetypes included in this group, by impacting the following SDGs: 2, 3, 4, 8 and 10. This is because the archetypes' goals completely meet the SDGs' targets. Considering indirect positive archetype-SDG relationships, there are many (See Appendix 2.19) but perhaps the more remarkable ones are with SDGs 11, 12, 13, and 15. Regarding negative indirect impacts, the following ones are identified: i) Encourage sufficiency (ES) archetype on SDG 1, and ii) Deliver functionality not ownership (DFNO) and ES archetypes on SDG 12. Lastly, regarding neutral contributions or not impact, those are identified with the SDGs 3 (Only ES), 6 (ES and MRU), 7 (ASR, ES and MFSRUP), 10 (only DFNO), 14 (ES, DFNO and MFSRUP),15 (DFNO and MFSRUP), 16 (all) and 17 (ASR, ES and DFNO). The reason for this is the same as in 5.3.3.1.

The reasons behind the significant positive and negative impacts in their integration with sustainable benefits (environmental, social, and economic) from their application are explained in the next subsections.

- Environmental benefits

Significant environmental benefits can be expected by applying the ASR, MFSRF and DFNO expressed in protected environment, reduced carbon emissions and waste which is positively and indirectly related to the SDG 11, 12, 13 and 15.

While the ES contributes to using less product and stimulates the reuse across generations (Bocken et al., 2014) which supposes an indirect positive impact on SDG 12. While MFSRF helps the reduction of global waste by offering surplus and rejected food has a direct positive contribution to the achievement of SDG 12 (Target 12.5).

Additionally, DFNO and ES archetypes can be related negatively (indirectly) to SDG 12 since if they are not combined with efficiency improvements, and solutions to reduce and halve waste, these archetypes may have negligible environmental impact improvement (Lüdeke-Freund et al., 2016).

- Social benefits

There are many significant social benefits related to direct positive impacts on the SDGs among them stand out i) educated society in the case of the ASR (Cityplot, 2021; Go Explorer, 2020; Rooftop Republic, 2021) and the ES (Bocken et al., 2014) (SDG 4); ii) health improvement which is related to the ASR (SDG 3) , iii) gender equity (SDG 5) and social inclusion (SDG 10) (MADRE, 2018); iv) improved access to previously expensive food/growing solutions (SDG 2) such as organic food regarding MFSR archetype and hydroponic considering the ES one (MADRE, 2018; Circular X, 2021b).

The MFSRF archetype is identified to have a direct positive impact on SDG 2 (Targets 2.3 and 2.c) since can contribute to increasing the incomes of small-scale urban food producers and leads to reduced prices of otherwise expensive products such as organically produced vegetables and fruits because of adopting measures to ensure the proper functioning of urban food markets and their derivatives and facilitate timely access to market information (UN, 2015).

However, the ASR can also be negatively and indirectly related to the SDG 2 as social goal since increased agricultural production (even small scale) can create new pathogen habitat and increase the risk of animal-human disease transmission (Griggs et al., 2017).

Moreover, the ES is also found to have a negative indirect impact on the SDG 1 (Target 1.4) having a social purpose since long-lasting UA technological innovations and solutions promoted by this archetype are mainly premium-priced (Bocken et al., 2014), which might impede their application in poor, less developed countries.

- Economic benefits

Additional revenues and thus profit at long term is expected from the ASR and the ES archetypes (Bocken et al., 2014). Regarding ARS, this is because customers are prone to pay a premium for local fresh and/or organic UA products assumed to be of higher quality, better tasting (Willis et al., 2016) and environmentally friendly (Ercilla-Montserrat et al., 2019). While, concerning the ES since the growing solutions are made from long lasting material are offered (Circular X, 2021), they are usually premium priced.

Regarding MFSRF, increased revenues and thus profit for urban farmers can be obtained at long term because of short supply chains where there is not or few intermediaries. Lastly, regarding DFNO, there is possibility for obtaining additional revenues and thus increase profit from providing additional services not included in the service package. For instance, Hollbium offers hydroponics unit as a service, where the full service includes watering, organic nutrients, plants, and general maintenance (Hollbium, 2021). However, not at all cases, these additional services are included.

However, the ASR can also impact negatively (indirectly) the SDG 8 as economic goal since economic growth might have negative adverse impacts (water, air, and soil pollution and ecosystem change) which can increase the risk of communicable disease, illness, and death (Griggs et al., 2017).

5.3.3.3. Economical UA-SBMs archetypes. Sustainable benefits and relationships with the SDGs

Concerning direct positive contributions of the archetypes included in this group, the RSE is identified to be related with 5 SDGs (more impacts), following by the IVC and DSSS that separately impact 3 SDGs and the SM related with 2 SDGs. Regarding negative indirect impacts, the following ones are identified: i) RSE on SDG 9 (Target 9.3), and ii) SM and IVC archetypes on the SDG 12 (Targets 12.3 and 12.5).

Regarding indirect impact, there are many but maybe one of the most notable is on the SDG 3 because all of the four economical UA-SBMs by improving the access to UA fresh products or promoting UA as a tool for creating loverhoods can contribute to overall

SDG 3 aim to ensure healthy lives and promote well-being for all at all ages. Finally, regarding neutral contributions or not impact, those are identified with the SDGs 5 (Only SM), 6 (RSE and IVC), 7 (RSE and IVC), 10 (only SM), 14 (RSE and DSSS),15 (SM and DSSS), 16 (all) and 17 (SM). The reason for this is the same as in 5.3.3.1. and 5.3.3.2.

The next sections explain the reasons behind the most significant sustainable benefits and their connection with the SDGs are explained below.

- Environmental benefits

Since the archetype RSE includes activities aiming to protect local biodiversity, this can help for reducing significatively the GHG emission, indirect positive impact on the SDG 13 (MADRE, 2018) While the implementation of the SM and IVC archetypes can contribute to reduce the carbon mission of transportation in the cities thanks to the short supply chains which is indirectly positively related to the SDG 11 (Oudwater et al., 2013)

The implementation of the DSSS also has an indirect positive impact on the environment. From instance, due to the promotion promoting of diverse sustainable UA initiatives such as implementing an organic compost plant facility (The Plant, 2021) that can contribute to mitigating the environmental problems associated with agricultural waste accumulation and the excessive use of syntenic pesticides (SDG 12). However, since it is found that SM and IVC archetype can be connected negatively with the SDG 12 (Targets 12.3 and 12.5), the expected positive impact on the environment would be minimal and make difficult the fulfilment of the SDG 12, if these archetype does not provide resource-efficiency solutions (resource-efficient management, waste recycling) as a service.

- Social benefits

Great social benefits can be expected from implementing the archetype in this groups related directly and positively to the following SDGs i) SDG 1 -poverty alleviation in the case in the case of RSE and DSS archetypes; ii) SDG 2-household food security and improved access to food in the case of RSE and SM archetypes; iii) SDG 8- jobs and training for people in an unfavourable situation in the case of, local entrepreneurship in the case of IVC and DSSS; iv) SDG 11-establishment of sustainable cities in the case of the RSE, and v) SDG 15-biodiversity protection (ASR).

Regarding indirect impact, there are many but maybe one of the most notable is on SDG 3 because all the four economical UA-SBMs by improving the access to UA fresh products or promoting UA as a tool for creating livelihoods can contribute to the overall SDG 3 aim to ensure healthy lives and promote well-being for all at all ages.

- Economic benefits

Concerning RSE, economic profit is not a priority however it is needed to maintain self-sufficiency, but revenue is not the principal objective. Possible cost reductions can be possible by using voluntaries to do the urban farming operations (Gittins & Morland, 2021) (SDG 8).

Regarding SM, regular and predictable revenues and thus profit for the producers/distributors from established a long-term relationship with the customers. Moreover, great costs reduction in the labour for harvest in community supported agriculture (CSA) model can be expected since subscribed member do the harvest (Krul & Ho, 2017).

While, concerning the IVC and DSSS, in the first case economic costs are reduced thanks to sharing resources and financial return might be possible as result of successful sustainable scale-up in the second.

However, the RSE can also be related negatively with the SDG 9 since the supporting innovations associated with this archetype such as social enterprise, non-for-profit are dependent on external financing and donors (Gittins & Morland, 2021), and this can contradict target 9.3.

5.3.4. Application to the case study of ICTA-UAB

Description of the case study is presented in section 5.2.6.

Analysing the possible implementation of the UA-SBMs for the case of ICTA-UAB, the three environmental types of archetypes (WBSR, MRU, SRNP) seem to be more applicable. This is based on i) the previous studies examining the sustainable potential of using biomass waste (Manríquez-Altamirano et al., 2020 and 2021) and recirculating water/nutrients (Rufí-Salí et al., 2020b); and ii) the i-RTG concept itself that was designed with the main objective to reduce environmental impacts through the exchange of flows (water, energy, gases) between the building and its greenhouse.

Regarding the WBSR, the sustainable potential of using biomass waste (tomato streams) for substrates and for high quality local materials (e.g., fences and trellises, packaging, and boards, panels, and blocks). These options also can help for reducing raw material costs and the obtaining of additional revenues apart from contributing to the mitigation of environmental impact. Another possible source of income can be gained through selling biomass waste to other industries for bioplastics, heating, etc (ORHI, 2019). Moreover, the actual practice of reusing cultivation materials (e.g., clips for tomato plants, bags for collecting biomass waste) can also help to reduce their costs.

Concerning the MRU, this archetype can also help for designing a SBM for the ICTA-UAB thanks to i) the automatic irrigation system that reduces the consumption of manual labour, and ii) the water recirculation system that minimises the consumed water, nutrients, and waste (Rufí-Salís et al., 2020a, 2020b) and contributes to the reduction of the costs of raw materials.

Finally, regarding the SRNP, using rainwater for irrigation in the i-RTGs can help not only for the reduction of the use of the non-renewable resources but also for decreasing the tap water costs (Semaan et al., 2020).

Based on this, the future SBM for the case of ICTA-UAB can benefit from combining the three types of environmental UA-SBMs to improve the environmental performance of the systems and contribution to the reduction of main costs drivers (labour, raw materials) (Bocken et al., 2014; Lüdeke-Freund et al, 2016). However, the focus only on the technological innovations typical for these archetypes aiming to reduce primarily environmental impacts can distract from the achievement of social goals. Hence, the future SBMs for the case of ICTA-UAB can also take advantage of the ASR archetype to guarantee the provision of social benefits on large scale though involving customers in the production process which leads to the reduction of labour cost. Its selection is also because it is the most frequently used UA-SBMs according to the results of this study.

In this regard, an interesting example for reducing labour cost in the literature is through using customers to do the harvest (pick-your-own) which is the highest labour consuming task (Ernst and Woods, 2014). This also can provide them with valuable experience in UA and increase their awareness about the benefits of developing UA in the cities. Moreover, it was argued that offering complementary leisure/educational services (e.g., recreation events, gastronomy, education) to the main production activity related to the ASR can provide notable social benefits and economic revenues (Peña et al., 2022). However, the possibility to running these kinds of services should be future analysed.

The proposed SBM for ICTA-UAB combining four UA-SBM archetypes (WBSR, MRU, SRNP, ARS) can be seen in Table 5.2.

However, this "ideal" combination type was based on internal factors such resources and technological potential, while some external factors such as regulations, governmental restrictions were not considered. In this regard, currently the agricultural production from the i-RTG (ICTA-UAB) cannot be sold since is not possible a commercial license to be obtained due to legal barrier from the General Metropolitan Plan of Barcelona which considers the public land of Barcelona as urban and restricts any UA activities within its metropolitan area (Comisión Provincial de Urbanismo de Barcelona, 1976). Nevertheless, this restriction is for the specific case of the city of Barcelona and does not impede the proposed archetype combination to be implemented for UA cases with similar characteristics if there are not legal obstacles.

Table 5.2 Proposed SBM for ICTA-UAB combining four UA-SBM archetypes: WBSR, MRU, SRNP, ASR. Acronyms: SBM=Sustainable business model; UA=Urban agriculture; ICTA-UAB= Institute for Environmental Science and Technology at Universitat Autònoma de Barcelona; WBSR=Waste-based solutions and reuse; MRU=Maximise the resource use; SRNP=Substitute with renewable and natural processes; ASR= Adopt a stewardship role

VALUE PROPOSITION	Offer	• Urban greens (tomatoes, lettuce, green beans) produced with less resources (water, nutrients, energy) and irrigated with rainwater instead to tap water • Biomass-based (tomato streams) high-quality local materials (e.g., fences and trellises, packaging, boards, panels, and blocks) • Biomass waste for other purposes (heat, bioplastics) • Educational/leisure services (e.g., recreation events, gastronomy, education). • Experience for the customer in UA (pick-your-own)
	Customer segments	• Local people interested in consuming environmentally responsible urban greens (fewer resources, rainwater use) • Local municipalities • Building & construction sector • Other industries interested to use biomass waste as raw material
	Customer relationship	• Mainly direct customer relationship
VALUE CREATION & DELIVERY	Key activities	• Collecting and collecting waste • Reusing cultivation materials • Producing and selling urban greens • Producing and selling biomass-based local materials (e.g., fences and trellises, packaging, boards, panels, and blocks) • Selling biomass waste • Running leisure/educational activities
	Key resources and technology	• Human resources: agricultural workers, qualified personnel • Technology (e.g., automated irrigation system, recirculating system) • Customer to do the harvest task • Raw materials: substrates made from waste, water, energy
	Key channels	• Direct sales (on-farm)
	Key partners:	• Technological I+D centres for research • Universities • Local farmers • Food markets

		• Local municipalities
VALUE CAPTURE	Cost structure	• Labour • Amortisation of technologies • Costs of raw materials
	Revenues streams	• From selling: i) urban greens; ii) biomass-based local material; iii) biomass as raw materials for other uses • From offering leisure/educational services
SUSTAINABLE BENEFITS	Economic benefits (profit):	• Great cost savings thanks to reduced production inputs (e.g., water, energy) lead to increased profit in long term. • Great costs saving from using waste as raw material and reuse materials instead of buying them. • New sources for generating revenues and thus profit, e.g., selling waste as inputs for manufacturing companies producing bioplastics or selling and biomass-based materials. • Great cost savings and thus increase profit in the long term by using renewable sources and/or energies instead of non-finite sources (e.g., tap water) and conventional energy. • Additional revenues and thus profit from running education, leisure/cultural events.
	Environmental benefits (planet)	• Minimising the excessive use of precious scare resources (e.g., fresh water, land) • Reduced waste and emissions as results of improved resource efficiency • Reusing used materials can contribute for reducing the exploitation of virgin materials • Reducing the emissions associated with burning fossil fuels
	Social benefits (people)	• Possible jobs opportunities for people for qualified people (e.g., engineers, architect) and people that maintain the technological innovations related to these archetypes. • Educated society • Improved health • Gaining experience for the customers and raising their awareness about the benefits of developing UA at large scale in the cities.

5.4.Discussion

This section discusses the most relevant findings of this research important to making decisions about the selection of archetypes, their application, and future research to enhance the analysis and development of UA-SBMs.

5.4.1. Four archetypes to be selected for the analysis and design of UA-SBMs

The results of this research demonstrated that the created 11 UA-SBMs have the strong potential to facilitate the deployment of more sustainable UA systems but four of them (WBSR, ASR, MRU, RSE) can be particularly important for the future analysis and development of UA-SBMs due to their i) coverage in the analysed cases (57% from the total 54 analysed references), ii) more positive direct impacts on the SDGs which might be an indicator of their increased sustainable potential since the achievement of the archetypes ´goals lead to immediate one step effect on the SDGs (GMV, 2020), and iii) greater sustainable benefits expected of their implementation since as has been demonstrated in section, these archetypes, especially the ASR and WBSR are characterised with more value propositions and key activities leading to further environmental, social, and economic benefits.

Regarding the ASR, its frequent use is not surprising because it was previously demonstrated that UA has a huge potential to positively contribute to the social and emotional well-being of the urban society (Wakefield et al., 2007) which agrees with the main objective of this archetype to ensure the long-term health and well-being of all stakeholders (Bocken et al., 2014). Moreover, its major implementation in the food sector was previously demonstrated by Ulvenblad et al., (2019) who explained that the common use of the ASR in this industry is a consequence of the unique characteristics of agri-food where there is a commitment to all stakeholders (Harvey, 2001; Bocken et al., 2013). This UA-SBM archetype can be also useful for application in the case of ICTA-UAB since it mainly involves customer participation in the production process which can lead to important labour costs reductions, e.g., through implementing strategies such as pick-your-own where customers do the harvest (the most labour-consuming task) by themselves (Ernst and Woods, 2014). In this regard, reductions in labour costs are important not only for building up successful UA-SBMs but also for introducing UA systems at a large scale in the cities since high labour costs can be an important obstacle (Peña et al., 2022).

Concerning the WBSR, its wide application to enhance the deployment of sustainable UA systems is not unusual because the disposal of waste is a serious problem in many cities (Cofie et al., 2006).

5.4.2. Recommendations for application of UA-SBMs. A research agenda

According to the key findings, the selection and application of archetypes to develop UA-SBMs depends on each individual case, e.g., technologies applied, cultivation practices, main activities, and strategies to reduce main cost drivers. In this regard, a combination of four archetypes was proposed to build up future SBM for the case of ICTA-UAB however due to legal restrictions this combination cannot be currently applied.

Based on this constraint, the first recommendation of this study regarding the application of the archetypes for future analysis and development of future UA-SBMs is about carrying out a previous exhaustive study to evaluate more exactly their selection for a specific case study and if there are some restrictions that can impede their application.

As has been mentioned in section 5.4.1., four archetypes can be relevant for the future analysis and design of UA-SBMs. Thus, despite the archetype being chosen based on a concrete UA case, if it is combined with some of the four UA-SBMS archetypes, greater sustainable benefits might be delivered. Hence, the second recommendation is ASR, WBSR, MRU, and RSE archetypes should be taken seriously into account for the evaluation and design of UA-SBMs.

In this regard, although every single SBMs archetype contributes to sustainable development, this effect will be stronger if different archetypes are combined (Lüdeke-Freund et al, 2016). Moreover, this was also argued by Bocken et al., (2014) who explained that some archetypes would benefit from their combination with other, for instance by combining the ASR and the WBSR. This would be important to overcome their limitations related to negative-side effects expected from their implementation (Boons & Lüdeke-Freund, 2013; Stubbs & Cocklin, 2008).

This was also demonstrated by the results of this study where many successful SBMs examples of UA enterprises combining economical with environmental UA-SBM e.g., Permafungi (Circular Economy Europe, 2021b; PermaFungi, 2021) and Rotterzwan (Circulator, 2021b) where the RSE with the WBSR were combined. Other examples of combining archetypes were the RSE with ASR in the case of Harvest to hope (Oudwater et al., 2013), or the SM with the MRU in the case of Hollbium (Circular X, 2021b). However, future research should analyse which combinations of UA-SBMs can be more successful for this purpose.

Another important consideration for future research is about using a quantitative analysis to reenforce the finding of this study. This is because, sustainable benefits associated with the 11 UA-SBM archetypes and these relation with the SDGs were described by qualitative way. Hence, quantitative methods should be included to quantify the reduction of environmental impacts, and social economic benefits from implementing each sustainable business model for urban agriculture. In this regard, the first would be possible through employing life cycle assessment (LCA), while social life cycle assessment (S-LCA) and life cycle cost (LCC) can be using to calculate social and economic benefits.

Concerning the SDGs, they would be quantified by using some statistical programs, e.g., SPSS, R Studio.

Finally, the improve the research on UA-SBMs, future research should also study the sustainable potential of the rest 7 UA-SBMs which were not frequently in the analysed references.

5.5. Conclusions

The aim of this research was to present a categorisation and characterisation of UA-SBMs to facilitate the deployment of more resource efficient, socially responsible, economically viable and environmentally suitable UA systems.

This paper has a significant contribution to the field since is the first including comprehensive classification of archetypes to be used for future analysis and development of sustainable business models for urban agriculture as far as the authors of this paper are aware.

As a result, a list of 11 UA-SBM archetypes to facilitate the deployment towards more sustainable urban food systems. For its creation, an innovative methodological approach combining four research methods (literature review, content analysis, sustainable development impact analysis, and case study analysis) was used which can be also applied for future SBMs categorisation and characterisation in different research areas.

Each archetype was detailly characterised (value propositions, value creation & delivery; and value capture) and presented by archetype group (environmental, social and economic), where possible limitations of them were also addressed. Moreover, the sustainable potential of the UA-SBMs archetypes to deliver sustainable benefits (environmental, social and economic) was analysed including their relationship with the SDGs 2030. Finally, the archetypes were tested with the ICTA-UAB case study, where a combination of four archetypes was selected to develop a SBM.

Based on the results of this study, it can conclude that four archetypes (Adopt a stewardship role, Waste-based solution and reuse, Maximise the material reuse, and Repurpose for society and environment) have the strongest potential to deliver further sustainable benefits thus they should be necessarily considered for future analysis and development of UA-SBMs.

Another important conclusion is about that the selection of archetype(s) depends on the particular UA case and previous exhaustive study can be conveyed to verify if there some restrictions (e.g., restrictive politics towards UA) that can impede their successful implementation.

Debes concluir algo más sobre la relevancia de aplicar esto a nivel de las ciudades y cómo ello puede apoyar la toma de mejores decisiones por productores de alimentos, urbanistas y políticos, etc.

Although the important contributions of this paper, it has the following limitations. Firstly, the UA-SBMs are elaborated from articles from the academic literature and case studies from the grey literature, and additional database. Therefore, it is difficult to predict new revolutionary innovations that can lead to establishment of new archetypes. Secondly, there was a lack of empirical study to validate externally the list of 11 UA-SBMs and the combination of four archetypes proposed for the future analysis and development of SBM for the case of ICTA-UAB. In this regard, future research should try to prove both empirical studies such as workshops, surveys, or interviews with UA expert.

Despite these limitations, the proposed classification of UA-SBMs could be highly relevant for the future implementation of sustainable UA systems at a large scale since it trying to alleviate emerging problems in the cities, among many are the accumulation of resources, exploitation of resources, social exclusion. Moreover, the archetypes can be useful to design innovative UA-SBMs i) to attract local government investors to make decisions about the implementation of sustainable UA systems in the cities, and ii) to motivate change towards the UA restrictions that still exist in some cities.

PART 5: DISCUSSION, CONCLUSIONS, AND FUTURE RESEARCH

Chapter 6

Discussion

Chapter 6 Discussion of main contribution

This chapter discusses the main contributions of this dissertation to the overall aim to analyse the sustainability urban agriculture (UA), especially integrated rooftop greenhouses (i-RTGs) as innovative forms of UA for sustainable city development, from an life cycle cost (LCC) and sustainable business models (SBM) approach.

The chapter has been organised into three main topics for discussion addressed by **Chapters 3,4,5** as can be seen in Fig.6.1: "Urban agriculture", "Life cycle cost" and "Sustainable business models".

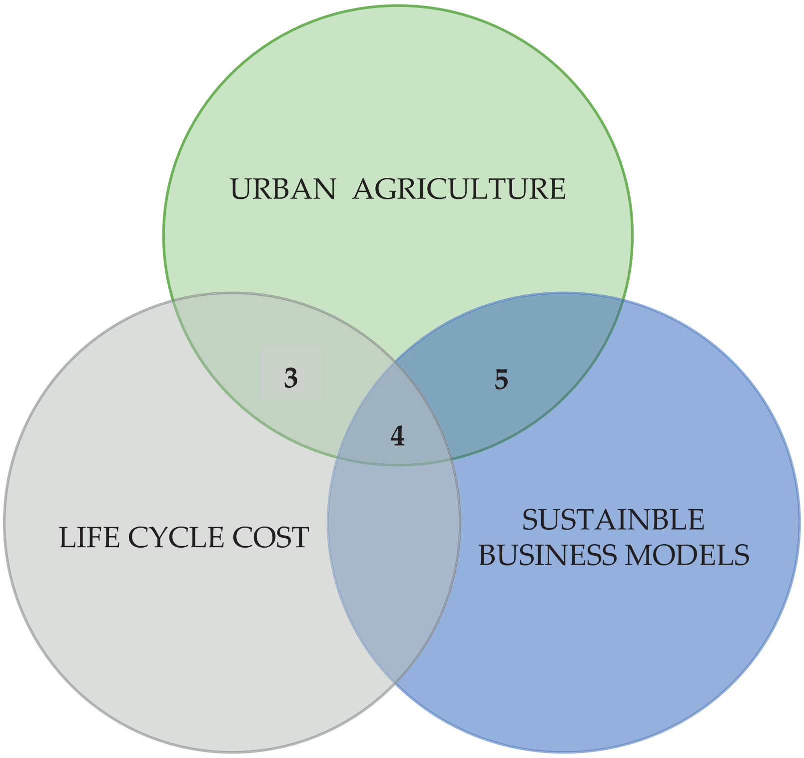


Figure 6.1 Sections in Chapter 6 and interrelation between them in Chapters 3,4,5

6.1. Urban agriculture

Chapters 3,4,5 of this dissertation addressed UA as main research topic and its crucial role to improve the economic sustainability of the urban areas. However, **Chapter 3** and **Chapter 5** did not focus on specific UA form, while **Chapter 4** analysed the economic viability of tomato production in i-RTGs as innovative UA systems.

In this regard, **Chapter 3** main contribution is about the growing tendency in analysing the economic sustainability of economic sustainability of further innovative UA form that take advantage of buildings space and helps for optimisation of main production resources (e.g., water, energy) for their future implementation on large scale. The main reason for this is the insufficient space for traditional agriculture in the cities and the lack of main resources used for production such energy and waters (Specht et al., 2014; Thomaier et al., 2015) as negative outcome of the increased urban population.

This valuable contribution of **Chapter 3**, served to justify the selection of the i-RTGs as advanced form of UA to study the economic viability of urban food production. Finally, in **Chapter 5** built on the results of section 5.3.4, an important contribution regarding UA was that the selection and later application of archetypes to develop sustainable business models (SBMs) for UA depends on each individual case, e.g., UA form (e.g., rooftop greenhouses, indoor farms, rooftop gardens) technologies applied, cultivation practices, main activities, and strategies to reduce main cost drivers.

6.2. Life cycle cost

Chapter 3 main contribution by analysing the use of LCC for the UA sector over a period of 22 years was to give recommendations for improvement of the use of LCC to be applied in **Chapter 4** and forthcoming UA studies.

These recommendations were based on common problems detected in i) the integration of LCC with the LCA, ii) use of additional financial tools, and iii) costs by life cycle stage.

Regarding the integration of the LCC of the LCA, the results of *section 3.3.2.1* clearly demonstrated that the LCA was the principal methodology since the environmental impacts were extensively studied with LCA while the economic evaluation through LCA was incomplete. One possible reason for the deficient LCC analysis was perhaps because the authors who integrated the LCC with LCA had less experience in cost accounting since they main background was environmental sciences. This is important restriction since to make balanced decisions for sustainability improvement in the UA context, the three analyses (LCA, LCC, S-LCA) within the LCSA framework should have same or similar weigh (e.g., 33% for each type of analyses).

Concerning the use of additional financial tools (e.g., net present value, internal rate of return, payback period, break-even point analysis), the results of *section 3.3.2.2* showed that their application is limited. However, ISO (2008) and authors such as Kim et al., (2015), Wong et al., (2003), and Farreny et al., (2011) have suggested their use for complementing the LCC analysis. Therefore, to improve the LCC application in future research, additional financial tools should be considered. Following this recommendation, in **Chapter 4**, an additional break-even point (BEP) analysis was applied to find the optimal level of production to be sold and determine the maximum level of fixed costs at different selling prices.

About the type used of cost by stage, ISO (2008) recommended life cycle cost to be classified in four life cycle stages: i) construction/initial stage including initial investment (Jeong and Lee, 2009; Kim et al., 2015, Wu and Longhurst, 2011; ISO, 2008) or capital costs such infrastructure (e.g., greenhouse structure in Benis et al., 2018; Sanye-Mengual et al., 2015), technical installations (e.g., aquaponic production system in Fochino et al., 2018), and other equipment such as office furniture (Liaros et al., 2016); ii) operation stage covering the following costs accrued during the usage of the asset (ISO, 2008): labour (Benis et al., 2018; Liaros et al., 2016), rent (Liaros et al., 2016), distribution of the gardener transports (Sanye-Mengual et al., 2018a), and production/crop inputs such plants/seeds, water, energy (Love et al., 2015, Sanye-Mengual et al., 2015a; Dorr et al.,2017; Fochino et al., 2018; Benis et al., 2018; Sanye-Mengual et al., 2018; Kim and Zhang, 2018; Opher et al., 2018); iii) maintenance stage including replacement or repair costs of construction materials., e.g., in Zhao and Meng, (2014); Zidar et al., (2017), Kim and Zhang, (2018); and iv) end-of-life (EoL) stage comprising decommissioning/dismantling, demolition, disposal and recycling costs (Fuller and Peterson 1996, ISO, 2008; Jeong et al., 2015) identified in Benis et al., (2018) and (Liarios et al., 2016) (dismantling costs of greenhouse structure and building installations), and Dorr et al., (2017) (recycling costs of water and materials). However, the results of *section 3.3.2.3* highlighted that there was poor use of life cycle stage when calculating LCC and it was difficult to identify how the authors classified costs in each of the life cycle costs. The main explanation for this is that some authors used own classifications when refereeing to the life cycle stage for both LCA and LCC. Nevertheless, the lack of classification of costs in the life cycle stages is not irrelevant since it could restrict the comparison between similar UA studies. Even though ISO (2008) does not require all the stages to be included, for the advance of the UA and its contribution to improve sustainability in the cities, it is fundamental to know the complete LCC cost including all four stages, otherwise , the information generation will be not enough for decision-making.

Another important limitation regarding the use of costs by life cycle costs is the frequent not inclusion of important costs at the life cycle stage, more specially infrastructure at the initial/construction stage and labour at the operation stage. These costs were mainly not considered since they were not considered relevant or due to lack of information (Love et al., 2015), study constrains (Dorr et al., 2017), or concerns about the increase in the total cost when the labour cost was included (Algert et al., 2014). However, the infrastructure costs at the construction/initial stage and the labour at the operation stage should be necessary considered in future research and this could an important condition to improve the LCC application for UA. Regarding the infrastructure cost, it is not inclusion at the initial/construction stage could be a big hurdle in the use of LCC for UA. As has been mentioned before, the growing interest in innovative building-integrated forms of UA will continue in the forthcoming years, hence information about investment costs will be crucial for implementing or not these new systems in the cities. Concerning labour cost, some authors strongly recommend its inclusion at the operation stage since it was characterised as a key operation cost (Woodward 1997; Sanye-Mengual et al., 2015) and its exclusion was the main reason for the incomplete LCC analysis. Another argument labour cost to be necessarily considered in future research is because labour is an important production factor in addition to raw materials and utilities (i.e., energy and water) (Baumgartner and Belevi, 2001). The principal aim of UA is to produce and provide plants and food, in this respect, labour is integral part of the production process. Based on the high importance of costs of the infrastructure at the initial/construction stage and labour at the operation (production) stage, these were indispensably included in **Chapter 4**.

The results of *section 3.3.2.3* also showed that maintenance and end-of-life costs were also mainly avoided because they were considered irrelevant since were times lower than initial/construction or operation costs (Opher et al., 2018), and due to the lack of information about them (Llorach-Massana et al., 2016). Nonetheless, there is also recommendation to be considered in future research for more complete LCC for UA. Regarding end-of-life costs, this is mainly because Lu et al., (2017) explained that disposal and demolition costs, as well as labour cost are principal reason for insufficient LCC analysis for UA. Concerning maintenance costs, since they depend on construction costs, their importance will increase in future.

Regarding the application of LCC in **Chapter 4**, this chapter not only contributed to the identification of four costs drivers (labour, rooftop greenhouse structure, external pest control specialist, rainwater) responsible for 61.8% of the total cost but also provided recommendations for their reduction which is the basic condition to achieve economic viability.

Regarding the first, labour was the core driver accounting for 50.8% of the total variable cost (TVC) and 24.7%of the total cost (TC). The results are consistent with other studies in the literature highlighting that labour is the main cost driver in tomato production (Çetin and Vardar, 2008; Keskin et al., 2010; Barrett et al., 2012; Taki et al., 2013; Testa et al., 2014; Sanyé-Mengual et al., 2015a; Albaladejo-García et al., 2018; Cáceres Hernández et al., 2018). This happens, for example, in Turkey, China and India who are among the top 10-tomato producers worldwide (Çetin and Vardar, 2008) and also applies in Spain and The Netherland, the biggest European tomato producers (Ibarrola-Rivas et al., 2020).

Recently, a study analysing the economic costs for an rooftop greenhouse (RTG) producing tomatoes also demonstrated that the labour was the most important production cost, accounting for more than half of the total cost (54%) (Scattareggia et al., 2022).

Moreover, since it was found that labour cost strongly depends on the working hours, common strategies for reducing labour cost is through using frequently non-paid working hours. For instance, the use of volunteer work is one of the most commonly applied in UA projects (Lui, 2015). Another way is through the “self-pick” strategy. This strategy also called “you-pick”/ “pick-your-own” is a direct marketing approach where customers do the harvest task themselves requires many working hours (Ernst and Woods, 2014; Lui et al., 2015).

The second most important cost was the rooftop greenhouse (122.14 m^2) calculated as 813.3 €/cycle or 6.7 €/cycle (11.4 m^2/year) and it was an integrated part of the building (Sanjuan-Delmás et al., 2018b). This cost was estimated as an average for rooftop greenhouse as described in 4.2.3.1 due to the lack and information being 22.6% higher than the average cost for high tech RTG of 9.3 €/m^2/year (calculated with the average of 329 €/m^2 and 600 €/m^2). However, this cost could have been reduced if a study for optimisation of construction materials had been carried out during the building design phase (Sanjuan-Delmás et al., 2018b). This was also supported by the sensitivity analysis results (4.3.1.1) where the potential variability in the total cost was analysed by comparing the structure of the studied case to the three structural systems suitable to be situated to the roof (e.g., intensive green roof for open-air farming, medium-tech rooftop greenhouse, and high-tech rooftop greenhouse). Moreover, Sanye-Mengual et al., (2015) argued that the rooftop greenhouse could be a possible barrier for future development of UA in the cities so it should be necessarily reduced in forthcoming research.

The third main cost driver was the external pest control specialist (24.5% of the TFC and 12.6% of the TC). It was the service provided from external specialist for monitoring the crops for signs of insect, rodents and other pests. This significant cost could be omitted or avoided in the future by proving specialised training on sustainable pest prevention and control to the personnel responsible for the tomato production. However, this could suppose a possible increase in the cost of labour of the main agriculture worker since more working hours will be needed to complete this task.

Rainwater was the fourth key driver (19.6% of the TVC and 9.5% of the TC) and it was calculated as amortisation of the available rainwater harvest system (RWHS) (pipes, water tank, materials), part of ICTA-UAB building. This cost was more than three-times higher than the cost of tap water, estimated at 2.5 €/m^3 based on 150.9 €/cycle (Aigües de Barcelona, 2020). This was due to the great capacity of the RHWS (water tank, materials used) which was designed to supply rainwater to the toilets, ornamental plants of the building and all crops in the rooftop greenhouses (Sanjuan-Delmás et al., 2018).

Even though the higher cost of the rainwater in comparison with the tap water, at long term rainwater capturing and use may help to reduce tap water consumption and the energy for water treatment and pumping and thus contribute to sustainability. Unlike tap water which scarcity is one of the main environmental concerns (EC, 2010), rainwater is a relatively abundant renewable sources, especially in the Mediterranean region. For instance, it has been predicted that on average in 2051, tap water availability for Catalonia will decrease by 17.8% and in Southern Catalonia, the reduction could be higher 70-75% (Duran et al., 2015). Also, there is an uncertainly with the price of the tap water since a report from the Catalan Water Agency highlighted that in the period 2005-2015, the price of the tap water raised by 50% (5% annual) and this tendency will continue in the next years (Vargas-Parra et al., 2019). Moreover, a previous case study explained that in a Mediterranean climate with low and variable precipitations, the use of RWHSs covered most of the water need for flushing toilets and 60% of the demand for landscape irrigation (Domènech and Saurí, 2011). Similarly, Fragkou et al., (2016) demonstrated the high potential of the Mediterranean region to supply its water needs from rainwater runoff, considering all urbanized areas as collectors, where the water self-sufficiency potential varies from 8% to 500% with an 35 overall average above 100% for the regional system.

Based on the expected contribution of rainwater to improve the water security in urban areas, the RWHS should be optimized in future research in terms of design, materials, and cost. This recommendation is also supported by Sanjuan-Delmás et al., (2018b) where the authors explained that both the rooftop greenhouse structure and the RWHS were exaggerated in size, and the material used for its construction could have been reduced if a study of its optimization had been completed during the building design

6.3. Sustainable business models

The need for study and develop SBMs for UA was firstly mentioned in **Chapter 4** and **Addendum B: Business models** where it was argued that because of the transformative potential of UA to enhance the sustainability of urban food systems and cities, the development of SBMs for UA can contribute to overcoming the limitations related to higher production costs as additional value is offered and delivered to a wide number of stakeholders (Opitz et al., 2016; Sanyé-Mengual et al., 2017; Specht et al., 2014). Moreover, since the balance between expenditure and profits is a key element of each business model (Osterwalder and Pigneur, 2010), the development of SBMs for UA can contribute to cost reductions without increasing the impact on the environment and/or society.

While **Chapter 5** main contribution to the research and practice of UA and SBMs was the elaboration of a comprehensive categorisation and characterisation of SBMs for UA (UA-SBMs) including their relationship with the sustainable development goals (SDGs) to facilitate the deployment of more resource efficient, socially responsible, economically viable and environmentally suitable UA systems. Moreover, recommendations for its application for the analysis and development of future SBMs for UA were as well presented.

This categorisation and characterisation UA-SBMs resulted in 11 archetypes with the strong potential to facilitate the implementation of more sustainable UA systems however the results of sections 5.3.1.2, 5.3.2, and 5.3.3 demonstrated that four (Adopt a stewardship role; Waste-based solution & reuse, Maximise the resource use, Repurpose for society & environment) of them can be especially significant for the future analysis and development of UA-SBMs. This was because of i) their major presence in the analysed cases (57% from the total 54 analysed references); ii) more positive direct impacts on the SDGs which might be an indicator of their increased sustainable potential since the achievement of the archetypes ´goals lead to immediate one step effect on the

SDGs (GMV, 2020), and iii) greater sustainable benefits expected of their application since as has been demonstrated in section, particularly the ASR and WBSR that characterised with more value propositions and key activities leading to further environmental, social, and economic benefits.

Nevertheless, the results of the study indicated that the Adopt a stewardship and the Waste-based solution & reuse archetypes were to some extent better as compared to the rest 2 (Maximise the resource use, Repurpose for the society & environment) since they are considered to have more value propositions and key activities driving to further environmental, social, and economic benefits.

Concerning the Adopt a stewardship , its common application is not surprising since it was earlier demonstrated that UA has a huge potential to positively contribute to the social and emotional well-being of the urban society (Wakefield et al., 2007) which meet completely the main objective of this archetype to ensure the long-term health and well-being of all stakeholders (Bocken et al., 2014). Additionally, its major implementation in the food sector was previously demonstrated by Ulvenblad et al., (2017) who explained that the common use of the Adopt a stewardship in this industry is a consequence of the unique characteristics of agri-food where there is a commitment to all stakeholders (Harvey 2001; Bocken et al. 2013). This archetype was also proposed to develop a SBM for the case of ICTA-UAB since it mainly involves customer participation in the production process which can lead to important labour costs reductions, e.g., through implementing strategies such as pick-your-own where customers do the harvest (the most labour-consuming task) by themselves (Ernst and Woods, 2014). In this regard, reductions in labour costs are important not only for building up successful UA-SBMs but also for introducing UA systems at a large scale in the cities since high labour costs can be an important obstacle (Peña et al., 2022).

Regarding the Waste-based solution & reuse, its extensive application to enhance the establishment of sustainable UA systems is not unusual because the disposal of waste is a serious problem in many cities (Cofie et al., 2006).

Concerning recommendations for applications of the UA-SBMs archetypes, since it was argued the selection and later application of archetypes to develop UA-SBMs depends on each individual UA case, the first recommendation is about carrying out a previous detailed to assess more exactly the selection of UA-SBMs for a specific case study. This can be useful also to detect if there are restrictive politics which might impede their application.

Moreover, despite the archetype being chosen id based on a concrete UA case, if it is combined with some of the four UA-SBMS archetypes, greater sustainable benefits might be delivered. Hence, the second recommendation is ASR, WBSR, MRU, and RSE archetypes should be taken into account for the evaluation and design of UA-SBMs.

In this regard, although every single SBMs archetype contributes to sustainable development, this effect will be stronger if different archetypes are combined (Lüdeke-Freund et al, 2016). Moreover, this was also argued by Bocken et al., (2014) who explained that some archetypes would take advantage from their combination with other, for instance by combining the Adopt a stewardship role and the Waste-based solution & reuse. This would be important to overcome their limitations related to negative-side effects expected from their implementation (Boons & Lüdeke-Freund, 2013; Stubbs & Cocklin, 2008).

This was also confirmed by the results of this study where many successful SBMs examples of UA enterprises combining economical with environmental UA-SBM archetypes, e.g., Permafungi (Circular Economy Europe, 2021b; PermaFungi, 2021) and Rotterzwan (Circulator, 2021b) where the Repurpose for society & environment with the Waste-based solution & reuse were combined. Other examples of combining archetypes were the Repurpose for society & environment with Adopt a stewardship role in the case of Harvest to hope (Oudwater et al., 2013), or the Subscription model with the Maximise the resource use archetypes in the case of Hollbium (Circular X, 2021b).

Chapter 7

General conclusions and future research

Chapter 7 General conclusions and future research

The general conclusions of the dissertation based on specific objectives established in Chapter 1 are presented in section 7.1. While Chapters 3,4,5-specific recommendations for further research are included in section 7.2.

7.1. General conclusions

a) *To analyse the evolution of the use of LCC in UA to identify tendencies and common problems, and to propose recommendations for improvement*

The study carried out in **Chapter 3** is a significant contribution to the field since it is the first attempt to systematize the existing academic literature on the use of LCC for the growing UA sector. The results were useful to identify tendencies and common and to propose recommendations for improvement to be applied in **Chapter 4**.

Regarding important research tendencies, the need for analysing building-integrated forms of UA (e.g., indoor farms, rooftop greenhouses, rooftop gardens) and further innovative forms of UA though using LCC is highlighted since it was found that these are becoming more popular.

Concerning common problems, one of the most important ones was the complementary role of LCC in its integration with LCA since the principal analysis was always LCA, while the LCC was secondary. Moreover, the findings of **Chapter 3** also indicated that LCC analysis was quite limited regarding the costs considered in each life cycle stage. We found that 25% of 16 analysed papers (groups 1, 2, and 4) did not include costs at the initial/construction stage nor did some important costs such cost of infrastructure were not considered. At the operation stage, labour cost, the principal cost of operations, was mainly ignored in 11, or 69%, of the 16 papers from groups 1, 2, and 4. As well as this, the costs at the maintenance and end-of-life stages were also generally excluded by the authors. Only three authors accurately classified the costs by LCC stage (Benis et al. 2018; Liaros et al., 2016; Sanyé-Mengual et al. 2015a), which we consider the basic characteristic of LCC analysis. Additionally, since we found that only Benis et al. (2018) applied all three types of LCC (conventional, environmental, and societal), it can be concluded that the use of LCC analysis for UA is still in its early stages.

Based on the limitations, the first recommendation for improvement is LCA and LCC analyses to be applied at the same level. To accomplish this, LCC should be executed by people with relatively more expertise in cost accounting. Secondly, the inclusion of costs at the initial or construction stage is a necessary condition in order to improve the current use of LCC for UA and to evaluate its economic sustainability. In this regard, special attention needs to be paid to the labour costs at the operation stage, as it is an essential part of the production process. To this effect, lack of information should not be an excuse for not including essential costs. Lastly, all four main LCC stages should be considered in future research for more complete LCC analyses for UA. The use of additional financial tools, such as NPV, IRR and PBP, would be advisable to complement LCC analysis.

In **Chapter 4**, some of these recommendations were applied. For instance, the inclusion of important initial and operational costs such infrastructure (rooftop greenhouse structure) and labour. Moreover, a break-even point (BEP) analysis was applied as additional financial tool to find the optimal level of production to be sold and determinate the maximum level of fixed costs at different selling prices.

b) *To analyse the economic viability of urban food production from an i-RTG through LCC to (i) identify main cost drivers and propose different approaches to reduce them; and (ii) to examine production level output as an important variable affecting the economic viability and profitability*

The study performed in **Chapter 4** is the first study analysing the life cycle economic viability of tomato production in i-RTGs including essential costs such as labour and infrastructure, which tend to be missing in research on UA.

The results showed that the production stage had a major contribution to the total cost and five cost categories (direct labour, external services, raw materials, buildings, and technical installations) account for 90.2% of it. The main cost drivers are labour, rooftop greenhouse structure, external pest control specialist and rainwater, defining nearly 62% of the total cost. Therefore, the reduction of these costs is an essential requirement to achieve economic viability.

An important finding that makes a valuable contribution to the literature on innovative rooftop greenhouse tomato production is that there was the same efficiency in the main cost driver, labour (hours spent per m^2) both (i) in two different tomato production systems (conventional greenhouses versus innovative i-RTG) and (ii) in two different size productions (large versus small).

The managerial implications obtained from findings to facilitate the economic viability and contribute to the implementation of i-RTG production are derived from (i) the reduction strategies of cost drivers and (ii) to stablish the adequate production level output. Concerning the reduction of cost drivers (labour, rooftop greenhouse structure, external pest control specialist and rainwater cost), labour and rooftop greenhouse structure are crucial. As the core cost driver (50.8% of total variable cost and 24.7% of total cost) considered strategies for labour cost reduction were: (i) use of volunteer work, and (ii) customers' participation in harvest task. In regard to the second cost driver, the rooftop greenhouse structure, that could be a possible barrier for implementing these innovative UA systems on a large scale (Sanyé-Mengual et al., 2015) it is a key condition to reduce its cost optimising prototypes, materials, and sizes (e.g., small, medium and large) to allow making decisions for this initial investment. Regarding the third and fourth cost drivers, the external pest control specialist could be reduced or avoided if staff training was provided, and the rainwater cost could be decreased by optimising the rainwater tank size according to the productive area. Last, the size of production area is relevant for the role of production level output. As break-even point demonstrated, high fixed costs and low yields is a combination that impede the economic viability and profitability of i-RTG tomato production.

c) *To create a comprehensive categorisation and characterisation of sustainable business models for urban agriculture and to provide recommendations for their selection and posterior application to facilitate the deployment of more sustainable UA systems*

The aim of research performed in **Chapter 5** was to present a categorisation and characterisation of UA-SBMs to facilitate the deployment of more resource efficient, socially responsible, economically viable and environmentally suitable UA systems.

This is a significant contribution to the field since is the first study including comprehensive classification of archetypes to be used for future analysis and development of sustainable business models for urban agriculture. Moreover, this classification can help to building up innovative UA-SBMs useful to attract local government investment to implement sustainable UA systems at large scale and to inspire change towards restive UA politics that exist in some urban areas.

As a result, a list of 11 UA-SBM archetypes to facilitate the deployment towards more sustainable urban food systems. For its creation, an innovative methodological approach combining four research methods (literature review, content analysis, sustainable development impact analysis, and case study analysis) was used which can be also applied for future SBMs categorisation and characterisation in different research areas.

Each archetype was detailly characterised (value propositions, value creation & delivery; and value capture) and presented by archetype group (environmental, social and economic), where possible limitations of them were also addressed. Additionally, the sustainable potential of the UA-SBMs archetypes to deliver sustainable benefits (environmental, social and economic) was analysed including their relationship with the SDG 2030. Finally, the archetypes were tested with the ICTA-UAB case study, where a combination of four archetypes was selected to develop a SBM.

Based on the results of this study, it can conclude that four archetypes ("Adopt a stewardship role", "Waste-based solution and reuse", "Maximise the material reuse", and "Repurpose for society and environment) can be especially relevant for the future analysis and development of UA-SBMs because of their major presence in most analysed references and increased sustainable potential.

Regarding the application of the archetypes for analysis and development UA-SBMs, the following recommendations can be drawn: i) the selection of archetype(s) depends on the particular UA case and previous exhaustive study can be conveyed to verify if there some restrictions (e.g., restrictive politics) that can impede their implementation; and ii) since the four archetypes were demonstrated to have the strongest potential to deliver further sustainable benefits therefore they should be essentially considered for future analysis and development of UA-SBMs.

7.2. Future research

Chapter 3,4,5-specific recommendations for further research are detailed below.

Chapter 3	**Perform** similar literature review on the use of LCC for UA considering other UA agricultural activities (e.g., production and sale of agricultural inputs, post-harvesting, marketing, and commercialization of agricultural production).
	Apply the LCA and the LCC analyses for UA at the same level to make balanced decisions about sustainability.
	Include essential initial and operating costs such as infrastructure and labour to improve the current use of LCC for UA.
	Complete the LCC analysis for UA by including additional financial tools, such as net present value (NPV), internal rate of return (IRR), and payback period (PBP).
	Perform more complete LCC by including costs at the maintenance stage, if they were significant, and at the EoL stage with the cost of decommissioning the greenhouse structure
Chapter 4	**Perform** more complete LCC by including costs at the maintenance stage, if they were significant, and at the end-of-life stage with the cost of decommissioning the greenhouse structure.
	Optimise the rooftop greenhouse structure and the rainwater harvesting systems (design, materials and cost) for different sizes (e.g., small, medium and large) to achieve economic viability.
	Consider cold climatic zones to perform the same LCC analysis since some costs such as energy for heating to guarantee an adequate temperature for plants could be bigger.
	For fuller LCC analysis, the economic costs of innovative technical installations (e.g., water recycling system and other future systems) used to reduce environmental impacts and external environmental costs should be considered.
	Develop a sustainable business model for rooftop greenhouse food production to contribute to economic cost reductions and improved environmental and social impacts**.**
	Analyse the social aspects of UA in rooftop greenhouses could contribute to the promotion of food production for self-sufficiency in urban areas, in line with the promotion that energy production for the self-sufficiency is being strongly encouraged by all levels of public administrations.
Chapter 5	**Analyse** which combinations of UA-SBMs archetypes can be more successful to facilitate the deployment of more sustainable UA system and to overcome limitations related to negative-side effects expected from their implementation.
	Employ LCA, S-LCA and LCC analyses to quantify the reduction of environmental impacts, and social economic benefits from implementing each UA-SBM archetype.
	Quantify the impacts of the UA-SBM archetypes on the SDGs by using some statistical programs, e.g., SPSS, R Studio.
	Study the sustainable potential of the rest 7 UA-SBMs which were not frequently in the analysed references.
	Conduct an empirical study to validate externally the list of 11 UA-SBMs and the combination of four archetypes proposed for the future analysis and development of SBM for the case of ICTA-UAB.

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Appendixes

Appendix 1. Supporting data related to Chapter 4

Appendix 2 Supporting data related to Chapter 5

Appendix 1. Supporting data related to Chapter 4

Appendix 1.1 The i-RTG on the ICTA-ICP LEED-Gold certified building. Source: Fertilecity project. https://www.fertilecity.com/en/

Appendix 1.2 Coeur de boeuf tomatoes cultivated in a hydroponic system. Photos from the beginning of the crop and from the first harvest

Appendix 1.3 Full life cycle cost inventory of RTG tomato production in 2019

Life-cycle stage	Cost category	Item and units	Lifespan (years)	Quantity (physical units)		Cost (€)[1]	
				Cycle° (1.608 kg)	1 kg	Cycle° (1.608kg)	1 kg
INFRASTRUCTURE							
	INTANGIBLE ASSETS:						
	1. Computer software	Computer software for sensors data	10	5.46E-05	5.46E-05	35.9	0.03
	TANGIBLE ASSETS:						
	1.Buildings	i-RTG structure (122.14 m 2)	50	1.17E-02	1.09E-05	813.3	0.8
	2. Technical installations[2]	2.1. Rainwater harvest (RHW) system (ICTA-UAB):	50	1.17E-02	1.09E-05	Check rainwater	
		Galvanized channel					
		HDPE pipe D 200 (collection of rainwater)					
		HDPE pipe D 250 (entry of rainwater)					
		Rainwater filtration set of ionfilter with pumping equipment for external tank. filtration. chlorination and Ph regulation					
		HDPE pipe between tank filter. D250					
		2.1.6. Horizontal tank for burial (GFR). capacity 100 m3 length 11.20m x inner diameter 3.5m					

		Submersible pump. 230V. Power HP = 2. 1.5KW. flow 6m3 / h-59 m.c.d.o					
		Pipe PE-50 between the tank and the irrigation collector					
		Irrigation collector					
		Distribution pipe (PE-32) to the water tank in i-RTG Lab1					
		2.2. System of sensors (i-RTG)	10	5.83E-02	5.46E-05	260.7	0.24
		2.2.1. Part I: Temperature and relative humidity:					
		CS215 probe temperature / relative humidity. digital output SDI-12. 40 m wire					
		Radiation and rain protector for C215					
		Aluminium arm 60cm X D.34mm with anchor to vertical pole					
		Part 2: Solar radiation:					
		LP02-TR Pyro thermometer with levelling plate					
		Solar Sensor platform for LP02-TR					
		2.3. Irrigation system (i-RTG):	10	5.83E-02	5.46E-05	236.6	0.22
		2.3.1. Part I: Headboard:					
		Rainwater tank (300 L)					
		Nutrient tank (80 L)					

		Tank hose					
		Deposit fitting. 3/4 x 3/4 x 70mm					
		Water pipe D.25 (connection)					
		Water pipe D.32 (connection)					
		Irrigation Pump. MH-104M					
		Metal support for the irrigation pump					
		Hydraulic dosing machines “Dosatron”					
		Solenoid valves					
		Irrigation programmer					
		Glycerin pressure gauges					
		Water meter					
		Plastic table 71cmx102cm (support headboard)					
		Metal rings D.28 (headboard support)					
		Screws for metal rings					
		Square 4-socket strip					
		Ball valve for gluing (EPDM) d = 32 PE					
		Ball valve for gluing (EPDM) d = 25 PE					
		Ball threaded valve EPDM 1¨ PE					
		Smooth non-return valve PVC EPDM 32x32					

		Valve with polyethylene buoy B.P. 1/2 ¨					
		PVC elbow PN16 90 ° D.25					
		PVC elbow PN16 90 ° D.32					
		PVC elbow PN16 45° D.25					
		PVC elbow PN16 45 ° D.32					
		Smooth 3-piece link. D.32					
		Smooth 3-piece link. D.25					
		Mixed 3-piece link. D.32					
		Acrylic Electric Cable 3x15					
		Tap 3/4 "					
		2.3.2. Part II: Irrigation distribution:					
		Main distribution pipe (PVC) D.25					
		Distribution pipe (PVC. D.16) to production lines with integrated drippers					
		Metal collar 25 MM 1/2 for thr main pipe					
		Elbow 90º for 16 mm tubes					
		End cap 16 mm					
		Shut-off valve 16mm for irrigation system					
		Microtube for a hydroponic crop with a dropper					

		2.4. Curtains and partitions system (i-RTG):	10	5.83E-02	5.46E-05	139.9	0.13
		Translucent curtain for solar reflection 4.5 x 19m					
		Translucent curtain 4.5 x 6.5 m					
		Aluminized thermal insulation curtain 4.5 x 19 m					
		Aluminized curtain 4.5 x 6.5					
		2.5. Production supporting system (i-RTG):	3	1.94E-01	1.82E-04	45.1	0.04
		Perlite substrate bags					
		Bobbin for tomato plant					
	3. Machinery	Balance; maximum: 6.5 kg	5	1.17E-01	1.09E- 04		
		Balance; maximum: 60 kg		1.17E-01	1.09E- 04		
		Conductivity tester		1.17E-01	1.09E- 04		
		Ph tester		1.17E-01	1.09E- 04		
		Backpack Sprayer. capacity 12L		1.17E-01	1.09E- 04		
		Backpack Sprayer. capacity 1L		1.17E-01	1.09E- 04		
		High pressure cleaner		1.17E-01	1.09E- 04		
		Hand pallet truck up to 300 kg		1.17E-01	1.09E- 04		
		Security camera		1.17E-01	1.09E- 04		
		Total				*323.1*	*0.3*
	4. Equipment	Hose.25 meter	5	1.17E-01	1.09E- 04		
		Hose holder		1.17E-01	1.09E- 04		
		Broom		2.33E-01	2.18E-04		
		Dustpan		1.17E-01	1.09E- 04		

		Nylon working gloves		4.67E-01	4.37E-04		
		Goatskin working gloves		1.17E-01	1.09E- 04		
		Pruning scissors		3.50E-01	3.28E-04		
		Belt (pruning scissors)		1.17E-01	1.09E- 04		
		Cover for pruning scissor		2.33E-01	2.18E-04		
		Drill. 710W		1.17E-01	1.09E- 04		
		Protective glasses		1.17E-01	1.09E- 04		
		Protective mask		1.17E-01	1.09E- 04		
		Tool case		1.17E-01	1.09E- 04		
		Pliers		3.50E-01	3.28E-04		
		Blade cutter		1.17E-01	1.09E- 04		
		Screwdriver		4.67E-01	4.37E-04		
		Flexometer. 5m		1.17E-01	1.09E- 04		
		Wrenches		2.33E-01	2.18E-04		
		Hammer		1.17E-01	1.09E- 04		
		Handsaw		1.17E-01	1.09E- 04		
		Flange tension gun		1.17E-01	1.09E- 04		
		Polyethylene shovels.		4.67E-01	4.37E-04		
		Electrician scissors		1.17E-01	1.09E- 04		
		Total				*60.2*	*0.06*
	5. Furniture	Wooden wardrobe (120x50x189 cm)	5	1.17E-01	1.09E- 04		
		Wooden table (180 cm x 68 cm)		1.17E-01	1.09E- 04		
		Aluminium ladder. 8 steps. platform height 1.72m		1.17E-01	1.09E- 04		
		PVC rolling stool		1.17E-01	1.09E- 04		

		Plastic bin. capacity 60kg and 120L		1.17E-01	1.09E- 04		
		Total				*24.6*	*0.023*
	6. Information technology equipment	Desktop computer	10	5.83E-02	5.46E-05	20.9	0.02
	Total Infrastructure stage (I)					1,960.30	1.8
PRODUCTION	*PRODUCTION INPUTS:*						
	1. Labour	Direct labour (hrs)		239.00	2.21E-01	1339.7	1.3
	2. External services	External pest control specialist (euro)		estimation	estimation	682.2	0.6
		Electrical energy (Kwh)		1903.00	1.78E+00	189.3	0.18
		Pruning waste (unit)		1.00	1.78E+00	142.8	0.13
	3. Raw materials						
	3.1. Water (m3)	Rainwater[3]		59.5	5.57E-02	517.4	0.5
	3.2. Biological control	Macrolophus caliginosus 500 individuals (Kg)		0.2	1.87E-04		
		Phytoseiulus persimilis2.000 individuals (Kg)		0.5	4.68E-04		
		Food for organism (Kg)		0.01	9.36E-06		
		Total				*167.3*	*0.16*
	3.3. Fertilizers	Monopotassium phosphate (KH2PO4)		15.29	1.43E-02		
		Potassium nitrate (KNO3)		7.46	6.99E-03		
		Calcium chloride (CaCl2);		7.19	6.73E-03		
		Magnesium nitrate Mg (NO3)2		9.61	9.00E-03		
		Potassium sulfate (K2SO4)		19.86	1.86E-02		

		Calcium nitrate Ca (NO3)2		28.85	2.70E-02		
		Sequestrene (Fe)		0.61	5.71E-02		
		Hortrilon (Fe. Mn. Zn. Cu. B. Mo)		0.61	5.71E-02		
		Total				*92.2*	*0.09*
	3.4. Plants	Tomatoes plants		171.00	0.16	68.2	0.064
	3.5. Sudry materials	Clips for tomato plant		2565.00	2.40E+00		
		Protection clothing		16.00	1.50E-02		
		Disposable gloves		50.00	4.68E-02		
		Biomass collection bags		30.00	2.81E-02		
		Recyclable plastic bags		4.00	3.75E-03		
		Total				*65.8*	*0.062*
	3.6. Pesticides (Kg)	Sulfur (S)		0.155	1.45E-04		
		Heliosufre (sulfur 72%)		0.432	4.04E-04		
		Insecticidal soap		0.076	7.12E-05		
		Neemazal (natural insecticide)		0.269	2.52E-04		
	3.7 Waste management (unit)	Final biomass waste collection		1.00	9.36E-04	169.4	0.2
		Total				*27.2*	*0.03*
	Total Production stage (II)					5.3	3.1
TOTAL (I+II)						5,421.8	5.1

Appendix 1.4. Template used for registering the working hours spent on the crop by cultivation tasks and their periodicity

		Occupation	Daily task				Frequently tasks			Punctual tasks					Other tasks	TOTAL TIME
Date	Name	Phd Student, Student on an internship, Technician, etc.	Plants monitoring	Water monitoring	Staking	Pruning	Cleaning	Harvest	Nutrient solution (preparation)	Planting	Incident management	Purchase (materials and others)	Preparation before planting (mounting included)	Dismantling of the crop (end-of-life)	Please specify	Daily in minute

Appendix 1.5 Costs of different rooftop farming system used in the sensitivity analysis

Cost(€/m^2)	*intensive green roof for open-air cultivation*	*Medium-tech greenhouse*			*High-tech greenhouse*			*i-RTG (ICTA-UAB)*
		ground	*roof (average)*	*average cost (roof)*	*ground*	*roof (average)*	*average cost (roof)*	*average cost (roof)*
	130	26-88	78-264	171	126-252	329-600	465	570

Appendix 1.6 Results of BEP analysis based on 1 kg of tomatoes has an average of 5 units and that all produced tomatoes are commercialized

Selling price *(VAT excluded)*	Fixed cost *(2019)*	Variable costs *(2019)*	Variable cost *(unit)*	Selling price *(unit)*	Units to be produced and sold	
					Total	*Average*
3.0 €				0.60 €	25,321	
3.1 €				0.62 €	21,425	
3.2 €				0.64 €	18,569	19,272
3.3 €				0.66 €	16,384	
3.4 €				0.68 €	14,659	
3.5 €				0.70 €	13,263	
3.6 €				0.72 €	12,110	
3.7 €				0.74 €	11,141	11,287
3.8 €				0.76 €	10,316	
3.9 €				0.78 €	9,604	
4.0 €				0.80 €	8,985	
4.1 €				0.82 €	8,440	
4.2 €	2,785.3 €	2,636.5 €	0.49 €	0.84 €	7,958	8,011
4.3 €				0.86 €	7,528	
4.4 €				0.88 €	7,142	
4.5 €				0.90 €	6,793	
4.6 €				0.92 €	6,477	
4.7 €				0.94 €	6,190	6,089
4.8 €				0.96 €	5,926	
4.9 €				0.98 €	5,684	
5.0 €				1.00 €	5,461	
5.1 €				1.02 €	5,255	
5.2 €				1.04 €	5,064	
5.3 €				1.06 €	4,886	4,898
5.4 €				1.08 €	4,721	
5.5 €				1.10 €	4,566	

Appendix 1.7 Level of fixed costs at different selling prices for tomato

Selling price per kg (VAT excluded)	Fixed cost at selling price (€)		Fixed costs (2019)	Variable cost (unit)	Selling price (€ per unit)	Units (average) (2018-2019)	Variation % (Fixed cost at selling price-Fixed costs 2019)	
		Average						*Average*
3.0 €	596				0.60 €		-78.6%	
3.1 €	704				0.62 €		-74.7%	
3.2 €	812				0.64 €		-70.8%	
3.3 €	921	920.6			0.66 €		-66.9%	-66.9%
3.4 €	1,029				0.68 €		-63.1%	
3.5 €	1,137				0.70 €		-59.2%	
3.6 €	1,245				0.72 €		-55.3%	
3.7 €	1,354				0.74 €		-51.4%	
3.8 €	1,462				0.76 €		-47.5%	
3.9 €	1,570				0.78 €		-43.6%	
4.0 €	1,679	1,678.7			0.80 €		-39.7%	-39.7%
4.1 €	1,787				0.82 €		-35.8%	
4.2 €	1,895		2,785.3 €	0.49 €	0.84 €	5,415	-32.0%	
4.3 €	2,004				0.86 €		-28.1%	
4.4 €	2,112				0.88 €		-24.2%	
4.5 €	2,220				0.90 €		-20.3%	
4.6 €	2,328				0.92 €		-16.4%	
4.7 €	2,437	2,436.8			0.94 €		-12.5%	-12.5%
4.8 €	2,545				0.96 €		-8.6%	
4.9 €	2,653				0.98 €		-4.7%	
5.0 €	2,762				1.00 €		-0.8%	

Appendix 2 Supporting data related to Chapter 5

Appendix 2.1 Case studies selected

Reference	Case/Name of reference	Description or objective	Source
The Plant (2021)	The Plant	A collaborative community of urban food production businesses	Ellen MacArthur Foundation (2021)
Lufa Farms (2021)	Lufa Farms	A rooftop greenhouse (RTG) urban agricultural company	
Circle-lab (2018a) and Square roots(2021)	Square Roots	Vertical urban farm	
Circle-lab (2018b) and Cityplot (2021)	Cityplot	A collective of urban food growers, educators and permaculturedesigners	
Circle-lab (2019) and Robert-Jan Vos(2018)	The Green House	Restaurant, urban farm, green hub and city terrace	
Circle-lab (2020) and Grocycle (2021)	GroCycle	Murshooms urban farming	
Circle-lab (2021b) and Atlas Obscura(2021)	Floating farm	A floating urban farm	
Circle-lab (2021c) and AgFunder (2016)	BrightFarms	An indoor urban farm	
Circle-lab (2021d)	Abalimi Bezekhaya	An non-profit that aims to increase food supply and create livelihoodsthrough home gardening	
Circle-lab (2021e) and Weber de Morais (2013)	Acca Working Group	A wastewater aquaculture	

			Circle-lab (2021a)
SINTRA (2017a), Silmusalaatti (2021)	Silmusalaatti	Urban farm in Helsinki, Finland	SINTRA Circular Economy Europe (2021a)
SINTRA (2017b) and Helseni (2021)	Helseni	Mushrooms urban farm	
SINTRA (2017c)	Finsect	Insect urban farm	
European circular economy stakeholder platform (2021b); PermaFungi (2021)	PermaFungi	Mushrooms urban farm	
European circular economy stakeholder platform (2021c)	De potteri	Incubator of urban agriculture	European circular economy stakeholder platform (2021a)
Go Explorer (2018a) and Local Food Nodes (2021)	Local Food Nodes	App connects local food producers and consumers through a digitalmarketplace and physical pick-up nodes	Go Explorer (2021)
Go Explorer (2018b)	Artemis	Intelligent indoor farming platform	
Go Explorer (2018c)	OLIO	App that connects communities through food sharing	
Go Explorer (2018d) and Sky Greens(2021)	Sky Greens	The world's first low carbon, hydraulic driven vertical farm	
Go Explorer (2018e)	Terreform	Modular, dual-purpose insect farm	
Go Explorer (2019) and Agricool (2021)	Agricool	Urban aeroponic farming in shipping containers	
Go Explorer (2020) and Rooftop Republic (2021)	Rooftop republic	Urban farming solutions. Rooftop gardens	
State of green (2021b)	BioPod	Container solution for vertical farming	State of green (2021a)

Circulator (2021b)	Rotterzwan	Mushrooms urban farming	Circulator (2021a)
Circular X (2021b); Hollbuim, (2021)	Hollbuim	Hydroponics-as-a-service that supports indoor vertical farming	Circularx (2021a)
Oudwater et al., (2013)	Prove	A federal programme on processing and marketing of small-scale family production in Brasilia (Brasil).	
	Harvest of Hope	A vegetable box scheme in Cape Town (South Africa)	
	Schaduf	It supports low-income families and individuals to generate additional income by helping them to grow vegetables on their roofs and to market their produce	
	Belo Horizonte Food securityprogramme	Municipal Food security programme which serves to facilitating andassuring the right to food for all in Belo Horizonte (Brasil)	
	Jinghe	Online membership farm	
	Amir Women´s association	Packaging, marketing and selling of the onions	
	Canasta Comunitaria	A grass-root movement which strives to make healthy food affordablefor low-income city dwellers	
	PAU Argentina	Municipal programme for urban agriculture PAU, Rosario Argentina	
	Jagrashisha Farm	Wastewater-fed aquaculture in Kolkata (Calcutta), India	
	Yaonde Gameroon	Reuse of faecal sludge for forage production	
	Buobai Co-composting Plant	Co-composting faecal sludge and solid waste in Kumasi, Ghana	

Cofie et al., (2013)	ECOSAN	Reuse of urine as liquid fertilizer in Ouagadougou (Burkina Faso)	Cordis projects database (CORDIS, 2021): SUPURBFOOD (Towards sustainable modes of urban and peri-urban food provisioning)
	Sulabh	Biogas generating enterprise	
	Waste Enterprisers	Faecal sludge to energy in Kumasi (Ghana)	
	Balangoda Urban Council	Production of compost from household waste	
	Deco	Decentralized composting for sustainable farming and development	
	Thai Biogas Energy Company (TBEC)	Biogas production	
	Waste Concern	Conversion of solid waste to compost in Dhaka (Bangladesh)	
	Cess pit	Use of fecal sludge (FS) fertilizer in Tamale (Ghana)	
Instagreen (2021) and InstaGreen (2016);	Instagreen	Microgreens urban farming	Cordis projects database (CORDIS, 2021):InstaGreen (Bringing Local and Sustainable Produce Back to the City)
Infarm (2018) and Infarm (2021)	Infarm	Urban farms in grocery stores	Cordis projects database (CORDIS, 2021): INFARM (The vertical farmintg revolution, urban Farming as a Service)
R2π (2019)	ECF farms	An aquaponic urban farm	Cordis projects database (CORDIS, 2021): R2PI (TRANSITION FROM LINEAR 2 CIRCULAR: POLICY AND

			INNOVATION)
	Menjadors Ecològics	Initiative to ntroduce more healthy, educational and sustainable models in school canteens	
	Terra Coopa	Initiative to support job creation related to urban farming and short marketing channels	
	Chez les Producteurs	A collective outlet	
	Campi Aperti	An association which brings together organic and biodynamic farmers	
	Mia organic	organic farming and the sale of organic food produced by other Albanian farmers	
	Farmers markets	Physical marketplace	
	Can Pinyol	Social gardens in Sant Boi de Llobregat	
	CPIE Bassin	Non-profit association that supports local authorities in their sustainabledevelopment actions	
	Jardin des Aures	An eco-site combining cultural, educational and gardening activities	
	Fattoria urbana	Educational activities on sustainability and food quality	
	Luan Balili	Green area for growing fruits and vegetables	
	Neapoli Sykies	Allotment gardens and cultivation activities	
	Aplec Aplec	An annual event dedicated to raise awareness on urban agriculture	

MADRE (2018)	Pic’assiette	A non-profit association aiming to raise awareness on healthy lifestyles and fair food practices	Interreg Mediterranean projects (Interreg Mediterranean, 2021): MADRE (Metropolitan agriculture for developing an innovative, sustainable, and responsible economy)
	Filière Paysanne	A network of grocecy stores	
	Arvaia	Distribution of organic products, cultivation of vegetables and educational activities	
	Blerina Bombaj	Agro-ecological farm and restaurant	
	Perka	An informal group promoting urban agriculture	
	Baix Lobregat	Urban agrarian park in Barcelona Metropolian area	
	Mercadis	A wholesale market in the promotion of local and organic agriculture	
	Le Serre dei Giardini Margherita	A multi-functional place for many local activities, including urban agriculture	
	Green Belt of Tirana	A project involves the planting of shrubs and fruit trees to control soil erosion	
	Urgenci	A non-profit association, which brings together national community suported agriculture (CSA) networks	
ORHI (2019)	Freight farms	A vertical hydroponic farm	Interreg PROCTEFA projects (Interreg POCTEFA, 2021): ORHI project
	Fresh Guru	High-tech greenhouses	

Eung-Jik et al., (2012)	Green Community Rediscovery Center (GCRC)	Ecopark and community gardens with environmental education programs	Journal paper
Krul & Ho (2017)	Alternative Approaches to Food: Community Supported Agriculture in Urban China	Community supported agriculture (CSA)	
Usman and Nanda, 2017	Green business opportunity of coffee ground waste through reverse logistics	Green business opportunity of coffee ground through reverse logistics in supporting urban farming.	
Balcarová et al., 2016	Farmers Market: Customer Relationship	Farmer market as a sustainable business model	
Aston, 2014	Intellectual capita in social enterprises	Social enterprise as a business model	
Heckmann, 2018	A case report on inVALUABLE: insect value chain in a circular bioeconomy	Sustainable resource-efficient industry for animal production based on insects	
Smith-Nonini, 2016	Inventing Eco-Cycle. A Social Enterprise Approach to Sustainability Education	Social enterprise project based on education	
Vitiello and Wolf-Powers, 2014	Hantz farms	Urban farm in Detroit	Journal paper
	Urban farming organizations Growing Power and Growing Home	Urban agriculture social enterprises	
	Milwaukee-based Growing Power		

	Growing Home in Chicago		
	Detroit Garden Resource Program’s Grown in Detroit Cooperative	Non-profit community gardening programme	
Vieira et al., 2019	City farm	City farm is used for growing food and educational activities	Journal paper
	Community garden facilitator	Community garden on private and public lands	
	Pop-up market	Fruit and vegetable markets	
Recasens et al., 2016	ALL1	Wineries in a peri-urban wine region	Journal paper
	ALL2		
	ALL3		
	BDN		
	MRTLLS		
	SMM		
	TN1		
	TN2		
	TN3		

Armanda et al., 2018	Farm 360 80-acre farm Gotham Greens Green Girls Aerofarms Farmed Here The Plant Broklyn Grange Green Spirit Farm Growing underground La Cavere Urban Farmers Plant Lab Badia Farm Nuvege Sky Greens Pasona O2 i Farm	Indoor vertical hydroponic farming Indoor vertical hydroponic farming Rooftop and indoor hydroponic farming Greenhouse/indoor hydroponic farming Aeroponic, indoor/greenhouse farming Indoor vertical greenhouse with aquaponic and aeroponic Aquaponics and greenhouse Soil based open rooftop farming Indoor farming Hydroponics vertical farming Hydroponics indoor vertical farming Aquaponics indoor and rooftop greenhouse Greenhouse indoor vertical farming Hydroponic indoor vertical farming Hydroponic indoor vertical farming Soil based and hydroponics indoor vertical greenhouse Hydroponic indoor and rooftop greenhouse Vertical greenhouse/indoor farming	Journal paper
Martin & Bustamante, 2021	Growing-Service Systems: New Business Models for	Growing-service systems for urban farming	Journal paper

	Modular Urban-Vertical Farming		
Daves & Garrett, 2018	Technology for Sustainable Urban Food Ecosystems in the Developing World: Strengthening the Nexus of Food–Water–Energy–Nutrition	The role of the innovative technology for fostering sustainable business development for urban agriculture	
Gittins & Morland, 2021	Is 'Growing Better' ripe for development? Creating an urban farm for social impact	Urban farming with social impact	
Scharf et al., 2019	Foodsharing Mundraub The Peace of Land Urban Garden	An open online platform where the self-organized community organizes the collection of food waste in different retail companies throughout Germany. An open online platform for the discovery and usage of edible landscapes and enables the community to map fruit trees and other edible plants in public spaces worldwide. A self-governed community garden in the district of Prenzlauer Berg has provided space for workshops and other educational offers regarding (social) permaculture, community building and organization, architecture, self-sufficiency, and urban food production.	Journal paper

	Food Coop Wedding-West	A 30-year-old food cooperative, decisions regarding production, distribution, and the type of food product are independently made by cooperative members	
	Baumhaus	An open socio-cultural, self-organized initiative “grown out of the neighborhood. “The initiative is a growing community, building project, and event space that supports and hosts different social and ecological projects in their rooms"	
	The Food Council of Berlin	A civic-society institution, consisting of different actors that are committed to ecological, sustainable, and equitable food production and distribution in the area of Berlin	
	The Urban Research Group	A self-organized collective of five doctoral and postdoctoral researchers from different backgrounds with current research foci on urban commons and new developments in critical urban studies	
		Commons support the ability for self-empowerment and initiate the engagement of the citizens	

	The Leibniz Centre for Agricultural Landscape Research: Grünflächenamtt	This interviewee is head of project development and citizen participation in one of Berlin’s District Departments of Parks and Green Areas (Grünflächenamt). This department attends structural and horticultural issues of public green spaces and parks.	
Yang et al., 2010	Agro-tourism enterprises as a form of multi-functional urban agriculture for peri-urban development in China	Xiedao Green Resort (XGR) (agro-tourism enterprise)	Journal paper
Ma et al. 2019	Co-creation, co-evolution and co-governance: understanding green businesses and urban transformations	A small urban agri-food enterprise in Venice, Italy	
Gehani, 2014	Innovative Public–Private and Philanthropy Partnership for Local Food Supply-Chain Infrastructure: Countryside	A start-up by Cuyahoga Valley National Park (CVNP) for managing urban farming technology and local food production and supply chain	Conference proceeding

	Initiative of Cuyahoga Valley U.S. National Park		
Robinson et al., 2017	Examining the Business Case and Models for Sustainable Multifunctional Edible Landscaping Enterprises in the Phoenix Metro Area	Multifunctional edible landscaping business model	Journal paper
Sanyé-Mengual et al., 2017	Community rooftop garden of Via Gandusio – Bologna, Italy	Community garden	Conference proceeding
	Ecco Jäger Farm – Bad Ragaz, Switzerland.	Integrated rooftop greenhouse	
	Topager – Paris, France	Designing, building, and managing rooftop gardens mainly for food production (fruits and vegetables)	
	Jardin Atlantique Montparnasse rail station	Roof garden	

Appendix 2.2 Keywords combinations used in the literature search

Literature searches	Search streams	Keywords	Hits	
			Scopus	WoS
1	Stream 1	"urban agriculture" OR "urban farm*" OR "metropolitan and peri-urban agriculture" OR "peri- urban agriculture" OR "peri-urban farm*" OR "urban garden*" OR "urban food*" OR "vertical agriculture" OR "vertical farm*" OR "zero-acreage farm*" OR "vertical greenhouse*" OR "indoor farm*" OR "interior garden*" OR "building-integrated agriculture" OR "rooftop greenhouse*" OR "rooftop garden*" OR "rooftop farm*" OR "community garden*" OR "home garden" OR "agricultural garden*" OR "allotments of urban land" OR "urban park*"	112	159
	Stream 2	"business model*" OR "business model innovation*" OR "value proposition*" OR "value creation" OR "value delivery" OR "value capture" OR "value recovery" OR "value opportunit*" OR "value offer*" OR "value generation*" OR "value configuration*" OR "value network*" OR "value chain*" OR "customer interface*" OR "financial model*" OR "key partner*" OR "key stakeholder*" OR "key activit*" OR "key resource*" OR "customer relationship*" OR "distribution channel*" OR "customer segment*" OR "cost structure*" OR "revenue stream*" OR "revenue model" OR "revenue mechanism*" OR "financial architecture*" OR "partnership*" OR "partner network*" OR "infrastructure management" OR "financial mechanism*"		
2	Stream 1	"urban agriculture" OR "urban farm*" OR "metropolitan and peri-urban agriculture" OR "peri-urban agriculture" OR "peri-urban farm*" OR "urban garden*" OR "urban food*" OR "vertical agriculture" OR "vertical farm*" OR "zero-acreage farm*" OR "vertical greenhouse*" OR "indoor farm*" OR "interior garden*" OR "building-integrated agriculture" OR "rooftop greenhouse*" OR "rooftop garden*" OR "rooftop farm*" OR "community garden*" OR "home garden" OR "agricultural garden*" OR "allotments of urban land" OR "urban park*"	19	15
	Stream 2	"sustainable business model*" OR "sustainable business practice*" OR "sustainable business innovation*" OR "sustainable business case*" OR "sustainable business format*" OR "sustainable business model innovation*" OR "sustainable business innovation*" OR "business model* for sustainabl*" OR "business practice* for sustainable*" OR "business innovation* for sustainable*" OR " business case* for sustainab*" OR "business		

		format* for sustainab*" OR " business model innovation* for sustainable*" OR "practice* of sustainable business*" OR "eco-innovation" OR "green business*" OR "social enterprise*" OR "shared value creation" OR "corporative responsability" OR "industrial sustainability" OR "sustainable manufacturing" OR "green manufacturing"		
3	Stream 1	urban agriculture OR "urban farm*" OR "metropolian and peri-urban agriculture" OR "peri-urban agriculture" OR "peri-urban farm*" OR "urban garden*" OR "urban food*" OR "vertical agriculture" OR "vertical farm*" OR "zero-acreage farm*" OR "vertical greenhouse*" OR "indoor farm*" OR "interior garden*" OR "building-integrated agriculture" OR "rooftop greenhouse*" OR "rooftop garden*" OR "rooftop farm*" OR "community garden*" OR "home garden" OR "agricultural garden*" OR "allotments of urban land" OR "urban park*"	65	55
	Stream 2	"business model*" OR "business model innovation*" OR "value proposition*" OR "value creation" OR "value delivery" OR "value capture" OR "value recovery" OR "value opportunit*" OR "value offer*" OR "value generation*" OR "value configuration*" OR "value network*" OR "value chain*" OR "customer interface*" OR "financial model*" OR "key partner*" OR "key stakeholder*" OR "key activit*" OR "key resource*" OR "customer relationship*" OR "distribution channel*" OR "customer segment*" OR "cost structure*" OR "revenue stream*" OR "revenue model" OR "revenue mechanism*" OR "financial architecture*" OR "partnership*" OR "partner network*" OR "infrastructure management" OR "financial mechanism*"		
	Stream 3	"sustainability" OR "sustainable development" OR "circular*"		

Appendix 2.3 Keywords describing the sustainable business model archetypes of Bocken et al., (2014) further developed by Bocken et al., (2016) and Lüdeke-Freund et al. (2016) also called base archetypes

ARCHETYPE	KEYWORDS
Maximize material & energy efficiency (MM&EE)	low carbon manufacturing lean manufacturing additive manufacturing low-carbon solutions dematerialization increased functionality cleaner production approaches eco-efficiency resource efficiency little resources fewer resources
Closing resource loops (CRL)	cradle-to-cradle (cradle-2-cradle) industrial symbiosis extended producer responsibility circular economy closed loop reuse

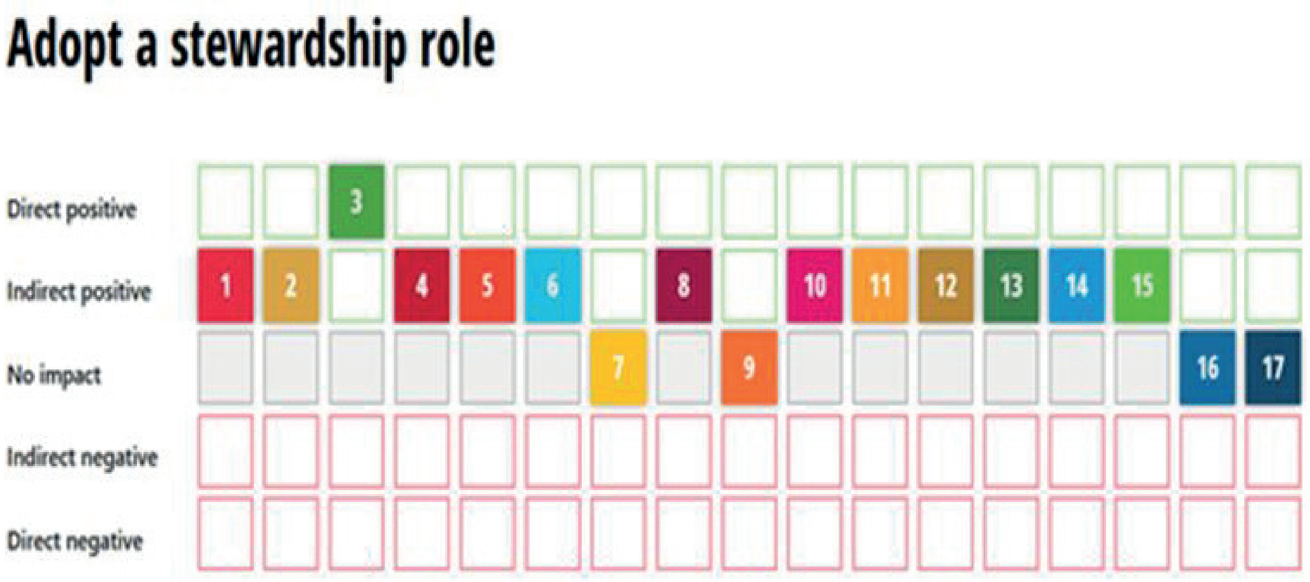
	recycle remanufacture take back management waste streams as useful inputs recapture material(s) lost waste into value
Substituting with renewables and natural processes (SRNP)	cleantech renewable energy (e.g., solar, wind) biomimicry move from non-renewable to renewable energy zero-emission initiatives slow manufacturing blue economy the natural step natural processes replacing metals with natural and fiber-based materials environmentally benign materials and production processes (e.g., replacing chemical dyes with organic/benign dyes in textile production green chemistry
Delivering functionality, not ownership (DFNO)	Rental/lease Pay per use

	Product-service combinations product service systems (PSS) servitisation pay-per-use results-oriented PSS-pay per use use-oriented PSS-rental, lease, shared product-oriented PSS-maintenance, extended warranty use oriented PSS-rental, lease, shared private finance initiative (PFI) design, build, finance, operate (DBFO) chemical management services (CMS)
Adopting a stewardship role (ASR)	community development: education, health, livelihoods biodiversity protection choice editing by retailers customer care-promote consumer health and well-being ethnical trade (fair trade) radical transparency about environmental/social impacts upstream stewardship employee welfare and living wages environmental resource and bio-diversity protection and regeneration

	sustainable growing and harvesting of food downstream stewardship resource stewardship
Encouraging sufficiency (ES)	consumer education, communications, and awareness slow fashion demand management frugal businesses sustainable consumption energy saving companies (ESCOs) product durability and longevity marketplaces for second-hand goods premium branding/limited availability responsible product distribution/promotion
Repurposing for society/ environment (RSE)	social enterprises and benefit corporations non-profits hybrid models (non-for profit and for profit) net positive initiatives alternative ownership cooperative, mutual, collectives social and biodiversity regeneration initiatives

Inclusive value creation (IVC)	collaborative platforms collaborative consumption peer-to-peer and sharing models collaborative approaches (sourcing, production and lobbying) inclusive innovation base of pyramid (BOP) solutions sharing resources, knowledge, ownership, and wealth creation inclusive approach to innovation
Developing sustainable scaleup solutions (DSSS)	open innovation (platforms) incubators and entrepreneur-support models slow/patient capital franchising licensing impact investing/capital crowdsourcing/funding peer-to-peer lending

Appendix 2.4.An example of graphical visualisation of impacts together with motivation report for their classification



Adopt a stewardship role

Direct positive			3														
Indirect positive	1	2		4	5	6		8		10	11	12	13	14	15		
No impact							7		9							16	17
Indirect negative																	
Direct negative																	

Description

UA-SBM archetype focuses on delivering a positive impact on the environment and society for community development, environmental/biodiversity/ local culture protection, social inclusion, and shifting towards sustainable agriculture practices and healthy diets through the implementation of UA initiatives in the cities

NO POVERTY

End poverty in all its forms everywhere

Impact

INDIRECT POSITIVE

Motivation

SDG 1 (Overall): Achieving good health is a strong enabling factor (indirect impact) for effective poverty reduction.

ZERO HUNGER

End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Impact

INDIRECT POSITIVE

Motivation

SDG 2 (Target 2.3): a) Increasing the agricultural productivity and incomes of small-scale producers will improve access to food and economic resources, which supports the health of mothers,

GOOD HEALTH AND WELL-BEING

Ensure healthy lives and promote well-being for all at all ages

Impact

DIRECT POSITIVE

Motivation

Since the archetype "Adopt a stewardship" aims to ensure their long-term health and well-being (Bocken et al., 2014) by engaging all stakeholders, it directly impacts the overall SDG 3 " Good health and well-being" which seeks to ensure healthy lives and promote well-being for all at all ages.

QUALITY EDUCATION

Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

Impact

DIRECT POSITIVE

Motivation

Target 4.7: The role of education is crucial for raising awareness about the health benefits of UA and educating agricultural workers on the safe and sustainable use of chemicals. Target 4.5: The ASR focuses on delivering a positive impact for social inclusion

GENDER EQUALITY

Achieve gender equality and empower all women and girls

Impact

DIRECT POSITIVE

Motivation

Human health and well-being are about gender quality

CLEAN WATER AND SANITATION

Ensure availability and sustainable management of water and sanitation for all

Impact

INDIRECT POSITIVE

Motivation

Target 6.3: Improving water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally can impact indirectly the human health and well-being.

AFFORDABLE AND CLEAN ENERGY

Ensure access to affordable, reliable, sustainable and modern energy for all

Impact

Motivation

Increasing the share of clean renewable energy is related with technology innovation and not with

NO IMPACT

social

DECENT WORK AND ECONOMIC GROWTH

Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

Impact

INDIRECT POSITIVE

Motivation

Targets 8.1, 8.5, 8.6 (Indirect positive) on human health and well-being. However, there might have negative adverse impacts on the environment associated with Economic growth including water, air, and soil pollution and ecosystem change, which can increase the risk of communicable disease, illness and death.

INDUSTRY, INNOVATION AND INFRASTRUCTURE

Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Impact

NO IMPACT

Motivation

Technology innovation is not of the focus of this archetype

REDUCED INEQUALITIES

Reduce inequality within and among countries

Impact

DIRECT POSITIVE

Motivation

Human health is well-being is about reduce inequality within and among countries

SUSTAINABLE CITIES AND COMMUNITIES

Make cities and human settlements inclusive, safe, resilient and sustainable

Impact

DIRECT POSITIVE

Motivation

SDG 11 (Targets 11.6, 11.7): Working on reducing the environmental impacts of cities and facilitating access to green spaces throughout UA in the cities may have positive impacts on human health, both physical and mental

RESPONSIBLE PRODUCTION AND CONSUMPTION

Ensure sustainable consumption and production patterns

Impact

INDIRECT POSITIVE

Motivation

Indirect impact of SDG 12.4

CLIMATE ACTION

Take urgent action to combat climate change and its impacts

Impact

INDIRECT POSITIVE

Motivation

Target 13.2: Integrating climate change policy local policies is crucial for improvements in air quality and thus for human health improvement.

LIFE BELOW WATER

Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Impact

INDIRECT POSITIVE

Motivation

This SDG is not in the focus of the archetype

LIFE ON LAND

Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Impact

INDIRECT POSITIVE

Motivation

SDG 15.1 and SDG 15.5

PEACE, JUSTICE AND STRONG INSTITUTIONS

Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

Impact

NO IMPACT

Motivation

No relevant for the human health

PARTNERSHIPS FOR THE GOALS

Strengthen the means of implementation and revitalize the global partnership for sustainable development

Impact

NO IMPACT

Motivation

No relevant for this archetype

Appendix 2.5 Results and keywords related to the archetype “Adopt a stewardship role”

“Adopt a stewardship role” archetype			
REFERENCE/CASES	**Total number of cases (references)**	**NO. CASES**	**% CASES**
		40	**74.1%**
	KEYWORDS IDENTIFIED		
Yang et al., (2010); Polling et al., (2017); Eung-Jik et al., (2012); Circle-lab (2021b)and Grocycle (2021); Vitiello & Wolf-Powers (2014); Daves & Garrett, 2018; Gehani (2014); Smith-Nonini (2016); Krul & Ho (2017); Vieira et al., (2019); MADRE (2018) (cases: Menjadors Ecològics; Terra coopa; Campi Aperti; Mia organic; CPIE Bassin; Fattoria urbana ;Aplec Aplec; Pic; Filiere; Arvaia; Blerina; Mercadis; Le Serre; Can Pinyol; Jardin des Aures; Perka; Baix Llobregat AgrarianPark); Agoston (2014); Go Explorer (2020) and Rooftop Republic (2021); Robinson et al., (2017); Recasens et al., (2016); The Plant (2021); Armanda et al.,(2018); Oudwater et al., (2013)(Cases: Prove ; Harvest to hope; Schaduf; Jinghe online farm; Municipal Food security programme; Amir Women; Canasta Comunitaria; PAU Argentina); Cofie et al., (2013)(Cases: Sulabh; DeCo; Thai Biogas Energy Company (TBEC); Waste Concern; Cess pit; Jagrashisha Farm; Buobai Co-composting Plant; Waste Enterprisers; Balangoda Urban Council); Circle-lab (2021d); Sanyé-Mengual et al., (2017); Instagreen (2021) and InstaGreen (2016); Gittins & Morland (2021); European circular economy stakeholder platform (2021b) and PermaFungi (2021); Circulator (2021); Circle- lab (2018b) and Square roots (2021); Martin & Bustamante (2021); Scharf et al.,(2019); Circle-lab (2018a) and Cityplot (2021); SINTRA (2017b) and Helseni (2021); Go Explorer (2019) and Agricool (2021); Infarm (2018) and Infarm (2021);State of green (2021b); Circular Economy Europe (2021a); R2π (2019); Usman &Nanda (2017); SINTRA (2017a) and Silmusalaatti (2021); Ma et al., (2019)	EDUCATION*	21	38.9%
	TRAINING*	20	37.0%
	EDUCATIONAL*	20	37.0%
	WORKSHOP*	14	25.9%
	LEISURE*	5	9.3%
	ORGANIC_FARMING	9	16.7%
	ORGANIC_FOOD	7	13.0%
	ORGANIC_PRODUCTS	4	7.4%
	ENVIRONMENTAL_PROTECTION	4	7.4%
	NO_PESTICIDE*	2	3.7%
	RECREATIONAL_ACTIVITIES	3	5.6%
	HEALTHY_ORGANIC_FOOD	3	5.6%

	PESTICIDE-FREE	2	3.7%
	CERTIFIED_ORGANIC*	1	1.9%
	DISADVANTAGED_GROUPS	2	3.7%
	ENVIRONMENT_PROTECTION	2	3.7%
	FAIR*_PRICE*	2	3.7%
	ORGANICALLY_GROWN	3	5.6%
	RAISE_AWARENESS	3	5.6%
	BIODYNAMIC_AGRICULTURE	2	3.7%
	BLOCKCHAIN_FOR*	1	1.9%
	EL_USO_DE_PESTICIDAS	1	1.9%
	FAIR*_MARGIN*	1	1.9%
	FREE_OF_PESTICIDES	2	3.7%

Appendix 2.6 Results and keywords related to the archetype " Waste-based solutions and reuse”

REFERENCE/CASES	Total number of cases (references)	NO. CASES	% CASES
	54	33	61.1%
	KEYWORDS IDENTIFIED		
Sanyé-Mengual et al., 2017 (Cases: Community rooftop garden of Via Gandusio; Ecco Jäger Farm – Bad Ragaz, Switzerland); R2π (2019); Armanda et al., (2018) (Case: Aerofarm;); Usman and Nanda (2017); SINTRA (2017b) and Helseni (2021); Circular Economy Europe (2021b) and PermaFungi (2021); Circle-lab (2021b)and GroCycle (2021); Circulator (2021); The Plant (2021); Eung-Jik et al., (2012); Paiho et al., (2021); Cofie et al., (2013) (Yaonde Cameroon, Sulabh, Waste Enterprisers, Jagrashisha Farm, ECOSAN, Balangoda Urban Council, The Bombai Co-Composting plant, Cesspit emptiers,Thai Biogas energy company, Waste Concern); Oudwater et al., (2013) (Cases: Harvest of hope, PAU Argentina); Circular X (2021b); Instagreen (2021) and EU Cordis InstaGreen (2016); Circle-lab (2021a); Interreg PROCTEFA ORHI (2019) (Case: Fresh Guru); Circle-lab (2019) and Robert-Jan Vos (2018); Heckmann (2018); Circular Economy Europe (2021a); Circle-lab (2021c) and Atlas Obscura (2021); Gittins and Morland (2021); Go Explorer (2019) and Agricool (2021); Circle-lab (2018a) and Cityplot (2021); Yang et al., (2010); Smith-Nonini (2016); Vieira et al., (2019); Lufa Farms (2021); MADRE (2018) (Cases: Jardin des Aures); Go Explorer (2020) and Rooftop Republic (2021); SINTRA (2017c); Go Explorer (2018b) and Sky Greens (2021)	COMPOST*	19	35.2%
	BIOGAS*	6	11.1%
	ANAEROBIC_DIGES*	5	9.3%
	COFFEE_GROUND* (coffee ground waste)	5	9.3%
	REVERSE_LOGISTICS	2	3.7%
	AQUAPONIC_FARM*	3	5.6%
	INDUSTRIAL_SYMBIOSIS	2	3.7%
	WASTE_HEAT	2	3.7%
	ENERGY_RECOVERY	2	3.7%
	CLOS*_THE_LOOP*	4	7.4%
	CO-PRODUCT_RECOVERY	1	1.9%
	BIODEGRADABLE_CUPS	1	1.9%
	CLOS*_THE_RESOURCE*	1	1.9%
	COFFEE_CHAFF*	1	1.9%
	MATERIAL_REUSE	1	1.9%
	RESIDUO_COMO_NUTRIENTE	1	1.9%
	REUSE_OF_URINE	1	1.9%
	UPCYCLED_PRODUCTS	1	1.9%
	WASTEWATER-FED_AQUACULTURE	1	1.9%
	BIODEGRADABLE_COIR_MATS	1	1.9%
	CLOSES_THE_METABOLIC_CYCLE*	1	1.9%
	DESIGN_FOR_BIODEGRADABILITY	1	1.9%
	DESIGN_FOR_REUSE	1	1.9%
	FORMER_PALLET*	1	1.9%
	INSECT_BIOMASS_AS_FEED*	1	1.9%
	RE-CYCLED_SHIPPING_CONTAINER*	1	1.9%

	RECYCLED_PLASTIC_CONTAINER*	1	1.9%
	RETROFITTED_SHIPPING_CONTAINER*	1	1.9%
	REUSABILITY_OF_PRODUCTS	1	1.9%
	REUSABLE_CLOTH_MEDIUM	1	1.9%
	SEEDBEDS_MADE_OF_LOCAL_ORGANIC	1	1.9%
	URINE_CAPTURE	1	1.9%
	WASTEWATER_CAPTURE	1	1.9%
	BIO_GAS*	1	1.9%
	MARSH_GAS	1	1.9%
	WASTE_TO_ENERGY	1	1.9%
	FOOD_WASTE_RECYCLING_SYSTEM	1	1.9%

Appendix 2.7 Results and keywords related to the archetype " Maximise the resource use"

REFERENCE/CASE	**Total number of cases (references)**	**NO. CASES**	**% CASES**
	54	30	55.6%
	KEYWORDS INFENTIFIED		
Go Explorer (2018c); State of green (2021); Circle-lab (2021e) and AgFunder (2016); EU Cordis Europe R2π (2019); Sanyé-Mengual et al.,(2017) (Case: Community rooftop garden of Via Gandusio – Bologna, Italy); Usman and Nanda (2017); Vitiello and Wolf-Powers (2014); Circular X (2021b); Daves and Garrett (2018); Instagreen (2021) and InstaGreen (2016); Gittins & Morland (2021); Armanda et al., (2018); Lufa Farms (2021); Oudwater et al., (2013) (Cases: Schaduf); Martin & Bustamante (2021); Go Explorer (2018b) and Sky Greens (2021); Go Explorer (2020) and Rooftop Republic (2021); Heckmann (2018); Paiho et al., (2021); MADRE (2018) (Cases: Mercadis); SINTRA (2017a) and Silmusalaatti (2021); Go Explorer (2019) and Agricool (2021); Circle-lab (2021c) and Atlas Obscura (2021); ORHI (2019); Circle-lab (2018b) and Square roots (2021); SINTRA (2017c); Infarm (2018) and Infarm (2021)	HYDROPONIC*	18	33.33%
	AUTOMATION	6	11.11%
	ENERGY_EFFICIEN*	4	7.41%
	LESS_WATER	4	7.41%
	ROBOT*	4	7.41%
	LOWER_ENERGY	4	7.41%
	LED_LIGHT*	3	5.56%
	ENERGY_SAVING	3	5.56%
	LED_GROW*	2	3.70%
	PRECISION_AGRICULTURE	2	3.70%
	LOW_WATER_USE	2	3.70%
	CONSERVING_RESOURCES	2	3.70%
	SMART_FARM*	2	3.70%
	WATER-EFFICIEN*	2	3.70%
	AGRICULTURA_DE_PRECISIÓN	1	1.85%
	AUTOMATIZACIÓN	1	1.85%
	DRIP_IRRIGATION	1	1.85%
	LOW_CARBON_HYDRAULIC	1	1.85%
	ARTIFICIAL_INTELLIGENCE*	1	1.85%
	FEW*_RESOURCES	1	1.85%
	INTELLIGENCE_PLATFORM	1	1.85%
	LED_TECHNOLOGY	1	1.85%
	LITTLE_WATER	1	1.85%
	LOWER_WATER_CONSUMPTION	1	1.85%
	SAVING_WATER	1	1.85%
	SMART_TECHNLOGY	1	1.85%
	SMART_VERTICAL_FARM*	1	1.85%

Appendix 2.8 Results and keywords related to the archetype "Repurpose for society and environment"

	Total number of cases (references)	NO. CASES	% CASES
	54	20	37.0%
REFERENCE/CASE	KEYWORDS IDENTIFIED		
Vitiello et al., (2014); Smith-Nonini (2016); Gittins and Morland (2021); Vieira et al., (2019);Circular Economy Europe (2021b) and PermaFungi (2021); Agoston (2014); Go Explorer (2020) and Rooftop Republic (2021); Circulator (2021); Robinson et al., (2017); Cofie et al., (2013) (Deco; Waste Enterprisers; Waste Concern; Sulabh); Polling et al., (2017); Scharf et al., (2019); Smith-Nonini (2016); Krul & Ho (2017); Interreg Mediterranean MADRE (2018) (Cases: Aplec; Campi Aperti; Arvaia; Filière Paysanne; Le Serre dei Giardini Margherita; Terra coppa, CPIE bassin, Menjadors Ecològics; Pic’assiette, Perka,Neapoli Sykies); Oudwater et al., (2013) (Cases: Amir Women´s association; Jinghe online farm; Harvest of Hope); Circle-lab (2021d); The Plant (2021); Agoston, 2014	COOPERATIVE	13	24.1%
	SOCIAL_ENTERPRISE	10	18.5%
	NON-PROFIT*	8	14.8%
	SOCIAL_BUSINESS	3	5.6%
	SOCIAL_MISSION	3	5.6%
	SOCIAL_SUPPORT	2	3.7%
	NON-PROFIT_ASSOCIATION	1	1.9%
	CITIZEN_INITIATIVE	1	1.9%
	FOR-PROFIT/NON-PROFIT_PARTNERSHIP	1	1.9%
	INFORMAL_GROUP	1	1.9%

Appendix 2.9 Results and keywords related to the archetype "Encourage sufficiency"

REFERENCE/CASE	Total number of cases (references)	NO. CASES	% CASES
	54	8	14.8%
	KEYWORDS IDENTIFIED		
Martin & Bustamante (2021); Lufa Farms (2021); SINTRA (2017b) and Helseni (2021); Circular X (2021b); EU Cordis Europe Infarm (2018) and Infarm (2021); Go Explorer (2018e); Go Explorer (2018b) and Sky Greens (2021)	**MODULAR*** (modular design; modular structure; modularity; modular insect farm; modular insect farm)	6	11.1%
	FOR_DURABILITY (design for durability)	3	5.6%

Appendix 2.10 Results and keywords related to the archetype " "Develop sustainable scale-up solutions"

REFERENCE/CASES	**Total number of cases (references)**	**NO. CASES**	**% CASES**
	54	7	13.0%
	KEYWORDS INDENTIFIED		
The Plant (2021); MADRE (2018) (Case Mercadis; Case Terracopa); European Circular Economy Stakeholder platform (2021a) ; Cofie et al., (2013) (Case Deco); Oudwater et al., (2013)(Schaduf); Vitiello et al., (2014); Vieira et al., (2019)	INCUBATOR* (incubator, incubator for business)	4	7.4%
	CIRCULAR_BUSINESS_HUB	1	1.9%
	FRANCHISING_SYSTEM	1	1.9%
	FRANCHISE-TYPE_BUSINESS	1	1.9%
	SOLIDARITY_FINANCE	1	1.9%

Appendix 2.11 Results and keywords related to the archetype "Delivering functionality, not ownership"

REFERENCE/CASES	**Total number of cases (references)**	**NO. CASES**	**% CASES**
	54	6	11.1%
	KEYWORDS INDENTIFIED		
Martin & Bustamante (2021), Balcarová et al., (2016); Cofie et al., (2013) /Case Sulabh; Polling et al., (2017); Circular X (2021b); Paiho et al., (2021)	PSS	2	3.7%
	GROWING_AS_A_SERVICE	2	3.7%
	PRODUCT-SERVICE_SYSTEM	1	1.9%
	PAY-PER-USE	1	1.9%
	GSS	1	1.9%
	RENT_A_FIELD	1	1.9%
	GROWING-SERVICE_SYSTEM*	1	1.9%
	HYDROPONICS-AS-A-SERVICE	1	1.9%
	FARMING_AS_A_SERVICE	1	1.9%
	TOMATOES_ AS_ A_ SERVICE	1	1.9%

Appendix 2.12 Results and keywords related to the archetype "Marketplace for fresh, and surplus or rejected UA products "

	Total number of cases (references)	**NO. CASES**	**% CASES**
	54	17	31.5%
REFERENCE/CASES	**KEYWORDS INDENTIFIED**		
Polling et al., (2017); Vitiello & Wolf-Powers (2014); Gehani (2014); Gittins and Morland (2021); Krul (2017); Lufa Farms (2021); MADRE (2018) (Cases: Filière Paysanne, Mercadis, MIA Organic, Farmers' markets); Go Explorer (2020) and Rooftop Republic (2021); Robinson et al., (2017); Recasens et al., (2016); The Plant (2021); Armanda et al., (2018); Oudwater et al., (2013)(Cases: Prove and Jinghe Online Farm); Balcarová et al., (2016); Go Explorer (2018d) and Local Food Nodes (2021); Go Explorer (2018a)	FARMER*_MARKET*	14	25.9%
	DIGITAL_MARKETPLACE	2	3.7%
	ONLINE_MARKET_PLACE	1	1.9%
	AREA_FOR_THE_MARKET_PLACE	1	1.9%
	COMMERCIAL_OUTLET	1	1.9%
	SALES_PLATFORM*	1	1.9%
	THE_MARKETPLACE	1	1.9%

Appendix 2.13 Results and keywords related to the archetype "Substituting with renewables and natural processes"

	Total number of cases (references)	**NO. CASES**	**% CASES**
	54	17	31.5%
REFERENCES/CASES	**KEYWORDS INDENTIFIED**		
Go Explorer (2019) and Agricool (2021); Circle-lab (2021e) and AgFunder (2016); Eung-Jik et al., (2012); SINTRA (2017b) and Helseni (2021); Paiho et al., (2021); Armanda et al., (2018); Cofie et al., (2013)(Jagrashisha Farm in Kolkata, India); Martin & Bustamante (2021); Circle-lab (2021c) and Atlas Obscura (2021); Lufa Farms (2021); Daves & Garrett (2018); Polling et al., (2017); Yang et al., (2010); Instagreen (2021) and InstaGreen (2016); European Circular Economy Stakeholder Platform (2021b) and PermaFungi (2021); R2π (2019); Smith-Nonini (2016)	RENEWABLE_ENERG*	9	16.7%
	RAINWATER	4	7.4%
	WIND	3	5.6%
	SOLAR_ENERGY	3	5.6%
	SOLAR_THERMAL*	3	5.6%
	BY_BIKE	2	3.7%
	MELTWATER	2	3.7%
	RENEWABLE_SOURCES	2	3.7%
	GEOTHERMAL_ENERGY	1	1.9%
	BY_ELECTRIC_CAR	1	1.9%
	SOLAR_POWER	1	1.9%
	SOLAR_PUMP*	1	1.9%

Appendix 2.14 Results and keywords related to the archetype "Subscription model"

	Total number of cases (references)	NO. CASES	% CASES
	54	17	31.5%
REFERENCE/CASES	KEYWORDS INDENTIFIED		
Polling et al., (2017); Vitiello & Wolf-Powers (2014); Gehani (2014); Gittins and Morland (2021); Krul (2017); Lufa Farms (2021); MADRE (2018) (Cases: Filière Paysanne, Mercadis, MIA Organic, Farmers' markets); Go Explorer (2020) and Rooftop Republic (2021); Robinson et al., (2017); Recasens et al., (2016); The Plant (2021); Armanda et al., (2018); Oudwater et al., (2013)(Cases: Prove and Jinghe Online Farm); Balcarová et al., (2016); Go Explorer (2018d) and Local Food Nodes (2021); Go Explorer (2018a)	FARMER*_MARKET*	14	25.9%
	DIGITAL_MARKETPLACE	2	3.7%
	ONLINE_MARKET_PLACE	1	1.9%
	AREA_FOR_THE_MARKET_PLACE	1	1.9%
	COMMERCIAL_OUTLET	1	1.9%
	SALES_PLATFORM*	1	1.9%
	THE_MARKETPLACE	1	1.9%

Appendix 2.15 Results and keywords related to the archetype "Inclusive value creation"

	Total number of cases (references)	NO. CASES	% CASES
	54	11	20.4%
REFERENCE/CASE	KEYWORDS IDENTIFIED		
Sanyé-Mengual et al., (2017) (Case Topager-Paris); Vitiello et al., (2014); Gehani (2014); MADRE (2018) (Cases: Baix Lobregat Agrarian Park,Le Serre dei Giardini Margherita, Aplec Aplec, Campi Aperti, Deco,Perka,Chez les Producteurs,CPIE Bassin); Robinson et al., (2017); Oudwater et al., (2013)(Cases: The Buobai co-composting plant, Cesspit emptiers, Waste Concern); SINTRA (2017b) and Helseni (2021); Scharf et al., (2019); The Plant (2021); Balcarová et al., (2016); Go Explorer (2018a)	PUBLIC-PRIVATE*	6	11.1%
	SHAR*_KNOWLEDGE	4	7.4%
	SHARING_COMMUNITY*	2	3.7%
	SHAR*_RESOURCE*	2	3.7%
	COLLABORATIVE_COMMUNITY_OF_FOOD_BUSINESSES	1	1.9%
	COLLABORATIVE_PUBLIC_SPACE	1	1.9%
	HIRES_LOW-SKILLED_WORKERS	1	1.9%
	COLLABORATIVE BUSINESS MODEL		
	JOBS_FOR_THE_URBAN_POOR	1	1.9%
	MUTUALISE_RESOURCES*	1	1.9%

Appendix 2.16 Value analysis (value preposition, value creation & delivery, value creation) based on Richardson (2008) including sustainable benefits (economic, environmental and social) and limitations related to the three environmental type sustainable business model archetypes for urban agriculture

ARCHETYPE		*Maximise the resource use (MRU)*	*Waste-based solutions & reuse (WBSR)*	*Substitute with renewable energies and natural processes (SRNP)*
VALUE PREPOSITION	Offer	Products/urban growing solutions that use fewer resources (e.g., water, energy, space, labour) to reduce waste and emissions	The waste in UA is eliminated by turning waste into feedstocks for other products/processes and for energy and/or compost production. Reused products and materials.	1) UA fresh products using renewable sources/energies as production inputs instead of conventional ones (e.g., rainwater instead of tap water); 2) Urban growing solutions using renewable sources/energies.
	Customer segmentos	1) Urban farmers aiming to optimise the plant growth process and thus to reduce their operating expenses; 2) Local end-consumers interested in consuming local fresh products	1) Business clients: retailers, restaurants, wholesalers, food producers, pet shop, cosmetic industry, other urban farms; manufacturing industries; 2) Local individuals and community.	1) Local people interested to consume UA products made with renewable sources and/or energies; 2) Business clients interested to have UA farms that use renewable sources and/or energies
	Customer relationship	Most often individual (with clients), partly personal	1) Automated self-services (online ordering or store purchase); 2) Direct personal assistance	1) Business clients: close direct relations 2) End-consumers: automated self-services (online ordering or store purchase)
VALUE CREATION & DELIVERY	Key activities	Production and selling UA fresh products and UA growing solutions that use fewer resources (e.g., water, energy, land, labour).	1) Sourcing and collection of waste; 2) Recycling waste to create a) upcycled materials (e.g., biodegradable lamps, soap made from coffee waste); and b) compost/fertiliser and/or energy; 3) Use waste as production input for plants/growing (e.g., coffee waste grounds as substrates), for insect farming, or for feeding animals; 4) Reusing materials/products	1) Production of UA products and/or designing UA growing solutions (e.g., container farms) using renewable resources (e.g., rainwater, meltwater) and/or energy (e.g., solar energy, geothermal energy), and 2) Distribution of UA production by using low emission transportation means of transport., e.g., bikes, electric vehicles.
	Key resources and technology	The focus is on the technology/techniques used to i) use and recycling waste (WBSR) (e.g., aquaponic technology, digesters for compost and biogas), i) to minimise resources and labour in the case of the MRU, e.g., energy-saving LED lamps drip irrigation, automation of production, using advance technology (e.g., GPS, Internet of things, artificial intelligence,) iii) to take advantage of the renewable sources		

		and/or energy (e.g., rainwater harvest system, solar panel) related to the Substitute with renewable energies and processes archetype. For correct their correct. maintenance is needed. Other important resources: 1) human resources (qualified workers), 2) materials, and 3) reused materials (WBSR); 4) bikes and electric vehicles (SRNP)		
	Key channels	Diverse- direct sales (on-farm), online shops, local retailers and grocery stores, restaurants, etc.	1) on farm (direct sales); 2) local community; 3) social media, 4) website; 5) fairs and events	1) Direct sales (on farm; shops); 2) Business clients: restaurants, retailers, etc.
	Key partners:	1) Technological I+D centers for research; 2) Universities; 3) Local farmers; 4) Food markets.	1) café, restaurants, hotel (mushroom growing using coffee waste); 2) food and meat industries; 3) wholesalers; 4) local municipalities; 5) foundation; 6) retailers	Providers of technological innovations aiming to reduce the use of non-finite resources and/or energy.
VALUE CAPTURE	Cost structure	As a result of technology implemented: 1) annual amortisation of assets, 2) labour of qualified workers, 3) labour for maintenance, 4) installation costs		
	Revenues streams	From selling of urban fresh produce and UA growing solutions to reduce production inputs.	From selling additionally to the fresh UA products: 1) recycled/upcycled products, 2) compost and/or energy, 3) waste as production input for other industries.	From selling UA products and UA farms using renewable energy/sources.

Appendix 2.17 Value analysis (value propositions, value creation & delivery) based Richardson (2008) including sustainable benefits (environmental, economic, and social benefits) of the four social type sustainable business model archetypes for urban agriculture

ARCHETYPE		*Adopt a stewardship role*	*Marketplace for fresh, surplus, and rejected urban agriculture products*	*Encourage sufficiency*	*Deliver functionality not ownership*
VALUE PREPOSITION	Offer	UA products/services that seek to proactively engage with stakeholders to ensure their long-term well-being. such as organic fresh produce, education, leisure/cultural events.	UA products: fresh, surplus, or rejected due to aesthetic reason.	Urban growing solutions that seek to reduce demand-side consumption and hence reduce production (e.g., durable, modular design).	Services that satisfy the customers' needs without having their own products. In the case of the UA mainly is experience for the customers.
	Customer segments	1) Local people who are willing to pay a premium price for perceived environmental and/or social benefits from UA products and/or services; 2) Business clients: local restaurants, retailers, grocery stores.	1) BM clients: Large businesses/government organisations whose employees are interested in fresh vegetables. Mostly middle-class people; 2) End users: local community in general.	1) UA businesses; 2) Urban planners	1) other UA businesses; 2) local people interested to gain experience in UA by growing their own food.
	Customer relationship	Local people and business clients- direct contract with consumer to provide them with the full story of production/supply chain.	1) Automated self-service (online ordering); 2) Dedicated personal assistance (physical places).	Automated self-services (online ordering or store purchase).	There is a need for more direct consumer contact to motivate the shift away from ownership.
VALUE CREATION & DELIVERY	Key activities	Production and selling of UA fresh products and/or provision of services aiming to ensure the long-term health (e.g., organic farming without using synthetic nutrients and pesticides) and	Direct sales and/or distribution of fresh, surplus, or rejected (due to aesthetic reasons) UA products by	Designing, renting, and selling UA growing solutions having long lasting design and made from durable materials.	Renting or leasing UA growing solutions (e.g., hydroponic growing system) or urban land for growing food (vegetables, food, ornamental plants), mainly

		wellbeing (e.g., leisure and education activities) of all stakeholders (including society and the environment.	using digital platform/app or physical place.		accompanied by complementary services such as training, maintenance, software, etc.
	Key resources	1) human resources; 2) certifications (e.g., organically certified produces); 3) use of innovative technology to bring more transparency, e.g., blockchain.	1) labour; 2) online database and website; 3) vehicles; 4) facilities for storing the products and packaging	1) Skilled labour; 2) Materials; and 3) Software	1) qualified human resources; 2) software; 3) production inputs.
	Key channels	Diverse, but mainly short supply chains with few intermediaries.	1) Short distribution channels-very important for this archetype 2) Social media: Facebook, Instagram, etc,	1) Online; 2) Social media; 3) Ferias; and 4) News	Diverse but mainly short supply chains with very few intermediaries such as restaurants, local retailers.
	Key partners:	Enabling close partnership between the UA organisation, local authorities (e.g., local government; citizens) and other local farmers.	1) investors; 2) sponsors; 3) logistic companies; 4) customers cooperatives; 5) local municipalities; 5) local farmers	1) Grocery store; 2) Retailers; 3) Local authorities	Providers of growing inputs, and software solutions.
VALUE CAPTURE	Cost structure:	1) labour; 2) licences (certifications) maintenance of technology platforms; 3) costs of raw materials	1) rent; 2) salaries; 3) digital platform maintenance; 4) bank charges	1) Salaries; 2) Amortisations of assets; 3) Materials	1) qualified labour; 2) intangible assets; 3) variable costs.
	Revenues streams	From selling of UA fresh products and/or provision of services (e.g., education, events, tourism, etc).	1) sales of products; 2) subscription/taxes.	From selling	Revenues from leasing of renting UA growing solutions and UA land.

Appendix 2.18 Value analysis (value propositions, value creation & delivery) based on Richardson (2008) including sustainable benefits (environmental, economic, and social benefits) of the four economic type sustainable business model archetypes for urban agriculture

ARCHETYPE		***Repurpose for society and environment (RSE)***	***Subscription model (SM)***	***Inclusive value creation (IVC)***	***Develop sustainable scale-up solutions (DSSS)***
VALUE PREPOSITION	Offer	Prioritising delivery of social and environmental benefits rather than economic profits (i.e., stakeholder value) maximisation, through close integration between the firm and local communities and other stakeholders.	UA products/services obtained through paying a predefined fee via subscription	Inclusive value through joint initiatives (co-creation) aiming to sharing resources/ownership/knowledge or including previously neglected social groups (e.g., poor people) as value-creating partners instead of customers, e.g., as employees, suppliers, or distributors.	Sustainable scale-up solutions to maximise benefits for the environment and society.
	Customer segments	1) Local people, mainly those in not favourable situations such as people with mental health issues, immigrants, etc; 2) business clients (B2B) such local restaurants and retailers.	Subscribed members are two types: 1) business clients-urban farms, restaurants, retailers; 2) end consumers (local people) interested to consume fresh local products at reasonable prices or as a compensation to participate in the harvest.	Mainly local community. This archetype aims to reach a wide range of customers	UA organisations (e.g., early-stage entrepreneurs, small business; home-based businesses) interested in implementing sustainable practices in their business
	Customer relationship	Direct relations with the customers segments are important to successfully deliver social and/or environmental benefits.	Customer relationship is very important for this archetype since it aims to establish a long-term relationship with clients to guarantee stable revenues and profit. Direct and personalised relation with the clients is preferable.	1) Automated self-services (online ordering or store purchase).; 2) Dedicated personal assistance	This archetype is based on "dedicated personal assistance relation" since aims to satisfy all customers´ needs through personal assistance, technical support, and monitoring to facilitate the scale-up.
VALUE CREATION & DELIVERY	Key activities	UA business operations that are driven by social mission prioritising delivery of social and environmental benefits rather than economic profit)	1) Selling or distributing UA fresh products; 2) Selling or renting/leasing services. In both cases, the focus is on the	UA activities (e.g., production, selling, distribution, organising events on UA) that share resources (materials and human),	Activities aiming to stimulate and support sustainable UA entrepreneurship such as education/training, connection

		maximisation. For instance, through the implementation of programs aiming to promote UA and to increase food supply, create livelihoods, alleviate poverty, protect the environment and local biodiversity, etc	predefined fee/tax/prices (mainly fixed) paid via subscription.	ownership (e.g., public-private), or knowledge.	with possible investors, funding, etc.
	Key resources	1) human resources; 2) voluntaries; 3) production inputs: water, energy, etc.	1) human resources; 2) digital platforms/apps; 3) subscribed members to do the harvest in community-supported agriculture (CSA).	1) human resources: typically for this archetype is the provision of employment opportunities for previously neglected social groups (e.g., poor people, low-skilled persons); 2) space/land ; 3) materials; 4) know-how	1) education/trainers; 2) online platforms (e.g., crowdfunding); and 3) educational materials
	Key channels	Short supply channels with very few intermediaries	Mainly short supply chains with very few intermediaries.	Diverse, but mainly short supply (restaurant, shops, etc).	Online, Word-of-mouth
	Key partners:	The RSU is based close integration between the firm and local communities and other stakeholder groups. Moreover, it might require non-traditional business partnership (e.g., NGO, foundations, etc).	The is a need for strong cooperation between urban farmers and local organisations: universities, banks municipalities. In CSA, subscribed members are key partners and resource as well.	1) local community ; 2) urban farmers; 3) local authorities; 4) previously neglected social groups	There is a need for close cooperation between the company and the local authorities for successful scale-up.
VALUE CAPTURE	Cost structure:	1) operation labour; 2) costs of raw materials.	1) labour; 2) maintenance of digital platform/app	1) labour; 2) land/space; 3) materials	1) labour; 2) maintenance of online platforms; 3) materials
	Revenues streams	1) From selling of UA products or/and services; 2) From grants, sponsors, donors, etc.	1) From paying a predefined fee/tax/prices (mainly fixed) via subscription	From selling	Revenues from paying a variable (e.g., franchising, licensing) or fixed (e.g., participation in programs for incubating sustainable businesses) fee for scale up a solution.

Appendix **2.19 Sustainable benefits (environmental, economic, and social benefits) associated with the three environmental type sustainable business model archetypes for urban agriculture**

ARCHETYPE		*Maximize the resource use (MRU)*	*Waste-based solutions & reuse (WBSR)*	*Substitute with renewable energies and natural processes (SRNP)*
SUSTAINABLE BENEFITS	Economic benefits (profit):	• Great cost savings thanks to reduced production inputs (e.g., water, energy, labour) lead to increased profit in long term.	• Great costs saving from using waste as raw material and reuse materials instead of buying them. • New sources for generating revenues and thus profit, e.g., selling waste as inputs for manufacturing companies producing bioplastics or selling	• Great cost savings thanks to reduced production inputs (e.g., water, energy, labour) lead to increased profit in long term.
	Environmental benefits (planet):	• Minimizing the excessive use of precious scare resources (e.g., fresh water, land) • Reduced waste and emissions as results of improved resource efficiency	• Reduced waste in landfill • Alternative feed (i.e., insect farming) reducing pressure on conventional resources. • Closing the nutrient cycle. • No emission from waste transportation (compost on site) • Reusing used materials can contribute for reducing the exploitation of virgin materials • Reducing the emissions associated with burning fossil fuels	• Reducing the use of precious resources (water, land) and thus reduce their consumption. • Reducing greenhouse emissions through using low emission transportation means of transport., e.g., bikes, electric vehicles • Reducing the emissions associated burning fossil fuels
	Social benefits (people):	• Possible jobs opportunities for people for qualified people (e.g., engineers, architect) and people that maintain the technological innovations related to these archetypes • Indirect positive impact on the society as well thanks to reducing environmental impacts and waste.	• Possible jobs opportunities for people for qualified people (e.g., engineers, architect) and people that maintain the technological innovation related to these archetypes. • Indirect positive impact on the society as well thanks to reducing environmental impacts and waste. • Increased knowledge on sustainability, composting and home gardening	• Possible jobs opportunities for people for qualified people (e.g., engineers, architect) and people that maintain the technological innovation related to these archetypes • Indirect positive impact on the society as well thanks to reducing environmental impacts and waste. • Reduced stress on the city's infrastructure because of intercepting and using rain and meltwater water instead of directing it and wasting it in the sewers.

Appendix 2.20 Sustainable benefits (environmental, economic, and social benefits) associated with the three environmental type sustainable business model archetypes for urban agriculture

ARCHETYPE		***Adopt a stewardship role***	***Marketplace for fresh, surplus, and rejected urban agriculture products***	***Encourage sufficiency***	***Deliver functionality not ownership***
SUSTAINABLE BENEFITS	Economic benefits (profit):	1)The willingness to pay premium prices leads to great profit for the UA organisations. Stable revenues and thus profit in long term is also possible thanks to the customer relationship based on transparency and trust. 2) Additional revenues and thus profit from running education, leisure/cultural events.	1) Increased revenues and thus profit for urban farmers thanks to short supply chains	1) Premium pricing for long-lasting UA solutions. 2) Increased market share realized from the provision of better products (longer-lasting, durable/not subject to short cycles).	Possibility to obtain additional revenues and thus increase profit from providing additional services such as installation fees or other not included in the service.
	Environmental benefits (planet):	Significant environment benefits such as protected environment and reduced carbon emissions.	1) Reduced waste in landfills 2) Reduced carbon emissions thanks to locally sourced produce and short supply chains.	1) Using less product 2)Reuse across generations.	The improved access to UA solutions can contribute to further developing UA at a large scale which can have an indirect positive impact on the environment expressed in reduced greenhouse emission in the cities
	Social benefits (people):	Significant social benefits expressed in job creation, educated society, improved health, increased access to food, social inclusion. Moreover, engaging customers with the complete story of producing UA product leads to establishment of long-term relationships.	1) Reduced prices of otherwise expensive products such as organically produced vegetables and fruits (farm-gate prices); 2) Improved access to fresh UA products which have indirect effects on the customers´ health; 3) Jobs´ creation or decrease of family unemployment; 4) Increased customer awareness and community engagement.	1) Educated society 2) Using less product. 3) Reuse across generations.	1) Improved access to previously expensive UA growing solutions; 2) Local citizens can gain valuable experience in UA through learning how to cultivate their own food and improve their health by consuming fresh local food.

Appendix 2.21 Sustainable benefits (environmental, economic, and social benefits) associated with the three environmental type sustainable business model archetypes for urban agriculture

ARCHETYPE		***Repurpose for society and environment (RSE)***	***Subscription model (SM)***	***Inclusive value creation (IVC)***	***Develop sustainable scale-up solutions (DSSS)***
SUSTAINABLE BENEFITS	Economic benefits (profit):	Economic profit is needed to maintain self-sufficiency, but revenue is not the principal objective. Possible cost reduces by using voluntaries to do the urban farming operations.	• Regular and predictable revenue for the producers/distributors from established a long-term relationship with the customers. • Great costs reduction in the labour for harvest in CSA scheme since subscribed member do the harvest.	Economic costs are reduced thanks to sharing resources.	Possible financial return from successful sustainable scale-up.
	Environmental benefits (planet):	Great environmental benefits a result of activities aiming to protect local biodiversity, reduce greenhouse emissions.	Regarding the environment, the SM can help for reducing the carbon mission of transportation thanks to the short supply chains.	Indirect positive effect on the Environment expressed in reduced carbon emissions through promoting UA.	Positive impact on the environment from promoting diverse sustainable UA initiatives. For instance, UA organisations aiming to implement an organic compost plant facility can contribute to mitigating the environmental problems related to the great accumulation of agricultural waste and the excessive use of syntenic pesticides.
	Social benefits (people):	Great social benefits such as improved income and household food security, poverty alleviation, providing jobs and training for people in an unfavourable situation.	• Saving money and time for customers • Positive contribution to the human health.	• Increased employment/partnership opportunities for the urban poor • Increased social cohesion	• Creation of more UA jobs • Possible indirect impact on human health through supporting UA sustainable initiatives aiming to provide local people with fresh, organic, or pesticide-free produce.

Appendix 2.22 Relationships of the archetypes with the sustainable development goals

GROUP	ARCHETYPE	SUSTAINABLE DEVELOPMENT GOALS[a]																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ENVIRONMENTAL	WBSR	0	🟨 +1/-1	🟨 +1/-1	🟨 +1	0	🟩 +1	🟩 +1	🟨 +1	🟩 +1	0	🟨 +1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	0	🟨 +1
	MRU	0	🟨 +1	🟨 +1	0	0	🟩 +1	🟩 +1	🟩 +1	🟩 +1	0	🟨 +1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	0	0
	SRNP	🟨 -1	🟨 +1	🟨 +1	🟨 +1	0	🟨 +1/-1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	0	🟨 +1	🟨 +1	0	0	0
SOCIAL	ASR	🟨 +1	🟨 +1/-1	🟩 +1	🟩 +1	🟩 +1	🟨 +1	0	🟨 +1/-1	0	🟩 +1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	0	0
	ES	🟨 -1	🟨 +1	0	🟩 +1	🟨 +1	0	0	🟨 +1	🟩 +1	🟨 +1	🟨 +1	🟩 +1	🟨 +1	0	🟨 +1	0	0
	DFNO	🟨 +1	🟩 +1	🟨 +1	🟩 +1	0	🟨 +1	🟨 +1	🟨 +1	🟩 +1	0	🟨 +1	🟨 -1	🟨 +1	0	0	0	0
	MFSRUP	🟨 +1	🟩 +1	🟨 +1	0	🟨 +1	0	0	🟨 +1	🟨 0	🟨 +1	🟨 +1	🟩 +1	🟨 +1	0	0	0	🟨 +1
ECONOMIC	RSE	🟩 +1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	0	0	🟨 +1	🟨 -1	🟨 +1	🟩 +1	🟨 +1	🟨 +1	0	🟩 +1	0	🟩 +1
	SM	🟨 +1	🟩 +1	🟨 +1	🟩 +1	0	🟨 +1	🟨 +1	🟨 +1	0	0	🟨 +1	🟨 -1	🟨 +1	🟨 +1	0	0	0
	IVC	🟨 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	0	0	🟩 +1	🟨 +1	🟩 +1	🟨 +1	🟨 -1	🟨 +1	🟨 +1	🟨 +1	0	🟩 +1
	DSSS	🟩 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	🟩 +1	🟩 +1	🟨 +1	🟨 +1	🟨 +1	🟨 +1	0	0	0	🟨 +1

[a] Scale of impacts: -1= negative; 0= no impact;+1=positive; -1/+1= both positive and negative impact. Green colour=direct impact; Yellow colour= indirect impact

Acronomics: 1) ASR= Adopt a stewardship role, 2) WBSR= Waste-based solutions and reuse; 3) MRU= Maximise the resource use; 4) RSE= Repurpose for society or environment; 5) MFSR= Marketplace for fresh, surplus or rejected food; 6) SRNP= Substitute with renewable energies and natural processes; 7) SM= Subscription model; 8) IVC= Inclusive value creation; 9) ES= Encourage sufficiency; 10) DSSS= Develop sustainable scale-up solutions; 11) DFNO=Deliver functionality not ownership