Universitat Autònoma de Barcelona

Agro-urban solid waste from rooftop greenhouses in the framework of the circular economy: Eco-design strategies for its use

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Doctoral thesis

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

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By

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Dr. Xavier Gabarrell Durany   Dr. Jorge Sierra-Pérez   Dr. Pere Muñoz

Bellaterra (Cerdanyola del Vallès), September, 2020

“One has no right to love or hate anything
if one has not acquired a thorough knowledge of its nature.
Great love springs from great knowledge of the beloved object,
and if you know it but little you will be able to love it
only a little or not at all.”

Leonardo da Vinci

Contents

Abbreviations, acronyms and notations

▪ AUSW	Agro-urban solid waste
▪ CO_2 eq	Carbon dioxide equivalent emissions
▪ CO_2	Carbon dioxide
▪ DIY	Do it your-self
▪ CE	Circular economy
▪ EC	Electrical conductivity
▪ EPS	Expanded polystyrene
▪ EU	European Union
▪ GHG	Greenhouse gases
▪ HDPE	High density polyethylene
▪ ICP	Catalan Institute of Paleontology
▪ ICTA	Institute of Environmental Science and Technology
▪ i-RTG	Integrated rooftop greenhouse
▪ LAU-1,2,3	Urban Agriculture Laboratory
▪ LCA	Life cycle assessment
▪ LDPE	Low-density polyethylene
▪ N_2O	Nitrous Oxide
▪ OSW	Organic solid waste
▪ Pcs	Expanded perlite (control substrate)
▪ PE	Polyethylene
▪ PP	Polypropylene
▪ PVC	Polyvinyl chloride
▪ RTG	Rooftop greenhouse
▪ S1	Summer 1 crop (2015)
▪ S2	Summer 2 crop (2016)
▪ S3	Summer 3 crop (2017)
▪ S4	Summer 4 crop (2018)
▪ S5	Summer 5 crop (2019)
▪ SDG	Sustainable Development Goals
▪ SW	Solid waste
▪ TT	Disinfected tomato stems (treated)
▪ UA	Urban agriculture
▪ UT	Non-disinfected tomato stems (untreated)
▪ W	Winter crop (2016)

List of figures

List of tables

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… dedicada a la memoria de mi abuelo.

Summary

We are currently experiencing problems such as climate change and the shortage of resources largely related to overproduction and excessive generation of waste within cities. At the same time, a third of the present population is expected to grow by 2050, causing severe food insufficiency for 9.3% of the population. Taking into consideration that currently 55% of the world population lives in urban areas, and that by 2050 it will increase between 68 and 70%, strategies have been created to mitigate these problems.

Urban agriculture (UA) is one of these strategies in constant growth due to the multiple economic, social and cultural benefits it offers, in addition to helping to reduce food shortages while reducing the environmental impact related to transporting food from outside, to inside the cities. There are recent studies to improve environmental performance and efficiency in the use of resources by taking advantage of the flow of water, nutrients and gases from the UA, particularly from rooftop greenhouse (RTG), which are a type of UA that has demonstrated through different studies, to be an efficient system of food production. This, following the circular economy (CE) initiative that contributes to closing the life cycles of products by increasing the rate of reuse and recycling of materials through an action plan approved in 2015 from the European Union (EU). However, the flow of solid waste (SW) generated by the UA or agro-urban solid waste (AUSW), which represent a new type of waste within cities, has not yet been fully studied for its use. The AUSWs have not been clearly classified as municipally managed waste either, which in the future could represent a new problem for the waste management system within cities.

The general objective of this dissertation is to identify what type of AUSW has the potential to be used *in situ* to continue with the benefits offered by the UA and to generate application concepts for the waste through an interdisciplinary methodology based on eco-design and to generate an eco-material with added value through its upcycling. The above using RTG tomato crops with soilless fertirrigation system as a case study. In this way, it is also intended to make a new type of waste visible by providing data that could serve as a guide for future management regulations at the local level.

Based on the classification and quantification of the AUSW generated in RTG, the results of the research show that organic solid waste (OSW) or biomass is the most critical fraction regarding the volume and timing of its generation. In addition, according to the future growth scenario of the AU, the expected increase in the volume of OSW within cities could be 20% by the year 2030. It was also determined that biomass is the fraction that has the greatest potential for be used locally as an eco-material using “Do it your-self (DIY)” techniques, particularly tomato stems. The stems were used as a substrate to carry out two experimental lettuce crops in RTG. In this way, the AUSW *in situ* was used to close the UA cycle, considering that the substrate elaboration process implies less environmental impact than the compost elaboration process, which does not represent an additional value.

Following the methodology used, other of the main findings of the research are based on the results of the physical, chemical and mechanical characterization of the tomato stems. Data obtained served to identify possible areas of application for the stems, using the Ashby approach of material selection. The stems of the tomato plants were determined to be similar to the family of wood-like materials and thus possible processing techniques and application areas were identified.

Subsequently, a creative brainstorming session was held with specialists in the areas of UA, product design, eco-materials, and alternative materials for construction. Using different group techniques, three concepts were generated resulting from viable applications for the use of the stems. These concepts were qualitatively evaluated by the participants, providing comments that were used to finally carry out a semi-quantitative evaluation of the resulting concepts. This evaluation was performed using a metric based on eco-design factors. The resulting concepts according to the score obtained are, first "Fences and trellises"; second, "Packaging" and third "Boards, panels and blocks".

Accordingly, it was determined that the proposed methodology from the CE approach is useful to identify viable applications for the upcycling of the AUSW locally using DIY techniques. This is due in large part to the "creative nature" of eco-design, which allows the methodology to be adapted to different contexts, so that global problems can be solved starting from the local scale. In addition, this study provides data on the characterization of tomato stems, which are also applicable for the use of waste generated by conventional agriculture considering the large volume it generates.

The innovation presented by the study is based on:

- The identification of a new type of waste within cities, AUSW
- The contribution of data regarding the stems of tomato plants generated by the UA, scalable for use in conventional farming systems.
- The contribution of an interdisciplinary methodology that integrates knowledge in the area of UA, chemical, physical and mechanical characterization of materials and eco-design.
- Proposal of applications for the use of tomato stems in an urban context by the upcycling approach using DIY techniques to take advantage of AUSW *in situ*.

Resumen

Actualmente vivimos problemas como el cambio climático y el desabastecimiento de recursos relacionado, en gran medida, con la sobreproducción y a la generación excesiva de residuos dentro de las ciudades. Al mismo tiempo, se prevé un crecimiento de un tercio de la población actual para el 2050, provocando una insuficiencia alimentaria severa al 9.3% de la población. Considerando que actualmente el 55% de la población mundial vive en áreas urbanas, y que para el 2050 aumentará entre el 68 y el 70%, se han creado estrategias para mitigar estos problemas.

La agricultura urbana (UA en inglés) es una de estas estrategias en constante crecimiento debido a los múltiples beneficios económicos, sociales y culturales que ofrece, además de ayudar a reducir el desabastecimiento de alimentos mientras reduce el impacto ambiental relacionado al transporte de alimentos desde fuera hacia adentro de las ciudades. Actualmente hay estudios con el fin de mejorar el desempeño ambiental y la eficiencia en el uso de los recursos mediante el aprovechamiento de flujos de agua, nutrientes y gases de la UA, particularmente de los invernaderos en las azoteas (RTG en inglés), que son un tipo de UA que ha demostrado mediante diferentes estudios, ser un sistema eficiente de producción de alimentos. Esto, siguiendo la iniciativa de economía circular (CE en inglés) que contribuye a cerrar los ciclos de vida de los productos al aumentar la tasa de reutilización y reciclaje de materiales mediante un plan de acción aprobado en 2015 por la Unión Europea (EU en inglés). Sin embargo, el flujo de los desechos sólidos (SW en inglés) generados por la UA o desechos sólidos agro-urbanos (AUSW en inglés), que representan un nuevo tipo de desechos dentro de las ciudades, aún no ha sido estudiados del todo para su aprovechamiento. Los AUSW, tampoco han sido claramente tipificados dentro de los residuos gestionados a nivel municipal, lo que a futuro podría representar un nuevo problema para el sistema de gestión de residuos dentro de las ciudades.

El objetivo general de la presente disertación es identificar qué tipo de AUSW tiene el potencial de ser aprovechado in situ para continuar con los beneficios que brinda la UA y generar conceptos de aplicación para el residuo mediante una metodología interdisciplinar basada en el eco-diseño a través de la generación de un eco-material con valor agregado mediante su upcycling. Lo anterior usando como estudio de caso cultivos de tomate de RTG con sistema de fertiirrigación sin suelo. Además, de esta forma se pretende visibilizar una nueva tipología de residuos aportando datos que sirvan de guía para plantear directrices y normativas de gestión a nivel local.

Partiendo de la clasificación y cuantificación de los AUSW generados en RTG, los resultados de la investigación muestran que, los desechos sólidos orgánicos (OSW en inglés) o biomasa, es la fracción más crítica respecto al volumen y temporalidad de su generación. Además, de acuerdo con el escenario futuro de crecimiento de la UA, el aumento previsto del volumen de OSW dentro de las ciudades podría ser del 20% para el año 2030. Se determinó también que la biomasa es la fracción que tiene el mayor potencial para ser utilizada localmente como un eco-material mediante técnicas de “Hazlo tú mismo (DIY en inglés)”, particularmente los tallos de tomate. Los tallos se

utilizaron como sustrato para realizar dos cultivos experimentales de lechuga en RTG. De esta forma se aprovecharon los AUSW *in situ* para cerrar el ciclo de la UA considerando que el proceso de elaboración del sustrato implica menor impacto ambiental que el proceso de elaboración de compost que no representa un valor adicional.

Siguiendo con la metodología utilizada, otros de los principales hallazgos de la investigación parten de los resultados de la caracterización física, química y mecánica de los tallos de tomatera. Se obtuvieron datos que permitieron identificar materiales con características similares con el fin de identificar posibles áreas de aplicación para el aprovechamiento de los tallos utilizando el método de Ashby de selección de materiales. Se determinó que los tallos de las tomateras son similares a la familia de materiales tipo madera y de esta forma se identificaron posibles técnicas de procesamiento y áreas de aplicación.

Posteriormente se realizó una sesión creativa de generación de ideas con especialistas en las áreas de UA, diseño de producto, eco-materiales, y materiales alternativos para la construcción. Mediante diferentes técnicas grupales se generaron 3 conceptos resultantes de aplicaciones viables para el aprovechamiento de los tallos. Estos conceptos fueron evaluados cualitativamente por los participantes aportando comentarios que sirvieron para realizar finalmente una evaluación semicuantitativa de los conceptos resultantes. Esta evaluación se realizó mediante una métrica basada en factores de eco-diseño. Los conceptos resultantes de acuerdo con el puntaje obtenido son, en primer lugar "Cercas y enrejados", en segundo lugar "Envases" y en tercer lugar "Tableros, paneles y bloques".

De esta manera se determinó que la metodología propuesta desde el enfoque de CE es útil para identificar aplicaciones viables para el upcycling de los AUSW de forma local mediante técnicas de DIY. Esto debido en gran parte a la "naturaleza creativa" del eco-diseño, lo que permite adaptar la metodología a diferentes contextos, de forma que se pueda solucionar problemas globales partiendo de la escala local. Además, el presente estudio aporta datos de caracterización de los tallos de tomate, que también son aplicables para el aprovechamiento de los residuos generados por la agricultura convencional considerando el gran volumen que genera.

La innovación que presenta el estudio se basa en:

- La identificación de un nuevo tipo de residuo dentro de las ciudades, AUSW
- El aporte de datos sobre los tallos de las plantas de tomate generados por la UA, escalables para su uso en sistemas agrícolas convencionales.
- El aporte de una metodología interdisciplinar que integra conocimientos en el área de UA, caracterización química, física y mecánica de materiales y ecodiseño.
- Propuesta de aplicaciones para el uso de tallos de tomate en un contexto urbano mediante el enfoque de upcycling utilizando técnicas de DIY para aprovechar AUSW *in situ*.

Resum

Actualment vivim problemes com el canvi climàtic i el desabasto de recursos relacionat en gran mesura a la sobreproducció i la generació excessiva de residus dins de les ciutats. A el mateix temps, es preveu un creixement d'un terç de la població actual per al 2050, provocant una insuficiència alimentària severa a l'9.3% de la població. Atès que actualment el 55% de a població mundial viu en àrees urbanes, i que per al 2050 augmentarà entre el 68 i el 70%, s'han creat estratègies per mitigar aquests problemes.

L'agricultura urbana (UA en anglès) és una d'aquestes estratègies en constant creixement a causa dels múltiples beneficis econòmics, socials i culturals que ofereix, a més d'ajudar a reduir el desabasto d'aliments mentre redueix l'impacte ambiental relacionat a el transport d'aliments des de fora, cap a endins de les ciutats. Actualment hi ha estudis per tal de millorar l'acompliment ambiental i l'eficiència en l'ús dels recursos mitjançant l'aprofitament de fluxos d'aigua, nutrients i gasos de la UA, particularment dels hivernacles al terrat (RTG en anglès), que són un tipus d'UA que ha demostrat mitjançant diferents estudis, ser un sistema eficient de producció d'aliments. Això, seguint la iniciativa d'economia circular (CE en anglès) que contribueix a tancar els cicles de vida dels productes a l'augmentar la taxa de reutilització i reciclatge de materials mitjançant un pla d'acció aprovat en 2015 per la Unió Europea (EU en anglès). No obstant això, el flux de les deixalles sòlides (SW en anglès) generats per la UA o agro-urban solid waste (AUSW en anglès), que representen un nou tipus de deixalles dins de les ciutats, encara no ha estat estudiats de el tot per al seu aprofitament. Els AUSW, tampoc han estat clarament tipificats dins dels residus gestionats a nivell municipal, el que a futur podria representar un nou problema per al sistema de gestió de residus dins de les ciutats.

L'objectiu general de la present dissertació és identificar quin tipus de AUSW té el potencial de ser aprofitat in situ per continuar amb els beneficis que ofereix la UA i generar conceptes d'aplicació per al residu mitjançant una metodologia interdisciplinària basada en l'eco-disseny i generar un eco-material amb valor afegit mitjançant la seva upcycling. L'anterior usant com a estudi de cas cultius de tomàquet de RTG amb sistema de fertirrigació sense terra. D'aquesta manera es pretén a més, visibilitzar una nova tipologia de residus aportant dades que serveixin de guia per plantejar directrius i normatives de gestió a nivell local.

Partint de la classificació i quantificació dels AUSW generats en RTG, els resultats de la investigació mostren que, els organic solid waste (OSW en anglès) o biomassa, és la fracció més crítica respecte a l'volum i temporalitat de la seva generació. A més, d'acord amb l'escenari futur de creixement de la UA, l'augment previst de l'volum de OSW dins de les ciutats podria ser d'un 20% per a l'any 2030. Es va determinar també que la biomassa és la fracció que té el major potencial per ser utilitzada localment com un eco-material mitjançant tècniques de "Do it your-self (DIY en anglès)", particularment les tiges de tomàquet. Les tiges es van utilitzar com a substrat per a realitzar dos cultius experimentals d'enciam en RTG. D'aquesta manera es van aprofitar els AUSW in situ per tancar el cicle de la UA considerant que el procés d'elaboració de l'substrat implica

menor impacte ambiental que el procés d'elaboració de compost que no representa un valor addicional.

Seguint amb la metodologia utilitzada, altres de les principals troballes de la investigació parteixen dels resultats de la caracterització física, química i mecànica de les tiges de tomaquera. Es van obtenir dades que van permetre identificar materials amb característiques similars per tal d'identificar possibles àrees d'aplicació per a l'aprofitament de les tiges utilitzant el mètode d'Ashby de selecció de materials. Es va determinar que les tiges de les tomaqueres són similars a la família de materials tipus fusta i d'aquesta manera es van identificar possibles tècniques de processament i àrees d'aplicació.

Posteriorment es va realitzar una sessió creativa de generació d'idees amb especialistes en les àrees d'UA, disseny de producte, eco-materials, i materials alternatius per a la construcció. Mitjançant diferents tècniques grupals es van generar 3 conceptes resultants d'aplicacions viables per a l'aprofitament de les tiges. Aquests conceptes van ser avaluats qualitativament pels participants aportant comentaris que van servir per realitzar finalment una avaluació semiquantitativa dels conceptes resultants. Aquesta avaluació es va realitzar mitjançant una mètrica basada en factors d'eco-disseny. Els conceptes resultants d'acord amb la puntuació obtingut són, en primer lloc "Cercas i enreixats", en segon lloc "Empaquetatges" i en tercer lloc "Taulers, panells i blocs".

D'aquesta manera es va determinar que la metodologia proposada des de l'enfocament de CE és útil per identificar aplicacions viables per al upcycling dels AUSW de forma local mitjançant tècniques de DIY. Això degut en gran part a la "naturalesa creativa" de l'eco-disseny, el que permet adaptar la metodologia a diferents contextos, de manera que es pugui solucionar problemes globals partint de l'escala local. A més, el present estudi aporta dades de caracterització de les tiges de tomàquet, que també són aplicables per a l'aprofitament dels residus generats per l'agricultura convencional considerant el gran volum que genera.

La innovació que presenta l'estudi es basa en:

- La identificació d'un nou tipus de residu dins de les ciutats, AUSW
- L'aportació de dades sobre les tiges de les plantes de tomàquet generats per la UA, escalables per al seu ús en sistemes agrícoles convencionals.
- L'aportació d'una metodologia interdisciplinària que integra coneixements en l'àrea d'UA, caracterització química, física i mecànica de materials i ecodisseny.
- Proposta d'aplicacions per a l'ús de tiges de tomàquet en un context urbà mitjançant l'enfocament de upcycling utilitzant tècniques de DIY per aprofitar AUSW *in situ*.

Preface

This doctoral thesis was developed in compliance with the PhD program in Environmental Science and Technology of the Universitat Autònoma de Barcelona during the period between October 2016 and September 2020 within the research group on Sustainability and Environmental Prevention (Sostenipra; 3.0 2017SGR 1683) at the Institute of Environmental Science and Technology (ICTA) accredited as the "María de Maeztu" Unit of Excellence in R&D (MDM- 2015-0552; CEX2019-000940-M) at the Universitat Autònoma de Barcelona. The thesis was supported by a predoctoral grant awarded by the Mexican Council of Science and Technology (CONACYT) along with the Secretary of Energy (SENER), México.

The study presented in this thesis was developed in the framework of the FertileCity II project "Rooftop greenhouses: symbiosis of energy, water and CO_2 emissions with the building - Towards urban food security in a circular economy (MINECO / FEDER, UE: CTM2016- 75772-C3-1 -R)", financed by the Ministry of Economy and Competitiveness (MINECO). This project is coordinated by ICTA, with the participation of the Polytechnic University of Catalonia (UPC).

This dissertation takes place in the context of an urban agriculture laboratory (LAU1) on the roof of the ICTA building. SW flow is analyzed to take advantage of it locally, adding value from the perspective of the CE through eco-design, seeking to improve environmental performance of UA and the reduction of its waste, foreseeing a possible future problem within the cities due to poor management of this type of waste.

Previous studies in the Sostenipra research group addressed the use of residual biomass from tomato crops in the framework of the FertileCity project. This thesis continues in this line of research, also using information on the inventory of the agronomic system obtained from previous studies focused on life cycle analysis (LCA), information generated as part of the monitoring of crops and the experience of the research group.

To carry out this dissertation, the following facilities were accessed and used with the help or advice of other groups or institutions:

- Department of Design and Manufacturing Engineering, Universidad Zaragoza (UNIZAR). Advice and training for the methodological application.
- Barcelona Higher Polytechnic School for Building (EPSEB), UPC. Advice and use of the laboratory of materials for the physical characterization and mechanical tests of traction of lignocellulosic material.
- Department of Chemical, Biological and Environmental Engineering, UAB. Advice and use of equipment to carry out tests with lignocellulosic material.
- ELISAVA Barcelona School of Design and Engineering, UPF. Consulting and use in computer classrooms of software specialized in materials.

Dissemination and training

Part of the dissertation is based on the following published article in peer-reviewed indexed journal from the first quartile.

- Manríquez-Altamirano, Ana, Jorge Sierra-Pérez, Pere Muñoz, and Xavier Gabarrell. 2020. "Analysis of Urban Agriculture Solid Waste in the Frame of Circular Economy: Case Study of Tomato Crop in Integrated Rooftop Greenhouse." Science of The Total Environment 734: 139375. https://doi.org/10.1016/j.scitotenv.2020.139375.

Some preliminary results of the thesis were presented at the following congresses and conferences as posters and/or oral communications.

- 14th Mediterranean Congress of Chemical Engineering (MeCCE2020), Barcelona, ES.
  Oral presentation: "Eco-ideation techniques to identify potential applications for the organic waste from urban agriculture as eco-material". Authors: A. Manríquez-Altamirano, Jorge Sierra-Pérez, Pere Muñoz, X. Gabarrell.
  December 2020 (postponed to November 2021). Accepted

- International Sustainable Production and Consumption Conference, Manchester, UK.
  Poster and flash presentation: "Material valorization of rooftop greenhouses tomatoes stems as way to integral the biomass as part of the tomato production cycle". Authors: A. Manríquez-Altamirano, Jorge Sierra-Pérez, Pere Muñoz, X. Gabarrell. October 2018.

- 1st ICTA-UAB Spring Symposium, Bellaterra, Barcelona, ES.
  Oral presentation: "Eco-ideation and creative techniques for material valorization of residual biomass of RTG's: the case of tomato stems". Authors: A. Manríquez-Altamirano, Jorge Sierra-Pérez, Pere Muñoz, X. Gabarrell. May 2018.

- IV Torres & Earth Award for innovation within the framework of the VI Jornades Ambientals, Barcelona, ES.
  Poster: "Eco-ideation process to identify potential applications for tomato biomass". Authors: A. Manríquez-Altamirano, Jorge Sierra-Pérez, Pere Muñoz, X. Gabarrell. May 2017.

Participation in conference

- IV Torres & Earth Award for innovation within the framework of the VI Jornades Ambientals, Barcelona, ES.
  Poster: "Fertilecity II. Integrated rooftop greenhouses: symbiosis of energy, water and CO_2 emissions with the building – Towards urban food security in a circular economy". Authors: Ercilla-Montserrat, M., Barrell, X., Llorach-Massana,P., Nadal, A., Petit,A., Alabert, A., Casanovas, E., Cuerva, E., Planas,C., Pons, O.,

Josa, A., Montero, J.I., Muñoz, P., Villalba, G., Rovira, M.R., Puig, I., Cortés, F., Giampetro, M., Gassó, S., Zambrano, P., Rufí, M., Manríquez, A.M., Pomt, I., Rieradevall, J. May 2017.

As part of the dissertation, following the methodology used, a creative workshop was held to generate ideas.

- EcoWorkshop: Eco-ideation for eco-innovation, Barcelona, ES. Organizers: A. Manríquez-Altamirano, Jorge Sierra-Pérez, Pere Muñoz, X. Gabarrell. January 2019.

The following courses are part of the training to learn and improve skills for the development of the PhD.

- Creativity and ecoideation strategies course applied to eco-innovation (30h). UNIZAR, Jaca. July 2017.
- Training workshop "Core Communication Skills and Time & Task Management for Scientists" (9h). ICTA-UAB. Bellaterra. September 2017.
- Training sessions: Web Science (1.5h) and Scopus (1.5h). UAB, Bellaterra. October 2017.
- Research Design Short Course (14h). ICTA-UAB, Bellaterra. October 2017.
- Training session: Mendeley (2h). UAB, Bellaterra. February 2018.
- Oral and Poster Presentations (18h). ICTA-UAB, Bellaterra. April 2018.
- Elevator Pitch Course (20h). UAB, Bellaterra. February 2019.

Structure of the dissertation

This thesis is made up of four main parts, six chapters and an addendum to Chapter 3 as illustrated in Fig I.

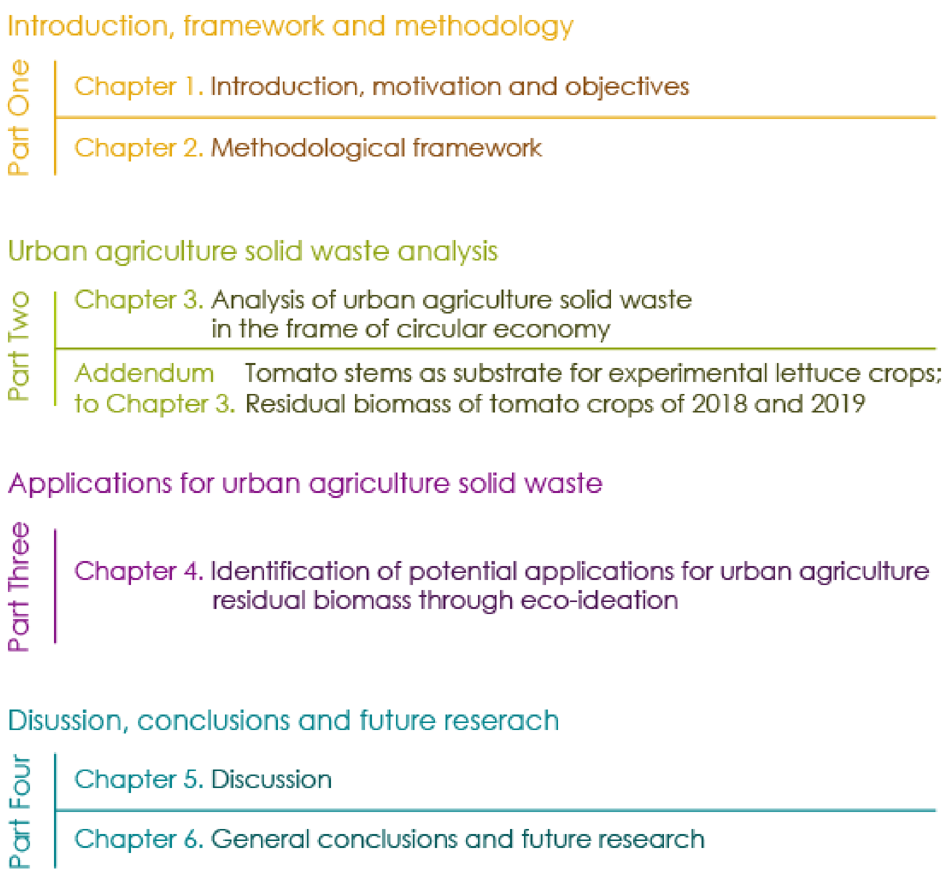

Fig I. Structure of the dissertation

Part One

Introduction, framework and methodology

Chapter 1

Introduction, motivation and objectives

Chapter 1. Introduction, motivation and objectives

This chapter presents an overview of the main concepts that are addressed in the dissertation going from the general to the particular. The importance of UA, its characteristics and relevance of RTGs in the framework of the CE are addressed. An introduction of urban solid waste and its type of management in order to take advantage of it with an upcycling approach through eco-design is provided, eco-materials are also included. Finally, the motivation and objectives of the dissertation are presented.

1.1 Introduction

Modern society is currently experiencing problems such as climate change and the scarcity of resources, due in large part to the need to satisfy the demand for food and products that grow along with the population, which has also caused excessive generation of waste. In order to mitigate these problems, movements such as sustainable development have emerged, a term used by the World Commission on Environment and Development in the Brundtland report (United Nations, 1987) to refer to development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This term is very broad and encompasses environmental, economic and social issues from which many initiatives and strategies have started at a global level, but with an urban scale focus recognizing that it is in cities that sustainable development strategies should be implemented (Farreny Gaya, 2010). Such as Agenda 21 that emerged at the Rio Earth Summit in 1992 that describes the principles of urban sustainability by proposing a "compact city" model with mixed land uses (Nadal et al., 2018), later in The UN-Habitat II summit that took place in Istanbul in 1996 addressed issues related to the living environment of cities since their urbanization to ensure sustainable human settlements for all (Farreny Gaya, 2010).

In September 2015, the United Nations developed the 2030 Agenda for sustainable development (United Nations, 2015b), combining the economic, social and environmental dimensions. This agenda is made up of 17 Sustainable Development Goals (SDG), of which Goal 2 focuses on achieving food security, improving nutrition and promoting sustainable agriculture; Goal 11 focuses on making cities and human settlements inclusive, safe, resilient and sustainable and Goal 12 focuses on ensuring sustainable consumption and production patterns.

On the other hand, in December of the same year, the Paris Agreement (United Nations, 2015a) was carried out, with the aim of strengthening the global response to the threat of climate change, in the context of sustainable development and the efforts to eradicate the poverty that it promotes, among other things, development with low greenhouse gas emissions, in a way that does not compromise food production.

Currently, 55% of the world population lives in urban areas and it is expected to increase between 68 -70% by 2050 (United Nations, 2018) as a result of the current population growth forecast by the United Nations Food Organization. and Agriculture (FAO), between 2009 and 2050, which will be one third, mainly in developing countries. As a result, one in ten people in the world could suffer from severe food insecurity, equivalent to approximately 689 million people (FAO et al., 2017).

1.1.1 Urban agriculture, rooftop greenhouses and solid waste

One of the strategies that helps meet this food demand is the implementation of UA, which refers to food production within cities including the peri-urban area (Fig. 1). UA covers different types and forms since it can be developed in community gardens, plots, back gardens, on the roof, vertical gardens, urban farms among others (Piorr et al., 2018). Since the 1990s UA has been developed in densely populated places and continues to grow, as in addition to addressing food demand and providing fresh fruits, vegetables and herbs, UA contributes to reducing environmental impact by providing food without the need for neither transport nor packaging from distant farms (Puri and Caplow, 2009).

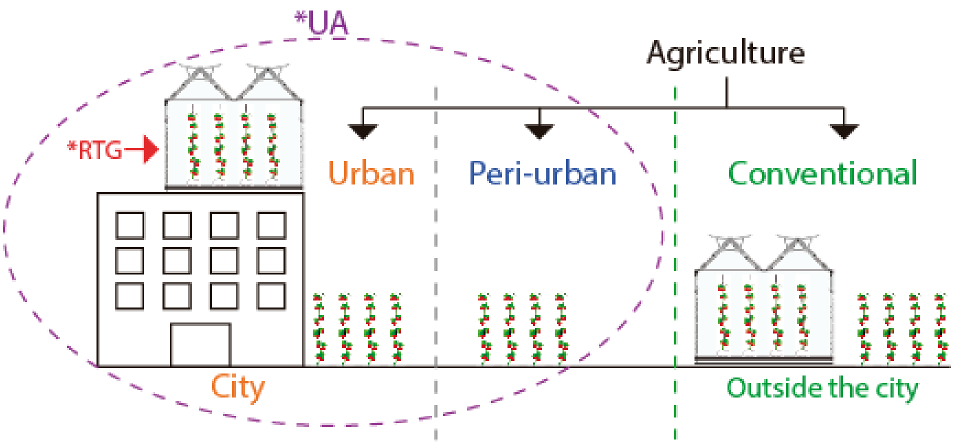

Fig. 1. Agriculture typology with respect to its location; *RTG- Rooftop greenhouse, *UA- Urban agriculture

To achieve sustainable cities, in 2013 the European Parliament adopted the "Green Infrastructure" strategy, which refers to natural and semi-natural areas in urban, rural and marine areas that provide economic and social environmental benefits through natural solutions, which represents a greater urban-rural connection (Piorr et al., 2018). Many densely populated compact European cities have adopted this strategy, as is the case of Barcelona, which launched the Barcelona 2020 Green and Biodiversity Plan. This program has promoted the generation of green roofs in municipal buildings and has endorsed their implementation in public and private spaces. For 2019, the forecast of the area covered by green roofs was of 5,431 m^2 and, through the mosaic roof project, between 2020 and 2030 the creation of 22,000 m^2 will be encouraged (Barcelona, 2017).

Currently, the European Commission presented "The European Green Deal" (European Commission, 2019) in order to make Europe the first climate-neutral continent by 2050 and thus give continuity to the United Nations SDG. The Green Deal proposes a series of actions to promote the efficient use of resources, among them is the "from farm to fork: designing a fair, healthy and environmentally-friendly food system" strategy that will act in the agricultural and fishing sectors, developing new innovative techniques with the objectives of ensuring food quality and sustainable, stop climate change, protect the environment and increase organic farming.

RTG is one of the UA systems that refers to the use of greenhouse methods with soilless cultivation systems with hydroponic techniques adapted for use on the top of buildings. This reduces the structural load required on the building and increases resource efficiency, which is why there presently an increasing number of RTG within cities. Studies show the great potential of implementing this UA system to help meet food demand in addition to reducing the carbon footprint in cities such as Singapore, Bologna (Italy), Dhaka (Bangladesh) (Safayet et al., 2018). The study by Toboso-Chavero et al. (2019), which presents the "RoofMosaic" approach, shows that in general, food production systems are the best option compared to the implementation of energy systems, since RTG has greater food self-sufficiency (69%) in comparison with the option of outdoor agriculture (52%). Furthermore, it has been demonstrated that the implementation of RTG on the roofs of schools is a viable strategy in compact cities to improve the environmental, socio-educational and economic development of the community (Nadal et al., 2018). On the other hand, like the rest of the agriculture, this system generates different waste flows, such as SW.

Agricultural SW can be classified into organic and inorganic. Additionally, it is necessary to differentiate the SW generated by protected agriculture (greenhouses) inside or outside the cities (conventional greenhouses), from the SW generated by conventional agriculture (open-air) outside the cities, since they differ greatly in their type and volume. In greenhouse crops, the hydroponic system that requires other types of tools, materials and substrate is used, in addition to many plastic elements such as collection tubes, bags of substrate and raffia threads, among others, speaking of the inorganic fraction (Antón and Muñoz, 2013).

On the other hand, in general OSW or residual biomass stand out for its seasonality, for their large volume generated for some crops and the great environmental impact they cause without proper management. Regarding the difference between the OSW coming from greenhouses and that of conventional agriculture crops, the volume generated stands out, mainly related to the cultivation area, which is generally greater in conventional agriculture.

Tomato production for 2018 in Europe was 16.7 million tonnes, 26.8% of total vegetable farm production. Of which, Spain produced 4.8 million tonnes, being the third country with the highest tomato production after Turkey and Italy (Eurostat,

2019) in Europe. In Southeast Europe, 3.63% of the total protected area is cultivated with tomatoes, being one of the most important greenhouse crops in the world (FAO, 2017). In Spain, the annual per capita consumption of tomato is 13.22 kg, 23.24% of the total consumption of fresh vegetables and the region of Catalonia, where Barcelona is located, occupies the first place of annual per capita consumption of tomato with 15.78 kg (MAPA, 2018). In addition, it is the second most consumed vegetable after the white potato in Barcelona and its surroundings (Mercabarna, 2017).

Within cities, the OSW according to the European Parliament (European Council, 2008) refers to biodegradable waste from gardens and parks, food and kitchen waste from households, offices, restaurants, wholesale catering services, among others, excluding waste from agricultural production. Regarding the "gardens and parks" fraction, it is mainly made up of stems, branches and leaves. Most of this residual biomass that is managed at the municipal level is composted and the rest goes to the landfill. In this case, the residual biomass generated in RTG, despite being generated within the cities, is still an agricultural waste that, according to its typology, would be added to the "gardens and parks" pruning waste of the collection selective waste managed by municipalities. This AUSW, for its lignocellulosic content and structure, unlike kitchen waste, takes longer to degrade, so it is generally pre-crushed for processing.

1.1.2 Circular economy and its strategies for the use of waste

CE emerged as an initiative to address the global problem of resource depletion and climate change, to try to change the way the entire economic system works from linear to circular flows (Korhonen et al., 2018). To this end, in December 2015, the Action Plan for the CE for the EU (European Commission, 2015) was approved, which will help to close the life cycles of products by increasing the reuse rate and recycling of materials (Camarsa et al. 2017; Korhonen et al., 2018). This through a "waste hierarchy" that includes a descending order of priority for waste management from a mainly environmental perspective. The first step is prevention, followed by preparation for reuse, recycling and recovery, and finally disposal (European Parliament, 2008).

Upcycling is one of CE's strategies to increase the quality, functionality or value of the material or product through recycling (Ahn & Lee, 2018; Sung, 2015). Extending the useful life of these products or materials, in addition to representing an economic benefit, helps to reduce impacts on the environment (Sung, 2015). So, its use has spread, mainly for the use of waste, which has allowed designers to experiment with new materials (Caliendo et al., 2020) and creative techniques to generate useful products in a given area with particular needs (Bridgens et al., 2018).

The DIY approach that relies on self-production using shared knowledge of simple production processes, affordable and inexpensive manufacturing tools (Rognoli et al., 2015) could be used as a means of recycling waste locally, continuing with the benefits sought in the CE. In this case, eco-ideation, which is a strategy characterized by search, experimentation, participation and exchange of knowledge (Sierra-Pérez et al., 2016; Demertzi et al., 2017) can help generate concepts to create ecological products or eco-materials within the eco-design methodology, which seeks to create sustainable solutions that meet human needs taking into account the entire life cycle of the product (Karlsson and Luttropp, 2006).

As mentioned above, there are different strategies and approaches to achieve circularity, most of them focused at the product level. However, these tools can be used at different levels to increase benefits at the "ecosystem" as mentioned by Konietzko et al., (2020) when referring to the five strategies that can be used to innovate for this purpose: narrow, slow, close, regenerate and inform.

On the other hand, a large number of eco-materials are currently being developed, either to create products with a short shelf life that can be rapidly degraded in a sustainable way (bio-degradation) to be used as single-use packaging or products, or to create products that can replace other materials with a greater environmental impact, such as plastics. In both cases, organic materials, either animal or vegetable, are generally used.

Depending on the type of product to be produced, they may or may not be mixed with binders to improve their resistance, moisture resistant products (Satyanarayana et al., 2009), insect and rodent repellents or treatments to increase their resistance to fire (Schiavoni et al., 2016). In the case of eco-materials made out of lignocellulose vegetable materials, most of the studies focus on the elaboration of bio-composites made out mainly of vegetable fibers as filler elements in polymeric or bio-polymeric matrices as mentioned in the "Biomass" Section in Chapter 3.

Studies have also been conducted for the development of thermal insulation in the form of panels, or even as part of the mixture for the manufacture of bricks for construction. However, these fibers are mostly not agricultural residues, they are considered fiber crops such as hemp, jute, flax, kenaf to make these eco-materials (Schiavoni et al., 2016).

1.2 Motivation

The benefits offered by the UA are multiples, as mentioned above. In addition to helping to meet food demand within cities, it reduces the environmental impact related to transporting food from outside cities and provides economic and social benefits at the local level. For this reason, this food production system is constantly growing and improving as in the case of RTGs.

There are studies that seek to extend the benefits of RTGs to make them more sustainable through the efficiency of their resources such as energy (Nadal et al., 2017), their ecological network (Piezer et al., 2019), air quality (Ercilla-Montserrat et al., 2017), N_2O emissions (Llorach-Massana et al., 2017a), the recirculation of nutrients (Rufí-Salís et al., 2020) and the use of SW for CO_2 fixation (Llorach-Massana et al., 2017a; Llorach-Massana et al., 2017b). The latter related to the elaboration of bio-chart and thermal insulation material in processing plants at 25 km from the RTG using the biomass of tomato plants (mixture of 50% of stems with 50% of branches and leaves).

In addition to the fixation of CO_2 using biomass, one of the main reasons to study biomass is because until now it is considered a waste that is generated in large volume, and it is difficult to manage as selective collection waste by the municipality.

However, from the CE approach, it is important to consider the use of waste *in situ* as raw material to avoid the environmental impact attributed to the transport of waste for its management, which would help to improve the environmental performance of the life cycle of the RTG. At the same time, the growth potential of the UA, and increase of SW within cities generated by this system is expected, which could hinder its future management (Llorach-Massana, 2017).

According to future government plans for the creation of sustainable cities, a critical point is the reduction of waste within cities. Using eco-design to take advantage of waste by adding value by upcycling it locally using DIY techniques, could help reduce AUSW. Thus, the environmental benefits for the life cycle of the UA would be extended. In addition, this would provide the possibility of creating eco-materials or eco-products which, by fixing CO_2, would help to improve the carbon footprint of the AU and could replace other eco-materials with greater environmental impact.

1.3 Objectives

The main objective of this dissertation is to take advantage of the flow of the AUSW at the local level in order to improve the environmental performance of the UA and reduce the potential increase of this type of waste within cities, anticipating a future management problem. The above through the eco-design methodology from the CE perspective. This seeks to identify applications for *in situ* use of the AUSW adding value, in a creative and innovative way (Fig. 2).

Fig. 2. Graphic abstract of the main objective of the dissertation. AUSW- Agro-urban solid waste; DIY- "Do it your-self" approach

To achieve the main objective, the following specific objectives are developed throughout the thesis:

a) Classify and quantify the AUSW flow to determine which type of AUSW has the greatest potential for local use from the CE perspective.
b) Characterize and test the AUSW with the highest potential selected to identify its properties as an eco-material.
c) Propose and evaluate viable applications for the selected AUSW through eco-ideation strategies for their upcycling.
d) Present the methodology used as an adaptable tool for the use of AUSW from the perspective of the CE.

Chapter 2

Methodological framework

Chapter 2. Methodological framework

This chapter describes the interdisciplinary methodological context in which this dissertation is inscribed in a general way since, in each chapter, the case study, the materials and methods used for each case are described in detail. This chapter also includes missing information for a better understanding of the following chapters.

First, the case study is described in detail. Then, in general the topics related to the materials and methods that appear throughout the dissertation between part 2 and part 3 are addressed. These topics have been included in four general sections that are "Agro-urban solid waste flow analysis", "Material characterization", "Eco-ideation process" and "Test as eco-materials" (Fig. 3).

The topics "Laboratory work" and the "Bibliographic review" that are covered in both Part 2 and Part 3, in this chapter will be addressed in the "Agro-urban solid waste flow analysis" section. The topic: "Tests with tomato stems as eco-material", which also appear in both parts, in the present chapter is addressed in the section "Test as eco-materials" as explained in Fig. 3 with the dotted lines.

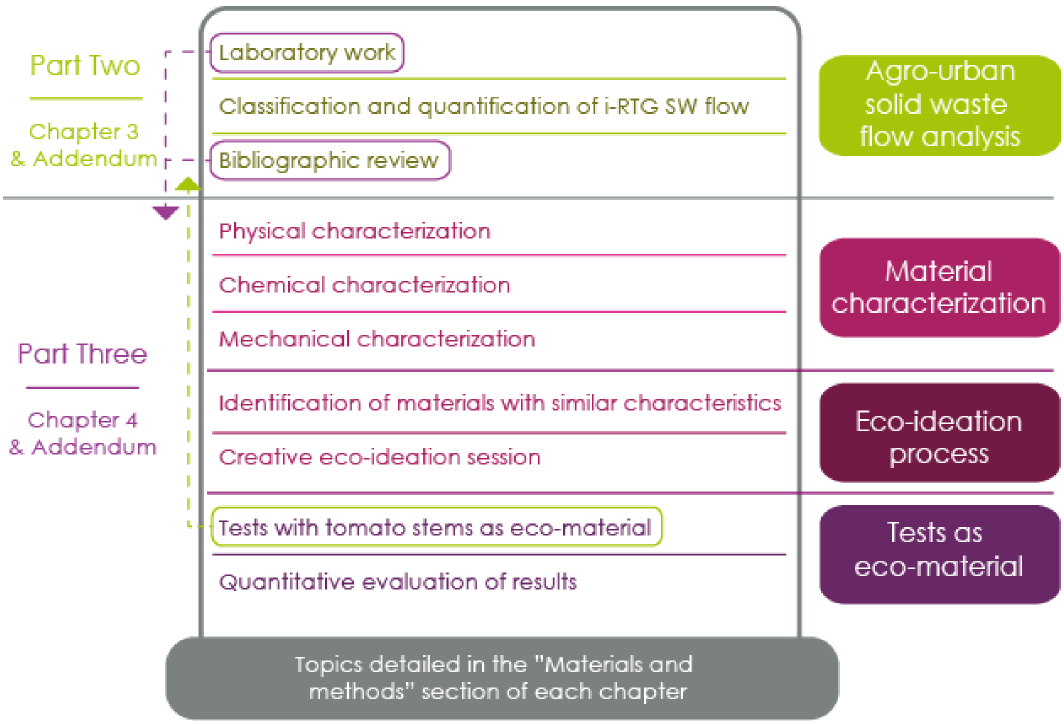

Fig. 3. Methodological framework structure

2.1. Case study

The case study is part of the FertileCity II project that has the general objective of deepening the research and empowerment of UA through RTG, providing information and tools that make it possible.

FertileCity project (www.fertilecity.com) was launched within a new RTG infrastructure on the top floor (4th floor) of the building of the Institute of Environmental Science and Technology and the Catalan Institute of Paleontology (ICTA-ICP)(Fig.4) within the campus of the Autonomous University of Barcelona (UAB) in Cerdanyola del Vallés, Barcelona (41° 29' 51.7" N 2° 06' 31.8" E).

Fig. 4. Institute of Environmental Science and Technology and the Catalan Institute of Paleontology (ICTA-ICP)

The building has a surface of 7500 m^2 distributed in 7 floors (5 levels above the ground and 2 below). The main structure and floors of the ICTA-ICP building are made out of reinforced concrete; the internal walls are made out of recycled wood, and the ceiling and exterior skins are made out of polycarbonate, which provides an ideal environment for growing crops and natural lighting for interior spaces.

The case study focuses on tomato crops planted between 2015 and 2019 in the LAU1 (Fig. 5). LAU1 has an approximate area of 122 m^2, where tomato plants are grown hydroponically in a growing area of 84.34 m^2. The greenhouse uses a thermal screen and low-density polyethylene (LDPE) curtains to improve internal heat conditions and to isolate the space from the rest of the building and the excessive influence of the outer layer. Both the curtain and the thermal screen work automatically depending on the temperature inside the greenhouse (Nadal et al., 2017). The water and nutrient solution required by the plants were provided through a drip fertigation system. Five control programs manage heating, cooling, and windows to optimize energy use

(Ercilla-Montserrat et al., 2017). This facility is currently connected to the building in terms of water, energy and CO_2 (Fig. 6) for research purposes on food production from a sustainable approach as an integrated RTG (i-RTG) (Sanjuan-Delmás et al., 2018b).

Fig. 5. Urban agriculture laboratory (LAU1) on the roof of the ICTA building.

Expanded perlite is used as a substrate in 57 LDPE plastic sacks OTAVI S&B brand (three tomato plants in each sack) 1 m long with a volume of 40 L (Sanjuan Delmás, 2017). They are placed in 9 rows of 5 bags and 3 rows of 4 bags (Fig. 7). Three plants are placed in each bag, so the total number of plants in the crop is 171, of which 47 are located on the perimeter and 124 are internal. The type of tomato grown in the LAU1 is heart of ox ("cor de bou") (Solanum lycopersicum), which stands out for its highly ribbed fruits with a heart shape. The color of the fruit at maturity reaches a good red color, they have a good consistently and good conservation (Syngenta, 2018).

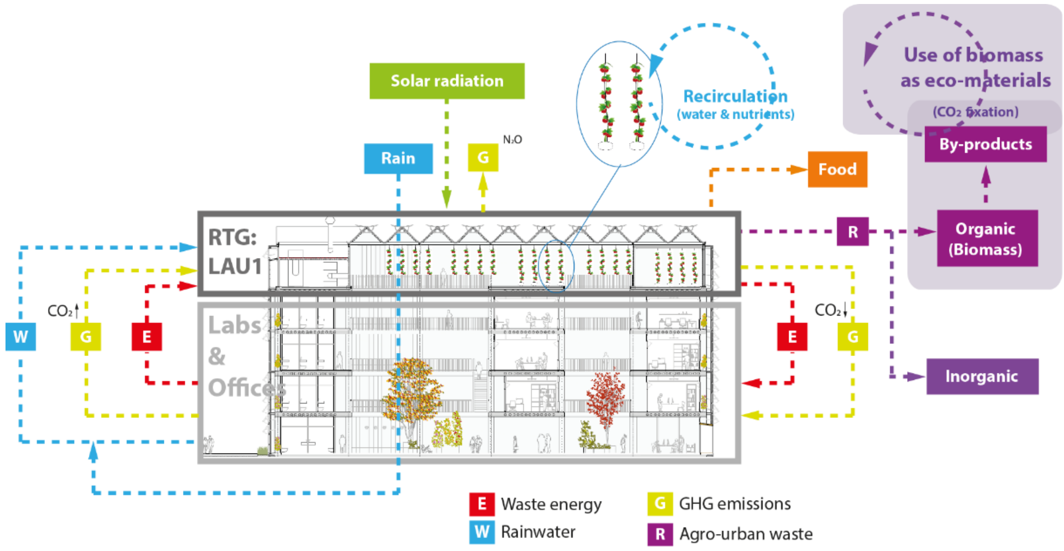

Fig. 6. Flow diagram of the ICTA-IPC building (adapted from: Sostenipra, 2018). RTG- Rooftop greenhouse; LAU1- Laboratory of urban agriculture; GHG- Greenhouse gases.

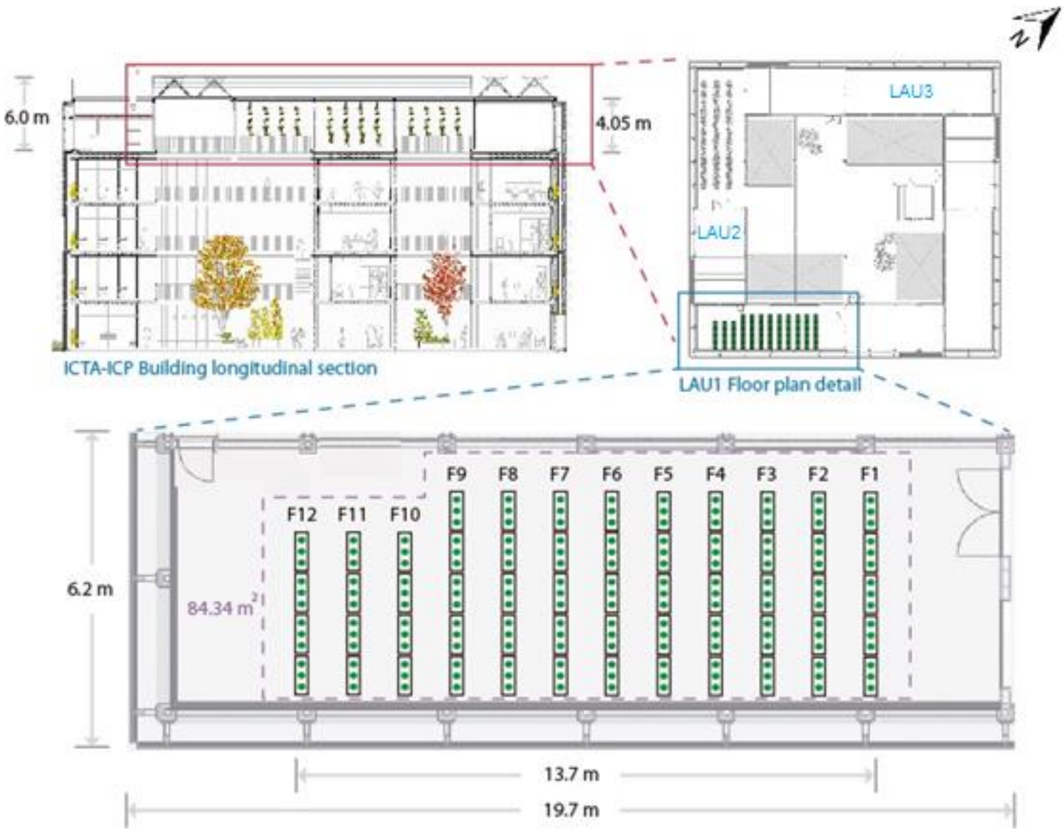

Fig. 7. Distribution scheme of LAU1 from RTG in ICTA-ICP building

2.2. Agro-urban solid waste flow analysis

The first part of the methodology focuses mainly on the agronomic area corresponding to the development of tomato crops and the classification and quantification of the SW flow as detailed in the "Materials and methods" section of Chapter 3.

In LAU1, six tomato crops have been developed between 2015 and 2019, following the methodology described by Sanjuan-Delmás, et al. (2018) , with some later modifications regarding the recirculation of leachates (Rufí-Salís et al., 2020). The crops are "summer 1 (S1)" in 2015, "winter (W)" between 2015 and 2016, "summer 2 (S2)" in 2016, "summer 3 (S3)" in 2017, "summer 4 (S4)" in 2018 and "summer 5 (S5)" in 2019 (Table 1).

Table 1. Details of LAU1 tomato crops

Crop	Season	Starts	Finishes	Duration (days)	
S1	Spring-summer	10/02/2015	23/07/2015	164	(Sanjuan-Delmás et al., 2018)
W	Fall-winter	15/09/2015	04/03/2016	169	
S2	Spring-summer	08/03/2016	20/07/2016	133	
S3	Spring-summer	12/01/2017	18/07/2017	159	
S4	Spring-summer	10/01/2018	30/07/2018	175	
S5	Spring-summer	17/01/2019	02/08/2019	198	

The methodology used for the quantification of AUSW is described in Chapter 3 between the "case study" section and "materials and methods", as well as in the "laboratory work" section in Chapter 4. However, the OSW management protocol used from 2017 (S3) is described in detail below in order to provide information that serves as a guide to continue and to improve the present study in future research.

Starting from the first 30 days of each crop approximately, the tomato plant should be pruned regularly (see the evolution of pruning biomass generation in Addendum B) as part of the maintenance of the crop. To quantify the pruning biomass of the crops, each time the leaves or branches were pruned, they were accumulated at the end of the corresponding row and weighed row by row each day, the information was recorded in special format (see Appendix A).

At the end of the 2017 crop (Fig. 8), while the stems were still hanging in the training system, the branches were separated together with the leaves, cutting them from the stems (Fig. 9) and the leaves and branches were weighed together by rows and a composite sample of approximately 5% was dried at room temperature (Fig. 10).


Fig. 8. Tomato crop 2017


Fig. 9. Separation of branches and leaves from the main stem

Fig. 10. Samples of tomato leaves and branches put to dry at the end of the 2017 crop

After cutting the stems 20 cm from the base (Fig. 11), and taking them off the trellis, the clamping rings were removed (approximately 15 per stem). The first 20 cm of the stems next to the roots were considered as part of these and they were weighed together considered as roots. Total length and diameters were measured at eight different points of the stem and 68% (116 stems approx.) of the total stems of the crop were weighed. Each stem was cut into 1m sections, and tied separately to dry on the ground, under similar conditions to LAU1 and labeled with the plant number and row number to identify it for further analysis and experimentation (Fig. 12).

Fig. 11. Perlite bag with the stems cut 20 cm from their base

Fig. 12. Sample of dried tomato stems from the 2017 crop

For the 2018 crop (Fig. 13), the biomass management protocol at the end of the crop was modified to obtain more detailed data and to be able to carry out tests and analyzes with the stems. In this year, 100% of the crop stems were measured, weighed (the information was recorded in special format, see Appendix A) and dried (171 stems approx.). Dry weight was obtained through an estimate considering the percentage of lost moisture obtained in the previous crops. To test the stems more efficiently, it was decided to dry the uncut stems and spread them as straight as possible on the ground in LAU3 (Fig. 7) under similar conditions to LAU1 (Fig. 14).

Fig. 13. Tomato crop 2018


Fig. 14. Tomato stems of the 2018 crop extended for natural drying

The 2019 crop was different from the previous ones since, to carry out other experimental studies on water stress, the crop was divided into sector 1 and sector 2 (Fig. 15). Sector 2 had 12% less irrigation than the sector 1. For this crop, the pruning residual biomass management protocol throughout the crop and at the end of the crop was similar to that of 2018. An estimate of the dry weight was made considering the percentage of lost moisture obtained in the previous crops. 100% of the crop stems were measured, weighed and dried by rows and by sector, 160 complete stems and four partial stems in total. The extended stems were dried as straight as possible on the ground in LAU3 (Fig. 7) under similar conditions to LAU1, keeping the stems of sector 1 and sector 2 separate.

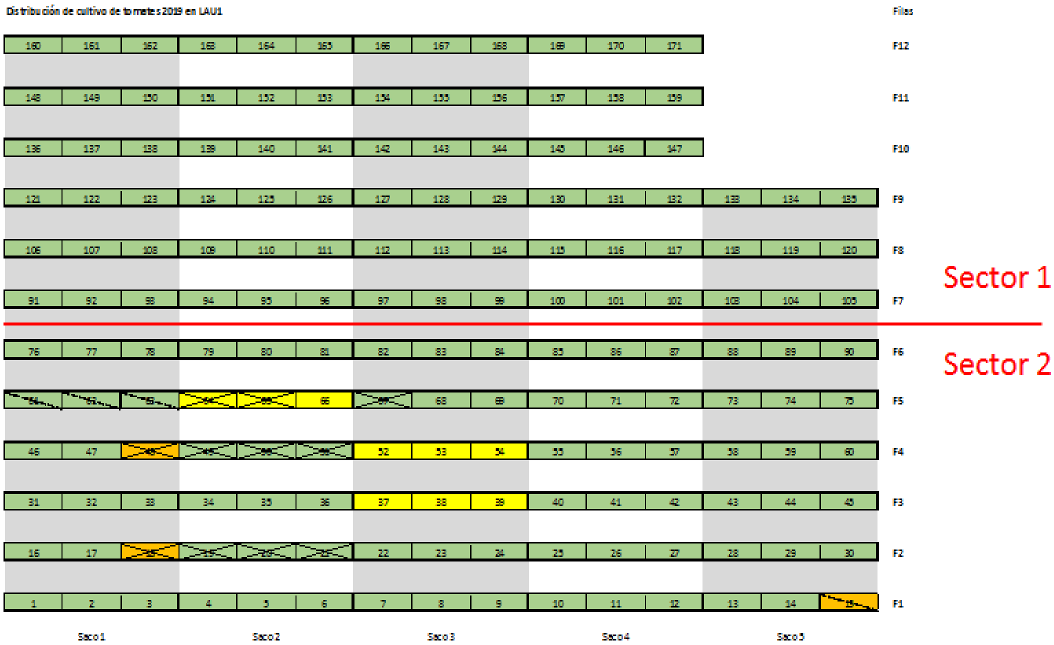

Fig. 15. Tomato crop distribution 2019 at LAU1

2.3. Material characterization

The interdisciplinary perspective addressed by the dissertation becomes more evident from the section on "Materials and methods" in Chapter 4. In this chapter, the sections of physical, chemical and mechanical characterization of the material are presented, a fundamental part to explore the possible applications of a non-commercial material, as can be seen in several studies (Henrique, Silvério, Flauzino Neto, & Pasquini, 2013; La Gennusa et al., 2017; Schettini et al., 2013). However, before the aforementioned characterization, a first characterization of the selected AUSW was carried out with the particular objective of elaborating substrate, as detailed in section 3.5.4 of Chapter 3 and which is fully explained in Addendum A of said chapter. This characterization considers only the physical and chemical aspect of the processed material to be used as a substrate, unlike the characterization detailed in sections 4.4.3, 4.4.4 and 4.4.5 of Chapter 4, which considers the material in its natural form, unprocessed and where its thermal behavior (Fig. 16) and mechanical characterization are integrated (Fig. 17).

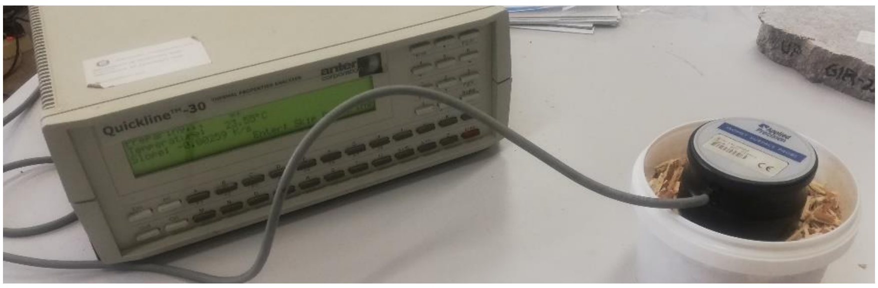

Fig. 16. Measurement of the thermal behavior of the selected AUSW.

Fig. 17. Mechanical tests of the selected AUSW

2.4. Eco-ideation process

Taking into consideration that the main objective of the dissertation is the use of a AUSW, which as mentioned above is a non-commercial material, after obtaining the largest amount of data based on its characterization, the next step is to identify materials with similar characteristics as described in the "Identification of materials with similar characteristics" section of "Materials and methods" in Chapter 4. As there are no precedents for their use, it is necessary to have references regarding their properties and thus identify viable areas of application. Continuing with the methodology used, these data serve as a guide for specialists who participate in the concept generation process through the creative eco-ideation session. The approach proposed by Ashby (1992) for the selection of materials was used as a tool to achieve this objective. This approach was created primarily to assist in the conceptual design stage, to efficiently choose the materials to be used from an estimated universe of 60,000 average materials and more than 1,000 ways to process them (M. F. Ashby et al., 2004).

The Ashby approach proposes a performance index (M. Ashby et al., 1993), which is a group of properties that can be maximized or minimized until obtaining the material that meets the desired characteristics, this through the use of graphics for identification with the assistance of software.

To select a material in the CES EduPack (GrantaDesign©, 2018) software, the first step is to select the properties to be related, both on the "Y" axis and on the "X" axis. Once this is done, a graph is generated showing all the materials available in the database located in the graph, depending on the selected properties (Fig. 18). In this fashion it is easy to visualize the different sets of materials divided by "balloons of different colors" creating families such as metals, polymers, ceramics, compounds and natural materials. It is even possible for several balloons to overlap maintaining the distinction between families. The next step is to specify an area of the graph to refine the search and reduce the amount of materials displayed. It is possible to put limits on the values of the properties used. In this manner, the program discards materials that do not meet the given criteria until the material that is closest to the desired performance is identified.

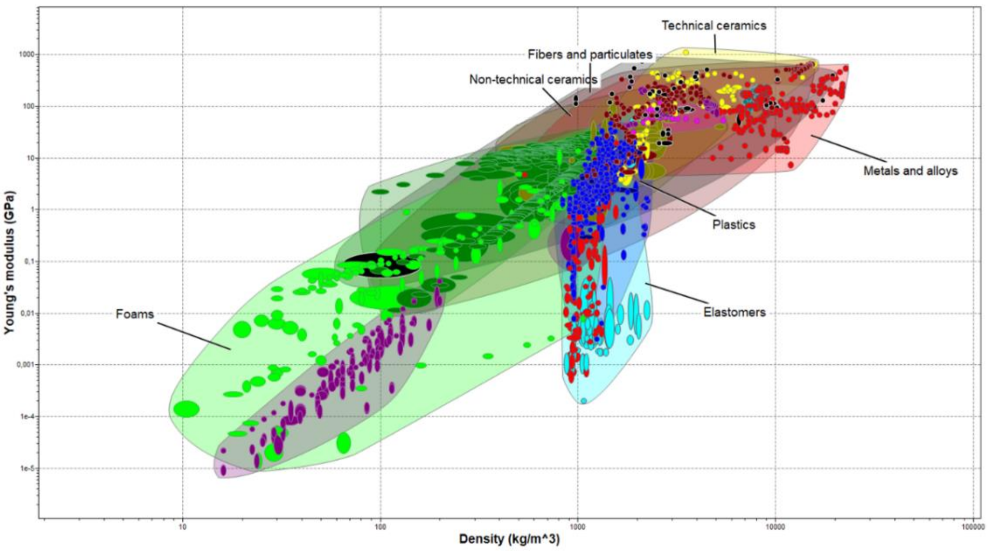

Fig. 18. Example of Ashby's graph relating Young's modulus and density of all available materials in the CES EduPack (GrantaDesign©, 2018) database divided by material families

In the case of this dissertation, as explained in Chapter 4, through the CES EduPack (GrantaDesign©, 2018) software, it was possible to use the characterization data of the selected material to "create" a new material in the base of program materials data.

As previously explained, to identify materials with characteristics similar to our material, the area on the graph was reduced by introducing limits on the values of the properties used for the different graphs that were made, thus the number of materials "close" to our material within the graph decreased. Subsequently, a relationship was made regarding the "closest" materials that appeared most frequently in the different graphs relating different properties to identify the five materials most similar to our material. This information was used to identify potential application areas for the selected AUSW (section 4.4.6 of Chapter 4) that would serve as a guide to identify potential applications during the creative eco-ideation session as detailed in section 4.4.8. of Chapter 4.

2.5. Test as eco-materials

To identify the feasibility of using the chosen AUSW, several tests were carried out at two different stages of the methodology development.

In the first stage presented in Chapter 3 and detailed as part of Addendum A, the material was tasted as substrate for two experimental lettuce crops. The tests were performed without considering a previous evaluation based on the eco-design methodology. In other words, the parameters that were considered to choose the type of experiment were based solely on the bibliographic identification of the possible current procedures for waste similar to the type of AUSW chosen, prior to its characterization, and on the comparison with respect to the environmental impact generated during the process of preparing the substrate with data from previous studies. This test and its results served as a reference during the creative eco-ideation session that took place later.

The second stage in which tests were carried out with the material, as detailed in section 4.4.10 of Chapter 4, was after the creative eco-ideation session, based on the concepts generated by the specialists. These tests were carried out following the DIY approach to identify the technical feasibility for carrying out the resulting proposals. This was one of the criteria considered in the semi-quantitative evaluation carried out at the end of the dissert detailed in section 4.4.11 of Chapter 4.

Part Two

Urban agriculture solid waste analysis

Chapter 3

Analysis of urban agriculture solid waste in the frame of circular economy

Chapter 3. Analysis of urban agriculture solid waste in the frame of circular economy

This chapter is based on the following published paper:

Manríquez-Altamirano, Ana, Jorge Sierra-Pérez, Pere Muñoz, and Xavier Gabarrell. 2020. "Analysis of Urban Agriculture Solid Waste in the Frame of Circular Economy: Case Study of Tomato Crop in Integrated Rooftop Greenhouse." *Science of The Total Environment* 734: 139375. https://doi.org/10.1016/j.scitotenv.2020.139375.

The authors acknowledge the contribution of Verónica Arcas Pilz for the design and participation in the development of experimental crops using tomato stems as substrate.

Data have been updated by Addendum to Chapter 3:

- Tomato stem as substrate for experimental lettuce crops
- Residual biomass of tomato crops of 2018 and 2019

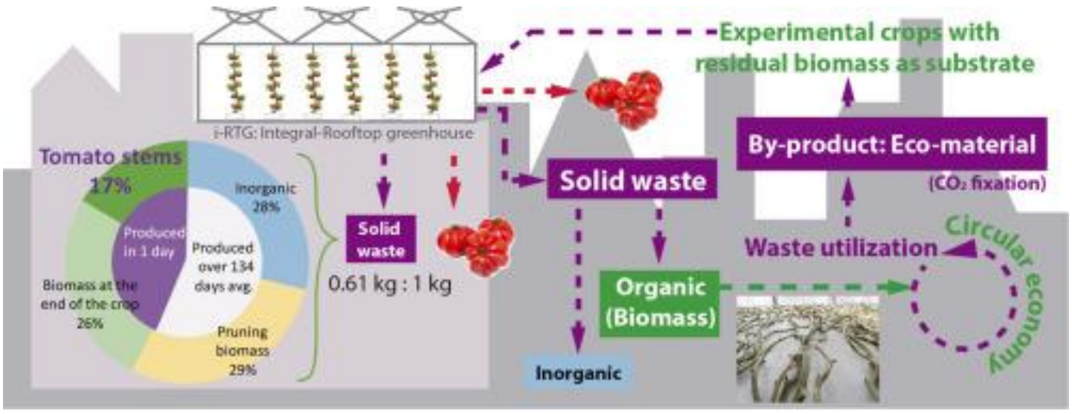

Fig. 19. Graphical abstract

Abstract

Within UA, i-RTG have great growth potential as they offer multiple benefits. Currently it is intended to improve environmental benefits by taking advantage of the water, nutrients and gases flows. On the other hand, SW generated by the UA is a new type of waste within cities that has not well been classified or quantified for its use.

Addendum

to Chapter 3

A: Tomato stem as substrate for experimental lettuce crops

B: Residual biomass of tomato crops of 2018 and 2019

C: Amendment

A. Tomato stem as substrate for experimental lettuce crops

This Addendum is based on Supplementary information B of the Supplementary data of the published document:

> Manríquez-Altamirano, Ana, Jorge Sierra-Pérez, Pere Muñoz, and Xavier Gabarrell. 2020. "Analysis of Urban Agriculture Solid Waste in the Frame of Circular Economy: Case Study of Tomato Crop in Integrated Rooftop Greenhouse." *Science of The Total Environment* 734: 139375. https://doi.org/10.1016/j.scitotenv.2020.139375.

Objective

As a proposal for the local use of tomato stems as a by-product, they were considered to be used as a substrate for lettuce crops because it is a short-term crop (approximately one month), in addition to being a type of reference crop for other experiments within the research group.

Specific objectives

- Identify the technical feasibility and the procedure to follow, from its obtainment as a waste at the end of the crop, to the elaboration of substrate with the i-RTG tomato stems as a by-product.
- Characterize tomato stems as a substrate.
- Obtain levels of EC, pH and drainage in leachate to identify the viability and behavior of the material as a substrate along two crops.
- Identify from an agronomic approach, deficiencies and possible improvements for use as a substrate with respect to another substrate used as a reference (control).
- Analyze production by comparing it with the control and identify the yield of each crop and its evolution through both.

Materials and methods of the experiment

In addition to the shredded stems for the lettuce crops, a sample of tomato stems was destined to be characterized as a substrate according to the methodology described by Martínez (1992) for granulometry, organic and mineral components; From De Boodt et al. (1974) for apparent density, porosity and water-air relation; Huerta et al. (2010) for total organic matter and carbon; Kjeldahl's method for organic nitrogen, in addition to calculations and estimates to obtain other physical properties such as real density and humidity (the results can be consulted in *Table 3*).

Half of shredded stems for crop were disinfected in an autoclave during 40' at 121 °C. This as a specialist's recommendation to rule out the generation of some fungus from the tomato crop, or the drying, or storage process.

The distribution of the substrate bags was made in nine rows alternating rows of control substrate (expanded perlite), UT and TT, as can be seen in Fig. 23. The lettuce stock was purchased in a 4-leaf state. Before transplantation, the substrates were irrigated to achieve good water saturation.

The crop period was, for the first: 07/05/2018 - 04/06/2018, and the second: 20/06/2018 - 18/07/2018 (approximately one month each).

Drip irrigation was used with a flow rate of 3 L/h for each dropper. Leachates were collected every day in 5-liter pails placed at the end of each row in order to measure the volume in liters of leachate (drainage), pH and EC. The mineral nutrient solution incorporated into the irrigation system was: 8 NO_3^-, 1 P^+ 5, 3 SO_4^{2-}, 3 Cl^-, 0 Na^+, 8 K^+, 4 Ca^{2+} and 1 Mg^{2+} (mEq / L).

Chemical and physical substrates characterization

Table 3. Chemical characterization of tomato stem (naturally dried and crushed) as substrate

		Physical Properties
72.75	Dm	Dry matter (%)
27.25	H	Humidity (%)
0.10	Ad	Apparent Density Dry (g/cm³)
-40.97	Ac	Air capacity (%)
4.36	Wea	Water easily available (%)
2.57	Rw	Reservoir water (%)
6.93	Wa	Water Available (%)
34.04	Wha	Water hardly available (%)
1.58	Drd	Determination of real density (g/cm³)
93.70	Tps	Total porous space (%v/v)
81.69	Om	Organic matter (%)
18.31	Mm	Mineral matter (%)
0.10	Ad	Apparent density (g/cm³)
10.74	EC	Electric conductivity (micro S/cm a 25º)
5.52	pH	pH (unfiltered at 20º)
5.41	pH	pH (filtered at 20 º)
0.46	Dah	Apparent wet density (g/cm³)

Perlite: The expanded perlite is used as control since it is an inert and inorganic substrate and free of potential diseases with which one can have greater control of the measurements. The one used is 100% v/v expanded perlite with granulometry from 0 to 6 mm, EC of 0.09 dS/m, pH of 7, total effective porosity of >90%, air volume >60%.

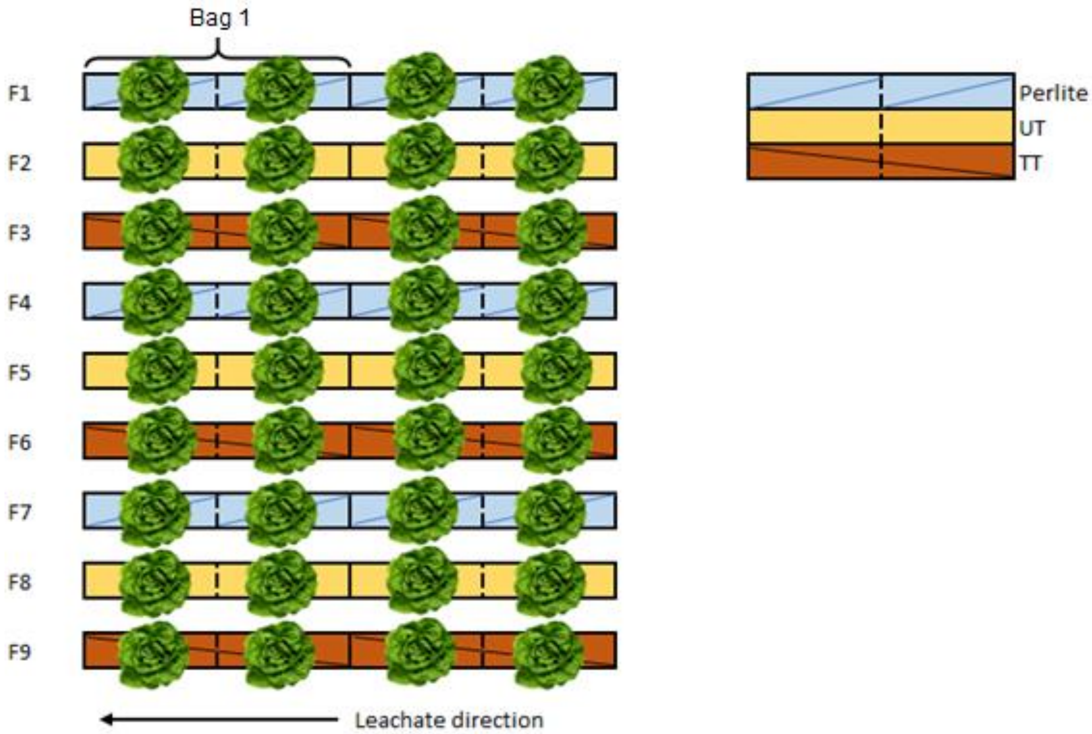

Fig. 23. Distribution of substrate bags for the two lettuce crops

Description of the experiments

Crop 1

At the beginning of the first crop, the leachates presented a high EC (13 mS/cm avg.) with respect to the control. For 26 days 2.6 L of irrigation was added per row to regulate the EC level. The crop lasted 29 days periodically adjusting irrigation to maintain drainage between 30% and 40%. At the end, the lettuces were removed along with their root, each sack of substrate was weighed again, and samples of the lettuces were taken separating them in aerial and root part, weighed and dried for analysis. Samples of leachate were also taken regularly throughout the crop for analysis.

Wash treatment

When seeing the high levels of EC at the beginning, it was considered to do substrate wash tests, for which the bags of rows 12 (UT) and 18 (TT) were used. The two sacks of each substrate were removed on day 14 of the culture, weighed without considering the lettuce plant and the TT and UTs were placed separately in containers with 10 liters of water each after making a first wash of the substrate with tap water. The pH and EC values of each of the washes were measured in addition to the tap water every 24 hours for 15 days. The values can be seen in the Table 4.

Table 4. pH and EC values of the substrate wash treatment.

May 2018		Measurement of leachate from substrate wash treatment every 24hrs. (7pm)					
		Tap water		UT6 (LAU2)		TT6 (LAU2)	
Day	#	EC	pH	EC	pH	EC	pH
14	1	0.68	7.9	8.10	6.8	3.90	7.2
15	2	0.66	8.3	6.30	6.3	3.60	6.4
16	3	0.64	8.2	3.50	6.6	1.91	6.4
17	4	0.54	8.0	2.00	6.2	1.21	6.1
18	5	0.56	8.0	1.43	6.3	0.94	6.1
Weekend							
21	6	0.57	6.3	1.68	5.3	1.04	5.3
22	7	0.63	6.4	1.12	5.7	0.76	5.9
23	8	0.53	6.7	0.91	5.6	0.71	6.0
24	9	0.50	6.8	0.77	5.4	0.59	5.9
25	10	0.49	6.6	0.63	6.0	0.54	6.8
Weekend							
28	11	0.48	6.6	0.76	5.8	0.67	6.0
29	12	0.54	8.0	0.63	6.3	0.62	6.6
30	13	0.55	7.4	0.79	6.7	0.67	7.0

Crop 2

The second crop was done under the same conditions as the first one. It began with levels of EC and pH more stable than the first, so it was not necessary to add water to the irrigation. The crop lasted 29 days, periodically adjusting the irrigation to maintain drainage between 30% and 40%. In the end, the lettuces were removed along with the root, each sack of substrate was weighed again, and samples of the lettuces were taken separating them in the aerial and root part, weighed and dried for analysis. Leachate samples were also taken regularly throughout the crop for analysis.

B. 2018 and 2019 residual biomass of tomato crops

Like the previous FertileCity project crops, the hydroponic tomato crops of the years 2018 and 2019 were carried out in the iRTG of the ICTA-ICP building in Barcelona, in LAU1 under similar conditions to the previous crops (see Chapter 3, section 3.2). The type of tomato grown was the beef heart ("cor de bou") (Solanum lycopersicum) Arawak variety, using expanded perlite as a substrate.

Throughout the crop, regular pruning was performed as part of the maintenance of tomato plants. The residual biomass that we considered for this research in both crops are the branches along with the leaves of the tomato plants and the stems. The residual biomass of the pruning, which are branches and leaves, they were weighed by rows to make a more detailed monitoring of their generation. At the end of the crop, for the purpose of this investigation, the stems were cut 20 cm from the base of the substrate bag. Subsequently, all branches along with the leaves were separated from the stems and weighed separately. The first 20 cm of the stems next to the roots were considered as part of these and they were weighed together considered as roots.

The stems were measured longitudinally, and during 2018 and 2019 crops, the approximate diameter of stems at five different stem heights of a sample of the total stems was measured. The biomass was placed on the ground for natural drying for two months, in a covered area, in the same building with similar conditions to those of LAU1 to be weighed, measured and analyzed later. Dry weight was obtained through an estimate considering the percentage of lost moisture obtained in the previous crops.

2018 crop

The 2018 tomato crop was an extended crop of 175 days and was carried out between January 10 and July 30 with a total production of tomatoes of 1073.67 kg. of which 1061.6 kg. were edible tomatoes. 171 tomato plants were planted, distributed in 12 rows (see Fig. 24), three plants in each sack of perlite, of which only 167 were completed at the end of the crop. Pruning began to take place 27 days after the start of the crop with intervals of four days average (Fig. 25). During approximately 147 days of cultivation, 430.88 kg of leaves and pruning branches were produced until before the end of cultivation. On the last day, all the branches and leaves of the main stems were separated and weighed 59.13 kg. (Fig. 26). Therefore, the total of branches and leaves of the 2018 crop was of 490.01 kg.

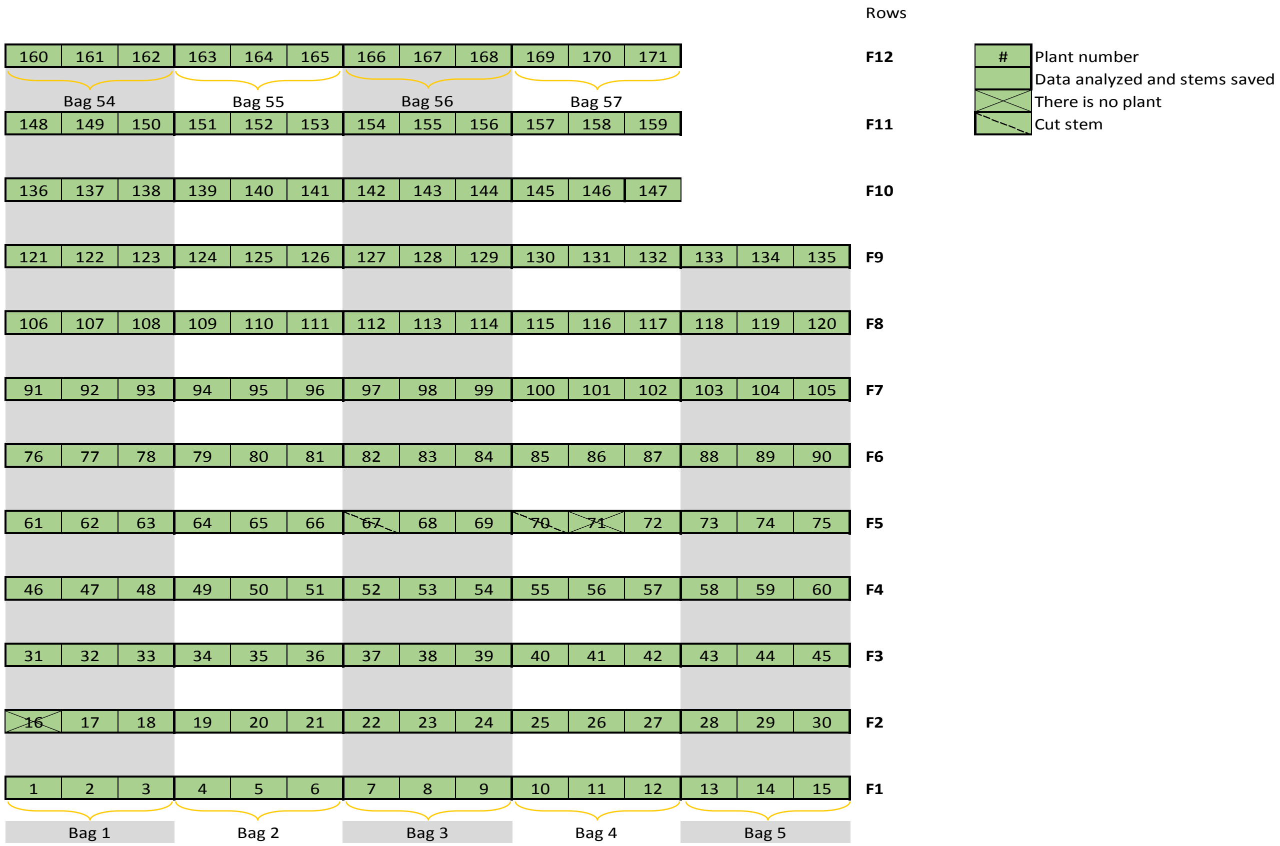

Fig. 24. Tomato crop distribution 2018 in LAU1

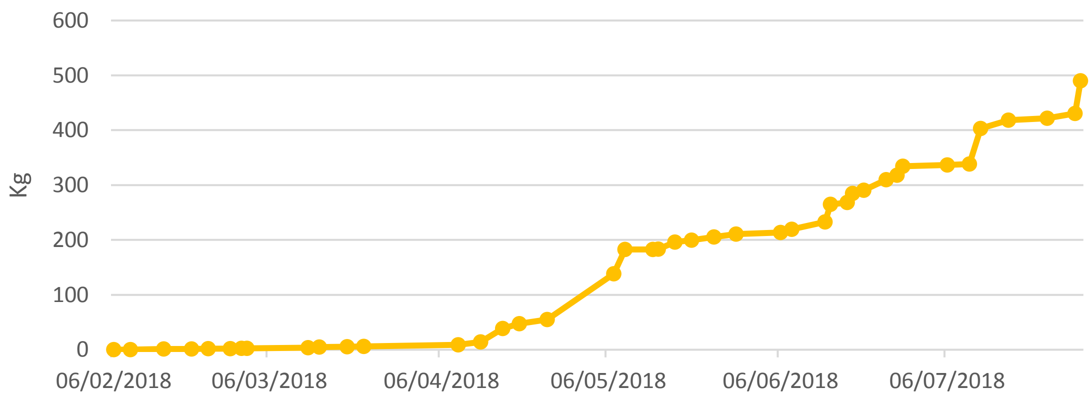

Fig. 25. Cumulative generation of residual pruning biomass during the 2018 crop

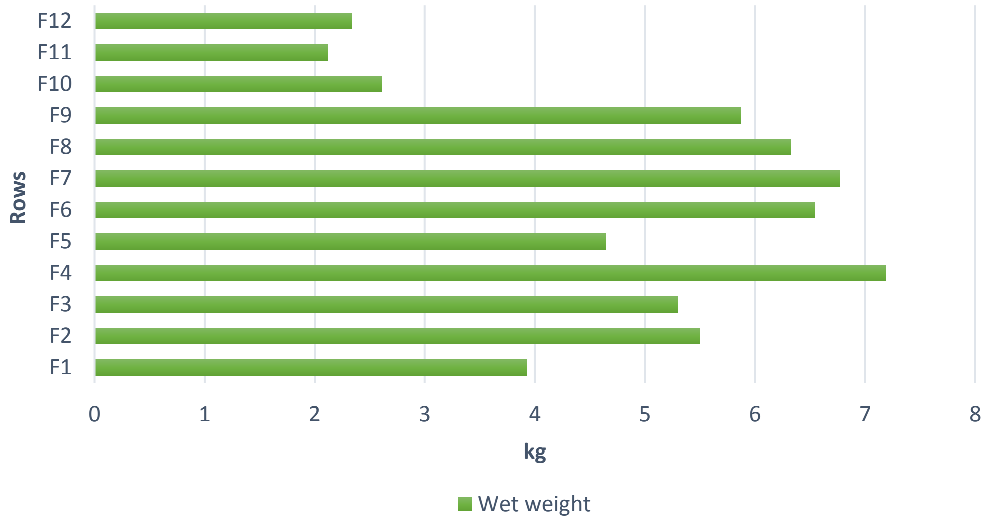

Fig. 26. Residual biomass by rows at the end of the 2018 crop

On the other hand, each stem without branches and leaves was weighed separately and 100% of the stems were measured longitudinally. The diameter was measured at five different heights of the 43 stems chosen in different areas of the crop to try to have a representative sample. The different heights at which the diameter was measured started from the base of the plant and were: 20 cm (starting the cut), 120 cm (1 m after the cut), 320 cm (approximately half of the stem), 520 (approximately 1 m before the end or tip) and 10 cm from the end (measuring from the tip in direction of the base). Table 5 shows the average results.

The average result by rows can be seen in Table 6 with a color analysis to identify which row generated the longest or shortest stems and in which row the heaviest or lightest stems were produced. The total wet weight of the stems was 165.49 kg. Therefore, the total residual biomass considering the pruning along the crop, the leaves and branches at the end of the crop along with the stems, is of 655.50 kg, which represents 62% of the weight of edible tomato production.

Table 5. Average measurement results of tomato stems

Wet stems	(m) Length	(kg) Weight	Ø As a function on the stem height starting from the root (cm) 20 cm	120 cm	320 cm	520 cm	10 cm from the tip*		
Máx.	7.74	1.45	1.90	1.90	2.00	2.30	1.80		
Mín.	4.20	0.55	1.20	1.40	1.10	0.70	0.45		
Mean	6.56	0.96	1.53	1.65	1.54	1.34	0.74	1.36	Ø Avg.
Median	6.65	0.95	1.50	1.60	1.50	1.30	0.70		
Mode	6.3	0.87	1.60	1.50	1.60	1.20	0.60		

* measuring from the stem tip in direction of the base

Table 6. Average results by rows of tomato stems

Average by rows (wet stems)		
Rows	Stems	
	Length (m)	Weight (kg)
F1	5.83	0.88
F2	6.31	1.05
F3	6.73	1.07
F4	6.75	0.99
F5	6.45	1.07
F6	6.54	0.96
F7	6.65	1.00
F8	7.01	0.98
F9	6.85	0.95
F10	6.49	0.91
F11	6.67	0.80
F12	6.34	0.86

2019 crop

The 2019 tomato crop was also an extended crop of 198 days, it was carried out between January 17 and August 2 with a total production of tomatoes of 1068.06 kg, of which 1012.0 kg were edible tomatoes. 171 tomato plants were planted distributed in 12 rows (See Fig. 27), three plants in each bag of perlite, of which at the end of the crop only 156 whole plants remained. However, only 146 were plants that were from the first day of cultivation, since the rest were planted later to compensate for some plants that were removed for other research purposes.

Unlike the 2018 crop, this time for other research purposes, the crop was divided into two sectors (six rows per sector) with different amounts of irrigation. Sector 2 (S2) remained with the same amount of irrigation as the previous years (30% leachate) and in Sector 1 (S1) 20% of irrigation was reduced.

Pruning began 32 days after the start of the crop with intervals of four days average (see Fig. 28). During approximately 165 days of the crop 210.16 kg of leaves and pruning branches were produced until before the end of the crop. On the last day all the branches and leaves of the main stems were separated and weighed 109.85 kg. (see Fig. 29). Therefore, the total branches and leaves of the 2019 crop was 320.01 kg.

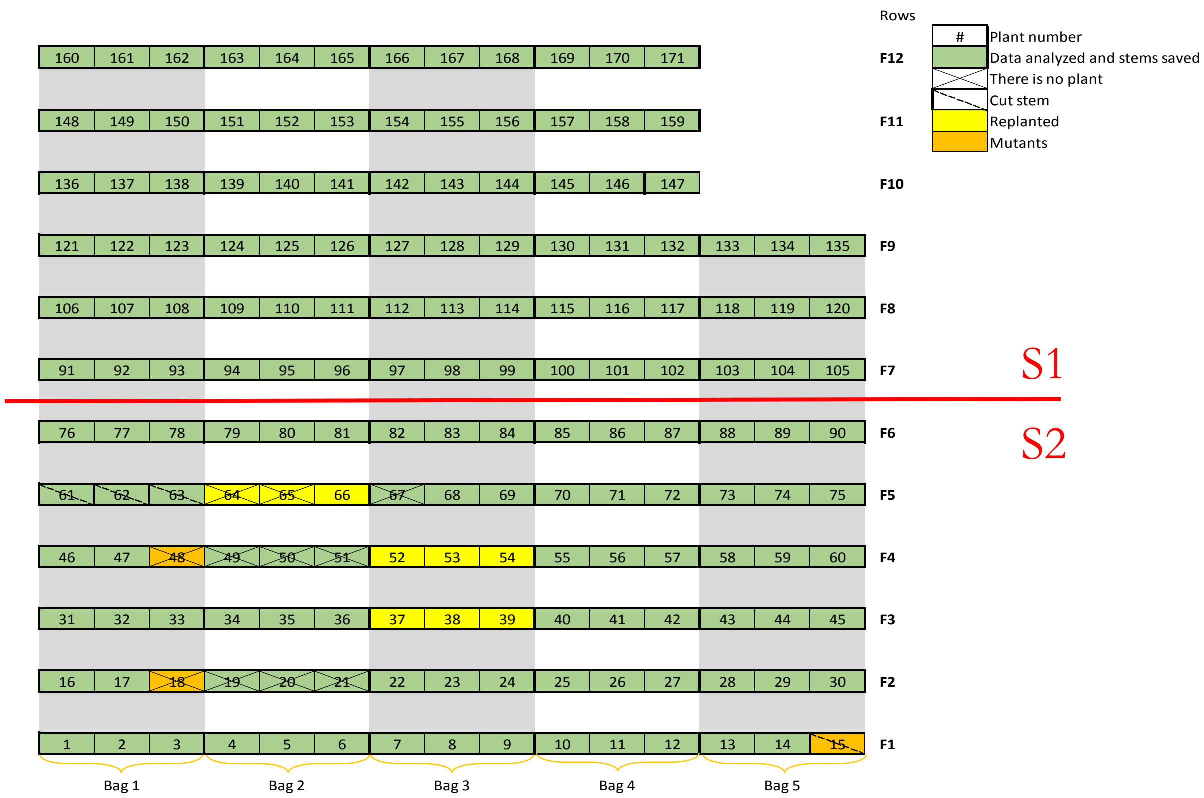

Fig. 27. Distribution of 2019 Tomato crop in LAU1

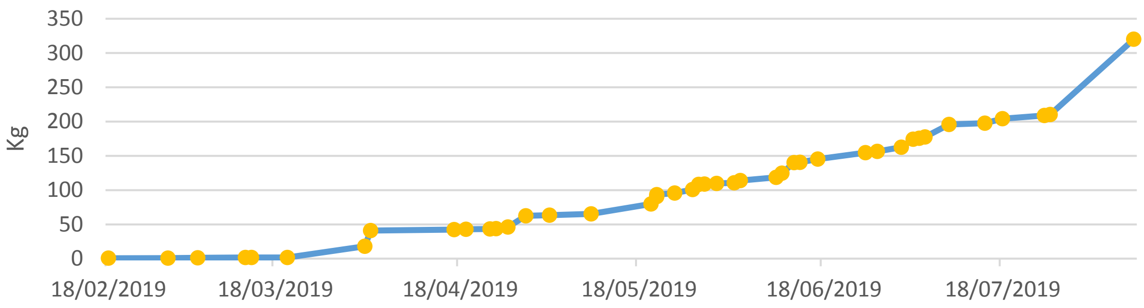

Fig. 28. Cumulative generation of residual pruning biomass during the 2019 crop

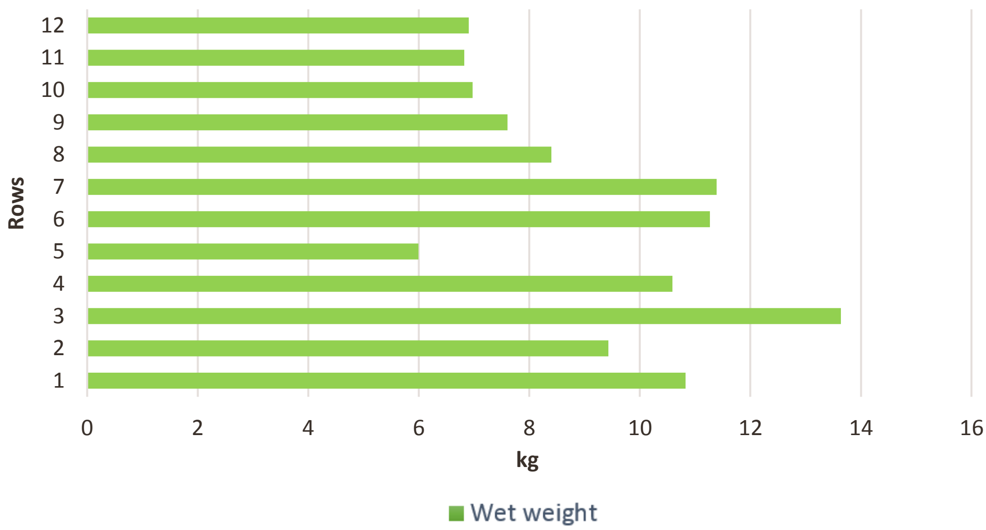

Fig. 29. Residual biomass by rows at the end of the 2019 crop

On the other hand, each stem without branches and leaves was weighed separately and 100% of the stems were measured longitudinally. Table 7 shows the general average results. The average result by rows can be seen in Table 8 with a color analysis to identify which row generated the longest or shortest stems and in which row the heaviest or lightest stems were produced. The total wet weight of the stems was of 149.67 kg. Therefore, the total residual biomass considering the pruning along the crop, the leaves and branches at the end of the crop along with the stems, is of 469.67 kg, which represents 46% of the weight of edible tomato production.

Table 7. Average measurement results of tomato stems

Wet stems	(m)	(kg)
	Length	Weight
Máx	7.02	1.53
Mín	3.07	0.36
Mean	5.89	0.96
Median	6.00	0.93
Mode	5.6	0.92

Table 8. Average results per rows of tomato stems

Average per rows (wet stems)		
Rows	Stems	
	Length (m)	Weight (kg)
F1	5.94	0.952
F2	6.28	1.131
F3	5.76	1.102
F4	5.78	1.071
F5	5.54	0.821
F6	6.11	1.034
F7	6.04	1.013
F8	5.68	0.846
F9	6.12	0.952
F10	5.89	0.902
F11	6.08	0.858
F12	5.35	0.787

On the other hand, Table 9 shows the results of each type of residual biomass divided by sectors. In Fig. 30 we can see the generation of the average pruning residual biomass per plant, per row in each sector.

Table 9. Results of each type of residual biomass divided by sectors

Wet biomass	Total (kg) S2	Total (kg) S1
Wet stems	76.94	72.72
Leaves and branches at the end of the crop	61.76	48.10
Pruning throughout the crop	117.88	92.28
Total biomass throughout the crop	256.58	213.09

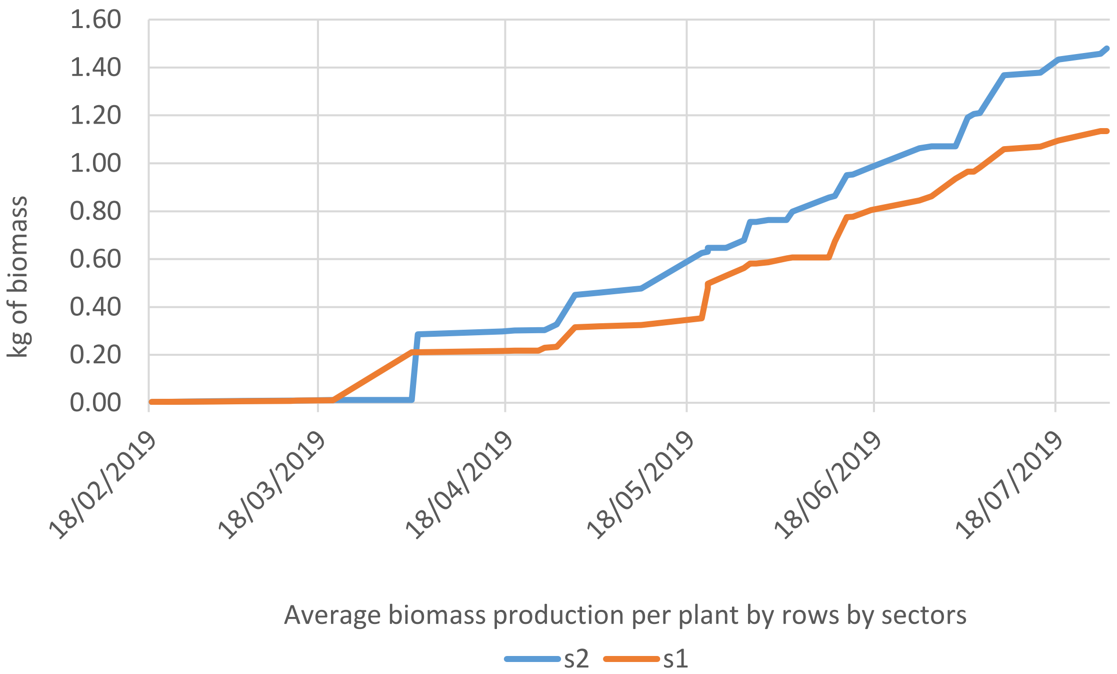

Fig. 30. Average pruning residual biomass per plant, per row in each sector

Table 10. Generation of residual biomass by crop

	10/02/2015 to 23/07/2015	15/09/2015 to 04/03/2016	08/03/2016 to 20/07/2016	12/01/2017 to 18/07/17	10/01/2018 to 30/07/2018	17/01/2019 to 02/08/2019
	S1	**W**	**S2**	**S3**	**S4**	S5
	Crop period (days)					
	164	169	133	189	175	198
	Pruning period throughout the crop (avg. days)					
	134	139	103	159	145	168
Pruning waste (kg/day)	0.89	0.72	1.29	1.59	2.97	1.25
	Generation at the end of the crop (1 day)					
Branches and leaves (kg/day)	90.85	106.8	103.65	71.6	59.13	109.85
Main stems (kg/day)	**72.9**	**63.8**	**57.6**	**167.99**	**165.49**	**149.67**
***Dry main stems (kg/day)**	**14.58**	**12.76**	**11.52**	**23.99**	**23.17**	**20.95**
Moisture lost in the stems	**80%**	**80%**	**80%**	**86%**	**86%**	**86%**

The data for the S1, W and S2 cultures were obtained from *Manríquez-Altamirano et al. (2020).*

*Placed on the ground for natural drying for 2 months in a covered area

C. Amendment

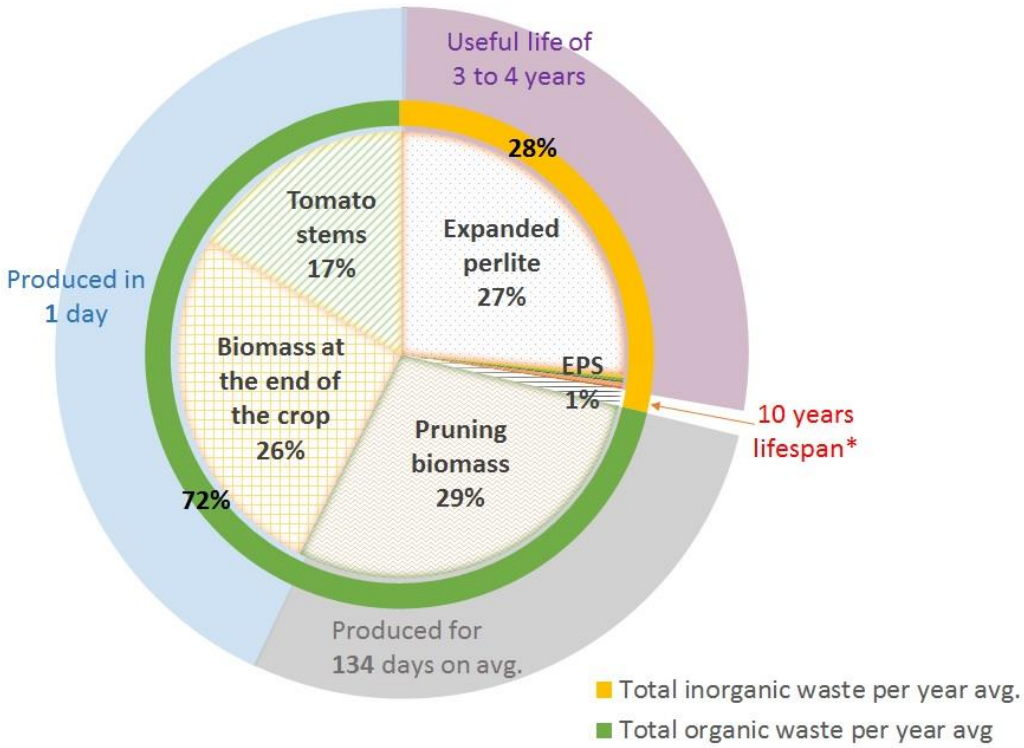

Fig. 31. Correction of Fig. 22. Percentages of generation of iRGT SW by materials and the timing of its generation. *(Sanjuan-Delmás et al., 2018)

Part Three

Applications for urban agriculture solid waste

Chapter 4

Identifying potential applications for residual biomass from urban agriculture through eco-ideation

Chapter 4. Identifying potential applications for residual biomass from urban agriculture through eco-ideation

Abstract

RTGs are among the UA systems that have grown considerably in recent years in dense cities. RTG have become popular because they have enabled food production to be brought into cities to mitigate food shortages and reduce environmental impacts related to transport and packaging, as well as having other social benefits. To make the RTG system more sustainable by improving its environmental performance and resource use efficiency, several studies have been performed to take advantage of the different flows. However, the flow of OSW or residual biomass has not been fully investigated to date for this purpose through *in situ* use.

The objective of this study is to improve the environmental performance of RTG by closing the cycle of residual biomass flow in accordance with a CE perspective. In addition, considering a future scenario of UA growth, the forecasted 20% increase in the volume of OSW will be difficult to address within the cities; therefore, this work may prevent the creation of a new problem to solve.

The results show that the proposed methodology is useful for identifying possible applications for upcycling UA biomass *in situ* through eco-design through a DIY approach. For this reason, the high relevance of the data on the material, the correct selection of specialists to participate in the creative session and experimentation with the material were identified. In this way, 3 possible applications for tomato stems were identified which, in order according to the results of the semi-quantitative evaluation, are "Fences and trellises", "Packaging" and "Boards, panels and blocks".

This study is the first to propose a methodology for the local use of residual biomass generated by UA. Furthermore, this study provides information on the physical, chemical, and mechanical characterization of tomato stems. The results of this study may help others to take advantage of the biomass generated during conventional agricultural activities.

Keywords

Circular economy, upcycling, creative workshop, residual biomass, eco-material.

4.1 Introduction

4.1.1 Residual biomass from rooftop greenhouses

RTGs are one of the UA systems involving the use of greenhouse methods with soilless cultivation systems and hydroponic techniques adapted for use on top of buildings. This system has grown considerably in recent years in dense cities (Sanyé-Mengual, 2015; Specht et al., 2014; Ercilla-Montserrat et al., 2017) since it has allowed food production to be brought to cities to mitigate food shortages and reduce environmental impacts related to transport and packaging as well as other social benefits (Puri and Caplow, 2009). Like other types of UA, this system generates different waste flows, and one of the primary ones is OSW, or residual biomass. This organic fraction represents a new challenge since it would add to the rest of the waste produced within cities, primarily due to its volume and amount, by approximately half of the resulting produce (Manríquez-Altamirano et al., 2020).

OSW within cities is usually managed by the municipality through a separate collection. In this case, the residual biomass generated in RTG would be added to the pruning waste (stems, branches and leaves). This type of waste, unlike kitchen waste, takes longer to degrade because it contains a larger volume of lignocellulosic material, so it is usually preshredded for processing. Of the total waste selectively collected at the municipal level in Spain (2016), the biomass fraction from parks and gardens represented 7%, and 60% of this type of waste was destined for composting (MITECO and INE, 2016), which is the most widespread traditional option for biomass management in addition to landfills (Quirós et al., 2014).

4.1.2 Circular economy and upcycling

To improve the environment, the CE initiative was created to encourage changes in the way the entire economic system works, to convert from linear to circular flows (Korhonen et al., 2018), which would help to close product life cycles by increasing the material reuse and recycling rates.

The CE seeks to maintain the value of products, materials and resources for as long as possible, minimizing the extraction of raw materials, the generation of waste and the emission of greenhouse gases related to the new production of products (Camarsa et al., 2017). In this regard, waste management plays a key role within the CE. In addition, it is important to consider that to maintain environmental benefits, it is ideal to use waste locally, eliminating the environmental impact related to waste transport (Specht et al., 2014).

Upcycling is one of the CE strategies, and it is about increasing the quality, functionality or aesthetic value of a material or product through recycling (Ahn & Lee, 2018; Sung, 2015). This term is a neologism that emerged in the 1990s (Bridgens et al., 2018) in contrast to downcycling, which represents a decrease in the value or quality of a material upon recycling (Vefago and Avellaneda, 2013). The use of this strategy has recently increased due to the interest in extending the lifetime of materials or products, which in addition to helping the environment also represents an economic benefit at the local level (Sung, 2015). Furthermore, upcycling has allowed designers to experiment with the potential new materials created from waste (Caliendo et al., 2020). This approach implies working with a material flow that may not be constant nor have a large volume, and its characteristics may vary, so it is necessary to use imagination and creativity to take advantage of these materials locally and generate useful products within a certain area with particular needs (Bridgens et al., 2018).

The DIY approach that is based on self-production using shared knowledge of simple production processes, low cost and affordable manufacturing tools (Rognoli et al., 2015) could be used as a means of upcycling waste.

In this context, OSW has great potential to be exploited for upcycling (Lasaridi and Stentiford, 2011) through the DIY approach.

4.1.3 Eco-materials from eco-ideation

When looking for environmental benefits in the framework of the CE, the design of a product or material plays a very important role. In this case, eco-design that seeks to create sustainable solutions and meets human needs by considering the entire life cycle of the product (Karlsson and Luttropp, 2006) is a methodology that can be used to take advantage of waste in an efficient and effective way. One of the critical stages of eco-design is the stage of development on the new concept for the product or material, in which creativity, innovation and the participation of many different actors are required (López-Forniés et al., 2017). At this time, eco-ideation is a strategy that is characterized by search, experimentation, participation, and the exchange of knowledge (Sierra-Pérez et al. 2016a; Demertzi et al. 2017) that can help generate concepts to create eco-friendly products or eco-materials.

The eco-material concept was created in 1991 to refer to materials designed to minimize environmental impacts by considering their entire life cycle (Halada et al., 2002; Wang et al., 2005). An example of this approach is the use of waste from the cork industry, which, in addition to its use in wine stoppers, is a material that can add value to the construction industry due to its physical characteristics (Sierra-Pérez et al., 2016b). The use of creative eco-ideation techniques was key to identifying this alternative use. In the same vein, residual RTG biomass can have great potential to become an eco-material, which would help to close the cycle of the waste stream while improving the environmental performance of the RTG life cycle.

4.2 Case study: Tomato stems from a rooftop greenhouse

This research starts from a previous study (Manríquez-Altamirano et al., 2020) on the classification and quantification of i-RTG solid waste to identify the potential for use from a CE perspective. The results of this study showed that the organic fraction or residual biomass was the most critical type of i-RTG solid waste to manage within densely populated compact cities, and it had the greatest potential for local use according to its volume, generation timing and type of management. This is particularly true for the stems of tomato plants, which are generated only at the end of the crop and represent 33% of the total biomass.

This research focuses on identifying applications for the use of tomato stems from the FertileCity ("Fertilecity", 2018) project within the 2015 to 2018 period (3 different crops). The crops were developed in the LAU1 of the ICTA-ICP building in Barcelona (Spain), with a total crop area of 84.34 m^2 and a production of 1269 kg/year avg. (Manríquez-Altamirano et al., 2020) of edible tomatoes. It is a soilless crop system with 171 plants using expanded perlite as a substrate to grow the Heart of ox ("Cor de bou") tomato (*Solanum lycopersicum*) variety Arawak (Sanjuan-Delmás et al., 2018).

4.3 Justification and aim of the study

To make the RTG system more sustainable by improving its environmental performance and the efficiency of its resource use, several studies have been performed to take advantage of different flows. However, the residual biomass has not yet been fully investigated for this purpose through its *in situ* use (Manríquez-Altamirano et al., 2020). There are different ways of taking advantage of biomass, with composting being the most traditional and most widespread option that could be used locally from a DIY perspective. However, the aim of this study is to find applications to add value to the residual biomass as a higher quality eco-material without losing the benefits of its development and use *in situ*. For this reason, energy use or chemical compounds (ingredients for the food or cosmetic industry) are also not considered.

The objective of this study is to improve the environmental performance of RTG by closing the cycle of residual biomass flow from a CE perspective. In addition, in considering a future scenario for UA growth, there is a predicted 20% increase in the volume of OSW, which is difficult to treat within cities, which could become a new problem to resolve (Manríquez-Altamirano et al., 2020). Taking advantage of tomato stems from the CE perspective shows us a path to follow for upcycling through eco-ideation strategies to identify useful and viable applications at the local level within densely populated compact cities, such as many in Europe, using a DIY approach.

4.4 Materials and methods

This research is based on a previous study by Manríquez-Altamirano et al. (2020), and uses an adaptation of the methodology presented by Sierra-Pérez et al. (2016b). The methodology is divided into three primary stages, and each one is separated into different sections (see Fig. 32) as described below.

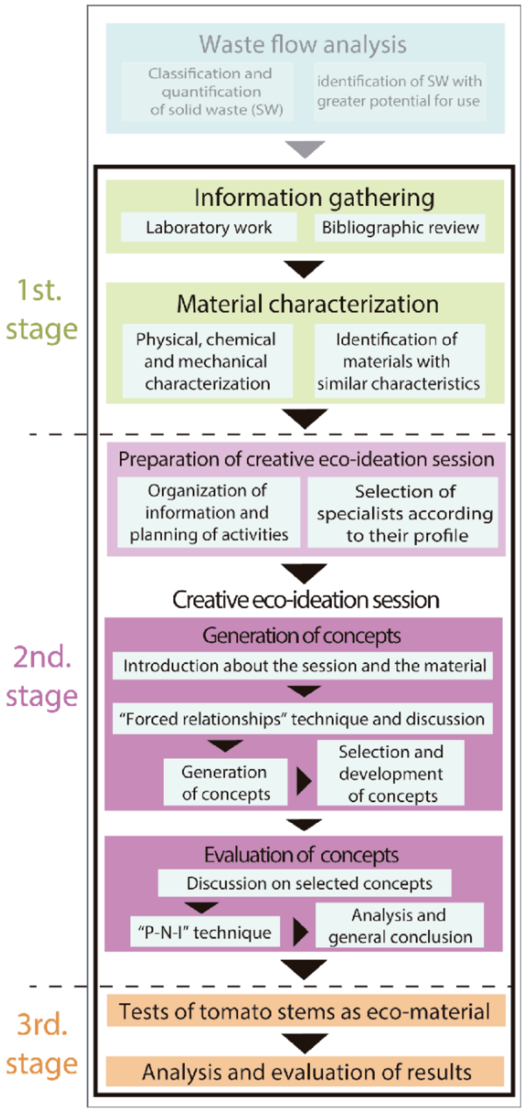

Fig. 32. Adapted from Sierra-Pérez et al. (2016b).

4.4.1 Laboratory work

For this research, data from five different tomato crops collected between February 2015 and July 2018 were used, from summer 2015 (S1), winter 2015 (W), summer (2016) S2, summer 2017 (S3) and summer 2018 (S4) (detailed information can be reviewed in Table 10 in Addendum B of Chapter 3). A specific procedure is followed at the end of each crop (Manríquez-Altamirano et al., 2020). The stems are unhooked from the crop holding system that consists of raffia guides hanging from cables 4 m from the ground, and each stem is attached to the guide by approximately 15 rings. The stems are manually separated from the system and cut 20 cm from the base of the substrate bag. Subsequently, all the branches along with the leaves are separated from the main stems and then weighed and measured separately. The stems are spread out in the soil to air dry for 2 months and are measured and weighed again. Samples equivalent to 68% of the total biomass were analyzed except for the 2018 samples, for which the total fresh biomass was analyzed.

4.4.2 Bibliographic review

First, relevant information was collected on the stems from the crops of the FertileCity project generated by the Sustainability and Environmental Prevention research group ("Sostenipra", 2018). Subsequently, a review of the body of knowledge was performed on the scientific literature through online catalogs (that is, Web of Science, Google Scholar and Scopus) using the term "tomato stems" as keywords, the search was also refined by adding each of the following words, "characterization", "characteristics" and "properties". Subsequently, the citations referenced in the resulting articles were reviewed to find information that was relevant to this research.

4.4.3 Physical characterization

A physical characterization was performed on the tomato stems of the S3 and S4 crops (fresh and dried naturally). For some of the tests, it was necessary to crush the dried tomato stems using a special crushing machine for compost (4 kW, 58 kg) (TECO Insaen, 2006).

- Measurements of the dimensions, weight and density

At the end of each crop, the process described in the "Laboratory work" section is followed to measure and weigh the stems. The diameter of each stem is measured with an analog Vernier caliper at 8 different heights, with the first starting from the cut point and then at 1 m, 2 m, 3 m, 4 m, 5 m, 6 m and finally 10 cm from the tip to the stems that exceed 6 m. The shape of the cross-section of the tomato stems is not completely circular; they usually have a semioval, amorphous shape, and therefore, when measuring the diameter, it is considered the broadest part of this shape. The stem density is calculated by gravimetric displacement method using Archimedes' principle with a balance (e= 1 g d= 0.1 g) and a graduated cylinder with a capacity of 50 ml using dried tomato stem samples of known masses.

- Degradation tests

The soil degradation tests are performed on fresh stems using 10 samples consisting of 10 cm-long fresh stems averaging 15.89 g each. Each one was placed in plastic containers with 90 g of soil (universal substrate) for 8 months. The tests are reviewed to verify the total weight of each container and the weight, approximate diameter, and appearance of each stem sample at 15-day intervals for the first month and thereafter for each month. For soil degradation tests with dry stems, 10 samples of 10 cm of dry stems of 1.86 g avg. are used. Each one was placed in plastic containers containing 104 g of soil (universal substrate) for 5 months. The tests are reviewed to verify the weight (balance: e= 0.1 g d= 0.01 g), diameter, and appearance of each stem sample at 15-day intervals for the first two months and each month thereafter. The outdoor degradation test is performed on 3 samples (A, B and C) of dry stems weighing 25 g each, which are placed on the roof for 12 months. They are weighed (balance: e= 1 g d= 0.1 g) and measured every month, yielding an average diameter of 1 cm and a length of A: 138 cm, B: 111 cm and C: 104 cm.

- Water absorption, moisture and ash content

The water absorption capacity is evaluated based on the standard 24-h water absorption or balance test ASTM D570 (ASTM, 1985) with 4 samples of 1.35 g stems that were oven dried at 105 °C for one hour. Each sample was placed in a 60 ml transparent polystyrene bottle with 60 ml of Elix® system-purified water. The moisture content was calculated by taking the difference between the weight of the fresh and dry samples based on Test D2216-05 (ASTM, 2005). The ash content is obtained by calculating the percentage difference between the initial weight of the dry stem samples and the weight of the ash after calcination in a muffle furnace, with a ramp of 5:30 h starting from room temperature (25 °C avg.) and increasing to 550 °C for 4 h with a drop in temperature due to thermal inertia. Four samples (a, b, c and d) measuring 35 g each (balance e= 1 mg d= 0.1 mg) of dried and crushed stems are used. After leaving the muffle furnace, the samples are placed in a Pyrex™ Borosilicate Glass Vacuum Desiccator for 24 h.

- Thermal characteristics

To determine the thermal conductivity (W/m · K) and heat capacity (J/m^3) at room temperature, we use a Quickline-30 multifunctional thermal properties analyzer from Anter Corporation (Pittsburgh, PA, USA), which is based on the principle of the transient heat line method. A surface sensor containing a heating coil was used directly on a sample of crushed tomato stems. This procedure was repeated at least three times (Haurie et al., 2014; Shin and Kodide, 2012).

4.4.4 Chemical characterization

A chemical characterization to obtain the cellulose, lignin and hemicellulose values as well as the basic elements of dry matter was performed using composite samples of stems from S3 and S4 crops, and data from the previous characterization of the S1, W and S2 crops were also used as references (Llorach-Massana et al., 2017). Stems located in different parts of the crop are chosen to make the composite samples representative, in addition to using pieces from different stem heights. The chemical characterization was performed for the dry material by an external laboratory to obtain the cellulose, lignin and hemicellulose data by gravimetry and the basic elements of organic matter, namely N (obtained by thermal conductivity/C5110096), P, K, Ca, Mg, S, Fe, Zn, Cu, Mn, B, Na and Mo, obtained by inductively coupled plasma optical emission spectrometry (ICP-OES), C (obtained by thermal conductivity), Cr, Ni, Pb, Cd, Hg, Si, Al, Se, and As, obtained by ICP-OES.

4.4.5 Mechanical characterization

The mechanical characterization was performed using 7 samples of dried stems with an average length of 13 cm from the S4 crop. This approach is based on tensile tests performed on a multiple electromechanical test press (Mecánica Científica, S.A.) through a built-in microprocessor and 300 kN load cell; it was performed in the Construction Materials Laboratory of the Barcelona Building Construction School (EPSEB-UPC) from which the break points of the samples were obtained. Through calculations, the following parameters were obtained: Young's modulus, elastic limit, tensile strength and elongation at break, and the values were averaged.

4.4.6 Identification of materials with similar characteristics

Once the characteristics of the material under study have been obtained, other materials that present characteristics similar to those of tomato stems were identified through the collected bibliographic information and the use of the graphical material selection approach (Ashby, 1992), using the assisted selection of materials and processes CES EduPack (GrantaDesign©, 2018). This approach is based on graphs that relate material property pairs. According to these properties, the materials are divided into families that can be visually located in particular areas of the graph depending on the related properties. Using the program, the "tomato stem" material was "created" by entering the values for the following characteristics:

- Composition overview
- Composition detail (polymers and natural materials)
- Physical properties
- Mechanical properties
- Thermal properties
- Optical, aesthetic and acoustic properties
- Absorption & permeability
- Durability
- Recycling and end of life

When the stem material appeared within the universe of materials, graphs were made and analyzed using tables to identify the materials with values closest to the tomato stems in each graph. According to the frequency of appearance in all the graphs, the 5 materials with the most similar characteristics to the tomato stems were selected. Later, the current applications of these materials were identified that would serve as a reference for the participants in the eco-ideation session.

4.4.7 Preparation of creative eco-ideation session

This session is organized by two specialists in eco-design who act as group coordinators in the session, with one specialist in urban agriculture and one specialist in environmental and urban agriculture. The objective of the creative session is to generate concepts to identify applications for tomato stems. The structure of the workshop should allow, first, in a divergent way, the participant to generate the greatest number of concepts and then, in a convergent way, to concretize the concepts to obtain those with the greatest potential to develop and subsequently be evaluated.

Based on the above approach, audiovisual material is prepared with an explanation on the objective of the creative session and the activities that will be performed. Equipment is prepared to record video and audio of the entire session to analyze it later. The interdisciplinary choice of the participants involves seeking diversity in the generation of concepts with a holistic approach. In addition to the area of knowledge in which they specialize, two different profiles can be defined that are sought in the participants. On the one hand, there is the “creative” profile related to the design area, which provides ideal unfocused thinking to generate divergent concepts with connections that allow different solutions to be identified. On the other hand, there is the "technical" profile related to the rest of the specialty areas that provide focused and specific thinking, which is ideal for generating concepts based on knowledge in a convergent way. A total of 10 specialists were invited to participate in the session.

4.4.8 Creative eco-ideation session: generation of concepts

At the beginning of the creative session, the participants were made aware of the objectives of the session and were shown the information that was collected on tomato stems in a concise manner, on the materials with similar characteristics and their uses. Participants were divided into two interdisciplinary groups. Each group was assigned to a coordinator who explained and directed the activities and indicated the duration of each activity.

The first part was the generation of application concepts using the “forced relationships” or “random stimulation” technique (De Bono & Zimbalist, 1970). Each group was given 10 pairs of cards to flip randomly, in ones in which the properties of the stems were found (identified with one color) and in the others containing the market sector (identified with another color). The cards were flipped such that when turning a pair of cards, the group would have to generate an application concept with the stems using the property indicated by the first card with the sector indicated by the second card. All the concepts were generated by "brainstorming". Subsequently, the second section began with the selection of the two concepts considered the most viable to develop, and based on these concepts, each group responded to a sheet on which the coordinator had posed the following key questions: "What is it?, How can it be done?, What difficulties does it have? and What differential factors does it have?" to develop each chosen concept in more detail. At the end of this activity, both teams got together.

4.4.9 Creative eco-ideation session: Qualitative evaluation of concepts

Each team coordinator presented their two proposed concepts to the other group, which were discussed, detailed and synthesized into 3 resulting concepts. After that, using the "Evaluation Grid" technique, the 3 resulting concepts were presented as a column placed in a table, with 4 criteria as a title for the following columns with which each proposal would be evaluated. The criteria were innovation, technical feasibility, environment, and market impact, and they and were evaluated using the "positive, negative and interesting (P, N, I)" technique (De Bono, 1994). This technique consists of each participant using self-adhesive color notes to evaluate the ideas in a positive (green), negative (red) or interesting (yellow) way by writing a comment on their decision and placing them in the corresponding cell. To conclude the session, a brief analysis of the activities was performed, with the contribution of each participant regarding their specialty and knowledge and the general results of the qualitative evaluations.

4.4.10 Tests on tomato stems as eco-material

Based on the concepts with the greatest potential to be developed from the creative session, tests were performed on the dried tomato stems of the S4 crop from the DIY perspective, by considering simple self-production processes on a local scale within the context of a compact city. This approach was used to visualize the technical feasibility of the local development of some proposed concepts in a practical way and to identify their performance as eco-material.

4.4.11 Semi-quantitative evaluation of results

To identify which of the resulting proposals is more feasible to develop as eco-material (em), the semi-quantitative evaluation of the concepts was carried out by adapting a metric developed by López-Forniés et al. (2017). It included the factors of Novelty (N), Usefulness (U), Technical feasibility (T), and an environmental factor of Circularity (C) using a four-point scale (0.1, 0.3, 0.7 and 1). Table 11 details the criteria assigned to each value to evaluate the factors. Once the concepts have been evaluated according to each factor, the measurement is performed using the equation 1 (Eq 1):

Eq 1: (em) = N x U x T x C.

Where (em) means "eco-materials", (N) means "Novelty", U means "Usefulness", T means "Technical feasibility", and C means "environmental factor of Circularity"

In this way, the concept with the highest score with respect to the evaluated factors is identified.

Table 11. Criteria assigned to each value to evaluate the factors. Adapted from López-Forniés et al. (2017).

FACTOR	CRITERION	SCORE	MEANS
Novelty (N)	High	1	The product derived from the concept will be new to the market; does not exist or cannot be compared with other products on the market.
	Medium	0.7	The concept already exists in the market but not using biomass or woody material and using these materials as a novel material could provide a conceptual difference to the market.
	Low	0.3	The concept is made from biomass or woody material and is already on the market, but for other applications or new for a specific application.
	Without	0.1	The concept is made of biomass or woody material and exists for the same application but differs in some respects.
Usefulness (U)	High	1	The concept solves an existing problem or is the solution for a new application.
	Medium	0.7	The concept solves part of an existing problem independently or the concept only applies to certain aspects of the solution.
	Low	0.3	The concept solves part of a problem under certain circumstances, depending on external factors.
	Without	0.1	The concept solves part of a problem under certain circumstances, but that problem has already been solved in an alternative and simpler way.
Technical feasibility (T)	High	1	Easy to achieve, can be performed using a DIY approach in the same place where the material is generated without an investment.
	Medium	0.7	The implementation of the concept requires some investment and possibly delays in production time and is performed in the same place where the material is generated.
	Low	0.3	The changes are relevant/important, and a high level of investment is needed. Technological implementation can be a problem.
	Without	0.1	The necessary structural or radical changes are difficult to achieve, and the need for investment is very high. Solutions will be time consuming.
Environmental factor of circularity (C)	High	1	Easy to achieve, the material is fully used. The new application ensures a low degree of material degradation, so its use will be maintained over a long time.
	Medium	0.7	The degree of material use is high, in that more than 50% of it is used. The material in the new product will remain in use for a long time.
	Low	0.3	The degree of material use is medium, in that less than 50% of the waste is used. The application of the material to the concept does not ensure prolonged use due to environmental issues (humidity, sunlight, etc.).
	Without	0.1	The degree of material use is limited, at less than 20% of the total. The functionality of the concept will be ephemeral, so the use of the reused material will be as well.

4.5 Results and discussion

This section is divided into three parts. The first is "Tomato stems: characterization and identification of materials with similar characteristics", the second part is "Creative eco-ideation session" and the third part is "Tests and evaluation of viable applications for tomato stems as eco-material".

4.5.1 Tomato stems: characterization and identification of materials with similar characteristics

Table 12 shows the average of the results obtained through the physical, mechanical and chemical characterizations of tomato stems from crops S3 and S4.

Table 12. Average characterization results of dried tomato stems from crops S3 and S4.

Physical characterization	Avg. Values	Chemical characterization (on the dry matter)	Avg. Values
*Length (m)	6.18	Cellulose content (%)	30 - 40
*Weight (kg)	0.933	Lignin content (%)	5 - 14
*Diameter (m)	0.0133	Hemicellulose content (%)	4 - 11
*Total moisture content (%)	89	Elementary carbon (%)	40.12
Density (kg/m^3)	300 - 580	Elementary nitrogen (%)	2.38
Degradation in soil (months)	2	Phosphorus (%)	0.89
Outdoor degradation (months)	9	Potassium (%)	5.08
Water absorption capacity (%)	372	Magnesium (%)	0.19
Ash content (%)	14 - 18	Sulfur (%)	0.37
Thermal conductivity (W/(m °C))	0.0582 - 0.0602	Iron (mg/kg)	50.83
Heat capacity (J/kg °C)	860 - 1050	Zinc (mg/kg)	76.5
		Copper (mg/kg)	12.5
Mechanical properties		Manganese (mg/kg)	35.83
Young's modulus (GPa)	0.82 – 2.41	Boron (mg/kg)	19
Elongation (%)	3 - 6	Sodium (mg/kg)	1451.67
Ultimate tensile strength (Mpa)	378 - 791	Molybdenum (mg/kg)	0.6
Yield strength (Mpa)	1.58 - 3.86	Chromium (mg/kg)	< 0.1
Tensile strength (Mpa)	10.20 - 34.32	Nickel (mg/kg)	< 0.5
		Lead (mg/kg)	< 0.5
		Cadmium (mg/kg)	< 0.1
		Silicon (mg/kg)	49.5
		Aluminum (mg/kg)	16.22
		Selenium (mg/kg)	< 2
		Arsenic (mg/kg)	< 1
		Mercury (mg/kg)	< 0.4

* Considering fresh stems

4.5.2 Physical characterization

The average results show (Table 12) that the length of the tomato stems is 6.18 m (see the avg. max. and min. values in Appendix B). This measurement is for an average crop length of 182 days. However, the weight of a fresh stems averaged 0.93 kg, and after 2 months of natural drying, the average weight of the dry stems was 0.13 kg; that is, 14% of the original weight. The avg. diameter of a fresh tomato stem is 1.33 cm. However, the avg. diameter along the stem is irregular, as can be observed in Fig. 33 (the avg. data per crop can be reviewed in Appendix B).

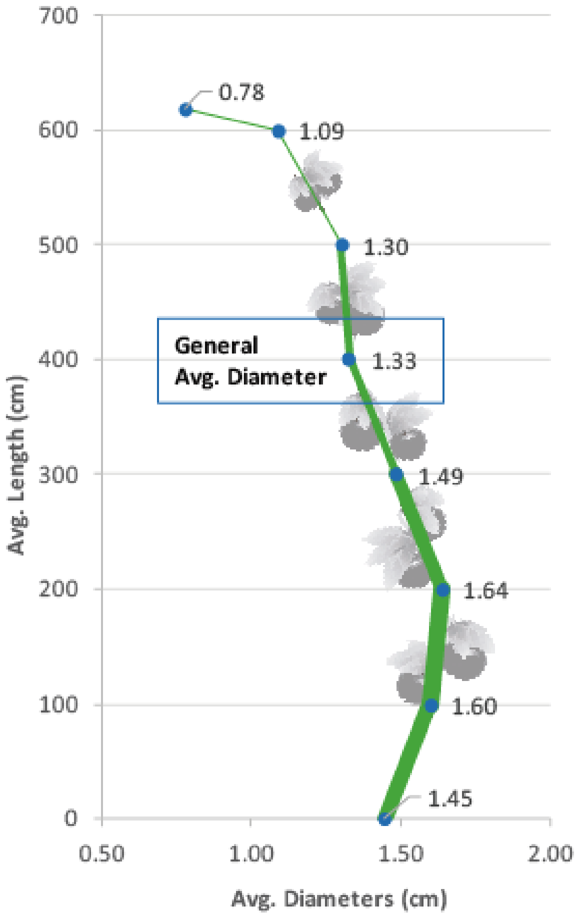

Fig. 33. Average stem: avg. length, avg. diameters depending on height and general avg. diameter

The average density of the tomato stems is 440 kg/m^3, the water absorption capacity is 372%, and the moisture content is 89%, similar to the 80% reported for the S1 crop by Llorach-Massana et al. (2017). By contrast, Zhang et al. (2016) shows that the average moisture content for the middle part of the stem was 64% for tomato stems harvested during the mature period, in July. The ash content is 16% on avg., while Llorach-Massana et al. (2017) reported a 12% avg for the S1 crop with a 164-day duration.

The thermal conductivity was 0.0582 - 0.0602 W/(m °C), higher than "cork" which is 0.035-0.048 W/(m °C) and less than "paper and cardboard" which is 0.06 -0.17

W/(m °C) and "woods" (0.15 - 0.38 W/(m °C)) and "natural fibers" such as sisal, ramie, kenaf (0.25 - 0.35 W/(m °C)) (GrantaDesign© 2018). The heat capacity was 860 - 1050 J/(kg °C) lower than "natural fibers" (1200 - 1220 J/(kg °C)), "paper and cardboard" (1340 - 1400 J/(kg °C)), and "woods" (1660 - 1710 J/(kg °C)) (GrantaDesign© 2018).

The avg. results of the soil degradation test (Fig. 34) for fresh stems after 8 months shows that the stems lose an average of 82% of their weight at a constant rate during the first 45 days, as well as its internal structure, making it more fragile. Later, the loss is slower until reaching a constant weight after 4 months, with a total loss of 90% avg. of the initial weight (Fig. 35). Notably, the results of the soil degradation test on dry stems at 5 months shows that the stems gain 313% avg. of their weight constantly during the first 15 days by absorbing moisture from the soil. Later, they lose 43% avg. of the weight during the following 15 days, reaching slightly higher weights than the initial ones. From the first month they begin to lose weight more slowly, in addition to the internal structure, making it more fragile, reaching a constant weight at 4 months with a total loss of 55% avg. of the initial weight.

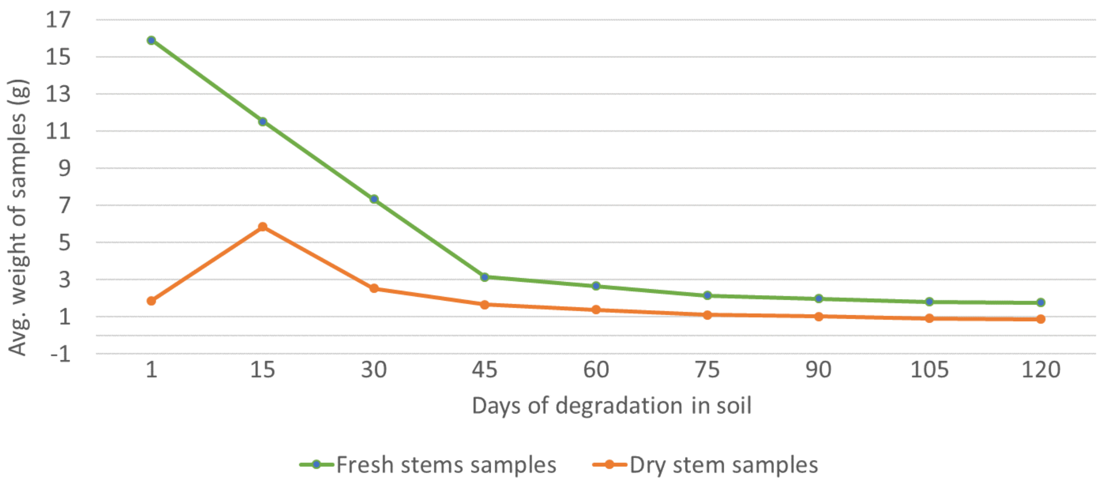

Fig. 34. Soil degradation test in samples of fresh and dry tomato stems.

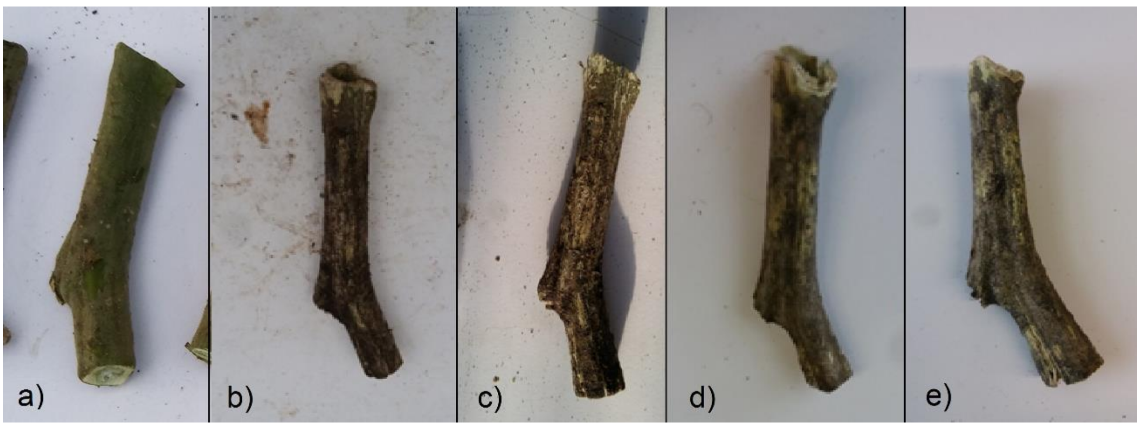

Fig. 35. Evolution of sample 2 from the soil degradation test on fresh tomato stems: a) Fresh stem; b) 1month degradation; c) 2 months of degradation; d) 3 months of degradation; and e) 4 months of degradation.

Fig. 36 shows the average evolution of the 3 dry stem samples from the outdoor degradation test, starting from natural drying for 2 months (indoors). During the first 15 days, the stems lose 60% of their weight as well as their flexibility. After one month, the stems have already lost 80% of their weight and in the following month, they lose 6% more, reaching a stable weight from natural drying. Starting from dry stems, the result of 12 months of outdoor degradation shows that dry stems lose 52% avg. of their weight constantly as well as their internal structure, making them more fragile, until they reach a constant weight at 9 months. Tomato stem samples at the end of the tests can be observed in

Fig. *37*, and detailed data on the degradation tests can be found in Appendix B.

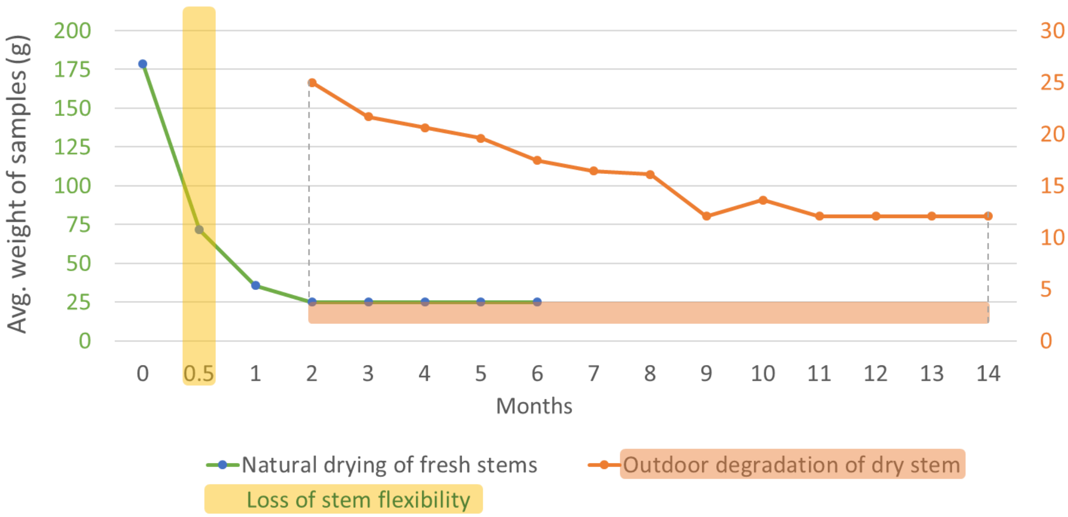

Fig. 36. Outdoor degradation test on dried tomato stem samples starting from natural drying (indoors).

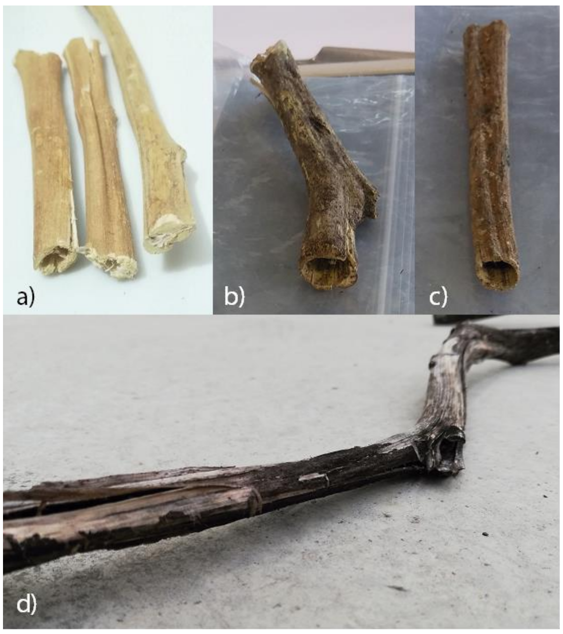

Fig. 37. Tomato stem samples at the end of the tests: a) Natural drying, b) Fresh stem degradation in soil, c) Dried stem degradation in soil, and d) Degradation outdoors.

4.5.3 Chemical characterization

The average results (Table 12) show that the cellulose content was 35.4%, a higher value than the 28.8% avg. reported by Llorach-Massana et al. (2017). The avg. lignin content is 9.5%, lower than the 19.9% avg. reported by Llorach-Massana et al. (2017). The hemicellulose content is 9.8% avg., and the 8.2% value obtained by Llorach-Massana et al. (2017) is very similar (the average values per crop can be reviewed in Table 10 in Addendum B of Chapter 3). Nisticò et al. (2017) refer to the chemical characterization of "Postharvest tomato plant" without detailing the part of the plant or giving data regarding the crop from which it comes, but they presented very similar results, with 33% cellulose, 8% lignin and 11% hemicellulose, indicating its low solubility in water (22%).

The averages from the elemental analyses (Table 12) show that the carbon content (C) was 40.1% and the nitrogen (N) content was 2.38%, while Llorach-Massana et al. (2017) found 35.7% C content. Nisticò et al. (2017) reported 36.4% C and 3.5% N contents. The toxic elements were below the detection limits (the averages for the elemental analysis per crop can be reviewed in Appendix B).

4.5.4 Mechanical characterization

The mechanical characterization of the tomato stems showed values between 0.82 and 2.41 for Young's modulus (GPa), similar to the 0.802 to 1.558 (GPa) reported by Zhang et al. (2016). We found 4% elongation, ultimate tensile strengths (Mpa) between 378 and 791, yield strengths (MPa) between 1.58 and 3.86 and tensile strengths (MPa) between 10.20 and 34.32, while for Zhang et al. (2016), the values ranged from 13.73 to 22.68 (MPa) (detailed data by sample can be reviewed in Appendix B).

4.5.5 Identification of materials with similar characteristics

According to the results of the stem characterization, several natural fiber-like materials with some similar characteristics were identified (see Appendix B). However, according to the graphic approach for material selection, the stems showed greater similarities to other natural materials, to the family of "woods or wood-type materials", than to the "natural fibers" category (Fig. 38).

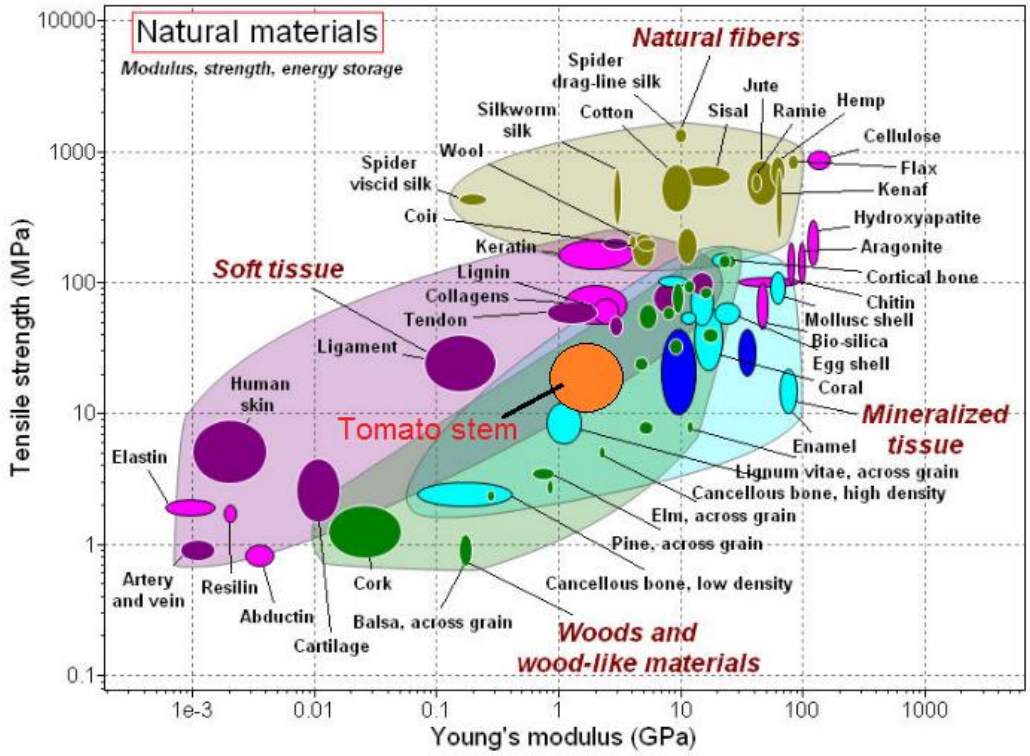

Fig. 38. Ashby graph of tensile strength/Young's modulus values for natural materials. Adapted from (Ashby, 2008) with the tomato stem values added indicated in orange.

As shown in Fig. 39, the combination of four Ashby graphs shows that the materials with the greatest similarity to stems appear within the circular areas indicating the properties used for each case, while the areas within the squares indicate the degree of general similarity to tomato stems (Ts) (see detailed information in Appendix B). The material with the highest similarity overall was “Willow, along grain (W-L)” followed by “Pine, across grain (P-C)”, “Palm, along grain (Plm-L)”, “Pine, along grain (P-L)” and "Spruce, across grain". All of them came from the "wood or wood type materials" group. The typical uses of this type of material are furniture, containers, building construction, floors, boxes, doors, frames, and decorative objects, among others (GrantaDesign©, 2018).

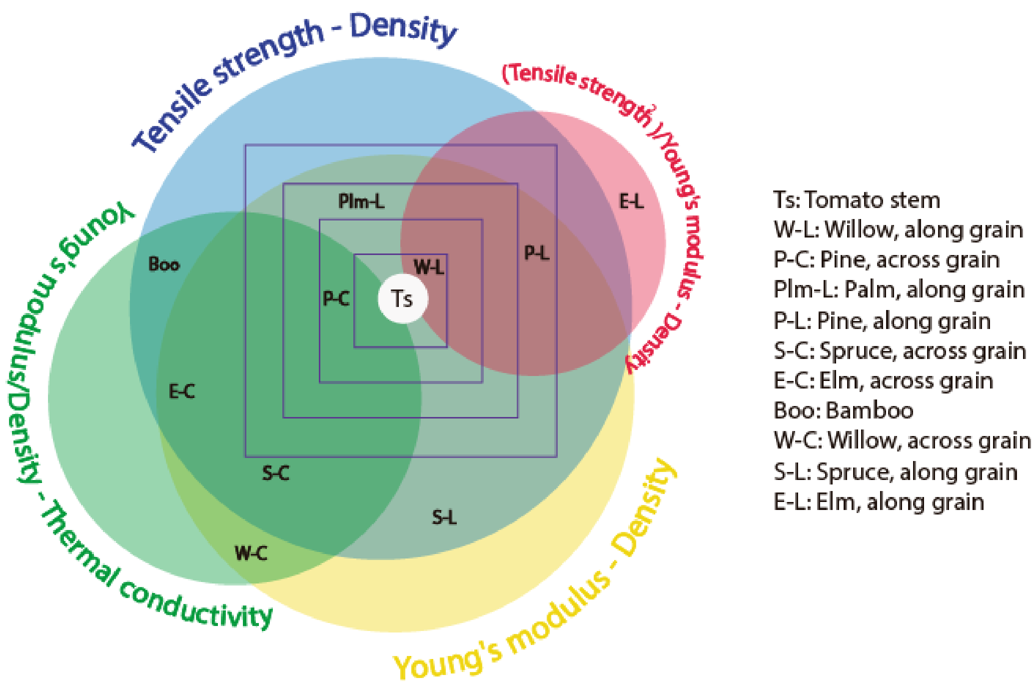

Fig. 39. Combination of the results from four Ashby graphs to identify materials with characteristics similar to those of tomato stems.

4.5.6 Creative eco-ideation session

This section is divided into "Generation and selection of concepts" and "Concept evaluation in the creative session" sections.

4.5.6.1 Generation and selection of concepts

Fig. 40 shows the specialties of the 5 people who made up each group on the dynamics of concept generation (photographs can be reviewed in Appendix B). Based on the bibliographic information and the results of the stem characterization, the pairs of terms used in the "forced relationships" technique (De Bono & Zimbalist, 1970) can be observed in Table 13. The details on the dynamic results can be reviewed in Appendix B.

Profile	Participants in each group	
Technical		Specialist in environment and urban agriculture
		Chemical specialist in eco-materials
		Specialist in lignocellulosic materials for construction
Creative		Specialists in product design

Fig. 40. Profile and specialty of the participants in the creative session by group

Table 13. Terms used for the "force relationship" technique during the dynamics of concept generation

Physical property	Market of application
Lightness	Building
Lignocellulosic	Automotive
Buoyancy	Decor
Woody	Furniture
Thermal insulator	Packaging
Biodegradable	Gardening
Sustainable	Home
Rigid	Agriculture (urban)
Compressible	Textile
Sawdust can be made	Fashion

In accordance with the tools described in the methodology, such as "forced relationships", the concepts described in Table 14 were generated, and the results of the concept development dynamics are included using the key questions. Although each group worked and selected different pairs of terms, both groups agreed on "Containers and Packaging" as one of the resulting concepts. For Group 1, the next resulting concept was "Multifunctional screens or fences" and for Group 2 it was "Multifunctional panels or blocks".

Table 14. Concept selection process and developing resulting concepts using key questions

Selected term pairs	Selected concepts	Resulting concepts/What is it?	How can it be done?	What difficulties does it involve?	What differential factors does it have?
Group 1					
Urban agriculture + Lightness	**Tomato container** **Seedbed**	**Containers and packaging**	Crushed and mixed with natural binder, can be easily degraded. Or without binder, just temperature and pressure, with the lignin itself as the binder for a thermoformed tomato container as an egg container. Others to be processed in isolation, trying to extend life.	None.	Sustainable, natural, close the cycle, the substitution of artificial materials, product and the packaging come from the same point. Tomato container, then you can use it for urban gardens as a seedbed or die cut to make lamps.
	Divider panel **Pergolas**	**Multifunctional screens or fences**	Minimizing the transformation processes, interlocking the stems while they are green. They can be used to shade and support deciduous plants. Although they are light, they would be made of standard dimensions that can be transported on pallets.	Customer orders must be anticipated. A base to install or to hang or stand up, which should also be biodegradable. Expensive for being handmade. It must be a very special use such as green facades.	Can be used indoors or outdoors, customizable as a unique element. It generates jobs and could provide social benefits such as in a civic center or for the elderly.
Group 2					
Packaging + Sustainable	**Packaging for vegetables and fruits** **Container for sale**	**Containers and packaging**	Drying the stems, crushing them, agglutinating them or not, compacting (compressing, pressing).	Toxicity with food contact, the type of food that can be contained, time of degradation, the quantity that can be produced, consider the distribution chain, see if it can be refrigerated or not, with humidity or not, temperatures.	Replacement of single-use, synthetic, biodegradable packaging, circular ecology, advertising the transport of tomatoes in tomato.
Rigid + Construction	**Chipboard ceiling panels** **Building blocks**	**Multifunctional panels or blocks**	Drying the stems, crushing them by agglutinating them or not, compacting (compressing, pressing) primarily for construction or furniture.	Logistics to manage waste, temporality and local use.	Lightness, versatility and being made from tomato plants.

4.5.6.2 Concept evaluation in the creative session

The 3 final concepts on applying the stems and the results of the qualitative evaluation are shown in Fig. 41 (photographs can be reviewed in Appendix B).

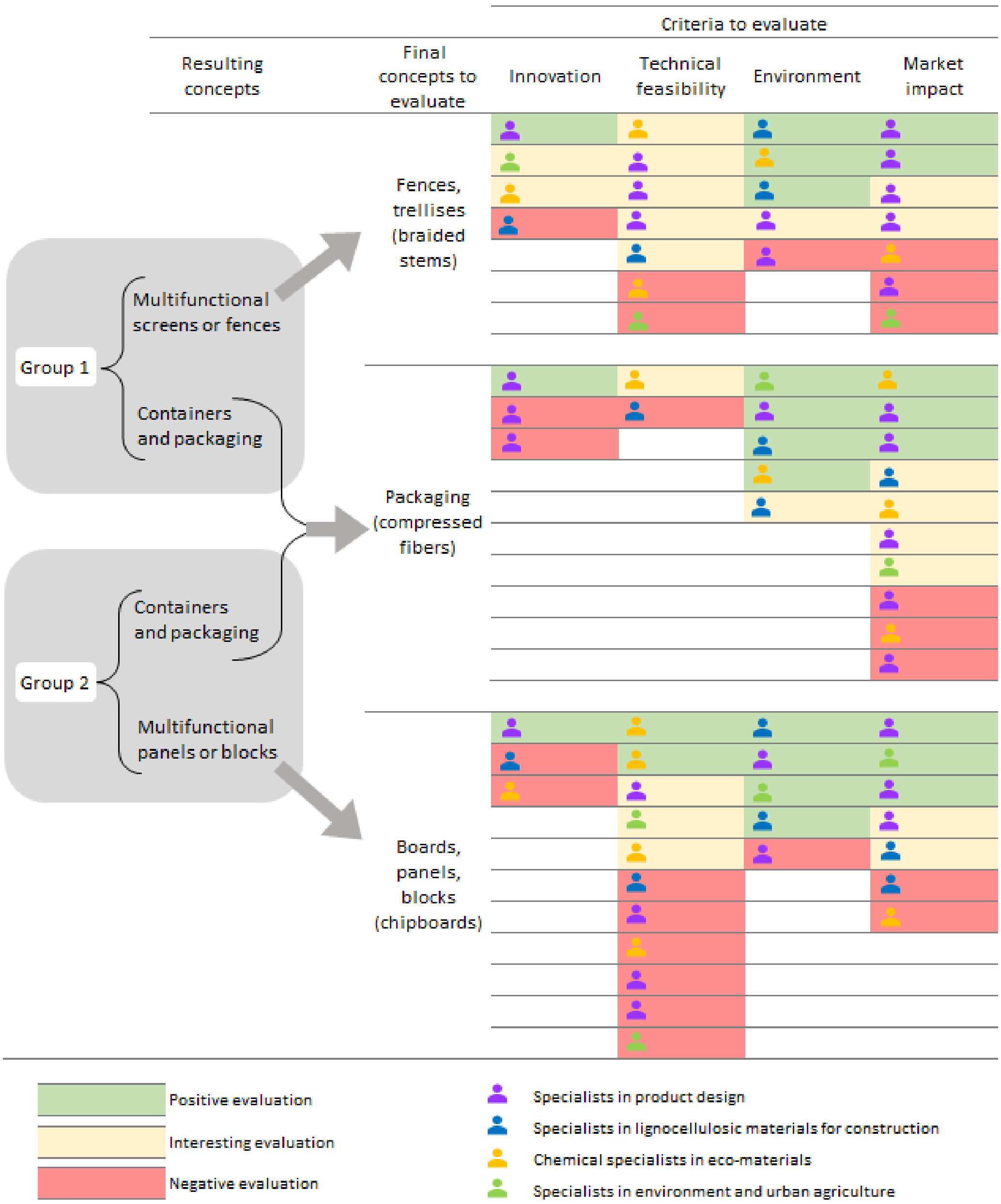

Fig. 41. P-N-I Evaluation of resulting concepts according to the specialization of the participants

Considering that each participant had 9 votes among the positive, negative and interesting evaluations, there was a total of 90 votes. However, only 69 votes (77%) were used. The concept that received the most votes in general was "Boards, panels and blocks (C3)" with 26 votes, with 11 negatives, 10 positives and 5 interesting. The concept “Fences and trellises (C1)” followed with 23 votes, with 10 interesting, 7 negatives and 6 positives. Finally, the “Packaging (C2)” concept received 20 votes, with 8 positives, 6 interesting and 6 negatives. Concept C3 was the one with the highest number of positive votes primarily due to the environmental criterion followed by the market impact criterion. However, it was also the proposal with the highest number of negative votes, surpassing the positive ones, primarily in the technical feasibility criterion. However, concept C1 was the one with the highest number of interesting votes in the technical feasibility criterion. The C2 concept was the one that generally had an average valuation, being the only concept without a negative vote in one of the criteria, which was the environmental one. The comments on each evaluation for each concept can be reviewed in Appendix B.

4.5.7 Tests and evaluation of viable applications for tomato stems as eco-material

Different tests were performed on the tomato stems based on the concepts generated through the creative session, which involve two primary processes. The first is braiding, which was considered for the "Fences, trellises" concept, and the second process is crushing, considered for "Packaging" and "Boards, panels, blocks". This process was used to visualize the performance of the stems in a practical way and later, together with the information obtained in the creative session, to evaluate the 3 final concepts semi-quantitatively, in a more accurate way.

4.5.7.1 Tests with tomato stems as eco-material

To test the braiding process, fresh stems were used because they maintain their flexibility before the first 15 days (Fig. 36) after cutting, and they were manually manipulated to bend them in different ways. The result was positive, to create circular bends with a diameter of not less than 70 cm, since making a tighter bend causes it to begin to break. Interestingly, an attempt was made to create lattices with the stems measuring approximately 5 m^2, but it was complicated because the stems were not completely straight, in addition to having knots (where the branches were cut) that make tissue manipulation difficult.

A three-stem braiding test was performed, which was performed manually without much difficulty (Fig. 42). It was hung on one end and a 10 kg weight was added at the other end to identify its resistance for 2 weeks in the RTG. During that time, the stems were drying and thinning. However, the result was positive since the stems did not show signs of rupture during that time.

Considering the results of the different degradation tests that show that the stems become fragile and brittle when they lose their internal structure completely, the naturally dried stems, despite losing moisture, had preserved internal structures and therefore retained their resistance.

Fig. 42. Braiding and resistance test of tomato stems: a) Braiding process; b) fresh braided stems carrying weight; and c) detail of braided dry stems.

The crushing process was previously tested to perform two experimental lettuce cultures using the tomato stems as substrates. Approximately 13.5 kg of dry stems were crushed, yielding fiber lengths between 0.5 and 10 cm, which was characterized for use as a substrate (Manríquez-Altamirano et al., 2020). In this way, we identified great similarity regarding the shared tomato stem characteristics and properties compared with common wood chips. Therefore, processes such as compaction by temperature or natural binders could be possible.

4.5.7.2 Semi-quantitative evaluation of results

The results of the semi-quantitative evaluation show (Table 15) that the application concept for the tomato stalks that had the highest score was C1. The best evaluation was high for the factor of "Technical feasibility (T)", and the worst was "Usefulness (U)", while there was an average evaluation for the factors "Novelty (N)" and "Circularity (C)". The C2 concept ranked second, with a mean evaluation for factors U and T and a low evaluation for N and C. By contrast, the concept with the lowest score was C3. The best evaluation was a medium for the T factor, low values for N and C, and the lowest was U.

Table 15. Evaluation of final concepts using four-point scale metrics.

	Factors to evaluate				Final score	Ranking
Final concepts	N	U	T	C	em	#
Fences and trellises (C1)	0.7	0.1	1	0.7	0.049	1
Packaging (C2)	0.3	0.7	0.7	0.3	0.044	2
Boards, panels and blocks (C3)	0.3	0.1	0.7	0.3	0.006	3

4.6 Conclusions

According to the existing body of knowledge, this study is the first to propose a methodology for the local use of a residual biomass generated by urban agriculture. Unlike a traditional use of biomass, such as composting, this study is aimed at finding applications that add value to the residual biomass for use as a higher quality eco-material without losing the benefits of its processing and local use. This approach was used to improve the environmental performance of the UA life cycle and reduce the volume of potential OSW within cities by providing an eco-ideation methodology as a guide for upcycling with a DIY approach. In addition, this study provides information regarding the physical, chemical and mechanical characterization of tomato stems that may lead to possibilities for new solutions. This information could also help users to take advantage of the biomass generated by conventional agriculture.

Even though tomato crops are one of the most widespread in Europe, according to the literature review, no study was identified that gathered these data for this purpose. The results show that the use of the proposed methodology is useful for identifying possible applications for upcycling the UA biomass *in situ*. For this purpose, the great relevance of the contribution of the data on the material, the correct selection of specialists for participation in the creative session and the experimentation with the material were identified. They considered indoor use to avoid degradation or the use of binders or varnishes that would isolate the stems from adverse conditions. They generated 3 possible applications for the tomato stems, which, according to the results of the semi-quantitative evaluation are ordered "Fences and trellises", "Packaging" and "Boards, panels and blocks".

Part Three

Discussion, conclusion and future research

Chapter 5

Discussion, conclusion and future research

Chapter 5. Discussion

This chapter presents the discussion on the main contributions of the dissertation to the scientific field and its practical applications from the CE perspective. The chapter has been divided into four main topics for discussion: "Agro-urban solid waste", "Tomato stems", "Eco-design" and "Eco-materials".

5.1. Agro-urban solid waste

As mentioned in Chapter 3, there is a big difference between agricultural SW from conventional systems to SW generated by the UA. Taking into consideration that in addition to having less volume, AUSW are generated within cities, which is a key point to consider their type of management. Currently, there is little research regarding this type of waste in the scientific field which is reflected in the fact that there is still no special classification for AUWS in European regulations or consideration of its type of management at the municipal level within initiatives to improve the environmental and sustainable development of cities, aspects promoted by the UA.

Most of the studies that contemplate the benefits of the UA for the use of waste, focus on the UA as a sink for the organic waste generated in the cities (kitchen, restaurants, catering services, food industries, parks and gardens) using it as a substrate (Grard et al., 2018) or as compost to provide nutrients to the soil (Ferreira et al., 2018; Specht et al., 2014; Goldstein et al., 2016) In this sense, it is not considered that the UA system itself generates SW mainly organic.

It is true that the generation of AUSW greatly differs with respect to the type of crop, in addition to the system used. In other words, a lettuce crop that is short-cycle does not generate the same residues as a long crop like that of tomatoes, which, in addition to the product, unlike lettuces, generates stems, branches and leaves.

The case study presented in the dissertation corresponds to one of the main products that is produced and consumed in Europe and in the world, tomatoes.

Considering the importance of tomatoes in the European diet and particularly in the Mediterranean, according to the data mentioned on its annual per capita consumption in section 1.1.1. of the Introduction, and in addition to being one of the crops that generates the most OSW, according to the approach made in Chapter 3 on the projection of OSW generation for 2030, which would be an increase of 20% of these residues within the cities, as shown in section 3.5.1 of Results and discussion. It is expected that this dissertation will provide data that will serve as a guide to make visible a new type of waste within cities and foresee a new problem in terms of its management in the future for densely populated compact cities.

5.2. Tomato stems

Part of the dissertation is based on the methodology mentioned in Chapter 4 applied to the identification of applications for cork (Sierra-Pérez et al., 2016). In this case, unlike cork, tomato stems are not considered a material that is fully characterized.

According to the results of the bibliographic search for information, based on the methodology used (detailed information can be reviewed in section 4.4.2 of Chapter 4), at this point in time, there are studies that provide data about different parts of the tomato plant such as the pulp to extract lycopene (Rath S & Olempska-Beer Z, 2007), husks and seeds for the production of biodegradable pots (Schettini et al., 2013) or the complete plant together with leaves and branches for the production of films made out of polyethylene-co-acrylic acid and soluble biopolymers (Franzoso et al., 2015), to study the uptake and distribution of metals by tomato plants (Trebolazabala et al., 2017), to study its leaves as a source of metabolites (Junker-Frohn et al., 2019) or to study the low cost of construction of the leaves, stems and fruits of tomato plants with respect to their high mineral content (Gary, 1998).

However, there are few studies that provide data on the stems of tomato plants in particular and they have different approaches, for example for the development of harvesting and processing machinery (Zhang et al., 2016), to study the performance, growth and physiological characteristics of the stems by means of their physical stimulation comparing the vertical or horizontal training of the stem (Ohta & Makino, 2019), for the development of a stem diameter growth model to predict the growth response of plants under different conditions (Qin et al., 2017), for a biomechanical study of the effect of a controlled flexion on stem lengthening (Coutand, 2000), for its use, but together with the rest of the parts of the plant to create plastic films (Nisticò et al., 2017) or bio-chart (Llorach-Massana et al., 2017).

Only two studies were found where tomato stems are used in particular, although mixed with other materials in different proportions, for the production of paper using the cooking process (Üner et al., 2016) and for the production of renewable thermal insulation material (Llorach Massana, 2017).

Up to this date, there was no study that collected and provided relevant data on the characterization of tomato stems to identify possible applications. As mentioned above, the cultivation of tomatoes is one of the most widespread in Europe in a conventional way, mainly in multi-tunnel greenhouses as in the case of Almería, which is the largest tomato producer in Spain (Sanye-Mengual et al., 2015).

However, tomato stems have been managed like other agricultural residues, through traditional recycling processes such as compost (Antón et al., 2005) or through energy recovery, the next option after recycling (European Commission, 2015). This type of management has worked based on results obtained in studies that show the advantages of this type of use for the OSW generated by conventional agriculture (Antón et al., 2005).

Nevertheless, based on the exploration of tomato stems for local use within cities, we identified particular characteristics of the stems with respect to their chemical composition, such as their high lignin content, which represents greater fracturing resistance (Zhang et al., 2016). It was also possible to identify the similarity of tomato stems with the family of wood-like materials that can be used both in its natural, unprocessed form thanks to its structure or by crushing it once dry to take advantage of processes such as compaction. According to the results obtained from the eco-ideation session (Chapter 4), the elaboration of "Fences and trellises", "Packaging" and "Boards, panels and blocks" were identified as possible applications, this on a local scale. However, the panorama could be opened in terms of the possibilities at different scales such as at the "ecosystem" level that would allow obtaining greater benefits related to circularity or allowing another type of exploitation considering higher volumes such as those generated by conventional agriculture.

In this way, the dissertation seeks to contribute to fill the knowledge gaps that can serve to make better decisions about the type of management or use that implies the use of tomato stems at any scale.

5.3. Eco-design

The eco-design methodology is very broad and has many strategies to achieve its goal. The strategies used in this dissertation originate from the main objective, which is to take advantage of AUSW locally, seeking to add value with the perspective of upcycling. In this way, the use of eco-ideation was determined in a creative workshop to generate ideas through group techniques, a format previously used successfully (Sierra-Pérez et al., 2016).

Nonetheless, each case is unique and requires a different type of specialization. As it seeks to solve specific local problems, the level of detail and particularity increase. That is, the data, techniques or circumstances considered to obtain a product that solves a need in some community, may not solve the needs of another community in a different context. Hence the importance of the use of creative techniques that allow flexibility in the methodology for its effective adaptation, in addition to generating innovative ideas.

On the other hand, it is also important to consider the people involved in this creative process. In the case of this dissertation, the participants, specialists in their area, based on the set of knowledge, enriched the quality of the concepts generated, which was key to identifying and evaluating viable applications with tomato stems to reduce the SW generated by the RTG and improve its environmental performance. However, one point that was not fully developed was the consideration of the context. In other words, to generate the concepts, the characteristics of the material and different areas of application were considered, but their practical use was not fully considered within the situation of the building where the RTG is located, although applications for own production of tomatoes such as the development of packaging were raised.

In this aspect, who are the people who interact within the building that could be the possible users of the viable applications of the stems should participate. This perspective could help envision other local needs that could be addressed by using the AUSW. On the other hand, the DIY approach was useful when considering processes, techniques and simple tools by means of which the AUSW can be recycled while preserving the benefits of their local use.

Currently, this DIY approach, which is closely related to upcycling, is widely considered for the use of objects or resources thought of as waste (Rognoli et al., 2015), in order to give it a second useful life for its own use. In other words, it is an approach for self-production and self-consumption when using materials that are not obtained in large quantities or constantly (Bridgens et al., 2018). That is the reason why this approach had not been fully explored in the scientific field, being more common the use of DIY for making crafts or for reusing products after making improvements or adaptations to extend its functionality.

Up to this date, a global concern for the use of local resources and the substitution of materials begins to appear, minimizing the environmental impact and reducing the generation of waste in cities. At present, there are studies where the DIY approach is applied to create eco-materials (Rognoli et al., 2015), for example treating potato waste (Caliendo et al., 2020) or peanut shells to create bioplastics (Troiano et al., 2018). This allows designers to experiment with new materials and processes by creating interdisciplinary links that drive eco-design.

Therefore, this dissertation aims to provide a guide regarding an interdisciplinary methodology adaptable to other circumstances and contexts to take advantage of the AUSW which, as mentioned above, are different with respect to their composition and volume for each case.

5.4. Eco-materials

Few studies focus on the use of agricultural residues for their use as eco-materials and most of them through chemical processes that are difficult to adapt to a local context. It is necessary to consider that when speaking of conventional agriculture, in general, large volumes of generated SW are considered, so it is possible that its use by more complex processes such as chemicals for the elaboration of eco-materials is an alternative with less environmental impact than making products with other materials. To carry out an environmental assessment using methodologies such as LCA can be a good way to verify it (Turner et al., 2016). The case of AUSWs at the local level (building, neighborhood) is different since, regarding the low volume generated, there are processes that could not be viable. Hence, the use as an eco-material is reduced to its elaboration with very basic or simple processes such as crushing, compacting, weaving or braiding, processes used to elaborate crafts generally. This is the case study that is addressed in the dissertation.

Beyond considering the use of AUSW as raw material a disadvantage through techniques with a DIY approach that could seem to be a limitation, we should consider the advantages that this implies. One of these advantages would be to be able to create socio-cultural dynamics at the local level, such as the implementation of workshops or courses that allow the development of eco-products with the AUSW to make the population aware of the importance of reducing waste within the cities in addition to reinforcing the message of self-production and self-sufficiency that continues from the UA itself.

There are studies regarding the social perception of self-production using DIY that mention other benefits such as reducing dependence on commercial services in addition to helping people to be willing to learn new skills (Sung et al., 2014; Rognoli et al., 2015).

On the other hand, it could also be considered to create networks between neighborhoods or nearby communities to exchange resources, not only for production, but also for AUSW or eco-products creating synergies to cover self-sufficiency needs (Keng et al., 2020; Rognoli et al., 2015). An initiative that is gaining more strength regarding self-production and self-consumption at the neighborhood level sharing resources and knowledge are the "Fab labs" (Bridgens et al., 2018; Prendeville et al., 2018) that function as a network of public workshops that provide access to machinery, tools and advice to the community with a rather technological focus. However, it would also be possible to create synergy with this type of initiative to take advantage of the AUSW.

The tests carried out with tomato stems as eco-material in the dissertation start from two points. The first one, based on the use within the RTG and based on the bibliographic information, the use as a substrate for two experimental lettuce crops was determined as shown in the Addendum A to Chapter 3.

Regarding the improvement of the environmental impact with respect to the studies prior to LCA, it was determined that its use represented an improvement based on the fact of using the residual biomass, not considering environmental impacts related to the transport of waste for its processing and the low impact related to the process of its elaboration compared to the elaboration of compost.

However, it is important to clarify that the environmental impact related to the use stage was not considered. As it was not a stable material such as compost, the tomato substrate had a visible degradation and decomposition process when used together with the soilless fertigation system, which generated gases that were not measured. In addition to presenting problems regarding the levels of EC as mentioned in the Addendum A.

Nonetheless, this experiment was carried out as an approach to identify the performance of the stems only as eco-material under the substrate conditions. In this way, the information could serve as a complement for future research with an agronomic focus. It also served as a guide when using the eco-ideation methodology to identify the viability of the stems as a substrate, ruling out the use of the stems in a unique way and without prior washing treatment.

On the other hand, after the workshop, based on the results obtained, the tests carried out with the stems only by braiding them showed great viability for their use without processing considering their great resistance and flexibility before drying and their great longitudinal resistance once they dry but with less tensile strength as they become more fragile cross-sectionally, results that agree with the mechanical study carried out by Zhang et al., (2016).

Once dry, it was also identified that, when the stems were crushed, they present characteristics similar to wood sawdust, which opens up the possibilities for their application in compressed or agglutinated products through more elaborate processes, perhaps considering their use on a larger scale, such as bio-composites for the production of furniture, panels, or blocks. Along these lines, it is intended with this dissertation to help to begin to visualize waste in general as a raw material from the beginning of its generation, and through its correct management, not only close cycles, but continue them.

Chapter 6

Conclusion and future research

Chapter 6. General conclusion and future research

This chapter presents the general conclusions of the dissertation based on the specific objectives set out in Chapter 1. At the end of this chapter, future lines of research are suggested based on this study.

6.1. General conclusions

a) Classify and quantify the AUSW flow to determine which type of AUSW has the greatest potential for local use from the CE perspective.

This is the first study in which i-RTG SWs are classified and quantified for on-site use from a CE perspective. Therefore, this study makes visible a new type of SW that is growing within cities and is not yet well classified within European regulations, either as agricultural waste or as municipal waste.

Considering the great potential for the implementation of food production systems on roofs (Safayet et al., 2018; Toboso-Chavero et al., 2019) and according to the growth projection for green roofs in Barcelona (Barcelona, 2017), a 20% increase in this type of SW was calculated for 2030 within the city. This situation could represent a new challenge for waste management at the municipal level that, if it is not foreseen and action taken, it could become a new environmental problem.

Based on the results of Chapters 3 and 4, we can say that the use of SW generated in i-RTG, mainly the organic fraction from a CE perspective, in addition to helping to minimize organic waste within cities, could help to close the cycles and to improve the environmental performance of the life cycle of the UA system, continuing with the multiple social, economic and cultural advantages that this new type of food production generates.

According to the results obtained in Chapter 3 and the bibliographic information, the best form of management was identified for the different types of SW generated in i-RTG, which are mainly plastics, substrate and biomass, the latter representing 72% of the total of the AUSW which considers branches and leaves of pruning and the stems, branches and leaves at the end of the crop. The results show that the biomass fraction, in addition to being the most critical for its management within cities, has a greater potential for on-site use. We identified that the biomass fraction generated in i-RTG is similar in composition (stems, branches and leaves) to the classification of "bio-waste" from the classification of "parks and gardens" that are part of municipal selective collection waste (European Council, 2008)

b) Characterize and test the AUSW with the highest potential selected to identify its properties as an eco-material.

Tomato stems were selected with respect to the rest of the biomass for their use in situ because, unlike the rest of the biomass that can be easily managed like the rest of the organic waste in cities, the stems are generated in large quantities in just one day, at the end of cultivation. In addition, when dried they become a woody material that, if not used as an eco-material, would have to be crushed for degradation, which implies a greater environmental impact for its management compared to the rest of the biomass.

This study provides information on the physical, chemical and mechanical characterization of tomato stems that would allow, in addition to their use within cities, to expand the application possibilities and also be used to take advantage of the biomass generated by conventional agriculture. Although tomato crops are one of the most widespread in Europe, according to the literature review, no study was identified that gathered these data for this purpose.

According to some of the results from Chapter 4, fresh tomato stems from an average 182-day crop have an average length of 6.18 m, weight 0.933 kg, diameter 0.013 m, moisture content of 89%. On dry matter, density 300-500 kg/m^3, 14-18% ash, 30-40% cellulose, 5-14% lignin and 4-11% hemicellulose. The high moisture content allows the stem to be flexible and has greater resistance to fracture. As it loses moisture, the stem becomes more fragile. On the other hand, the high content of lignin provides the ability to resist fracture (Zhang et al., 2016) and lower solubility in water (Nisticò et al., 2017) which helps to slow down its degradation. Based on the above and in accordance with the results obtained by Ashby's material selection approach, it was identified that tomato stems are closer to the family of wood-type materials than to materials such as hemp, jute, sisal, cotton, flax or kenaf from the family of natural fibers (Fig. 38).

c) Propose and evaluate viable applications for the selected AUSW through eco-ideation strategies for their upcycling.

According to the results obtained in Chapter 4, it was determined that the eco-ideation strategies used in the methodology are very useful for identifying applications that allow adding value to the AUSW through upcycling.

The circularity strategies for AUSW upcycling by DIY as classified by Konietzko et al. (2020) would be, “Close” at the “Business model” level, since an AUSW would be being used in the same place of its generation. , allowing to close the life cycle of the UA system; “Regenerate” at the “Business model” level, since it is an activity that manages and maintains the services of natural ecosystems; and "Narrow" at the "Business model" level, since for the use of an AUSW as an eco-material the DIY perspective is proposed, which implies the reduction of processes and resources for its transformation and use.

The great relevance of having data on the characterization of the material, the correct selection of the productive sectors where the material could be applied according to its relationship with other materials, and prior experimentation with the material to obtain favorable results were identified.

At the end of the creative session, the resulting concepts were three possible applications for tomato stems that were qualitatively evaluated by the participants, providing useful information to subsequently carry out the semi-quantitative evaluation.

According to the bibliographic information on the options for the *in situ* use of tomato stems, composting and preparing the substrate with them were considered. However, it was decided to take advantage of the stems as a substrate, since it implies less environmental impact during the elaboration stage, as it is a simpler process than composting. The proposal of its use as a substrate for two experimental lettuce crops showed negative results for the first crop with respect to pH and conductivity values. To improve its yield, a substrate washing treatment was performed with positive results that were confirmed in the second culture. These results served as a guide to identify the performance of the stems during the creative brainstorming session. Based on the results obtained in the creative session, tests were carried out manipulating the stems to visualize the technical feasibility for the elaboration of the three resulting concepts. This information was useful in the semi-quantitative evaluation stage, to identify the technical feasibility of each concept to take advantage of tomato stems.

As previously mentioned, one of the factors considered to evaluate the resulting concepts was "Technical feasibility", in addition to "Usefulness", "Novelty" and "Circularity". This, by adapting the metric developed by López-Forniés et al. (2017). In this way, it was determined, according to the results obtained, that the concept with the highest score and therefore the best evaluation is "Fences and trellises", secondly "Packaging" and finally "Boards, panels and blocks".

The whole process from the creative session allowed us to identify aspects regarding the material, its behavior, the context and the possibilities of tomato stems as eco-material from an interdisciplinary perspective that enriched the contribution of information and allowed obtaining much more accurate results and viable by meeting the objectives set out in this dissertation.

d) Present the methodology used as an adaptable tool for the use of AUSW from the perspective of the CE.

This study proposes a methodology for the local use of residual biomass generated by the UA. Unlike the traditional use of biomass, such as composting, the objective of this study is to identify applications that add value to the residual biomass for use as an eco-material, but without losing the benefits of its processing and local use that promotes the CE. The results obtained throughout the dissertation show that the use of the proposed methodology is valuable to identify possible applications for the upcycling of UA biomass in situ by means of eco-design.

Throughout the development of the methodology, information of an interdisciplinary nature was generated that, in addition to helping to meet the general objective of the dissertation, could serve as a contribution to other studies other than the UA, in areas such as conventional agriculture, management and use of urban waste, eco-materials and eco-design.

6.2. Future lines of research

Continuing with the aforementioned areas, the following are possible lines of research that could give continuity to the present dissertation or where the information from the present study can contribute knowledge.

6.2.1. Urban agriculture

Through this dissertation, it was identified among references from previous studies that the use of AUSW could close and improve the environmental performance of the life cycle of the UA system. However, no environmental assessment was made in this regard. For future research, environmental performance could be analyzed using methodologies such as LCA. In addition, the resulting concepts could be evaluated outside the UA system, identifying the environmental, social, cultural and economic benefits for the use of AUSW at the local level along with metrics or indicators that allow for a more comprehensive evaluation. In addition, the use of AUSWs at different scales within cities could be evaluated to create networks and allow the exchange of resources to satisfy other needs, expand the possibilities of use and promote self-sufficiency at the neighborhood level.

6.2.2. Conventional agriculture

The results obtained by characterizing tomato stems could help to make tomato production more efficient at the nutrient level, or to manufacture machinery, or to improve the technology used. In addition, regarding the possible uses for the upcycling of the stems, the discarded concepts (see annexes) for the use of the AUSW at the local level, could be good options for the conventional agriculture residual biomass considering a higher volume of waste, such as the production of single-use packaging.

6.2.3. Management and use of urban waste

Part of the general objective of this study is to raise awareness of the potential of the UA resources that we call waste to see them from the perspective of the CE and begin to manage them as by-products. Future research could raise from other perspectives such as legal, governmental and urban planning, the consideration of the AUSW to begin to make regulations and guidelines on its proper management and use.

6.2.4. Eco-materials

Starting from the physical, chemical and mechanical characterization, and considering the bibliographic information on the use of residual biomass from conventional agriculture, it was identified that tomato stems, being a wood-type material, could be used as an eco-material using higher volume.

For future research, the perspective of the inhabitants of the buildings that generate the AUSW, who do not have specialized tools or experience in handling this type of waste, could be incorporated.

On the other hand, considering that dried and crushed tomato stems are a material similar to wood sawdust, their use could be considered through simple processes such as compression with temperature or with a natural binder to create pots, bricks, panels, or used as fiber reinforcement in polymeric matrices to create bio-plastics.

6.2.5. Eco-design

The methodology used in this dissertation could be adapted to other contexts to take advantage of material considered waste, either at the local (neighborhood), community, city or at a larger scale. This methodology starts from eco-design, therefore it is "creative in nature", this makes it a flexible, adaptable, interdisciplinary methodology that allows solving particular problems and, at the same time, due to its "ecological nature", solving current global problems. Eco-design is a very broad discipline that focuses on sustainable production. Thus, beyond only considering ecological materials, through ecological design, the production of objects such as furniture and other functional objects from AUSW could be considered in order to replace other materials with greater environmental impact or industrialized processes through the use of public self-production workshops at the neighborhood level such as the "Fab labs".

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Appendixes

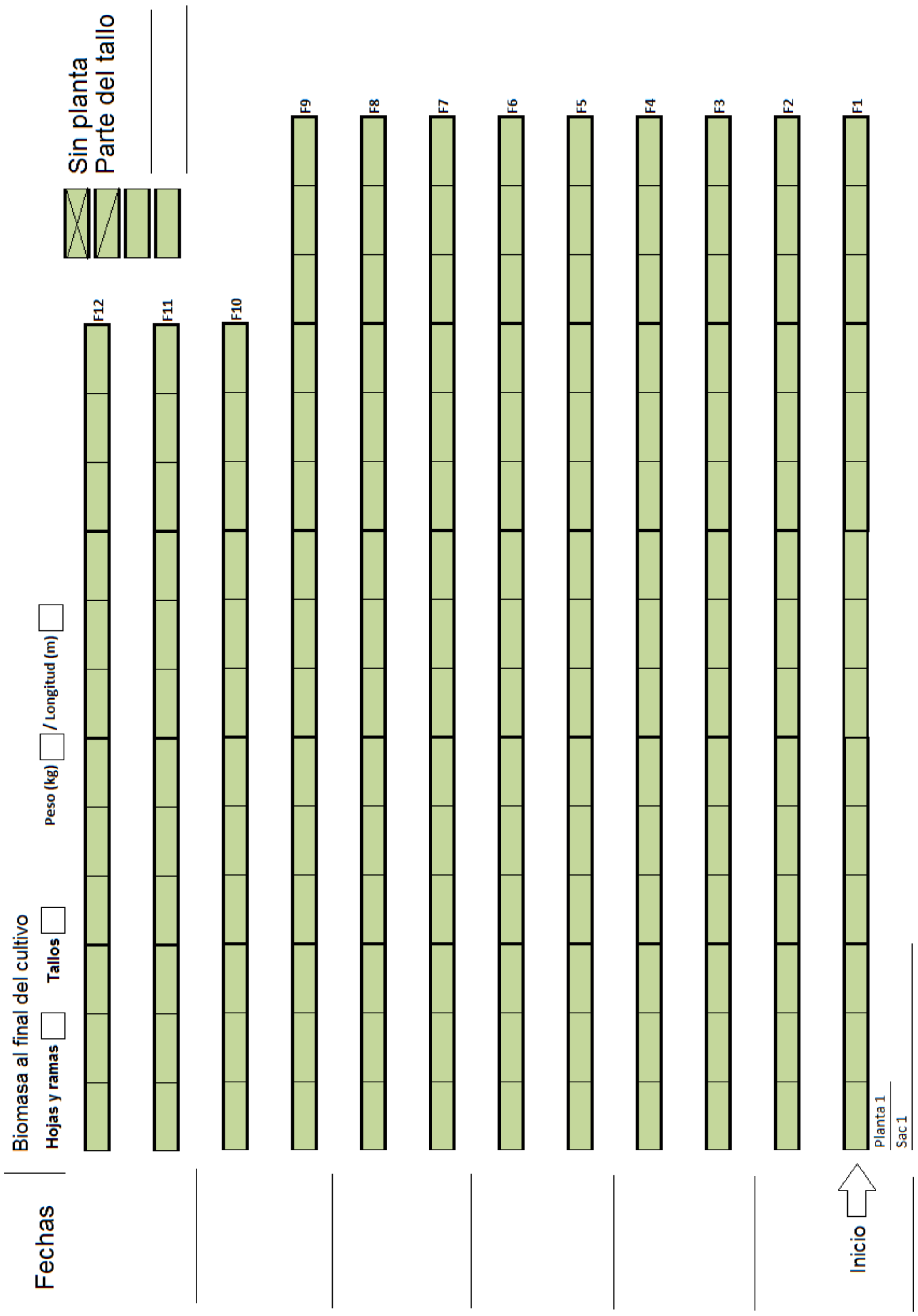
Appendixes

Appendix A

Table A 1. Pruning record format.

	Biomasa de podas en kilogramos por filas											
Fecha	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**

Table A 2. Format for registration at the end of the crop.



Appendix B

Physical characterization

Table B 1. Average length, fresh weight and dry weight of a tomato stem.

Crop days		189	175	182
Crop		S3	S4	Avg.
Length (m)	Max	6.77	7.74	7.26
	Min	4.58	4.20	4.39
	Avg.	5.800	6.560	6.180
Fresh weight (kg)	Max	1.140	1.450	1.30
	Min	0.452	0.550	0.50
	Avg.	0.906	0.960	0.933
Dry weight (kg)	Avg.	0.126	0.134	**0.13**

Table B 2. Average diameters depending on the height of the stem of crops S3 and S4.

	Average diameter depending on the height of the stem (cm)							
	Cut point	1 m	2 m	3 m	4 m	5 m	6 m	*Stem tip
S3	1.36	1.54	1.58	1.43	1.28	1.26	1.05	0.81
S4	1.53	1.65	1.69	1.54	1.38	1.34	1.12	0.74
Avg.	**1.45**	**1.60**	**1.64**	**1.49**	**1.33**	**1.30**	**1.09**	**0.78**

*10 cm from the tip to the stems

Table B 3. Soil degradation test of fresh stems.

		Days of degradation in soil of fresh stems																
		1	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240
Sample weight (g)	1	15.20	12.10	7.60	3.10	2.60	2.10	1.84	1.58	1.58	1.57	1.57	1.57	1.54	1.51	1.51	1.50	1.50
	2	16.20	8.40	5.60	2.80	2.50	2.20	2.13	2.05	2.01	1.96	1.94	1.92	1.91	1.89	1.89	1.89	1.89
	3	15.70	10.20	6.40	2.60	2.40	2.20	2.05	1.89	1.82	1.74	1.72	1.69	1.68	1.67	1.67	1.67	1.67
	4	15.80	12.40	7.80	3.20	2.55	1.90	1.71	1.52	1.52	1.51	1.48	1.45	1.44	1.43	1.43	1.42	1.42
	5	16.20	10.00	6.40	2.80	2.40	2.00	1.83	1.65	1.64	1.62	1.59	1.55	1.55	1.54	1.54	1.54	1.53
	6	15.30	12.30	8.00	3.70	2.90	2.10	2.19	2.27	1.96	1.65	1.63	1.60	1.60	1.60	1.59	1.59	1.58
	7	16.70	13.20	8.25	3.30	2.85	2.40	2.03	1.65	1.63	1.61	1.60	1.58	1.56	1.54	1.54	1.53	1.53
	8	16.00	11.90	7.10	2.30	2.25	2.20	1.89	1.58	1.56	1.53	1.50	1.47	1.47	1.47	1.46	1.46	1.45
	9	15.80	12.90	8.40	3.90	3.15	2.40	2.27	2.14	2.09	2.03	1.95	1.87	1.83	1.79	1.79	1.79	1.79
	10	16.00	11.80	7.75	3.70	2.85	2.00	1.88	1.76	1.75	1.74	1.71	1.68	1.68	1.67	1.67	1.67	1.66
Avg. weight (g)		15.89	11.52	7.33	3.14	2.645	2.15	1.9795	1.809	1.7525	1.696	1.667	1.638	1.6245	1.611	1.6075	1.604	1.6005

Table B 4. Soil degradation test of dried stems.

		Days of degradation in soil of dry stems										
		1	15	30	45	60	75	90	105	120	135	150
Sample weight (g)	1	1.40	4.80	1.50	1.22	0.97	0.72	0.66	0.60	0.59	0.58	0.58
	2	1.50	6.10	3.15	1.28	1.08	0.87	0.82	0.77	0.74	0.71	0.70
	3	1.70	7.00	2.10	1.37	1.21	1.04	0.90	0.75	0.72	0.69	0.69
	4	1.70	4.70	2.03	1.52	1.27	1.01	0.93	0.85	0.84	0.83	0.83
	5	1.90	4.50	2.28	1.56	1.33	1.10	1.01	0.92	0.90	0.88	0.87
	6	1.90	6.20	3.44	2.08	1.67	1.25	1.11	0.97	0.93	0.88	0.88
	7	1.90	4.40	2.14	1.74	1.49	1.23	1.15	1.07	1.05	1.03	1.03
	8	2.00	5.90	2.34	1.62	1.32	1.02	0.94	0.85	0.73	0.61	0.61
	9	2.20	7.20	3.49	2.20	1.76	1.32	1.22	1.12	1.07	1.02	1.02
	10	2.40	7.50	2.83	2.01	1.73	1.44	1.33	1.22	1.20	1.18	1.17
Avg. weight (g)		1.86	5.83	2.53	1.66	1.38	1.10	1.01	0.91	0.88	0.84	0.84

Table B 5. Outdoors degradation test of dried stems.

		Months of degradation outdoors												
		0	1	2	3	4	5	6	7	8	9	10	11	12
Sample weight (g)	A	25.00	20.80	19.76	18.71	17.20	16.00	15.00	11.80	12.70	11.80	11.80	11.80	11.80
	B	25.00	22.20	21.08	19.96	17.50	16.50	16.50	12.20	14.00	12.20	12.20	12.20	12.20
	C	25.00	22.00	21.08	20.15	17.60	16.80	16.80	12.20	14.13	12.20	12.20	12.20	12.20
Avg. weight (g)		25.00	21.67	20.64	19.61	17.43	16.43	16.10	12.07	13.61	12.07	12.07	12.07	12.07

Chemical characterization

Table B 6. Cellulose, lignin and hemicellulose content for S3 and S4 cultures.

	Cellulose content (%)	Lignin content (%)	Hemicellulose content (%)
2017 (S3)	39.9	5.3	9.43
2018 (S4)	30.91	13.85	10.21

Table B 7. Average result for the basic elements analysis of crops S3 and S4 and general average

Element	Units	S3	S4	Avg.
Humidity res.	%	2.10	1.60	1.85
Elementary nitrogen	% s.m.s	2.41	2.35	2.38
Phosphorus	% s.m.s	0.94	0.85	0.89
Potassi	% s.m.s	5.16	4.99	5.08
Calcium	% s.m.s	1.57	1.42	1.50
Magnesis	% s.m.s	0.16	0.22	0.19
Sofre	% s.m.s	0.39	0.34	0.37
Iron	mg/kg s.m.s.	43.33	58.33	50.83
Zinc	mg/kg s.m.s.	80.33	72.67	76.50
Copper	mg/kg s.m.s.	11.00	14.00	12.50
Manganas	mg/kg s.m.s.	40.67	31.00	35.83
Bor	mg/kg s.m.s.	19.67	18.33	19.00
Sodium	mg/kg s.m.s.	1404.67	1498.67	1451.67
Molybdenum	mg/kg s.m.s.	0.82	0.39	0.60
Elementary carbon	% s.m.s	39.73	40.52	40.12
Chrom	mg/kg s.m.s.	< 0.10	< 0.10	< 0.10
Nickel	mg/kg s.m.s.	< 0.50	< 0.50	< 0.50
Lead	mg/kg s.m.s.	< 0.50	< 0.50	< 0.50
Cadmium	mg/kg s.m.s.	< 0.10	< 0.10	< 0.10
Silicon	% s.m.s	49.00	50.00	49.50
Aluminum	mg/kg s.m.s.	16.08	< 16.37	< 16.22
Selenium	mg/kg s.m.s.	< 2.00	< 2.00	< 2.00
Arsenic	mg/kg s.m.s.	< 1.00	< 1.00	< 1.00
Mercury	mg/kg s.m.s.	< 0.40	< 0.40	< 0.40

Mechanical characterization

Table B 8. Mechanical characterization results per sample.

	Section (mm^2)	Length (mm)	Yield strenght (Mpa)	Young's modulus (GPa)			Tensile Strenght (Mpa)	Ultimate tensile strength (N)	Elongation at break (%)
Sample1	39.75	127.00	1.58	0.82	_	1.01	19.89	790.57	6%
Sample2	35.75	127.00	2.74	1.42	_	1.57	22.11	790.57	3%
Sample3	17.00	104.00	2.42	1.30	_	1.46	26.20	445.42	6%
Sample4	12.69	105.50	3.86	2.04	_	2.41	34.32	435.48	4%
Sample5	41.25	159.50	1.72	0.87	_	1.08	10.20	420.74	3%
Sample6	43.13	159.50	2.31	1.24	_	1.15	18.33	790.57	5%
Sample7	20.81	164.50	2.57	1.33	_	1.48	18.17	378.24	4%

Identification of materials with similar characteristics

Table B 9. Natural fiber-like materials with characteristics similar to tomato stems.

	Physical characteristics					
	Density (kg/m3)	Water absorption (%)	Moisture Content (%)	Ash Content (% s.m.s)	Thermal conductivity (W/m°C)	
Tomato stem	300 - 580	372	89	14 - 18	0.0582 - 0.0602	
Banana bagasse	610 - 730		82.5			(Lopes et al., 2011)
Bagasse	340 - 490					
Soft wood	460 - 1500					
Banana			85.6	8.3		(Jústiz-Smith et al., 2008)
Carnation stem	1710 -1820		84.16			(González-Velandia et al., 2016)
Coconut	85				0.058	(Benfratello et al., 2013)
	Chemical characteristics					
	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Carbon content (wt.%)	N content (%)	
Tomato stem	30 - 40	5 a 14	4 a 11	40.12	2.38	
Coconut fibre	32.65	59.4	7.95	51.5		Jústiz-Smith, Virgo, & Buchanan, 2008
Bagasse	30.27	13	56.73	53		
Sugarcane bagasse	32 - 44	19 - 24				Satyanarayana, Arizaga and Wypych, 2009
Banana	60 - 65	5 - 10				
Jute	59 - 71	11.8 - 12.9				
Pineapple	80 - 83	12				
Curauá wet	70.7 - 73.6	7.5 - 11.1				
Sisal	60 - 67	8 - 12				
Softwoods	38 - 46	22 - 34	23 - 31			(González-Velandia et al., 2016)
Hard woods	38 - 49	16 - 30	20 - 40			
Straw	28 - 42	12 - 21	23 - 38			
Bamboo	26 - 43	20 - 32	25 - 26			
Hemp fiber	88 - 90	1.5 - 2	7 a 10			(Amigó et al., 2008)
Sisal fiber	65	9.9	12			
Banana fiber	63 - 64	5	19			
Pineapple fiber	81	12.7				
	Mechanical characteristics					
	Young's modulus (GPa)	Ultimate tensile strength (Mpa)	Yield strength (Mpa)	Elongation at break (%)	Tensile strength (MPa)	
Tomato stem	0.82 - 2.41	378 - 791	1.58 - 3.86	3 - 6	10.20 - 34.32	
Cucumber stem	0.198				6.3	(Zhang et al., 2016)
Cotton straw	0.13				27.26	
Bagasse					29.6	Jústiz-Smith, Virgo, & Buchanan, 2008
Banana	27 - 32	700 - 800		2.5 - 3.7		Satyanarayana, Arizaga and Wypych, 2009
Jute	10 - 30	400 - 800		1.5 - 1.8		
Ramie	44	500 - 870		1.2		
Sisal	17 - 22	530–630		3.64 - 5.12		
Cotton	12	400				
Sisal fiber				2 - 2.5	444 - 552	(Amigó et al., 2008)
Banana fiber				5.0 - 6.0	550	
Pineapple fiber				3.0 - 4.0	413	

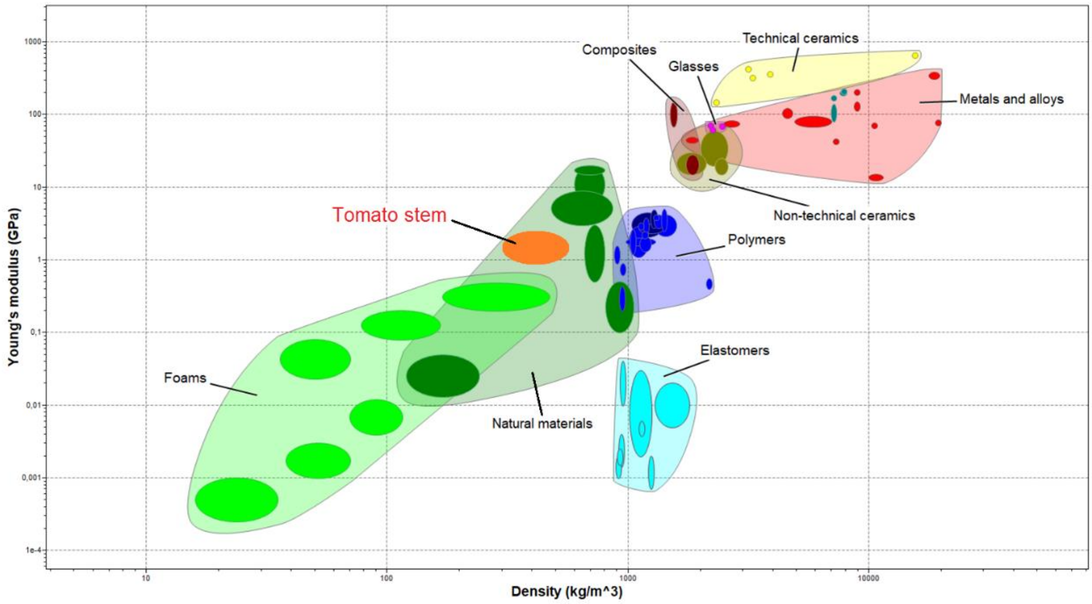


Fig. B 1. Ashby graph of Young's modulus / Density by material family.

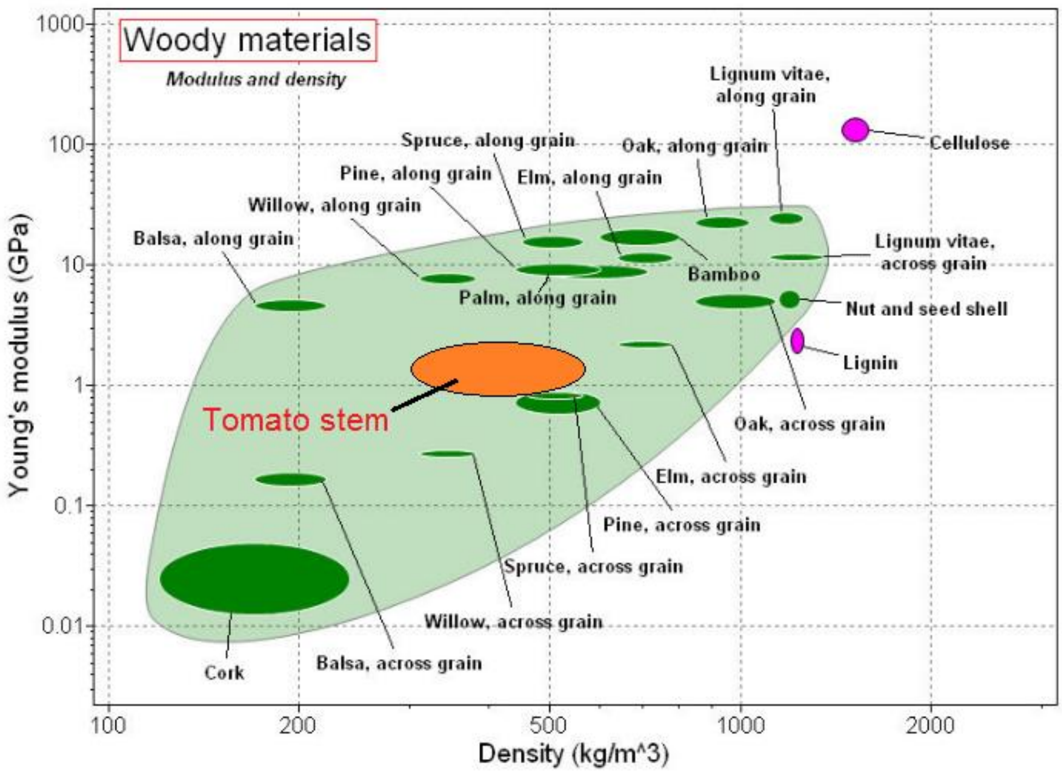


Fig. B 2. Ashby graph of Young's modulus / Density of woody materials. Adapted from (Ashby, 2008) with the values of the tomato stem in orange.

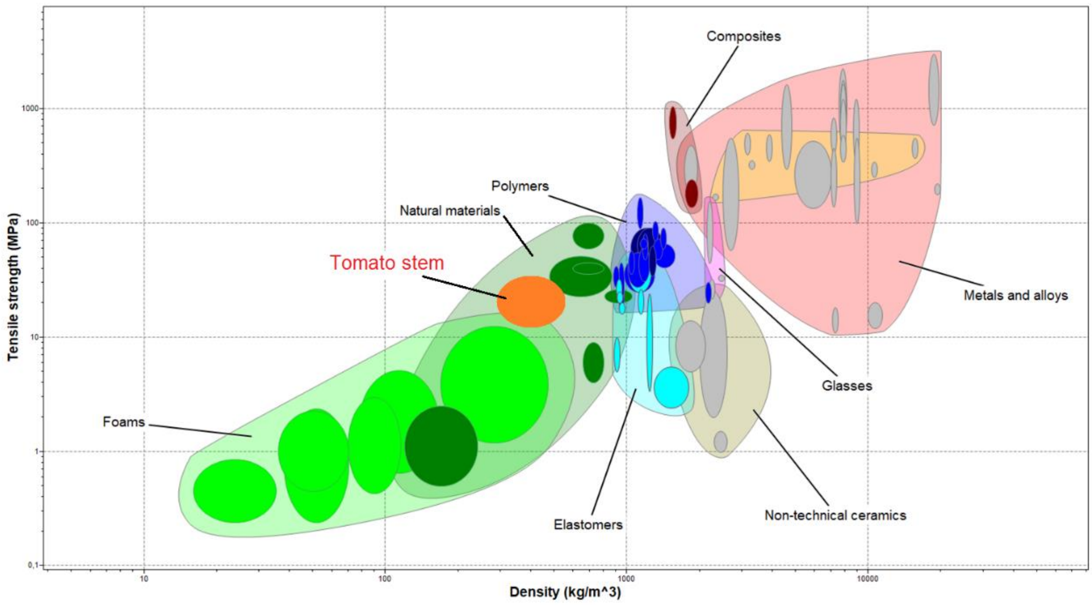


Fig. B 3. Ashby graph of Tensile strength / Density by material family.

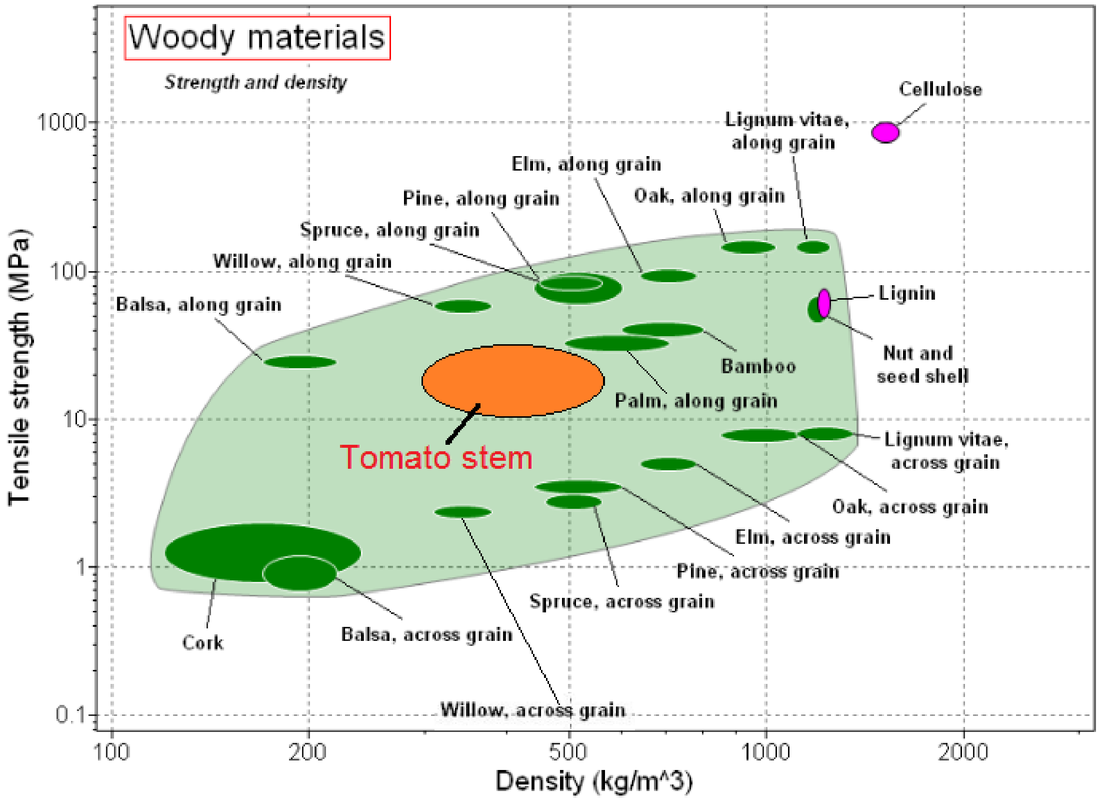


Fig. B 4. Ashby graph of Tensile strength / Density by material family.

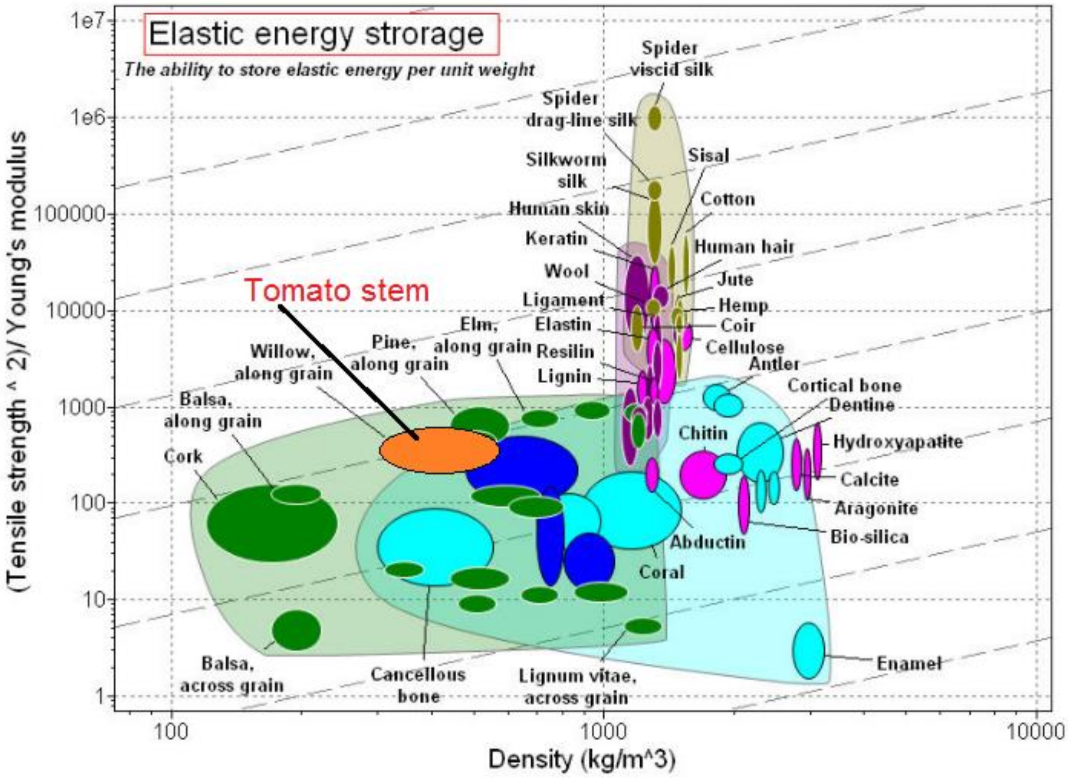


Fig. B 5. Ashby graph of ((Tensile strength²)/ Young's modulus) / Density of natural materials. Adapted from (Ashby, 2008) with the values of the tomato stem in orange.

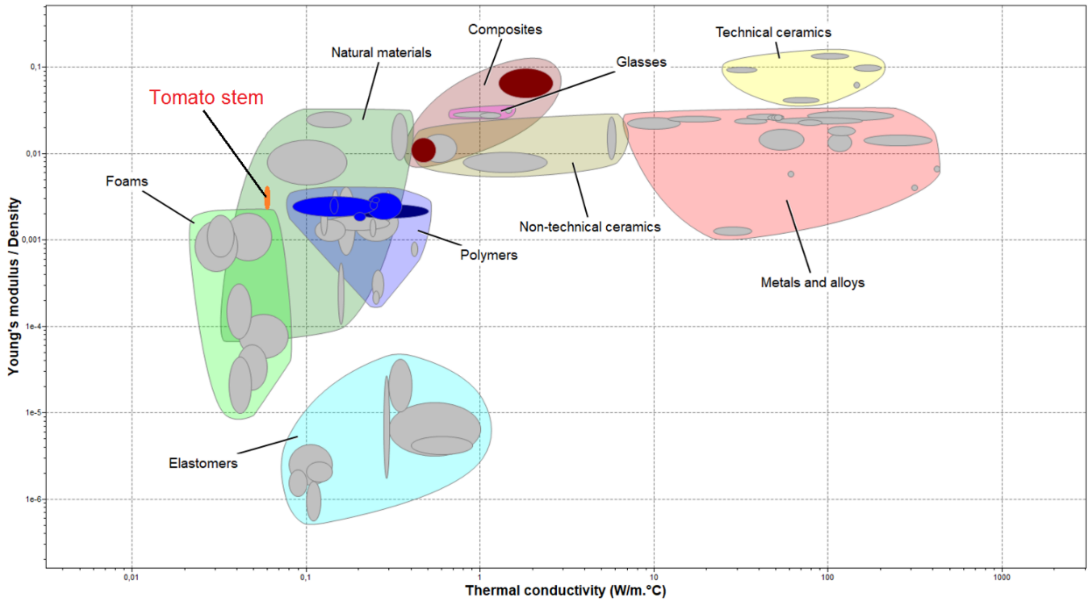


Fig. B 6. Ashby graph of (Young's modulus / Density) / Thermal conductivity by material family.

Generation and selection of concepts

Fig. B 7. Presentation of objectives and information at the beginning of the creative session.

Fig. B 8. Concept generation using the group technique of "forced relationships".

Fig. B 9. Dynamics of key questions to select the concepts with greater development feasibility.

Table B 10. Concepts generated by group 1 using the "forced relationships" technique.

Group 1		
Pair of words		**Application**
Sawdust + Textile	1	Tomato container
	2	Fashion accessories
	3	Filling
	4	Pillow filling for heating
	5	Diapers
	6	Filters in composters
	7	bioabsorbent wastewater filter
	8	table protector
Buoyancy + Automobile	9	Floating car
	10	Upholstery padding
	11	Composite materials like car panels
	12	Fillers for soundproofing the engine
	13	Bicycle helmet
	14	Lighter Amphibious Automobiles
	15	Thermal insulation in trains
	16	Buoys
	17	Kayaks
	18	Padding for vests
	19	Filling for packaging
	20	Baskets with different designs
	21	Soap holder
	22	Fence for greenhouses
	23	Ephemeral fences
	24	Green facades
	25	Low intensity protection systems
Lightweight + Construction	26	Plasterboard filling
	27	Wood chipboard filling
	28	Acoustic isolation
	29	Breathable windows
	30	Thermal insulator
	31	Ephemeral furniture
	32	Structures for fairs
	33	Carpets for fairs
Woody + Fashion	34	Jewelry
	35	Earrings
	36	Hats
	37	Bags
	38	Ephemeral pergolas
	39	Beach umbrellas
Urban agriculture + Lightness	40	Substrate
	41	Container for plants
	42	Divider panel
	43	Agriculture baskets
	44	Bench support
	45	Seedbeds
	46	Pots
	47	Urns for ashes
	48	Pergolas for urban agriculture
	49	Supports for crop
Compressible + Decoration	50	Lamp
	51	Straws
	52	Flutes
	53	Ephemeral sculptures
	54	Children's cabins
	55	Braided chair backs
	56	Protective fences for plants
	57	Improve the acoustics of a space

Table B 11. Concepts generated by group 2 using the "forced relationships" technique.

Group 2		
Pair of words		Application
Lightness + Fashion	1	Outerwear
	2	Shoe soles
	3	Shoe insole
Buoyancy + Packaging	4	Plates, glasses and cutlery
Packaging + Sustainable	5	Packaging for vegetables and fruits
	6	Flowerpot
	7	Container for sale
	8	Plates, glasses, cutlery and trays
Sawdust + Gardening	9	Mulch
	10	Soil amendment
	11	Substrate
	12	Plant trays
	13	"Sand" for animals
Rigid + Construction	14	Chipboard ceiling panels
	15	Building blocks
	16	Compressed panels for lost formwork
	17	Disposable molds
Decoration + Biodegradable	18	Air fresheners
	19	Chipboards for surface coating
	20	Wood look planks
	21	Coffins
	22	Ash container
	23	Toys for children
	24	Decorative branches
Textile + Woody	25	Non-woven fabrics
	26	Tomato or plant guide
	27	Fence
	28	Pergola roof
Automobile + lignocellulosic	29	Interior rigid laminate composite
	30	Seat padding
	31	Mattress padding
Home + thermal insulation	32	Cellulose filling that is pumped
Furniture / Urban agriculture	33	Furniture with compressed material

Concept evaluation in the creative session

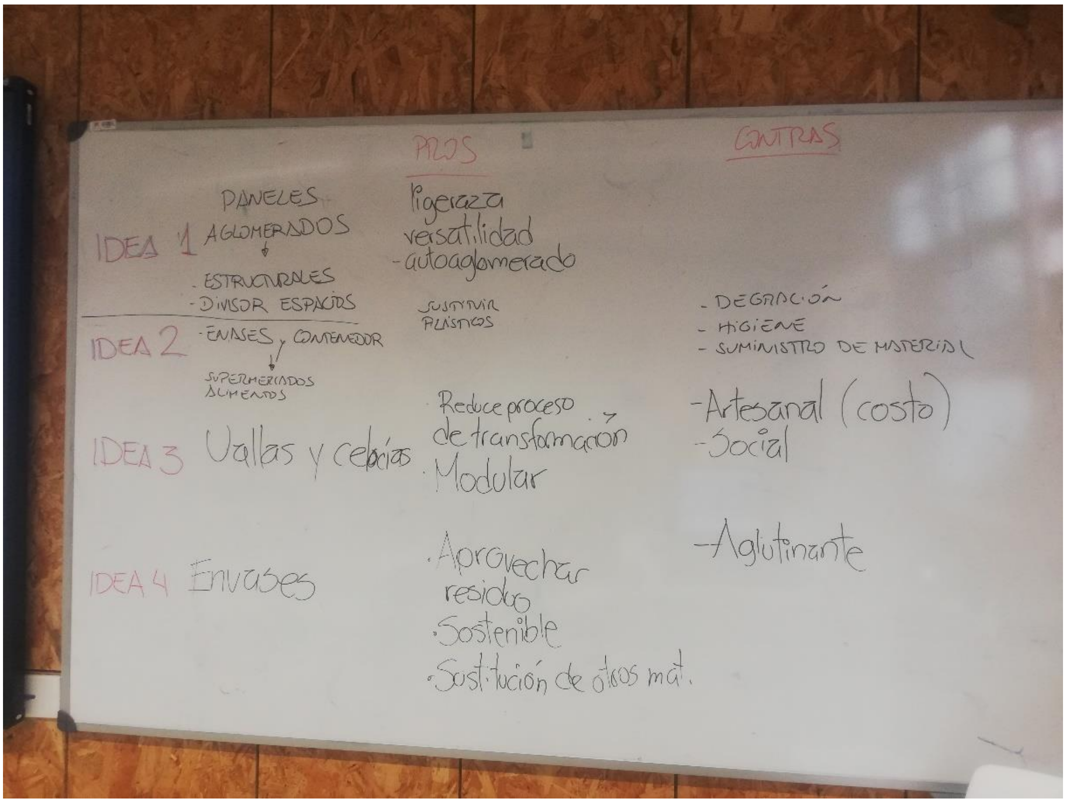


Fig. B 10. Concepts selected from both groups.

Fig. B 11. Guided discussion on the selected concepts of both groups by all participants.

Fig. B 12. Qualitative evaluation of the selected concepts using the techniques of "Evaluation Grid" and "positive, negative and interesting (P,N,I)".

Fig. B 13. Qualitative evaluation of the selected concepts by the participants.

Fences and trellises	Comment
Innovation	New architecture, naturalize city
	Good idea to reuse directly
	It can be an interesting solution locally. To make nearby products
	Little innovation
Technical feasibility	Possibility of technology development due to similarity with the textile industry
	New simple processes
	Nature appeal
	I like that the material is processed little to save processes
	Simple, artisan technology. Custom product
	Irregularity of regulations will make it difficult to standardize an industrial process
	Technological difficulty is little knowledge about feasibility
Environment	Versatile element, which can be integrated into various types of "green" buildings and parks or the like
	There is practically no processing of the material
	Waste disposal
	Low impact
	It can be negative that it is not used and ends up being a stored waste
Market impact	Very positive to be able to use it without almost treating the stems
	Self-consumption
	Attractiveness of the imperfect
	I don't know how it would work commercially ??
	Low commercial value or How to make it economically interesting?
	/
	Limitation of applications at present. Difficult to use on green fences. Attention to plant health (possible viruses, diseases)

Fig. B 14. Comments of each evaluation for "Fences and trellises (C1)" concept.

Concept	Criterion	Comment
Packaging	Innovation	Adapted to the product Packaging-product
		Containers: IT LOOKS LITTLE INNOVATIVE (ALTHOUGH VERY COMMERCIAL)
		It is not a very innovative idea since there are already many packages
	Technical feasibility	Food preservation must be guaranteed. Ensure that the packaging does not degrade throughout the chain
		If not covered hygienic problems
	Environment	Substitution of unnecessary materials. Reuse and disuse once the paper is completed as a container
		Reduce plastics
		Waste disposal
		They are short widow products that generate a lot of waste, it is necessary to find sustainable alternatives
		Allows reuse and degradation after use. According to its use, the easy degradation becomes a positive aspect
	Market impact	Very commercial packaging and containers, especially now that single-use product laws and regulations change.
		Packaging km0. Product poetic if it serves to package tomatoes or is reused with sense
		I see that commercially and at the volume level it can be a great opportunity
		Recycled sells
		Transporting tomatoes in containers from the crop itself is interesting
		Many economically cost-effective applications
		Great application viability
		Diversity of possibilities: packaging, boxes …
		Cheap, not economically viable
		Low value-added product that requires large-scale production
		Possible toxicity

Fig. B 15. Comments of each evaluation for "Packaging (C2)" concept.

Boards, panels and blocks

Criterion	Comment
Innovation	I find it very positive and with an added value to be able to use tomato plants to make furniture, formwork, panels, etc
	If the idea is to use crushed tomato plants to replace wood or bamboo, it really is not an innovation
	There are other products on the market, although being a high volume sector, perhaps there is room for all
Technical feasibility	Technology is highly developed for similar applications, easy for industrial scaling
	Similar experiences exist that allow us to glimpse technological feasibility
	Agglomerated - Self-Agglomerated
	Possibilities without being clear about the feasibility.
	Can dispose of large volumes of waste
	Material without standard characteristics, highly variable
	Difficult logistics
	Difficulty applying it to urban crops
	I find that maybe technologically or logistically it could be difficult
	“Panels and agglomerates” it takes a lot of volume of material to make panels, the same is not possible in all urban crops / orchards
	Difficulty in automation, material still to be verified
Environment	Waste disposal
	Do not cut down trees
	It replaces materials that are already used without environmental benefit.
	Natural product, can make a difference compared to others
	Binders impact
Market impact	“Chipboard panels” To make furniture or small products, I find it very positive using sustainable binders or the self-adhesive chipboard: IKEA CHAIR THE FORM US WITH LOVE.
	Reduction of environmental costs. Easily identifiable by the consumer and by the distributors as a good idea.
	Low cost
	It can be a very broad sector with many options
	"Ecological recycled" SOLD
	The existence of similar panels on the market can make it difficult to gain a foothold
	Much competition for the existence of similar publications

Fig. B 16. Comments of each evaluation for "Boards, panels and blocks (C3)" concept.