

**UNIVERSIDAD POLITÉCNICA DE MADRID**  
Escuela Técnica Superior de Ingenieros Industriales



**A Circular Economy Living Lab –  
Supporting the transition of a  
university campus towards a circular  
and regenerative system**

**DOCTORAL THESIS**

Submitted for the degree of Doctor by:

**David Andrés Hidalgo Carvajal**

M.Sc. in Industrial Engineering

Madrid, 2024



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Under the supervision of:

Dr. Ruth Carrasco-Gallego, ETSII, UPM

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*To my parents....*

*To my brother...*

*To you...*

*To my four-legged kids...*

*To everyone....*

*“...and everyone I've loved before, flashed before my eyes, and nothin' mattered anymore, I looked into the sky...”. Wheels. Foo fighters.*



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# Abstract

This PhD dissertation is framed in the fields of Sustainability, Higher Education Institutions (HEIs) and Supply Chain Management (SCM). Within the Sustainability field, the concept of Circular Economy (CE) was chosen due to its interdisciplinary nature and need for exploration. Thus, this thesis focuses on implementing CE concepts within HEIs, presenting a framework for embedding these through the development of a Circular Economy Living Lab (CELL), using Action Learning and Action Research (ALAR) methodologies. The framework aims to create a replicable model for other institutions to promote CE in teaching, research, and operational activities.

The literature review reveals that HEIs, often compared to small cities, have significant environmental impacts due to their resource consumption and waste generation. As such, they are uniquely positioned to promote CE through innovative strategies and interdisciplinary collaboration. Living labs (LL) in HEIs function as experimental spaces where sustainable solutions can be tested in real-world contexts. By combining these methodologies, HEIs can bridge the gap between theory and practice, enabling students and researchers to address real-world sustainability challenges, not only advancing academic knowledge but also providing scalable, practical solutions that can be implemented across various sectors. Additionally, the proposed framework promotes interdisciplinary collaboration and hands-on learning, preparing students for future challenges in sustainability. However, gaps remain in applying CE principles across campus operations, especially in aligning research and education with practical applications. Collaboration with external stakeholders and the local community is also crucial for driving broader CE initiatives outside of the HEI campus.

The CELL developed within Universidad Politécnica de Madrid (UPM) applies CE principles across its multiple campuses, integrating CE into key areas such as waste management, energy use, and sustainable procurement, with support from both public and private stakeholders. The initiative has grown into a collaborative platform, engaging a wide range of partners to drive sustainability efforts within the university and the surrounding community. Additionally, it serves as a model for other institutions seeking to implement CE principles through innovation, collaboration, and community engagement.

CELL's framework is built around six work areas that address different aspects of sustainability: Re-think, Re-naturalize, Re-connect, Re-duce, Re-experiment, and

Re-generate. Each area focuses on different sustainability goals, such as reducing single-use plastics, enhancing urban greenery, minimizing food waste, and creating spaces for hands-on learning and experimentation. These work areas guide UPM's efforts in reducing its environmental footprint, fostering industrial symbiosis, and promoting an applied circular economy model. Moreover, CELL provides a comprehensive strategy for embedding CE principles into campus operations and curricula, engaging both students and staff in the process.

Likewise, the supply chain (SC) perspective further supports the integration of CE within HEIs, where institutions manage both material and information flows. Traditionally, HEIs operate using a linear SC model, but transitioning to a circular supply chain (CSC) approach allows them to maximize resource recovery and waste reduction. The CELL initiative at UPM applies the CSC framework to improve campus sustainability, focusing on waste management and recycling. These efforts align HEIs with global sustainability goals and demonstrate the potential for CE practices in educational settings.

Research contributions under the CSC framework highlight advancements in servitization, e-waste management, and bioplastic and cardboard recoverability. On servitization, the shift from product ownership to service provision is examined, offering insights for HEIs to prepare students for new business models. On e-waste management, the integration of informal recycling systems is explored, while the bioplastic study focuses on the mechanical recycling of PLA, showing how HEIs can reduce environmental impacts by adopting circular practices. Additionally, the study on cardboard demonstrates the role that users play in supporting sustainable practices by reusing, recycling or even reselling the materials. By embedding CE principles into their operations and educational frameworks, HEIs serve as incubators for sustainability innovations, engaging students in hands-on learning experiences that align with CSC models, reducing environmental impacts and fostering a culture of sustainability on campus.

These findings emphasize the importance of collaboration between academia, industry, and government in promoting CE, highlighting the critical role of HEIs in advancing circular economy practices, leading the way in driving global sustainability efforts, providing real-world solutions to environmental challenges while contributing to the broader transition to a circular economy.

# Resumen

Esta tesis doctoral se enmarca en los campos de la Sostenibilidad, las Instituciones de Educación Superior (IES) y la Gestión de la Cadena de Suministro (GDS). Dentro del campo de la Sostenibilidad, se eligió el concepto de Economía Circular (EC) debido a su naturaleza interdisciplinaria y la necesidad de exploración. Por lo tanto, esta tesis se centra en la implementación de conceptos de EC dentro de las IES, presentando un marco para integrarlos a través del desarrollo de un Laboratorio Vivo de Economía Circular (CELL), utilizando metodologías de Aprendizaje en Acción e Investigación en Acción (ALAR). El marco tiene como objetivo crear un modelo replicable para que otras instituciones promuevan la EC en la enseñanza, la investigación y las actividades operativas.

La revisión de la literatura revela que las IES, a menudo comparadas con las ciudades pequeñas, tienen impactos ambientales significativos debido a su consumo de recursos y generación de desechos. Como tal, están en una posición única para promover la EC a través de estrategias innovadoras y colaboración interdisciplinaria. Los laboratorios vivos (LL) en las IES funcionan como espacios experimentales donde se pueden probar soluciones sostenibles en contextos del mundo real. Al combinar estas metodologías, las instituciones de educación superior pueden salvar la brecha entre la teoría y la práctica, lo que permite a los estudiantes e investigadores abordar los desafíos de sostenibilidad del mundo real, no solo avanzando en el conocimiento académico sino también brindando soluciones prácticas y escalables que se pueden implementar en varios sectores. Además, el marco propuesto promueve la colaboración interdisciplinaria y el aprendizaje práctico, preparando a los estudiantes para los desafíos futuros en materia de sostenibilidad. Sin embargo, siguen existiendo lagunas en la aplicación de los principios de EC en las operaciones del campus, especialmente en la alineación de la investigación y la educación con las aplicaciones prácticas. La colaboración con las partes interesadas externas y la comunidad local también es crucial para impulsar iniciativas de EC más amplias fuera del campus de la institución de educación superior.

El CELL desarrollado dentro de la Universidad Politécnica de Madrid (UPM) aplica los principios de EC en sus múltiples campus, integrando EC en áreas clave como la gestión de residuos, el uso de la energía y las compras sostenibles, con el apoyo de las partes interesadas públicas y privadas. La iniciativa se ha convertido en una plataforma colaborativa, que involucra a una amplia gama de socios para

impulsar los esfuerzos de sostenibilidad dentro de la universidad y la comunidad circundante. Además, sirve como modelo para otras instituciones que buscan implementar los principios de EC a través de la innovación, la colaboración y el compromiso comunitario. El marco de trabajo de CELL se estructura en torno a seis áreas de trabajo que abordan diferentes aspectos de la sostenibilidad: Repensar, Renaturalizar, Reconectar, Reducir, Reexperimentar y Regenerar. Cada área se centra en diferentes objetivos de sostenibilidad, como la reducción de plásticos de un solo uso, la mejora de la vegetación urbana, la minimización del desperdicio de alimentos y la creación de espacios para el aprendizaje práctico y la experimentación. Estas áreas de trabajo guían los esfuerzos de la UPM para reducir su huella ambiental, fomentar la simbiosis industrial y promover un modelo de economía circular aplicado. Además, CELL proporciona una estrategia integral para incorporar los principios de la EC en las operaciones y los planes de estudio del campus, involucrando tanto a los estudiantes como al personal en el proceso.

Asimismo, la perspectiva de la cadena de suministro (SC) respalda aún más la integración de la EC dentro de las IES, donde las instituciones gestionan los flujos de material e información. Tradicionalmente, las IES operan utilizando un modelo de SC lineal, pero la transición a un enfoque de cadena de suministro circular (CSC) les permite maximizar la recuperación de recursos y la reducción de residuos. La iniciativa CELL en la UPM aplica el marco de la CSC para mejorar la sostenibilidad del campus, centrándose en la gestión de residuos y el reciclaje. Estos esfuerzos alinean a las IES con los objetivos globales de sostenibilidad y demuestran el potencial de las prácticas de EC en los entornos educativos.

Las contribuciones de investigación en el marco del CSC destacan los avances en la servitización, la gestión de desechos electrónicos y la recuperabilidad de bioplásticos y cartón. En el caso de la servitización, se examina el cambio de la propiedad del producto a la prestación de servicios, lo que ofrece perspectivas para que las IES preparen a los estudiantes para nuevos modelos comerciales. En cuanto a la gestión de desechos electrónicos, se explora la integración de sistemas de reciclaje informales, mientras que el estudio de bioplásticos se centra en el reciclaje mecánico de PLA, lo que muestra cómo las IES pueden reducir los impactos ambientales mediante la adopción de prácticas circulares. Además, el estudio sobre el cartón demuestra el papel que desempeñan los usuarios en el apoyo a las prácticas sostenibles mediante la reutilización, el reciclaje o incluso la reventa de los materiales. Al incorporar los principios de EC en sus operaciones y

marcos educativos, las IES sirven como incubadoras de innovaciones en materia de sostenibilidad, involucrando a los estudiantes en experiencias de aprendizaje prácticas que se alinean con los modelos del CSC, reduciendo los impactos ambientales y fomentando una cultura de sostenibilidad en el campus.

Estos hallazgos enfatizan la importancia de la colaboración entre la academia, la industria y el gobierno en la promoción de la EC, destacando el papel fundamental de las IES en el avance de las prácticas de economía circular, liderando el camino para impulsar los esfuerzos globales de sostenibilidad, brindando soluciones del mundo real a los desafíos ambientales y contribuyendo al mismo tiempo a la transición más amplia hacia una economía circular.



# Table of Contents

<i>Acknowledgement</i> .....	v
<i>Abstract</i> .....	<i>xi</i>
<i>Resumen</i> .....	<i>xiii</i>
<i>List of Figures</i> .....	<i>xx</i>
<i>List of Tables</i> .....	<i>xxiv</i>
<i>Abbreviations and Acronyms</i> .....	<i>xxv</i>
<b>1. Introduction</b> .....	<b>1</b>
1.1. Background .....	1
1.2. Research goal and objectives .....	6
1.3. Outline of the document .....	9
<b>2. State of the art</b> .....	<b>11</b>
2.1. Introduction .....	11
2.2. Setting the scene .....	11
2.2.1. Circular Economy .....	11
2.2.2. Higher Education Institutions .....	13
2.2.3. Living Labs .....	15
2.2.4. Action Learning and Action Research .....	16
2.3. Exploring the literature.....	18
2.3.1. Data collection and evaluation .....	19
2.3.2. Academic literature .....	21
2.3.3. Grey literature .....	34
2.3.4. Contrasting the academic and grey literature .....	38
2.4. Mind the gap .....	41
2.5. Conclusions .....	46
<b>3. Research problem positioning and methodological approach</b> .....	<b>48</b>
3.1. Introduction .....	48
3.2. Thesis scope and research problem positioning .....	49
3.3. Research methodology .....	50
3.3.1. Real-world context methodologies .....	50
3.4. Methodological approach used in this thesis .....	52

<b>4. The Circular Economy Living Lab: the setup</b> .....	<b>55</b>
4.1. Introduction .....	55
4.2. Understanding the university context .....	55
4.3. Developing the Circular Economy Living Lab (CELL) .....	56
4.3.1. The CELL from a biology (counterpart) perspective .....	57
4.3.2. Expansion of the CELL.....	60
4.3.3. Creating networks.....	65
4.4. Conclusions .....	72
<b>5. The Circular Economy Living Lab: the framework and results</b> .....	<b>75</b>
5.1. Introduction .....	75
5.2. Setting up the framework .....	75
5.3. Defining the framework and work areas at CELL .....	77
5.4. Understanding the work areas at CELL.....	83
5.5. Results obtained under CELL’s framework.....	92
5.6. Conclusions .....	106
<b>6. The Circular Economy Living Lab from a Circular Supply Chain perspective</b> .....	<b>109</b>
6.1. Introduction .....	109
6.2. Understanding HEIs from a Supply Chain perspective.....	109
6.3. Allocating the academic literature within the CSC framework .....	114
6.4. Allocating CELL’s results within the CSC framework.....	120
6.5. Conclusions .....	122
<b>7. Academic pillars of the Circular Economy Living Lab</b> .....	<b>125</b>
7.1. Introduction .....	125
7.2. The contributions under the CSC framework .....	125
7.2.1. First contribution – on rethinking the system .....	126
7.2.2. Second contribution – on (e-)waste management .....	129
7.2.3. Third contribution – on (bio-)plastic waste management .....	133
7.2.4. Fourth contribution – on cardboard waste management .....	137
7.2.5. Fifth contribution – on regenerating biopolymers .....	140
7.3. Summarizing the contributions under the frameworks .....	143
7.4. Conclusions .....	146
<b>8. Conclusions, original contributions and future research lines</b> .....	<b>147</b>
8.1. Conclusions of this PhD dissertation .....	147
8.2. Original contributions.....	153

8.3. Future research lines .....	154
<b>References.....</b>	<b>157</b>

# List of Figures

<b>Figure 1.</b> Trends in number of publications on the topic of sustainability in universities. Own development. ....	3
<b>Figure 2.</b> Trends in academic publications on the topic of circular economy in general. Own development. ....	5
<b>Figure 3.</b> Trends in number of publications in academic journals on the topic of circular economy in higher education institutions. Own development. ....	6
<b>Figure 4.</b> A complete framework model (brain and academic work) for the CELL at UPM. Own development. ....	8
<b>Figure 5.</b> Outline of the PhD dissertation. Own development. ....	9
<b>Figure 6.</b> Research design using the PRISMA model. Own development. ....	20
<b>Figure 7.</b> Trends in number of publications in academic journal on the topic of circular economy in higher education institutions. Own development. ....	22
<b>Figure 8.</b> Distribution of research articles per journal. Own development. ....	23
<b>Figure 9.</b> Distribution of academic articles per region and year. Own development. ....	24
<b>Figure 10.</b> Academic article’s geographical impact location. Own development. ....	25
<b>Figure 11.</b> Distribution of academic articles per category in HEIs. Own development. ....	30
<b>Figure 12.</b> Distribution of best practices per region and year. Own development. ....	35
<b>Figure 13.</b> Number of best practices by HEI per geographical location. Own development. ..	36
<b>Figure 14.</b> Number of best practices presented by a single HEI. Own development. ....	36
<b>Figure 15.</b> Distribution of best practices per category and the implemented best practices in HEIs. Own development. ....	37
<b>Figure 16.</b> Alliances on best practices in HEI. Own development. ....	38
<b>Figure 17.</b> Distribution of best practices per group – academic vs grey literature. Own development. ....	39
<b>Figure 18.</b> Distribution of best practices per region – academic vs grey literature. Own development. ....	40

<b>Figure 19.</b> Distribution of best practices per region – academic vs grey literature. Own development. ....	41
<b>Figure 20.</b> Topics connecting CE and HEIs from six main themes. Own development using VOSviewer version 1.6.18.....	43
<b>Figure 21.</b> Example of multidisciplinary approach from different topics within the literature. Own development using VOSviewer 1.6.18.....	45
<b>Figure 22.</b> Most relevant gaps identified in the literature on CE in HEIs. Own development.	46
<b>Figure 23. (a)</b> Action learning cycle, and <b>(b)</b> Action research spiral of research cycles. Adapted from (Coughlan & Coughlan, 2002; Zuber-Skerritt, 2001).....	53
<b>Figure 24. a)</b> Structure of a neuron cell; <b>b)</b> interpretation of HEI as a neuron cell. Adapted from Betts et al ( <i>Betts et al., 2013</i> ).....	59
<b>Figure 25.</b> The Circular and Regenerative Campus community at UPM, showing its expansion to other schools. Own development.....	61
<b>Figure 26.</b> EELISA network. Source: ( <i>EELISA, 2020</i> ). ....	63
<b>Figure 27.</b> Academic and non-academic network of partners involved with CELL. Own development. ....	66
<b>Figure 28.</b> EELISA CRC community' total population, discriminated per HEI. Own development. ....	69
<b>Figure 29.</b> Waste of non-hazardous materials at ETSII-UPM (2007-2023). Own development. ....	78
<b>Figure 30.</b> Waste of hazardous materials at ETSII-UPM (2007-2023). Own development.....	78
<b>Figure 31.</b> Waste of construction and demolition at ETSII-UPM (2007-2023). Own development. ....	79
<b>Figure 32.</b> Expansion from idea to change in the system. Own development. ....	80
<b>Figure 33.</b> Structure the brain. Adapted from Nauta & Feirtag ( <i>Nauta &amp; Feirtag, 1979</i> ) and Carter et al ( <i>Carter et al., 2009</i> ). ....	81
<b>Figure 34.</b> The six work areas of CELL. Own development. ....	82
<b>Figure 35.</b> CircuLab facility and machinery. Own development. ....	89
<b>Figure 36.</b> Academic results achieved at CELL (2020-2023) allocated to the four influence areas at HEIs. Own development. ....	93

<b>Figure 37.</b> Academic results achieved at CELL (2020-2023). Own development. ....	94
<b>Figure 38.</b> Projects currently under development at CircuLab. Own development. ....	101
<b>Figure 39.</b> HEI’s value chain – adapted from (ETSII-UPM, 2014, 2016, 2018; Groves et al., 1997; Pathak & Pathak, 2010; Hutaibat, 2011; Morien, 2019). ....	111
<b>Figure 40.</b> HEI’s material flow as a linear system – adapted from ( <i>Ellen MacArthur Foundation, 2015; McDonough &amp; Braungart, 2002; Thierry et al., 1995</i> ) ....	112
<b>Figure 41.</b> HEI’s material flow following a product recovery management strategy – adapted from ( <i>Ellen MacArthur Foundation, 2015; McDonough &amp; Braungart, 2002; Thierry et al., 1995</i> ). ....	113
<b>Figure 42.</b> HEI’s material flow as a circular supply chain system. <i>Own development.</i> ....	114
<b>Figure 43.</b> Number of academic documents allocated per topic, following the proposed Circular Supply Chain approach at HEIs. Own development. ....	115
<b>Figure 44.</b> Number of projects allocated following the proposed Circular Supply Chain approach at HEIs. Own development. ....	121
<b>Figure 45.</b> Examples of servitization options from ownership perspective. Adapted from (Tauqeer & Bang, 2018). ....	126
<b>Figure 46.</b> Including informal recyclers within the Circular Supply Chain approach. Own development and available at (Hidalgo-Carvajal & Carrasco-Gallego, 2022). ....	130
<b>Figure 47.</b> Cycles of mechanical recycling for PLA-waste within the Circular Supply Chain approach. Own development. ....	135
<b>Figure 48.</b> Five R-“routes” for cardboard boxes from the “user’s” perspective within the Circular Supply Chain approach. Own development and available at (Hidalgo-Carvajal, Gutierrez-Franco, et al., 2023) ....	138
<b>Figure 49.</b> Composting the PLA-waste after recycling within the Circular Supply Chain approach. Own development. ....	141
<b>Figure 50.</b> Allocating the contribution of the five papers under the CELL’s framework. Own development. ....	143
<b>Figure 51.</b> Allocating the contribution of the five papers under the Circular Supply Chain approach. Own development. ....	144
<b>Figure 52.</b> A complete framework model (brain and academic work) for the CELL at UPM. Own development. ....	149



## List of Tables

<b>Table 1.</b> Topics covered by the academic articles analyzed. Own development.....	26
<b>Table 2.</b> Topics covered by the academic text analyzed. Own development.....	33
<b>Table 3 -</b> Academic results achieved at CELL allocated into the main categories. Own development. ....	95
<b>Table 4.</b> Topics covered by the academic text that cannot be directly allocated within the CSC model. Own development.....	120
<b>Table 5.</b> Summary of the academic papers, journal, area of knowledge and raking. Own development. ....	145
<b>Table 6.</b> Summary of the academic papers, journal, area of knowledge and raking. Own development. ....	146

# Abbreviations and Acronyms

ALAR	Action Learning and Action Research
[A]NN	Artificial [academic and non-academic] Neural Network
CE	Circular Economy
CELL	Circular Economy Living Lab
CDW	Construction and Demolition Waste
CIEC	Centro de Innovación en Economía Circular
CORT	Campus management, Outreach, Research and Teaching
CRC	The Circular and Regenerative Campus
CSC	Circular Supply Chain
EELISA	European Engineering Learning Innovation and Science Alliance
EMF	The Ellen MacArthur Foundation
ESD	Education for Sustainable Development
ETSII	Escuela Técnica Superior de Ingenieros Industriales
EU	European Union
HDPE	High Density Polyethylene
HEI	Higher Education Institution
ISCN	International Sustainable Campus Network
LDPE	Low Density Polyethylene
LL	Living Lab
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
PP	Polypropylene
SC	Supply Chain
SCM	Supply Chain Management

SD	Sustainable Development
SDG	Sustainable Development Goals
STEM	Science, Technology, Engineering, and Mathematics
STEAM	Science, Technology, Engineering, Arts, and Mathematics
UN	United Nations
UPM	Universidad Politécnica de Madrid
WEEE	Waste of Electric and Electronic Equipment
XBL	X-Based Learning

# 1. Introduction

*“Unless someone like you cares a whole awful lot...Nothing is going to get better. It's Not.” The Lorax, in Dr. Seuss.*

*“When I used to read fairy tales, I fancied that kind of thing never happened, and now here I am in the middle of one!”. Alice in Wonderland.*

## 1.1. Background

The concept of Circular Economy (CE) has continuously progressed over the last 30 years around the idea of creating a new business model that is regenerative and restorative by design (Korhonen et al., 2018), positively impacting the natural system in which it takes place. The concept is created from a collection of heterogeneous scientific and semi-scientific concepts such as, *“ecological economics, industrial ecology, cradle-cradle design, restorative economy or performance economy, biomimicry, ecoefficiency, resilience science, natural capitalism, cleaner production”* (Korhonen et al., 2018). Moreover, CE is a widely recognized issue but to which different meanings are assigned depending on the discipline, but all true to their individual scenario. Both in the academic and grey literature, the CE is still a term under debate as there is not a unique definition which can embed all its meaning (Kirchherr et al., 2017).

More recently, the European Commission document dedicated on a monitoring framework for the circular economy states that *“The transition to a circular economy will also help to meet the objectives of the 2030 Agenda for Sustainable Development”* (European Commission, 2018b). Prior research looks at closed-loop supply chain (Bressanelli et al., 2019; de Angelis et al., 2018; Östlin et al., 2008; Rashid et al., 2013), sustainable business model (Bocken et al., 2014; Bressanelli et al., 2019) and system thinking (Senge, 2006) as key tools and methods of this transformation.

Furthermore, previous research identify a discrepancy between the consensus related to objectives and means of the CE (Bressanelli et al., 2019; Korhonen et al., 2018) and the difficulty of properly stating a clear definition of what it is (Hopff et

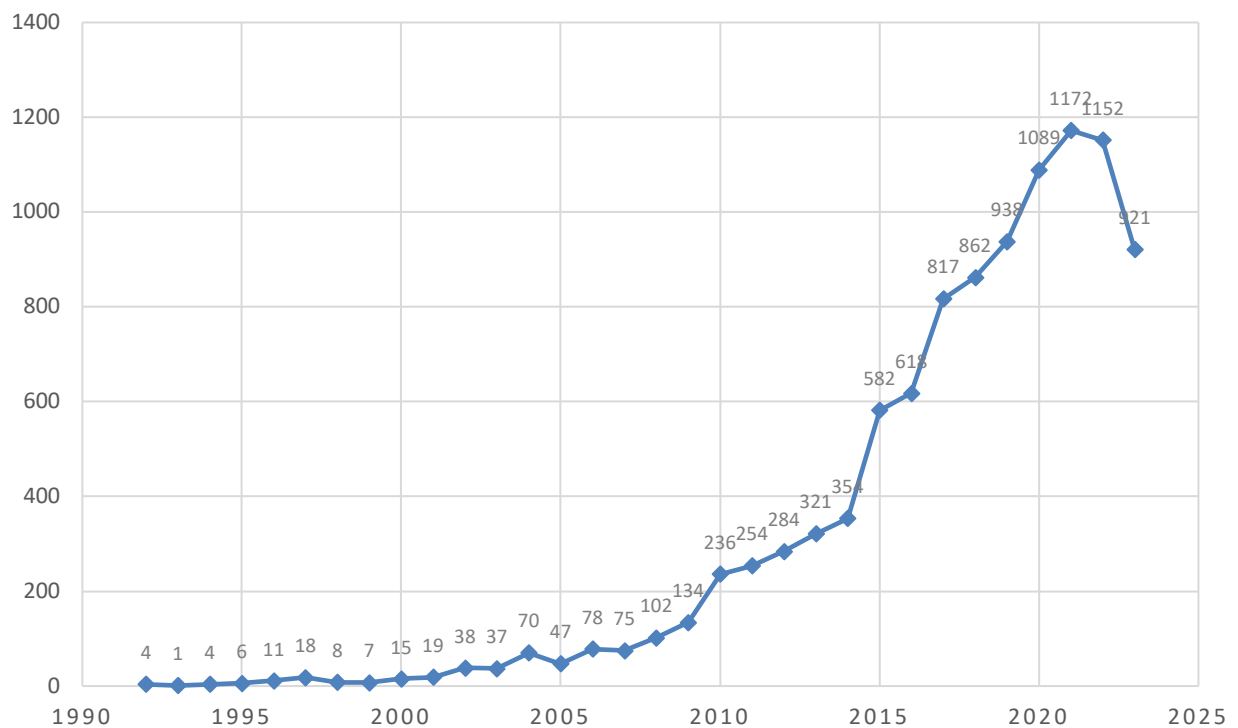
al., 2019; Mendoza et al., 2019a) and what the suitable investigation methodologies are. Moreover, there is a lack of a clear definition to determine the close relationship between the concepts of circular economy and sustainability (Hopff et al., 2019), as well as the role they play in Higher Education Institutions (HEI) from the Education for Sustainable Development (ESD) point of view (Masseck, 2017).

As the discussion evolves, and motivated by the proposition of the Sustainable Development Goals (SDG), universities have played an important role in the transition and implementation of the three pillars of sustainability both through the management of the campus and through education models (ISCN, 2018). Since the introduction of the concept of *sustainable campus*, a vast literature has been devoted to the various activities and measures to implement sustainability within university campuses. In particular, various studies focus on the role played by HEI in the dissemination of Sustainable Development (SD) principles through their education programs. Universities are in fact considered the decisive enablers to a change of mindset and values of the future since they form the next generations of leaders and citizens (Amaral et al., 2020; ISCN, 2018). As pointed out by Finnveden et al. (Finnveden et al., 2020), universities around the world aim – not only through courses, but also through practical activities – to provide the necessary tools to be able to analyze, understand, verify and apply the principles of SD.

Specifically, a growing number of publications mention the implementation of CE concepts and ideas in HEI (i.e., universities and colleges), showing a growing interest on the topic. Moreover, within their mission, HEI gather a wide set of stakeholders from both public and private sectors, and are hubs for innovation, economic activity, and intellectual growth. However, it is also important to consider the great environmental impact that university campuses have and where resources are consumed and waste is generated (Mendoza et al., 2019a). Furthermore, university campuses are developed in defined physical spaces and their management can be considered an important element for the implementation of circularity (ISCN, 2018). As mentioned by Amaral et al. (Amaral et al., 2020), university campuses include a large number of buildings with different functions used by a large number of users and inserted in vast and diversified urban spaces. Thanks to their configuration, university campuses can therefore be compared to small cities (or towns) with the same environmental concerns (greenhouse gas emissions (GHG), resources consumption, and waste generation) (Valls-Val & Bovea, 2021) and societal concerns (social relations, activity and stakeholders)

(Hidalgo-Carvajal, Picanço-Rodrigues, et al., 2023). Considering these premises, the implementation of circularity in HEI can vastly impact the global transition and the blooming of CE in our society (Nunes et al., 2018) through the management of university campuses, including its physical infrastructure, ideally, beyond the political agendas of education, research and innovation, to ensure a sustainable growth (den Heijer & Tzovlas, 2014).

Based on prior research and six reports on sustainable campus best practices - published by the International Sustainable Campus Network (ISCN) - this study intends to shed light on the increasing potential for circular economy in HEI campuses, and how the discussion around the sustainability topic has increased since its first academic discussion in 1992 to the most recent publications in 2023, as shown in Figure 1.



**Figure 1.** Trends in number of publications on the topic of sustainability in universities. Own development.

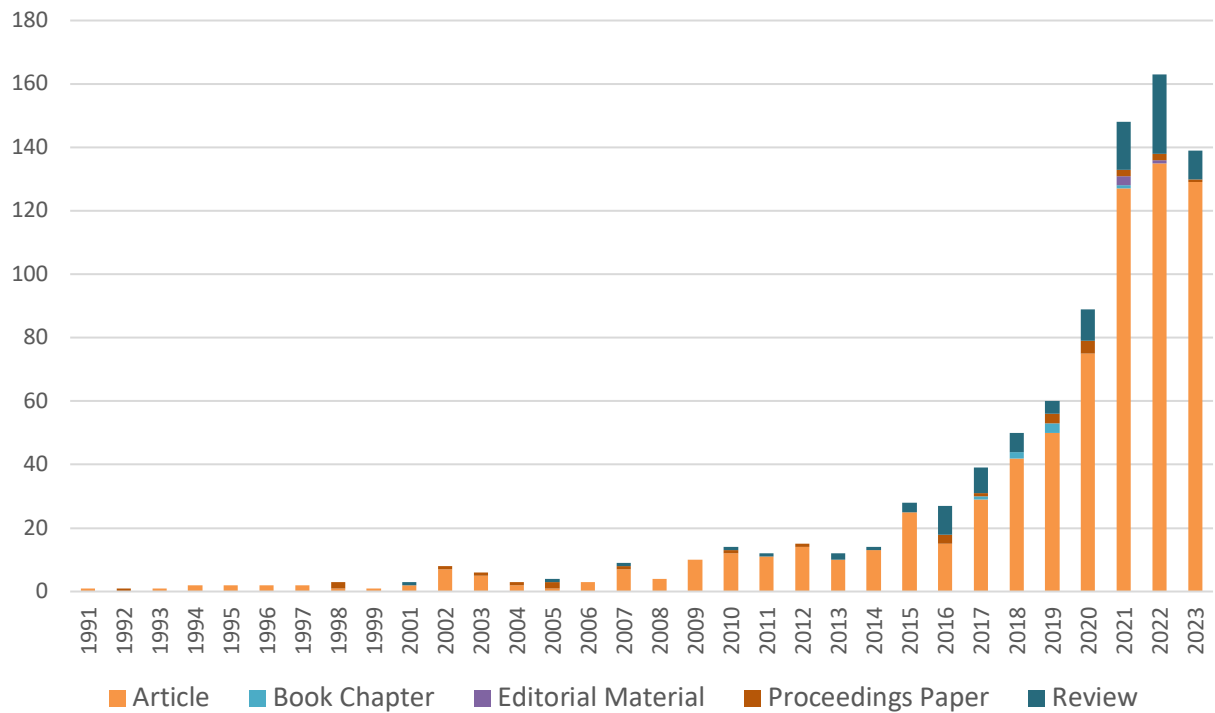
In Figure 1, we can observe an interesting pattern on which the HEIs have increased their publications around the sustainability topic which can be explained thanks to two pivotal events influencing HEIs: the university rankings (2004 and 2010) and the introduction of the SDGs (2015).

First, the university rankings were initially introduced in 2004 as a collaboration between the Times Higher Education (THE) and Quacquarelli Symonds (QS), creating the THE-QS World University Ranking (Times Higher Education, 2023b), although they will later go separate ways creating independent rankings. Since 2004, the QS World University Ranking collects data about university performance and currently ranks as the most popular ranking service, focusing on the metrics central to HEI's mission (QS World University Rankings, 2023). Since 2010, Times Higher Education presents THE World University Rankings as a separate ranking with a methodology intended to include additional indicators to complement HEI's mission and evaluate the impact in industry (Times Higher Education, 2010). In parallel in 2009, the Academic Ranking of World Universities (ARWU) also known as Shanghai Ranking, was created aiming to complement the other available rankings and relies heavily in the award factors for the ranking (Academic Ranking of World Universities, 2020). Furthermore, in 2010, the UI GreenMetric World University Ranking was introduced by the Universitas Indonesia (UI) as a way to measure campus sustainability efforts by universities around the globe (UI GreenMetric, 2023). Lastly, although UI Ranking has been the place to analyze campus sustainability, given the growing interest around sustainability and SDGs, since 2023 a review of other rankings has been done to include SDGs in THE Rankings (Times Higher Education, 2023a) and environmental and social sustainability in QS Rankings (QS World University Rankings, 2024).

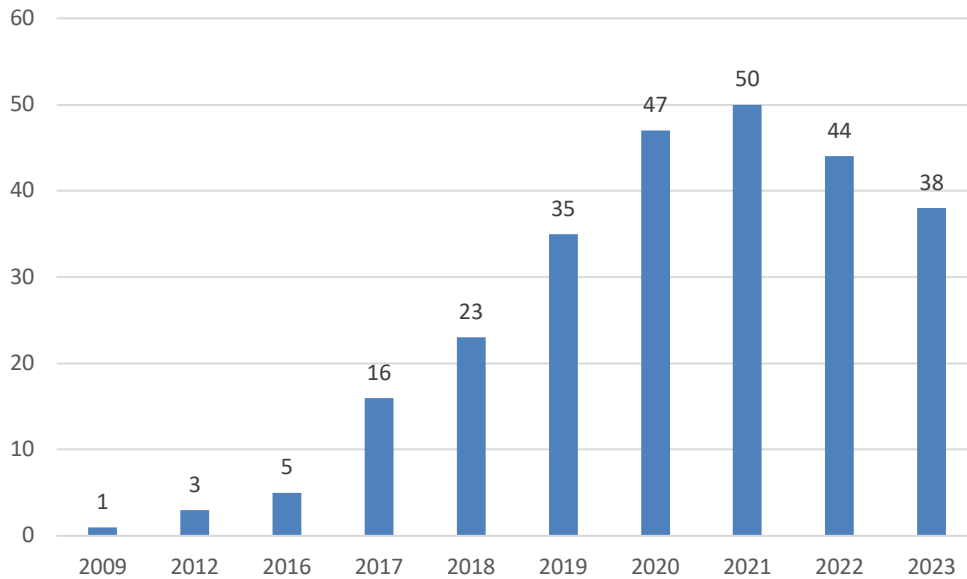
Second, the introduction of the SDGs since their conception in 2012 and later introduction in 2015 has also steered the direction of *teaching* and *research* in HEIs. Additionally, it has encouraged HEIs to perform actions to embrace SDGs as part of their sustainability strategy, with special focus on how to include these in their *campus management* operations and how to evaluate their *outreach* impact in the local community where the HEIs are deeply rooted. These concepts are here referred as CORT (Campus management, Outreach, Research and Teaching)

As the literature around sustainability has continued growing, so has the variety of topics sprouting from it, mainly focusing on the environmental sustainability. Circular Economy (CE) presents itself as a result of multidisciplinary approach, originating from different areas, ranging from life cycle assessment, waste management, environmental law, economics, agriculture, among others. Although it is not a new concept, as it was first introduced in 1988 by Allan Kneese (Kneese, 1988) and adapted later by Pearce & Turner in 1990 (Pearce & Turner, 1990),

building on the work by Walter R. Stahel from 1982 (Stahel, 1982), and later being discussed in a wide variety of academic works (i.e., conference papers, journal articles and book chapters) as can be seen in figure 2, it is evident that the circular economy concept has gained more traction since 2010, year on which the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2010) was launched aiming to promote the transition towards circular economy, partnering with public and private entities, and becoming a flagship and pivotal moment for the movement.



**Figure 2.** Trends in academic publications on the topic of circular economy in general.  
Own development.



**Figure 3.** Trends in number of publications in academic journals on the topic of circular economy in higher education institutions. Own development.

Publications on circular economy presented in figure 3 include the academic discourse around HEIs and originates from different areas, ranging from teaching to life cycle assessment, and from waste management to building a sustainable campus. Hence, the concept also encompasses all these areas and the different needs to be addressed in HEIs through circular economy. Figure 3 presents the growing trend focusing only on research on circular economy in higher education institutions, concentrating exclusively on the academic material published in academic journals.

## 1.2. Research goal and objectives

This PhD dissertation is framed within the crossroads between the emergent fields of circular economy (CE) and living labs (LL), and the more traditional fields of Higher Education Institutions (HEI) and Action Learning and Action Research (ALAR). Given the nascent interaction between these fields, it is necessary to develop a framework that allows integrating the four concepts and review the impact these have on the four core areas of HEIs (teaching, research, campus management and outreach).

The main goal of this thesis is not only to demonstrate that there is a growing interest around the globe on the CE topic and how HEIs are approaching it, but rather to showcase the use of LL as a demonstrator for these concepts following an ALAR approach. Furthermore, this approach intends to bridge the gap between theory and applied solutions. Therefore, **the core goal** of this PhD dissertation is to develop a framework for implementation of a Circular Economy Living Lab (CELL) within a HEI context and corroborate its impact across the four core areas where HEIs have direct influence.

The goals and objectives of this thesis are designed to ensure that the methodology developed to tackle the research problem not only serve as an education tool but also as a replicable model which showcases the implementation of CE practices across different institutions and sectors.

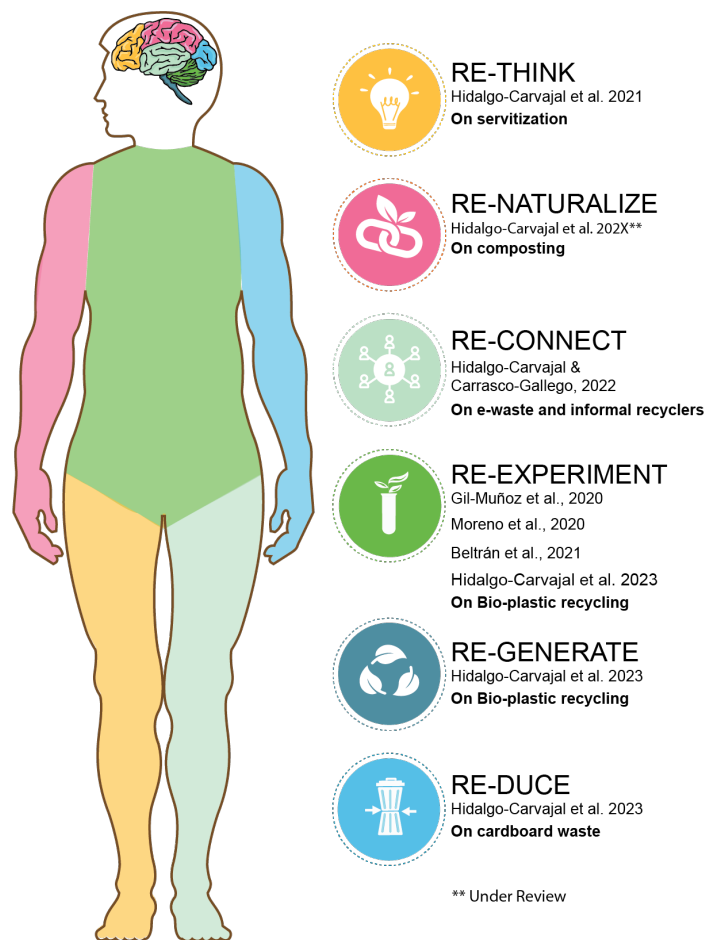
More precisely, the general goal of this thesis can be broken down into the following objectives:

1. To develop a comprehensive model for LL in HEIs which allow implementing CE principles, serving as a blueprint for other institutions.
2. To promote experiential learning and student engagement, demonstrating the usefulness of ALAR methodologies for continuous reflection and improvement.
3. To evaluate the impact that CE concepts have within the curriculum and research settings under both, the LL and ALAR methodologies.
4. To document and disseminate the different academic findings in diverse forums, contributing to the global body of knowledge.
5. To facilitate interdisciplinary collaboration which enhance sustainable practices within HEIs.
6. To generate external and internal alliances, creating stronger networks which allow further engaging local community in different projects.
7. To increase awareness and advocacy for sustainable practices by becoming a living proof of implementation of CE concepts.

By achieving these objectives, this thesis aims to demonstrate the transformative potential of ALAR and LL methodologies in HEIs, fostering a sustainable future through education, innovation, and collaboration, following the CE principles.

The methods used to tackle each objective within the general methodological approach are presented in Chapter 3.

The model presented in the figure below presents the framework developed for the Circular Economy Living Lab (CELL) which aims to address the different objectives. This framework, represented as a brain and explained in detail in Chapters 4 and 5, supports the advancement of the academic agenda in all four main HEIs impact areas through different lines of research. Furthermore, Chapter 7 presents the academic pillars generated by the author, represented as the body, on which the framework (brain) is supported and supports its continuous stability for the long term.



**Figure 4.** A complete framework model (brain and academic work) for the CELL at UPM. Own development.

### 1.3. Outline of the document

This PhD dissertation is structured in the following chapters. Chapter 2 presents the theoretical frameworks necessary to understand the role of Higher Education Institutions (HEI), Circular Economy (CE), Living Labs (LL), and Action Research (AR) and Action Learning (AR), and presents literature review (academic and grey) on CE concepts being applied in HEIs. Chapter 3 explains the methodology used to develop a LL at Universidad Politécnica de Madrid (UPM, *Polytechnic University of Madrid*). Chapter 4 presents the setup for implementing the Circular Economy Living Lab (CELL) within the UPM. Chapter 5 introduces the framework developed at CELL to incorporate CE concepts across all CORT areas within UPM and the obtained results. Chapter 6 proposes a circular supply chain (CSC) model to enhance CE's understanding at HEIs. Chapter 7 show the author's contributions to the academic body of the CELL. Finally, Chapter 8 closes this dissertation by presenting the conclusions and future avenues for research.

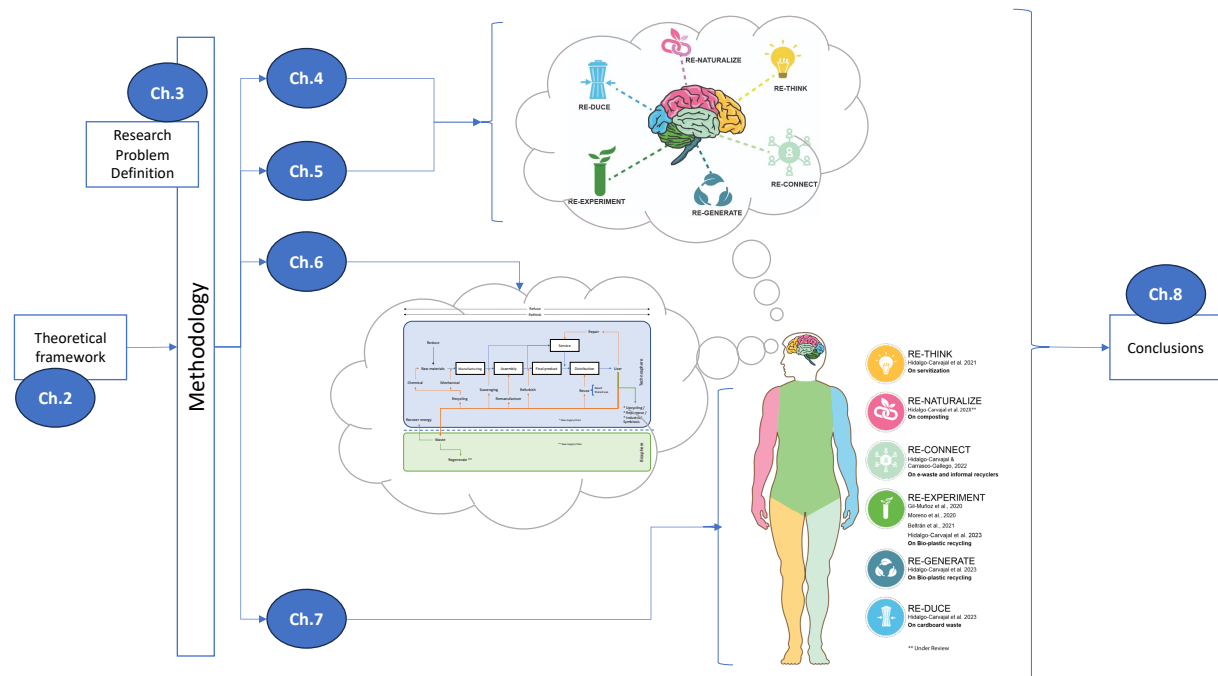


Figure 5. Outline of the PhD dissertation. Own development.



## 2. State of the art

*“If you can't explain it simply, you don't understand it well enough”. Attributed to Albert Einstein*

### 2.1. Introduction

In this chapter, the reader will be introduced to the main definitions necessary to navigate the discussion throughout the remainder of the dissertation. First, in a general review of the circular economy (CE), higher education institutions (HEIs), living labs (LL), and action learning and action research (ALAR) is drafted, aiming to explain how these are interconnected and how these can work together. Second, a literature review is presented, providing a broad examination of the application of the CE in HEIs from two distinct, yet complementary, perspectives: academic and grey literature. Third, the gaps and opportunities for research are identified, demonstrating the role of HEIs to applying CE principles beyond the campus borders, thanks to their interdisciplinarity nature and embeddedness within the social fabric of their surrounding communities. Finally, the main conclusions of this chapter are presented.

### 2.2. Setting the scene

Given that the scientific study of the topics covered in this PhD dissertation range from well-grounded concepts to relatively recent ones, it is important to understand the interconnectedness between them by first recognizing their contributions as stand-alone concepts.

#### 2.2.1. Circular Economy

The great quote by R. Buckminster Fuller, *“pollution is nothing but the resources we are not harvesting. We allow them to disperse because we've been ignorant of their value”* (Fuller, 1970) becomes more relevant in today's world. Understanding this powerful sentence allows us to understand that our current linear productions model creates plenty of issues in our planet, predominantly related to the amount

of waste and pollution generated, but mostly because the increasing quantity of misused resources. This is intensified as the traditional models neglect to consider planetary boundaries (Steffen et al., 2015) and incentivize companies to generate higher revenue by selling new products and triggering a culture of overconsumption (Hidalgo-Carvajal, Gutierrez-Franco, et al., 2023) along the supply chain. However, recently customers have become more aware of this issue and companies are facing pressure along the supply chain to improve their practices and reduce their waste (Carrasco-Gallego et al., 2012; Mahajan & Vakharia, 2016).

The introduction of sustainability insights and concepts has significantly changed the supply chain and how companies can introduce different practices to achieve these goals. Thierry et al., (Thierry et al., 1995) propose five alternatives for the recovery of products or elements after these have been manufactured and marketed: *a)* repair, *b)* refurbishment, *c)* remanufacturing, *d)* cannibalization, and *e)* recycling. A brief description of each alternative is presented as follows:

*a)* repair: this option corrects specific production errors.

*b)* refurbishment: this activity focus on the replacement or rebuild of important parts of a product. In any case, the final product has lower performance than the new product and therefore the associated guarantee also relates to the new levels of performance of the product.

*c)* remanufacturing: with this alternative, cores turn as new products. They have, thus, the same kind of warranty as a new item.

*d)* cannibalization: in this process we see how small parts of a core previously repaired, refurbish or remanufactured, can be still used.

*e)* recycling: is the last option of the closed loop and in this case the core is reduced to part level, processed, and then used for the creation of new products.

Additionally, Thierry et al., (Thierry et al., 1995) suggest that the selection of the product recovery option depends largely on different factors such as technical feasibility, supply of products and components, demand for reprocessed products or materials, and the environmental and economic costs and benefits. Moreover, Gaur and Mani (Gaur & Mani, 2018), suggest that the main activities for value recovery of the product and/or its internal elements rely on strong collaboration with stakeholders. To do this, there are plenty of different solutions that can help reach a circularity, one of them, was the introduction of the Closed Loop Supply

Chains (CLSC), which encompass two distinct material supply chains: forward (from manufacturer to customer) and reverse (from customer to remanufacturer) (Carrasco-Gallego et al., 2012; Gaur & Mani, 2018; Östlin et al., 2008). The lastly, is key in the development of ways to address the lack of environmental sustainability of our production and consumption models with a different approach (Saavedra et al., 2018), towards a model that guarantees that no usable resources go to waste. Circular Economy presents itself as an industrial economy, restorative by design, which considers biological and technical nutrients to be safely re-entered into the biosphere and techno-sphere systems, respectively (Rashid et al., 2013); thus, it suggests that in a perfect state, no virgin materials would be required (Figge et al., 2017) in the system as all materials and resources would be moving from different flows to fully close the system (Figge et al., 2023). Furthermore, during recent years, Circular Economy has emerged as a critical issue on the agenda of different industries, institutions and countries, especially in the European Union where it has been presented as an action plan to the European Commission in 2015 (European Commission, 2015) and confirmed in 2020 (European Commission, 2020a), as part of the European Green Deal of the von der Leyen Commission. Moreover, given its importance to the region, in 2022 and 2023 a new set of directives to revise different strategies for several sectors were approved, focusing on plastics (European Commission, 2018a), packaging and packaging waste (European Commission, 2022a), electric and electronic equipment (European Commission, 2022c) and waste (European Commission, 2023), textiles (European Commission, 2022b) and construction (European Commission, 2022d). However, the challenge of “closing the loop” of the European economy emerges as an achievable mission, aligned with the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015) and lever policies of the action plan for the implementation of the 2030 Agenda in Spain (Gobierno de España, 2018).

### **2.2.2. Higher Education Institutions**

Higher Education Institutions (HEIs) can be compared with towns or small cities due to their large number of “inhabitants” who consume goods and services. By generating waste and consuming resources, university campuses have, thus, a great environmental impact (Leal Filho et al., 2019; O. Owojori et al., 2020). Furthermore, the purchase of goods and services within the university campuses arouse economic businesses in supplier sectors, which consequently create

additional economic activity within broader supply chains having an economic impact not only at the local level but even at the regional and national level (Leal Filho et al., 2019). Through the implementation of circular strategies and policies for both the waste management and products acquirement, universities therefore have the opportunity of influencing their supply chains by establishing new types of relationships with them (Leal Filho et al., 2019). However, as pointed out by Mendoza et al. (Mendoza et al., 2019a), currently many of the HEI's environmental sustainability strategies are insufficient and mainly concentrate on the reduction of resource consumption, waste generation and carbon emissions rather than re-planning the prevailing linear processes and turn into circular actions.

Sustainable actions in HEIs have been largely discussed through declarations and commitments over the last decades. The first step was Stockholm Declaration of 1972 (UNESCO, 1972), followed by Talloires Declaration of 1990 (UNESCO, 1990), Halifax Declaration of 1991 (UNESCO, 1991), the Rio Declaration of 1992 (UNESCO, 1992), Swansea Declaration of 1993 (UNESCO, 1993b) and the Kyoto Declaration of 1993 (UNESCO, 1993a), the Thessaloniki Declaration of 1997 (UNESCO, 1997), the Lüneburg Declaration of 2001 (UNESCO, 2001), the Barcelona Declaration of 2004 (UNESCO, 2004), the Graz Declaration of 2005 (UNESCO, 2005), The Lucerne Declaration of 2007 (UNESCO, 2007), the Bonn Declaration of 2009 (UNESCO, 2009), the Rio Commitments of 2012 (UNESCO, 2012), the Nagoya Declaration of 2014 (UNESCO, 2014), the INGSA Manifesto of 2018 (UNESCO, 2018) and the International Association of Universities webinar of 2021 (UNESCO, 2021). These commitments around the world not only highlighted the roles of HEIs to promote sustainable development, but also paved the way for HEIs to embark on projects and initiatives to incorporate sustainability into their systems (Alshuwaikhat & Abubakar, 2008). Furthermore, these declarations helped to clearly define how HEIs can influence sustainability through their core elements: *teaching, research, operations (campus management)* and *outreach* (Corese, 2003; Lozano et al., 2015).

Thanks to these core elements, HEIs contribute to society at different levels and from different angles, being the main ones: educational (training of people and professionals), intellectual (production of knowledge and transfer of technology), social (supporting the development of society) and organizational (social and environmental footprint) (Vallaey, 2007). In light of the contributions, HEIs bear the responsibility to support society facing current challenges and creating tools to develop answers to future ones. Moreover, HEIs can serve as a “point of

experimentation” where radical and more sustainable models can be development through testing (Evans & Karvonen, 2014), and later be transferred to companies and society in general. For this to be a reality, the development of “living labs” is key.

### **2.2.3. Living Labs**

Collaborative endeavors between different entities, usually industry and research institutions, have become an effective tool to showcase the usefulness of the “demonstrators” to provide real solutions to diverse problems under a controlled environment (Gopinath et al., 2018). These demonstrators, becoming widely known as “living labs” (LL), are innovation ecosystems that bring together a multi-stakeholder vision and foster the connection between researchers from different disciplines, companies, organizations, public administrations, future professionals, etc., around the resolution of a challenge (Bajgier et al., 1991; Ballon & Schuurman, 2015; Bergvall-Kareborn & Stahlbrost, 2009; Molinari, 2011). These spaces encourage the co-creation and implementation of innovative solutions that can be tested and, if successful, replicated at larger scale in the cities or areas where these are located (Carrasco-Gallego et al., 2020). Moreover, one of the main contributions of the living labs, additional to experimentation in real-world settings, is involving users as co-creators along the entire process (Almirall et al., 2012), from the contextualization and conceptualization of the problem to the implementation and feedback, creating incremental and radical innovation (Leminen et al., 2015).

On the one hand, living labs play an important role in HEIs, as these institutions connect students with research (applied and theoretical) and offer real world settings on which different theories can be applied. Consequently, numerous research activities concerning urban innovation (Broto & Bulkeley, 2013), social and environmental impact (Evans & Karvonen, 2014), can be hosted and studied at HEIs. Furthermore, innovation in education can be addressed in living labs (do Paço & Azeiteiro, 2017; Maseck, 2017; Morales et al., 2023; O’Brien et al., 2021) to ensure that students develop the necessary tools to solve real-life problems after completion of their studies.

On the other hand, as the popularity of living labs and co-creation environments increase, there is also a challenge inherent to it as these words can easily become part of the buzzwords in science, as it “lacks a consistent or commonly accepted definition, and usually, a wide variety of activities are carried out under the

umbrella of living labs, featuring many different methodologies and research perspectives” (Leminen, 2015). Therefore, it is necessary to clearly identify the research goal, methodology and actors for a successful implementation of the living lab.

#### **2.2.4. Action Learning and Action Research**

Similarly to the concepts previously presented, Action Research has been accepted generally as an extensive set of ideas without a clear definition since it emerged (Altrichter et al., 2002; Avison et al., 1999; Clark et al., 2020; Zuber-Skenitt, 1993). It is generally conceived as a relationship between activities that require “actively taking action” (i.e., practical trials, experiments, set of experiences and applications, etc.) and the act of “learning” (Acero et al., 2017) or “researching” (Coughlan & Coughlan, 2002) with the intention to advance science and knowledge through constant review and critical assessment of the problems being faced. Nevertheless, and given this lax definition, scientific contributions made by Action Researchers has been frequently criticized as lacking profound “scientific” research (Greenwood, 2002) and contribution to quantitative theory.

Furthermore, we should consider that there is a thin barrier between the concepts of “Action Research” and “Action Learning”, as both are cyclical and iterative processes, and call for action through learning. Additionally, both include learning actively, identifying solutions to a problem, and analyzing the results in a methodical way. However, Action Research “is more systematic, rigorous, scrutinisable, verifiable, and always made public (e.g., in publications, oral or written reports)”(Zuber-Skerritt, 2001) than Action Learning. Nevertheless, it is important to note that neither of these terms are absolute or static.

Here are listed the definitions that seem more consistent and aligned to the objective of this dissertation.

- Action Learning (AL) is defined as “*a structured method that enables small groups to work regularly and collectively on complicated problems, take action, and learn as individuals and as a team while doing so*” (Serrat, 2017). Therefore, it needs “*at least a major problem which something ought to be done, a sponsor, a client, a fellow, a coordinator and a structure d'accueil*” (Revans, 1982).
- Action Research (AR) is defined as a “*comparative research on the conditions and effects of various forms of social action and research leading*

*to social action*” (Lewin, 1946) which use a set of cyclical steps (i.e., planning, action and fact-finding) to iterate the process and determine the result of the action, describing “*a continuous process of research and learning in the researcher’s long-term relationship with a problem*” (Cunningham, 1995).

As it can be seen from the definition, they are interconnected and support each other, without contradicting. Both Action Learning (AL) and Action Research (AR) are increasingly playing a key role not only in academia, but also in organizations and the community, as these methods help understanding and implementing change. ALAR support education by integrating research and teaching in HEI programs, improving practice by encouraging scientific skills in professionals (Fletcher & Zuber-Skerritt, 2008) and providing a “learning environment” to organizations (Zuber-Skenitt, 1993) interested in these professionals.

On the one hand it seems that the AL methodology has been consolidated in education through different proposals and activities intended to develop skills of independent problem solving through the different **X**-Based Learning (**XBL**) techniques, such as: case-based learning (B. Williams, 2005), challenge-based learning (Gallagher & Savage, 2020), community-based learning (Fischer et al., 2007), competency-based learning (Henri et al., 2017), cooperative-based learning (Clapper, 2015), design-based learning (Doppelt et al., 2008), game-based learning (Abdul Jabbar & Felicia, 2015), inquiry-based learning (Pedaste et al., 2015), problem-based learning (Dolmans et al., 2016), project-based learning (Ríos et al., 2010), and research-based learning (Huber, 1970, 2004). This methodology has been implemented in different universities (e.g., Massachusetts Institute of Technology (Dori & Belcher, 2005), Maastricht University (Dikboom, 2016), North Carolina State University (Wills et al., 2005), Rensselaer Polytechnic Institute (Beichner, 2014), Aalborg University (Kolmos et al., 2019), Instituto Tecnológico de Monterrey (Hernandez-de-Menendez et al., 2020), The University of Queensland (Coco et al., 2001), Universidad Politécnica de Madrid (López-Fernández et al., 2019), among others) mainly in STEM (Science, Technology, Engineering, and Mathematics)-related areas. Additionally, to increase multidisciplinary work and develop creativity and collaboration skills on top of problem-solving skills, Arts must be included among the areas taught at HEIs, generating STEAM learning models.

Furthermore, as education is in constant evolution, it is vital that there is a certain dynamism, since educational methods must be aligned with the changing needs of society and, consequently, with the needs of students. However, it is important to point out that dynamism in education should not be confused with Active Learning Method (ALM), which is related to techniques that focus on engaging students in the learning process through active participation in different activities such as: polling, debates, class work, working in groups, presentations, homework submission, concept mapping, among others (D'Silva, 2010; Gleason et al., 2011).

On the other hand, AR methodology has consolidated two main accepted fields known as Exploratory (EAR) and Participatory (PAR). The first one, EAR, can be characterized as a *gradualist approach, developed to be useful for induction into research* (Smith, 2015), where people are encouraged to explore and reflect on important issues *in their own experience and explore them by collecting and analyzing data* (Smith & Rebolledo, 2018). The second one, PAR, can be described as “*a collective, self-reflective inquiry that researchers and participants undertake, so they can understand and improve upon the practices in which they participate and the situations in which they find themselves*” (Baum et al., 2006), and has been largely used in projects which needed participation of different stakeholders. Exploration (e.g., (Benn & Dunphy, 2009; Calzada et al., 2023; C. Jensen et al., 2019; Rebolledo et al., 2016; Shani & Eberhardt, 1987)) and participation (e.g., (Foth & Brynskov, 2016; C. D. Jensen, 2016; Kemmis, 2006; Kindon et al., 2007; MacDonald, 2012; Reitan & Gibson, 2012)) research methods support the development of education and research.

These different approaches to ALAR come under one roof in Inquiry-Based Science Education (IBSE), which seeks the development of competencies complementary to those acquired in the classroom by students through experimentation and interaction with other peers and teachers, ultimately achieving the skills necessary for independent problem solving under the attentive guidance of the teacher (van Uum et al., 2016).

### **2.3. Exploring the literature**

The literature review presented here offers an overview of the body of knowledge from two perspectives, the academic and the so-called gray literature, providing a complete understanding of the topic. The importance of both perspectives is presented as follows.

On one hand, the academic literature incorporates publications in peer-reviewed journals, with the focus being on the articles as these are considered essential for the development of science, given the rigorous processes followed for their publication. On this review, book chapters and conference papers have been excluded as these can be considered as preliminary results, compared to academic peer-review published articles.

On the other hand, the gray literature includes information from less rigorous sources, such as working papers, and industry and government reports, which not necessarily follow the rigorous process as the academic literature. In the review, the yearly reports from the International Sustainable Campus Network (ISCN) which focus on the best practices for HEI's sustainable campuses were included. These reports offer valuable insights and practical perspectives from hands-on experiences that may not be fully captured by the academic literature.

Through the review of both types of literature, the goal is to deepen the understanding on how circular economy (CE) is being implemented in higher education institutions (HEI).

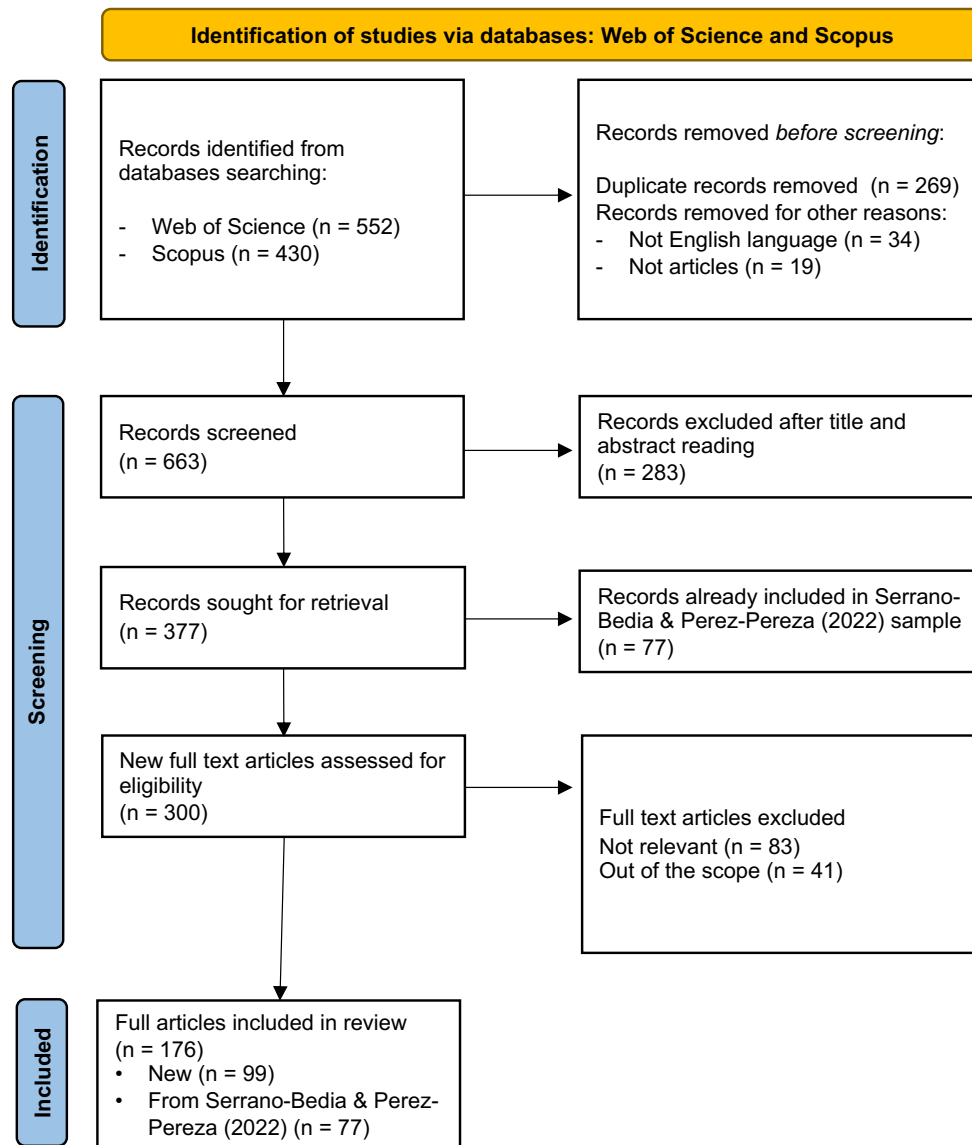
### **2.3.1. Data collection and evaluation**

As defined by Littell et al (Littell et al., 2008) “a systematic review aims to comprehensively locate and synthesize research that bears on a particular question, using organized, transparent, and replicable procedures at each step in the process”. Through a systematic literature review (SLR), researchers can analyze and assess the status of the current body of knowledge and recognize gaps for further examination.

The author followed a qualitative research methodology, through a review of academic literature and grey literature, following the insights from multivocal literature reviews methodologies (Tukker, 2015; Yasin & Hasnain, 2012). Two databases were used to perform this review given their wider subject and journal range: Scopus and Web of Science. The methodology described in figure 6 was followed, according to the recommended criteria by Newbert (Newbert, 2007), briefly summarized as follows:

- Theme—papers must be related to circular economy and universities
- Time range—papers had to be published in the period 2000–2023
- Language—papers should be written in English

- Journal type—papers must be part of peer-reviewed journals and be available in full text



**Figure 6.** Research design using the PRISMA model. Own development.

For this purpose, the author selected relevant key words to the focus of the research, from its two main sections: circular economy and higher education institutions. For the first one, the key words most related to the concept were “circular economy”, “close loop economy”, “zero waste economy” and “regenerative economy”. While, for the second one, “higher education institutions”, “campus”, “university” and “college” were selected as the key words. The search string

allowed the author to identify a wide variety of publications from which only academic peer-reviewed articles were considered, ranging from a large variety of topics and journals covering them.

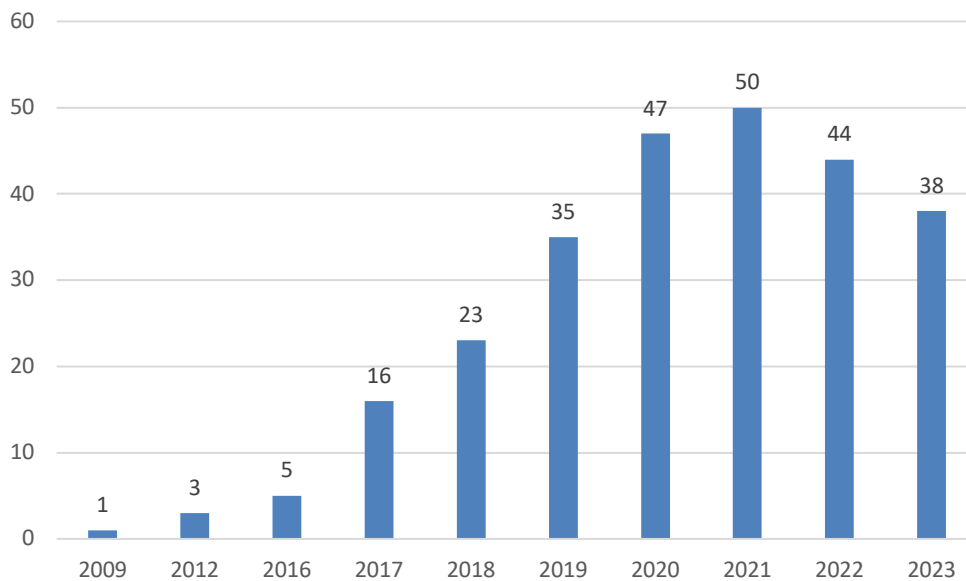
From this review, a total of 982 academic papers were originally retrieved. From here, the Titles, Abstract and Keywords (TAK) were screened to remove duplicates from both databases. After this step, TAK manual screening was useful to determine the initial number of relevant articles, which was later updated after discarding the non-relevant documents for this research. Additionally, when the document seemed relevant to the research, but was not clear from the previous screening, the body of the publication was screened.

Furthermore, to make sure that the whole body of academic literature is captured at the time when the literature review was latest completed and updated (December 15<sup>th</sup>, 2023), the author supplements the research performed by Serrano-Bedia and Perez-Perez (Serrano-Bedia & Perez-Perez, 2022) on which they reviewed 77 articles and discuss their findings along the discussion presented later on the results sections of this academic work.

On the grey literature, documents reporting best practices on achieving sustainability on HEI were identified, which are the closest to the circular economy practices at university level. For the grey literature, Google search engine was used to find university reports on circular economy. As the grey literature largely focuses on non-standardized sustainability reports, we focused our research on reports made by organizations devoted to the development of this field, specifically ISCN, which supports HEI in achieving sustainable campus operations and includes research and education around the topic.

### **2.3.2. Academic literature**

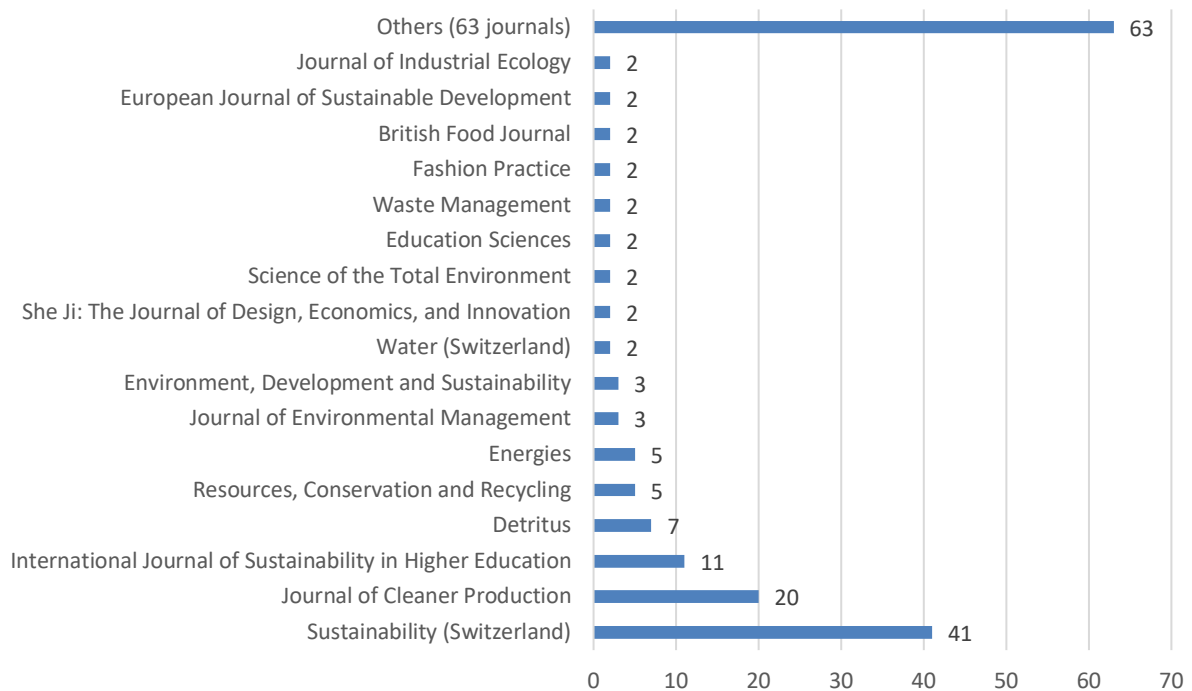
Whereas there is a consensus that circular economy is a theme with growing interest for all kind of industries, the topic has been largely developed around academia, and is proving to be relevant from theoretical and applied points of view. Specifically, for circular economy on higher education institution campuses, the increasing interest is attested in figure 7, on which the growing trend on research on circular economy on HEIs can be seen. The figure shows that the trend peaked in 2021, which could be an indicator of a period of high number of publications happening after the period of stagnation where the world went to during 2020, allowing researchers to focus mostly on document submissions rather than real-world action.



**Figure 7.** Trends in number of publications in academic journal on the topic of circular economy in higher education institutions. Own development.

Interestingly, the research discourse around campuses of higher education institution and circular economy appears to be scattered across a myriad of journals belonging to research fields other than sustainability studies, which could be assumed as the focus study field for circular economy research. Among the different areas, we can identify, although not limited to, the following: health, psychology, economy, policy making, production, chemistry, and technology. It should be mentioned that these are not the only areas where circular economy can have a strong influence but are the ones we have chosen as part of our final sample of 176 academic papers included in 80 academic journals (open access and subscription model).

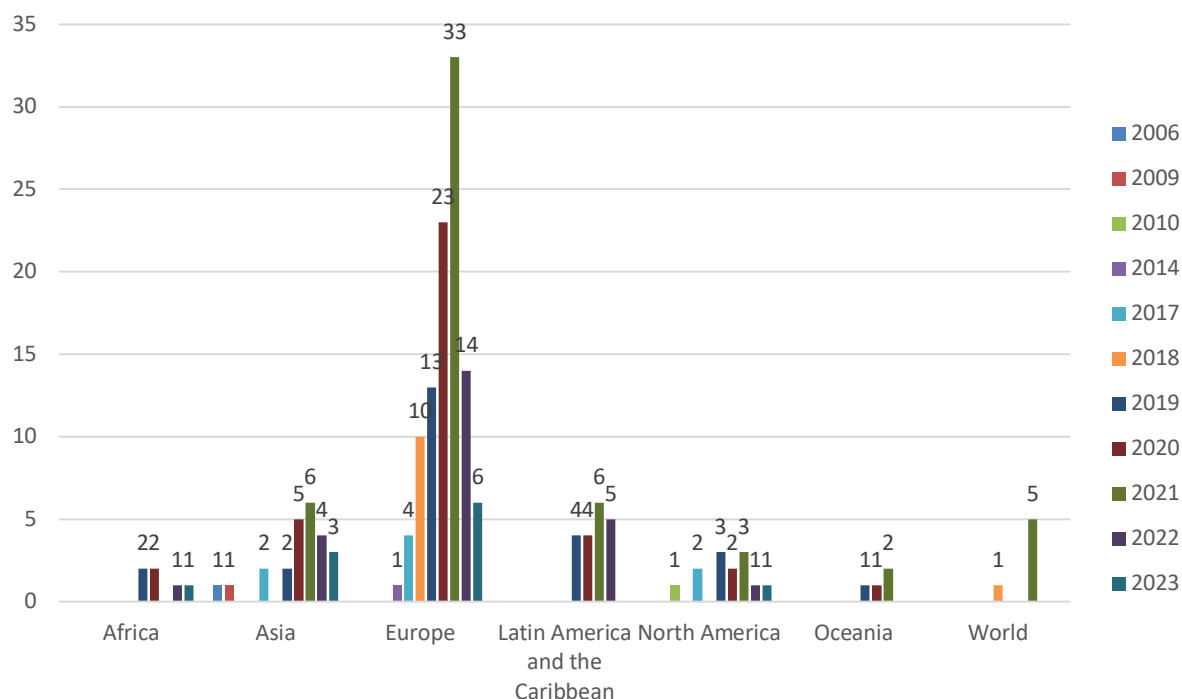
Regarding the article distribution per journal, *Sustainability*, *Journal of Cleaner Production*, and *International Journal of Sustainability in Higher Education* are the leading sources of published articles related to our research topic, with 41, 20 and 11 papers included in the final sample, respectively. These three journals account for the 40.9% of the total of the sample of academic papers. In contrast, 63 journals account for 35.8% of the total of the sample, which speaks about the variety of topics covered in these journals. This distribution can be seen in figure 8, which highlights the number of articles per journal included in the final sample.



**Figure 8.** Distribution of research articles per journal. Own development.

As can be seen from figures 7 and 8, the discussion around the topic has increased over time and covers a wide range of topics, which is attested by an extensive variety of academic publications in the area. Additionally, it is interesting to see that the topic discussion is not focused in one particular region or country, rather it is being discussed worldwide, as shown in figures 9 and 10.

Out of the 176 academic documents, it was found that 59.09% are located in the European region, 13.64% in the Asian region, 10.80% in the Latin American and the Caribbean region, 7.39% in the North American region, 3.41% in the African region and 2.27% in the African region. Interestingly, it was determined that 3.41% of the academic papers cannot be allocated to a particular region as these focus on reviews of best practices in different regions, thus these have been classified under the category “world”.



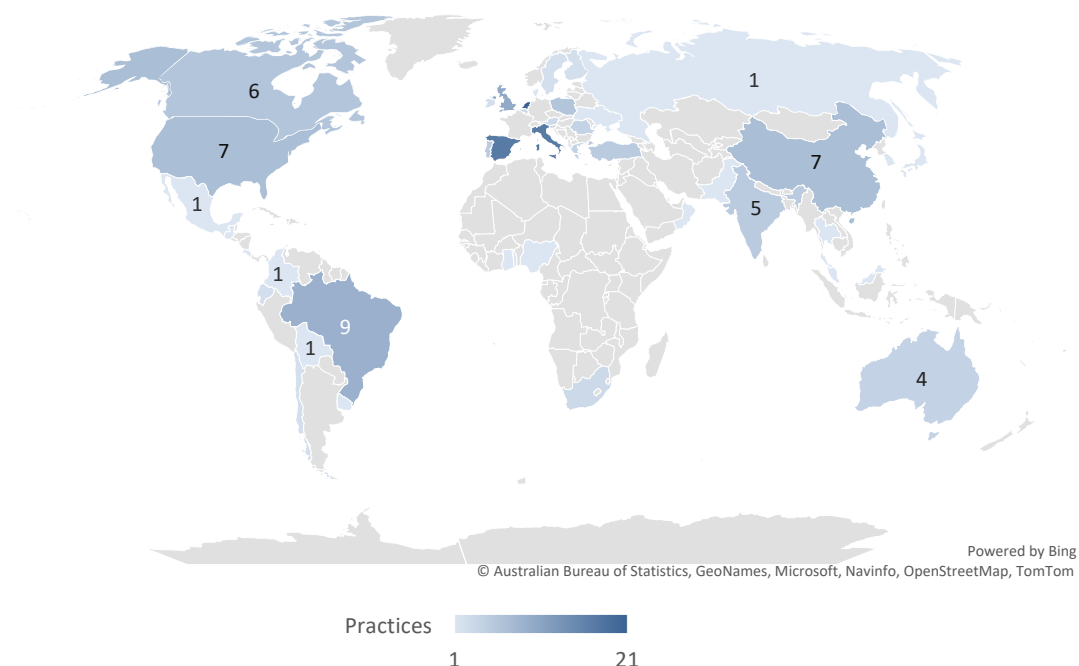
**Figure 9.** Distribution of academic articles per region and year. Own development.

Regarding countries, a total of 46 countries across the globe are represented by the 176 academic articles. The top 10 publishers represent 60.23% (106) of the total of publications, being the European region the sole responsible for 66.98% of these, distributed as follows: The Netherlands (21 publications), Italy and Spain (17 publications each), United Kingdom (10 publications) and Poland (6 publications). Asia represented by China (7 publications), and North America by United States (7 publications) and Canada (6 publications), comprise the 18.86% of the publications. In the Latin America and the Caribbean region, Brazil, with 9 publications, represent 8.49% of the 106 publications. Additionally, the remainder 5.66% of the publications belong to reviews (Manieson et al., 2021; Nunes et al., 2018; Omazic & Zunk, 2021; Salas et al., 2021; Sierra & Suárez-Collado, 2021; Watkins et al., 2021), that cannot be allocated to a single country.

Lastly, it is worth mentioning that 70 publications, representing 39.77% of the total of publications, originate from 35 countries, with 3 countries (Turkey, Portugal and India) contributing with 5 publications each, other 3 countries (Australia, Greece and Romania) adding 4 publications each, 4 more countries (Austria, Belgium, Slovenia and South Africa) with 3 publications each, 5 countries (Ecuador, Chile, Finland, Ireland and Sweden) contributing 2 publications each, and 21 countries (Albania, Bolivia, Colombia, Costa Rica, Denmark, Ghana, Guatemala, Hong Kong, Japan, Malaysia, Mexico, Nigeria,

Oman, Pakistan, Qatar, Russia, South Korea, Thailand, Togo, Ukraine and Uruguay) with 1 publication each. The distribution of academic articles around the globe can be seen in figure 10.

Evaluating the implementation of CE in HEI, the vast majority of topics considered in the sample range from solid waste management to life cycle assessment, and from applied initiatives to merely proposing ideas for campus development. Therefore, considering the topic’s heterogeneity, these have been grouped by similar characteristics and impact within the four core areas of HEIs. The grouping is presented in the table 1 below.



**Figure 10.** Academic article’s geographical impact location. Own development.

Core area	Groups	Number of articles
Campus management	Solid waste management	19
	Guidelines for greening the campus	12
	Strategies for campus development	7
	Waste of Electric and Electronic Equipment (WEEE)	5
	Frameworks for circularity in the campus	4
	Lighting management	3
	Water management	2
Outreach	Projects involving local communities	11

	University-industry-government partnerships	6
	Company projects	4
	Solid waste management in local community	3
	Living lab approach	2
	Waste of Electric and Electronic Equipment (WEEE)	1
Research	Food waste management	7
	Living lab approach	6
	Construction waste management	5
	Plastic waste management	4
	Developing bioenergy	3
	Waste of Electric and Electronic Equipment (WEEE)	2
Teaching	Design of courses with circular economy approach	15
	Developing circular competencies	14
	Enhancing academic content in classes	13
	Gamification as a tool for classes	9
	Developing circular course projects	8
	Developing teaching methodologies	6
	Educating for resource management (electricity, water, and solid waste)	5

**Table 1.** Topics covered by the academic articles analyzed. Own development.

On the *campus management* core area, focusing on the HEI campus management, academic articles largely discuss how solid waste management should be performed in HEIs considering the different materials and maximizing its recoverability through material identification and sorting. Although most of the research has focused on how to deal with the already existing waste, only a few articles discuss developing policies and guidelines to prevent the solid waste generation (Fleischmann, 2019; Gherheş et al., 2022; Lee et al., 2022; Ottoni et al., 2022; O. M. Owojori et al., 2022; Salguero-Puerta et al., 2019; Valls-Val et al., 2023). A few studies focus on estimating and measuring the quantity and type of solid waste generated (Gallo et al., 2017; Jakimiuk et al., 2023; O. Owojori et al., 2020; Rada et al., 2020; Smyth et al., 2010; Stephan et al., 2020), aiming to improve its sorting per material (plastic, glass and metal, paper and cardboard, furniture and textile) (Ferronato et al., 2020; Galati et al., 2022; Jaglan et al.,

2022; Maruyama et al., 2019; Mbama et al., 2023; Merchán-Sanmartin et al., 2021; Nolasco et al., 2021; Sawalkar et al., 2023; Tangwanichagapong et al., 2017), including special classification on chemicals and hazardous materials (Gutierrez et al., 2020), food waste (Leal Filho et al., 2023; Maçin et al., 2023; Torrijos et al., 2021), waste of electric and electronic equipment (WEEE) (Bonoli et al., 2018; Leclerc & Badami, 2022; Pierron et al., 2017; Saldaña-Durán & Messina-Fernández, 2021; Shittu et al., 2021), and as a particular case, water waste (Colares et al., 2019; Merchán-Sanmartín et al., 2022). It was interesting to find that discussion around furniture and textiles is relevant for campuses aiming towards circularity.

Additionally, to managing the waste, a few studies focus on developing guidelines and policies to develop the HEI's campus pondering circular economy principles (Ares-Pernas et al., 2020; Ebrahimi & North, 2017; Mendoza et al., 2019b, 2019a; Nunes et al., 2018; Omazic & Zunk, 2021; Ozdemir et al., 2020; Qu et al., 2021; Salas et al., 2021; Valls-Val & Bovea, 2021), considering how to improve the HEIs campus from different areas, such as lighting, energy and cooling options (Bakos & Schiano-Phan, 2021; Behi et al., 2021; Beu et al., 2018; Ciugudeanu et al., 2019; Díaz-López et al., 2022), creating sustainable spaces (Fortes et al., 2021; Hopff et al., 2019) that meet customer needs (Amenta & Qu, 2020), considering procurement policies (Zaidi et al., 2019) and understanding the specific role that it plays for the educational needs (Ramakrishna et al., 2020).

The main purpose of the *Outreach* area is to understand HEI's positive impact and influence in local communities (i.e., neighborhoods and surroundings, and cities), including their work not only with civil society but with public and private entities. It must be pointed out that, when a project includes the three areas (HEIs, public and private entities), this is known as the Triple Helix approach (Etzkowitz & Leydesdorff, 1995). Literature identifies a few projects under the scope of HEIs working hand-on-hand with private companies and public institutions (i.e., government entities) (Bakırhoğlu & McMahon, 2021; Christensen, 2021; De Medici et al., 2018; Newton & Frantzeskaki, 2021; Raeva et al., 2021; Wandl et al., 2019). Similarly, not all projects include the three stakeholders as in some cases the impact from HEIs is achieved directly thanks to private entities' participation (Bakırhoğlu et al., 2021; Kopnina, 2021a; Piekarski et al., 2019; Whitehill et al., 2022). While there are no academic records mentioning specifically the impact attributed to direct collaboration with (and solely with) public entities, it should be highlighted that there are some initiatives which have been achieved thanks to

the collaboration with local communities, including participation of public entities (Bas-Bellver et al., 2020; Bringsken et al., 2018; Erälinna & Szymoniuk, 2021; Fernandes et al., 2021; Gao et al., 2006; Hall & Velez-Colby, 2018; Kumble, 2019; Moustairas et al., 2022; Rigillo et al., 2018; Sacco & Cerreta, 2020; Sukiennik et al., 2021). Furthermore, some initiatives born from these collaborations have been allocated to specific areas of interest from the community, achieving interesting results in solid waste management (Mansour et al., 2020; Virsta et al., 2020; I. Williams & Powell, 2019), WEEE management (Sánchez-Carracedo & López, 2021) and multidisciplinary approaches where the community becomes creative on proposing cooperative approaches to solve other issues (Cerreta et al., 2020; Keng et al., 2020).

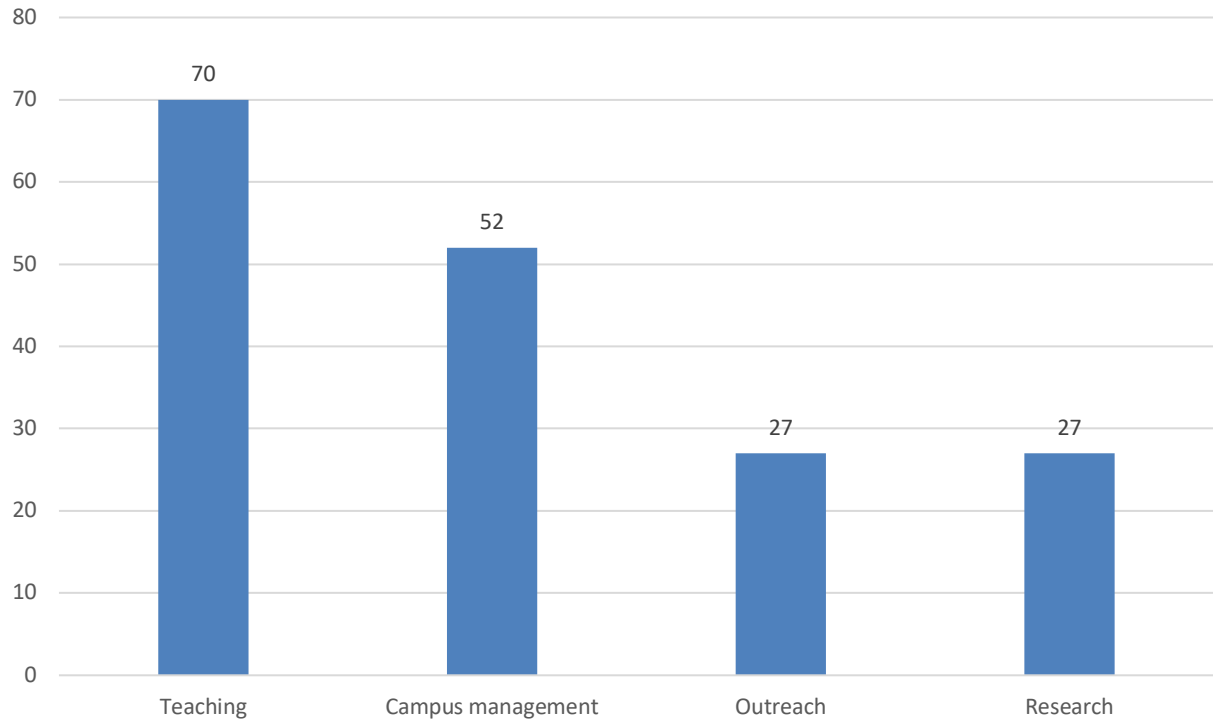
According to their mission, one of the core areas of a HEI is the *Research* area, which includes not only theoretical research but also applied and impactful research along the different CE approaches. Under this consideration, a myriad of topics can be covered under the same scope being grouped by themes, such as food waste management (Börühan & Ozbiltekin-Pala, 2022; Brenes-Peralta et al., 2020; Klammsteiner et al., 2021; Kooduvalli et al., 2020; Liang et al., 2022; Matrapazi & Zabaniotou, 2020; Yeo et al., 2019), plastic waste (Bianchini & Rossi, 2021; Gil Muñoz et al., 2020; Hidalgo-Carvajal, Muñoz, et al., 2023; Park et al., 2023) and WEEE (Bigerna et al., 2021; Bonoli et al., 2021), use of construction and deconstruction material for innovation (Blok et al., 2019; Iuorio et al., 2019; Korançe, 2021; Leblanc, 2020; Mahdi et al., 2021), and generation of bioenergy through different processes (de Sousa et al., 2022; Kılıkış & Kılıkış, 2017; Vaskalis et al., 2019). Although it could happen that not all research can be assigned to one particular topic, but rather it is understood works from a multidisciplinary approach, it must be understood that the diverse points of views should be included, usually from a living lab strategy (Hart et al., 2021; Kumdokrub et al., 2023; Mannina et al., 2021; Rizzo et al., 2017; Vink, 2020; Vuylsteke et al., 2022).

Finally, and probably considered the main mission of HEIs, is the *Teaching* area where most of the academic discussion has taken place, given the importance of education around the CE topics. Most of the articles focus on the content to be discussed within the lectures to include topics related to sustainability (i.e., Circular Economy, Industrial Symbiosis, environmental education, renewable energies, resource management, among others) to improve education for sustainable development (ESD) (Duane et al., 2020; Kopnina, 2014, 2019a, 2020; Leube & Walcher, 2017; Obrecht et al., 2022; Qu et al., 2022; Ryńska, 2020;

Senthil, 2022; Soto-Solier et al., 2023; Summerton et al., 2019; Venugopal & Kour, 2021; Villalobos et al., 2021; Widera, 2021). Others focus not on the content but rather on the teaching methodology, using a myriad of techniques and tools (Kirchherr & Piscicelli, 2019) such as gamification and simulation techniques (de la Torre et al., 2021; Deda et al., 2022; Fraccascia et al., 2021; Jääskä et al., 2021; Kioupi et al., 2022; Manshoven & Gillabel, 2021; O'Grady et al., 2021; Sierra & Suárez-Collado, 2021; Whalen et al., 2018), project and challenge based learning approaches (González-Domínguez et al., 2020; James & Kent, 2019; Kopnina, 2018, 2019b, 2021b; Manieson et al., 2021; Rodríguez-Chueca et al., 2020; Sánchez-Carracedo et al., 2020), visiting facilities (Kowasch, 2022), in class discussions with external experts on the field (Faludi et al., 2023; Geng et al., 2009; Hoffman et al., 2021; Mottese et al., 2021), and improving learning through the use of open access learning (i.e., massive open online courses (MOOC), non-mandatory courses, formal and informal learning, etc.) (Alonso-Calero et al., 2021; Liu & Côté, 2021; Loste et al., 2020; Prieto-Sandoval et al., 2022). Additionally, some documents pay special attention to topics related to the design of the product for different industries (Baeza & Quinn, 2021; Predan, 2020; Sadowski, 2021; Terzioğlu & Wever, 2021; Watkins et al., 2021), understanding the entire product life cycle through life cycle assessment (Bugallo-Rodríguez & Vega-Marcote, 2020; Gomes et al., 2022; Reichmanis & Sabahi, 2017), and considering how the different resources (electricity, water and solid waste) should be properly managed (Ibelli-Bianco et al., 2022; Mateus et al., 2020; Rokicki et al., 2020; Weissbrodt et al., 2020; I. D. Williams et al., 2018). Furthermore, it was found that there is a large interest in the skills and competences required by companies and how these are developed as a result of the learning experiences at HEIs (Baptista et al., 2021; Burger et al., 2019; Giannoccaro et al., 2021; Hudima & Malolitneva, 2020; Neto, 2019; Qu et al., 2020; Sumter et al., 2020, 2021; Vera-Puerto et al., 2020; Wolf et al., 2022), as well as competences for entrepreneurship (Atalay Onur, 2020; Del Vecchio et al., 2021; Janssens et al., 2021; Spreafico & Landi, 2022; Sumter et al., 2018) and, moreover, forging collaborations between HEIs to replicate the educational programs to develop competences in local contexts (Landrum, 2021).

As it can be seen, within the four core areas at the HEIs there are 176 documents, including the review by Serrano-Bedia & Perez-Perez (Serrano-Bedia & Perez-Perez, 2022) showing that most of the academic discourse has been around the *teaching* area, interestingly followed by the *campus management* area concerning how the CE initiatives are applied within HEI campuses, and followed (in equal numbers) by *outreach* and *research* areas, meaning that applied research and

work with local communities can be linked together as it seems to be part of a growing trend. This can be seen in the figure 11 below.



**Figure 11.** Distribution of academic articles per category in HEIs. Own development.

On the one hand, it was curious to identify that, although *teaching* and *research* are the core areas for HEIs, there is a huge gap between these two as publications regarding *teaching* for the CE is almost three times the publications on *research* within the context of CE within HEIs. Additionally, the publications on the *campus management* area show that the implementation of sustainable and CE initiatives is possible, serving the HEIs as demonstration environments. On the other hand, it is remarkable to see that the *outreach* area presents a large number of publications, showcasing the importance of CE practices being applied in real life contexts.

Finally, it is worth mentioning that the variety of topics covered by the academic articles cannot be allocated to a single discipline, but are rather transdisciplinary, and its influence it is also transversal to all areas of HEIs, as can be seen in the Table 2.

	Topic	Campus management	Outreach	Teaching	Research
<i>Management and development</i>	WEEE	(Bonoli et al., 2018; Leclerc & Badami, 2022; Pierron et al., 2017; Saldaña-Durán & Messina-Fernández, 2021; Shittu et al., 2021)	(Sánchez-Carracedo & López, 2021)		(Bigerna et al., 2021; Bonoli et al., 2021)
	Resource management (water & energy)	(Behi et al., 2021; Beu et al., 2018; Ciugudeanu et al., 2019; Colares et al., 2019; Merchán-Sanmartín et al., 2022)		(Ibelli-Bianco et al., 2022; Mateus et al., 2020; Rokicki et al., 2020; Senthil, 2022; Weissbrodt et al., 2020; I. D. Williams et al., 2018)	(de Sousa et al., 2022; Kılış & Kılış, 2017; Mannina et al., 2021; Vaskalis et al., 2019)
	Solid waste management (includes plastic waste)	(O. Owojori et al., 2020; Smyth et al., 2010; Tangwanichagapong et al., 2017; Gallo et al., 2017; Rada et al., 2020; Stephan et al., 2020; Jakimiuk et al., 2023; Merchán-Sanmartín et al., 2021; Sawalkar et al., 2023; Galati et al., 2022; Mbama et al., 2023; Ferronato et al., 2020; Nolasco et al., 2021; Maruyama et al., 2019; Jaglan et al., 2022; Gutierrez et al., 2020)	(Mansour et al., 2020; Virsta et al., 2020; I. Williams & Powell, 2019)		(Bianchini & Rossi, 2021; Gil Muñoz et al., 2020; Hidalgo-Carvajal, Muñoz, et al., 2023; Park et al., 2023)
	Food waste	(Leal Filho et al., 2023; Maçin et al., 2023; Torrijos et al., 2021)	(Bas-Bellver et al., 2020; Keng et al., 2020)		(Börühan & Ozbiltekin-Pala, 2022; Brenes-Peralta et al., 2020; Klammersteiner et al., 2021; Kooduvalli et al., 2020; Liang et al., 2022; Matrapazi & Zabaniotou, 2020; Yeo et al., 2019)
	Guidance and policies for management and development	(Amenta & Qu, 2020; Ares-Pernas et al., 2020; Bakos & Schiano-Phan, 2021; Bonoli et al., 2018; Díaz-López et al., 2022; Ebrahimi &	(De Medici et al., 2018; Gao et al., 2006; Moustairas et al., 2022; Newton & Frantzeskaki, 2021)		(Bonoli et al., 2021; Kumdokrub et al., 2023; Rizzo et al., 2017)

		North, 2017; Leclerc & Badami, 2022; Mendoza et al., 2019a, 2019b; Ozdemir et al., 2020; Ramakrishna et al., 2020; Valls-Val et al., 2023; Zaidi et al., 2019)			
<i>Innovation in education</i>	Product design		(Hall & Velez-Colby, 2018; Kopnina, 2021a; Mansour et al., 2020; Raeva et al., 2021)	(Atalay Onur, 2020; Baeza & Quinn, 2021; Leube & Walcher, 2017; Predan, 2020; Sadowski, 2021; Spreafico & Landi, 2022; Sumter et al., 2018; Terzioğlu & Wever, 2021; Watkins et al., 2021)	(Bigerna et al., 2021; Blok et al., 2019; Iuorio et al., 2019; Korançe, 2021; Leblanc, 2020; Mahdi et al., 2021; Vink, 2020; Vuylsteke et al., 2022)
	Project based learning		(Bakırhoğlu et al., 2021; Kumble, 2019; Sánchez-Carracedo & López, 2021; Whitehill et al., 2022)	(Deda et al., 2022; González-Domínguez et al., 2020; James & Kent, 2019; Kopnina, 2018, 2019b, 2021b; Manieson et al., 2021; Mateus et al., 2020; Rodríguez-Chueca et al., 2020; Sánchez-Carracedo et al., 2020; I. D. Williams et al., 2018)	
	Competences and skills		(Fernandes et al., 2021)	(Baptista et al., 2021; Burger et al., 2019; Del Vecchio et al., 2021; Giannoccaro et al., 2021; Gomes et al., 2022; Hudima & Malolitneva, 2020; Ibelli-Bianco et al., 2022; Janssens et al., 2021; Loste et al., 2020; Neto, 2019; Qu et al., 2020; Sumter et al., 2020, 2021; Vera-Puerto et al., 2020; Wolf et al., 2022)	
	Innovation in curriculum	(Hopff et al., 2019; Nunes et al., 2018; Omazic & Zunk, 2021; Qu et al., 2021; Salas et al., 2021)		(Alonso-Calero et al., 2021; Bugallo-Rodríguez & Vega-Marcote, 2020; Duane et al., 2020;	

				Faludi et al., 2023; Geng et al., 2009; Hoffman et al., 2021; Kirchherr & Piscicelli, 2019; Kopnina, 2014, 2019a, 2020; Kowasch, 2022; Landrum, 2021; Liu & Côté, 2021; Mottese et al., 2021; Obrecht et al., 2022; Prieto-Sandoval et al., 2022; Qu et al., 2022; Reichmanis & Sabahi, 2017; Ryńska, 2020; Soto- Solier et al., 2023; Summerton et al., 2019; Venugopal & Kour, 2021; Villalobos et al., 2021; Widera, 2021)	
Gamification and new tools	(Fortes et al., 2021)			(de la Torre et al., 2021; Fraccascia et al., 2021; Jääskä et al., 2021; Kioupi et al., 2022; Manshoven & Gillabel, 2021; O'Grady et al., 2021; Sierra & Suárez- Collado, 2021; Whalen et al., 2018)	(Hart et al., 2021)
Innovation for local impact			(Bakırhoğlu & McMahon, 2021; Cerreta et al., 2020; Christensen, 2021; Erälinna & Szymoniuk, 2021; Piekarski et al., 2019; Rigillo et al., 2018; Sacco & Cerreta, 2020; Sukiennik et al., 2021; Wandl et al., 2019)		

**Table 2.** Topics covered by the academic text analyzed. Own development.

Given the myriad of topics, these have been allocated within two main categories and 11 subcategories of topics that group all the findings. The *management and development* category collects 44.8% of the total of documents within its five

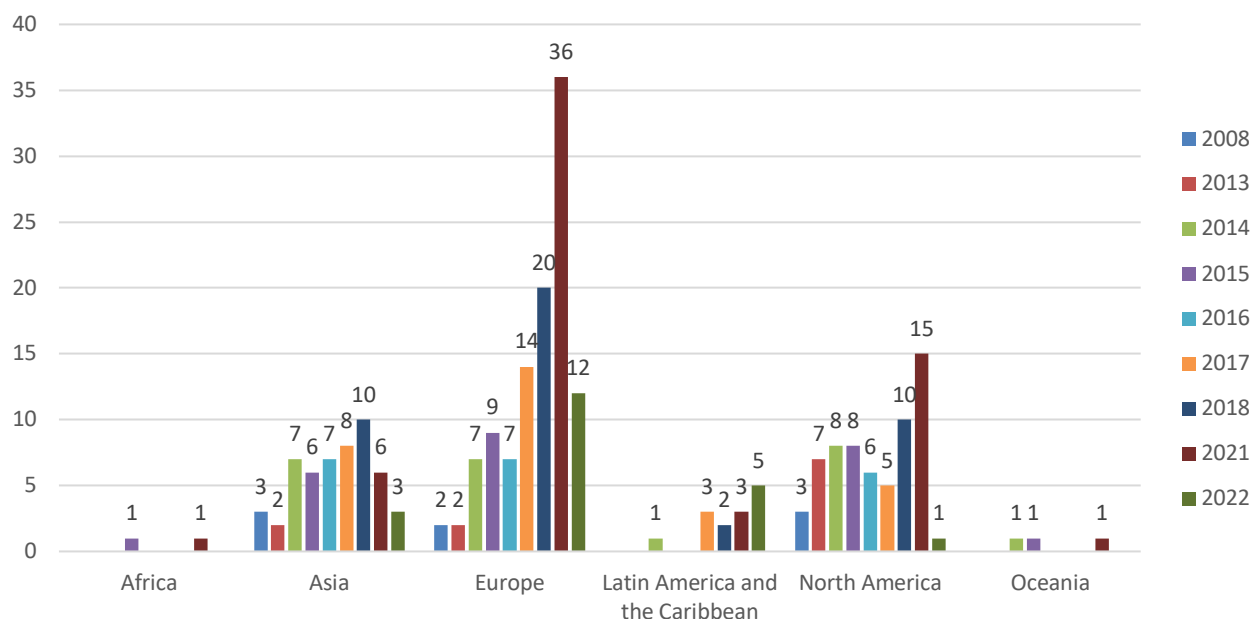
subcategories, which is in line with the fact that most of articles related to *research* and *campus management* make for most of this category. While the *innovation in education* category makes up for 55.2% of the academic articles, matching the fact that *teaching* is the main area shaping this category. In the case of *outreach*, it is interesting to see that this area has a large influence across almost all categories.

### 2.3.3. Grey literature

On the grey literature area, the International Sustainable Campus Network (ISCN), in collaboration with the Global University Leader's Forum (GULF) of the World Economic Forum, generate a yearly report on which the sustainable campus best practices from ISCN and GULF universities are presented, since 2013. A total of 102 institutions have contributed with a best practice in at least one of the nine reports, between 2008 and 2022 (ISCN, 2008, 2013, 2014, 2015, 2016, 2017, 2018, 2021, 2022), totaling 243 best practices. Furthermore, only four institutions (from Europe, North America, and Asia) have contributed with at least one best practice in seven out of nine reports, accounting for 30 best practices.

Figure 12 presents the growth pattern over time (2008-2022), exhibiting that European region has made the most contributions (109) on the topic, followed by the North American (63), Asian (52) and Latin America and the Caribbean (14) regions. Africa and Oceania are the regions with the least number of best practices, with 2 and 3 practices, respectively. The latest does not mean that a region is better than another one, rather it presents figures about growing opportunities for the different regions, as well as it demonstrates that there is traction around the topic globally.

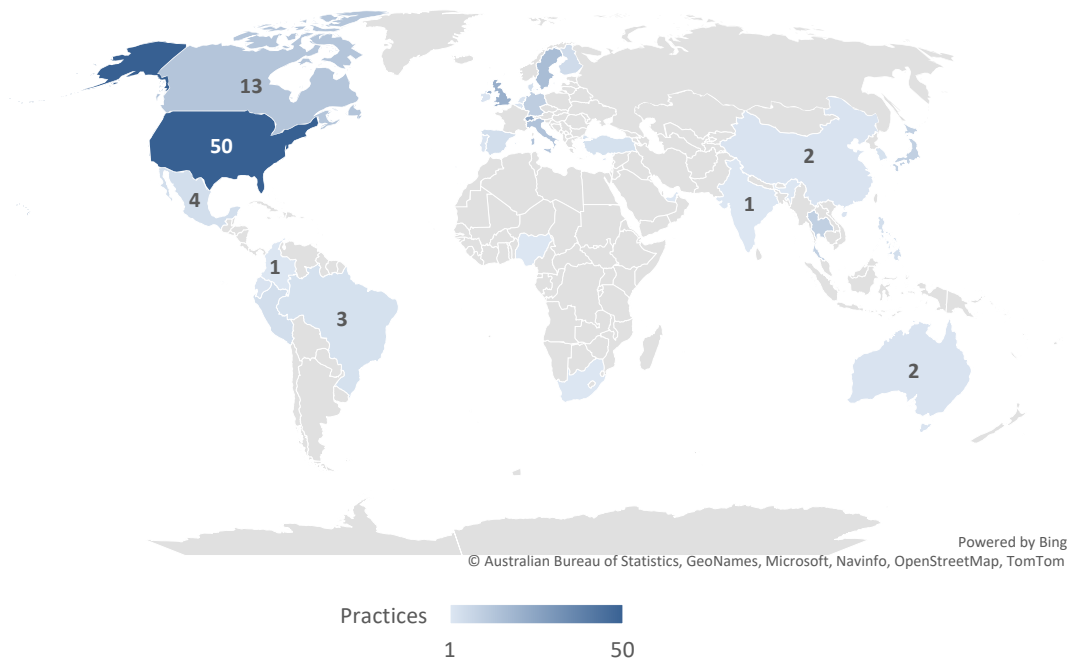
Remarkably, 2021 was the year on which most of the best practices (25.5%) were presented, followed by 2018 (17.3%) and 2017 (12.3%); understandably, the year with the lowest number of contributions was 2008 (3.3%) as it was the first year of reporting. However, 2008 was a key year for ESD as *New standards of European Accreditation of Engineering Programmes* (Bielefeldt, 2013) were introduced, and the United Nations promoted the *UN Decade of ESD (2005-2014)* (Liimatainen, 2013), becoming the “golden age to promote Higher Education for Sustainable Development (HESD)” (Gutierrez-Bucheli et al., 2022).



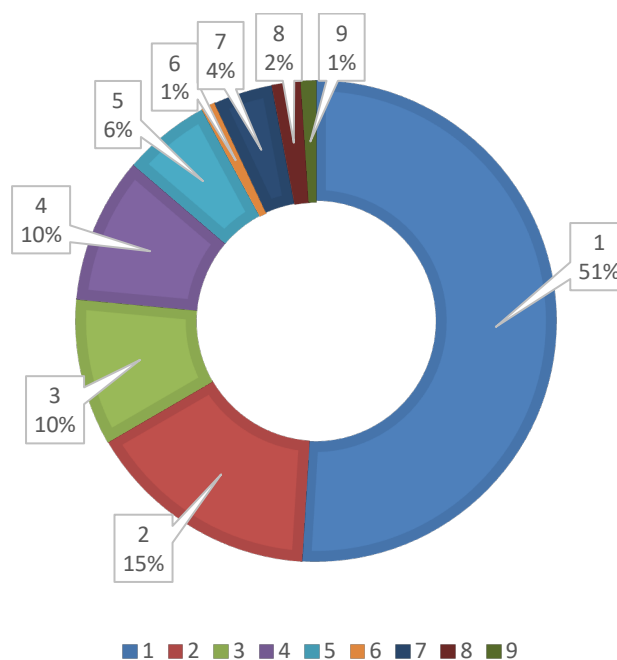
**Figure 12.** Distribution of best practices per region and year. Own development.

A total of 36 countries across the globe are represented by the 243 best practices. In the European region, Switzerland (24 practices), United Kingdom (21 practices), Sweden (16 practices) and Italy (14 practices), account for almost 31% of the total number of best practices by HEI around the globe. It is worth mentioning that the United States of America, a single country, single handedly accounts for 20.6% of the best practices around the globe, as can be seen in figure 13.

Additionally, out of the 102 HEI presenting their best practices, 51% have contributed with at least one best practice, while less than 14% contribute with more than 5 practices, and it was found only one case on which a HEI has contributed with 9 best practices over the years, as can be seen in figure 14.



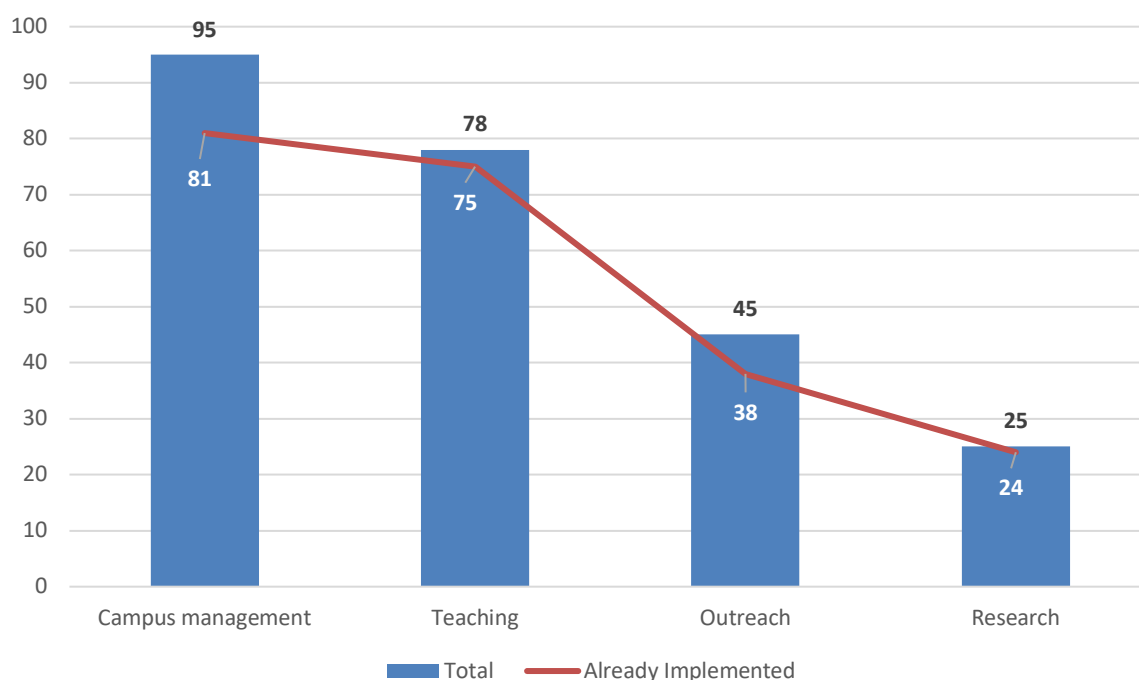
**Figure 13.** Number of best practices by HEI per geographical location. Own development.



**Figure 14.** Number of best practices presented by a single HEI. Own development.

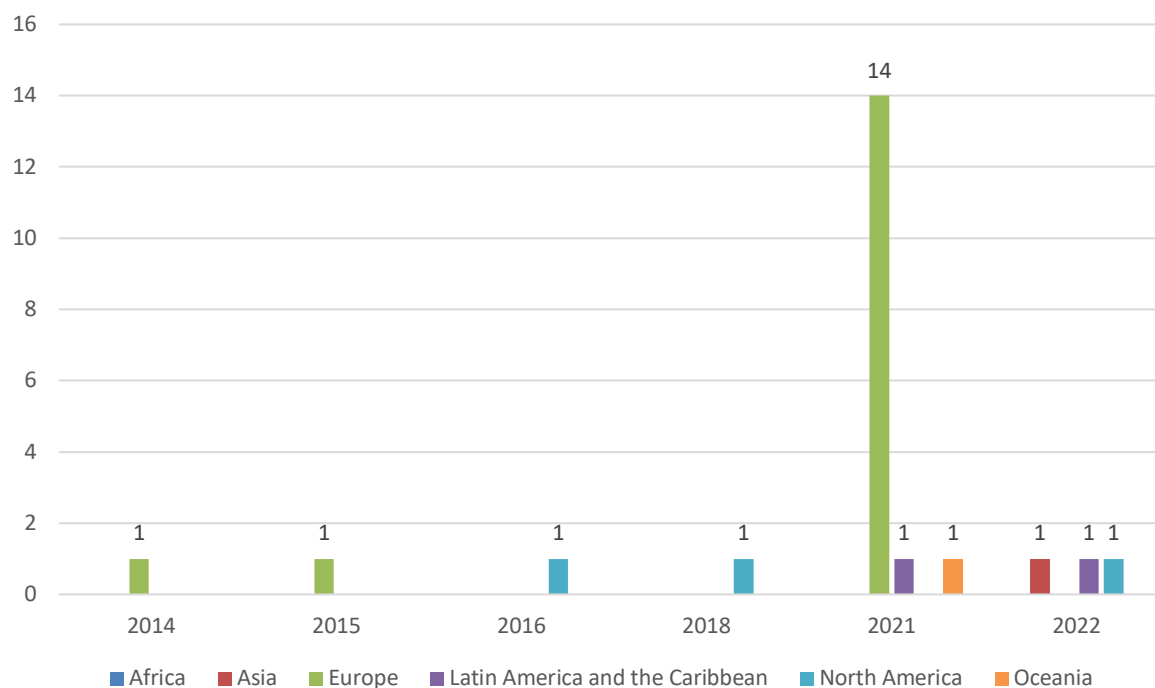
It has been identified that the best practices fall in one of the four main categories on which HEI have direct influence upon, as presented in figure 15: *Campus*

*management* (39.1%), *Teaching* (32.1%), *Outreach* (18.5%) and *Research* (10.3%). Considering that the primary purpose of HEI is education, it was expected that the category with the highest number of best practices would be *Teaching* and *Research*, however, it was interesting to see that HEIs are interested in improving their facilities and showcasing their campuses as sustainable, as proven by the *Campus management* category. Most of the best practices have already been implemented (89.7%), being *Campus management* and *Outreach* the areas where there is still a gap (roughly 15% for each) to be covered until full implementation of the practice; nevertheless, the implementation could be undergoing at the moment but has not yet been reported.



**Figure 15.** Distribution of best practices per category and the implemented best practices in HEIs. Own development.

Interestingly, it was found that over the years, several HEIs have formed diverse alliances (23 in total), either with other HEIs or through Public-Private Partnerships (PPPs), increasing the scope and impact of the best practices obtained, which can be seen on figure 16.



**Figure 16.** Alliances on best practices in HEI. Own development.

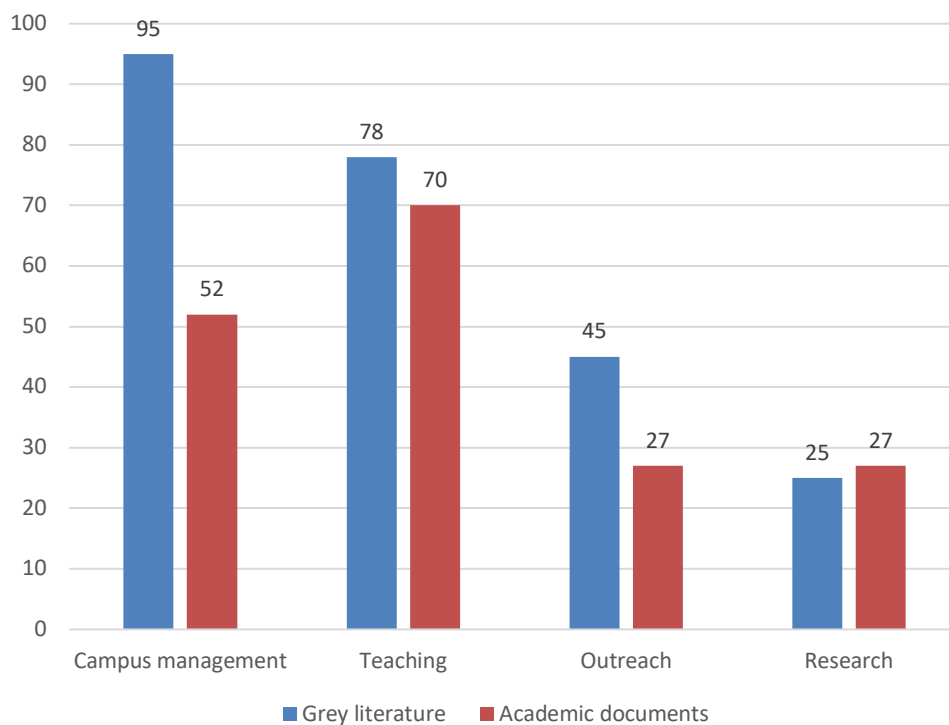
The report of 2014 presents, for the first time, a best practice resulting from an alliance between two HEIs in Europe. The reports from 2016 and 2018 introduce alliances from the North American region. Remarkably, 16 alliances were presented in the report of 2021, where the Oceania region introduced their first alliance. Although most of the alliances (69.6%) presented in the different reports are from the European region, it is encouraging to see other regions (Asian and Latin America and the Caribbean) finding value on these practices, as can be seen on figure 16.

### 2.3.4. Contrasting the academic and grey literature

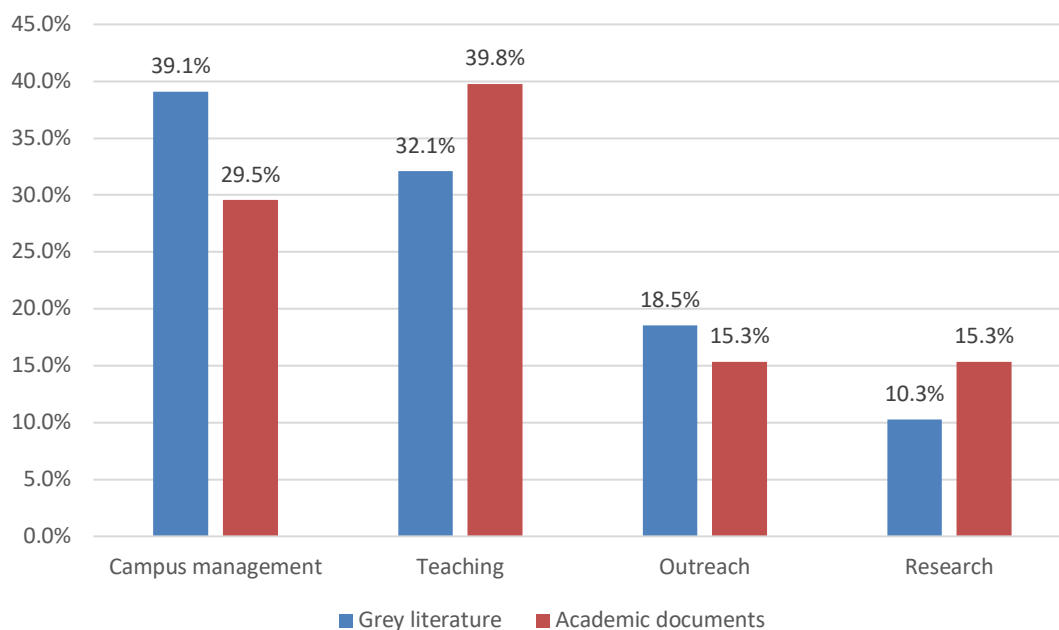
Lastly, when comparing grey literature and academic articles, it was found that there is a difference between the results being shared in both types of documents, given the nature of the publications. As it can be seen in figure 15, it is worth mentioning that large progress has been made on the implementation of sustainability and circular economy initiatives on *Campus management*, with 147 documents (95 best practices and 52 articles), representing the 35% of the total of documents. It might seem that there's a large difference between the number of publications from both sides, however, when given in percentage, it can be seen that there is less than 10% of difference, as presented in figure 18.

Similarly, and as expected, considering HEI's core areas, *teaching* and *research* in CE topics are an important focus from both perspectives, practical and theoretical, although it is evident that *research* plays a more relevant role from the academic articles given the nature of the publications. *Teaching* is largely populated with initiatives on circular economy as reported on the best practices (32.1%), while on the academic articles, as expected, the number of documents on this area is higher (39.8%), as in figure 18. Both types of documents account for a total of 148 documents (78 grey literature and 70 articles) as in figure 17.

Additionally, as it can be seen in figure 18, in the *Research* area the number of best practices is lower (10.3%) than the academic articles (15.3%) as per the nature of the publications. Likewise, the total number of documents is 52, being 25 from grey literature and 27 from academic articles, as in figure 17.



**Figure 17.** Distribution of best practices per group – academic vs grey literature. Own development.

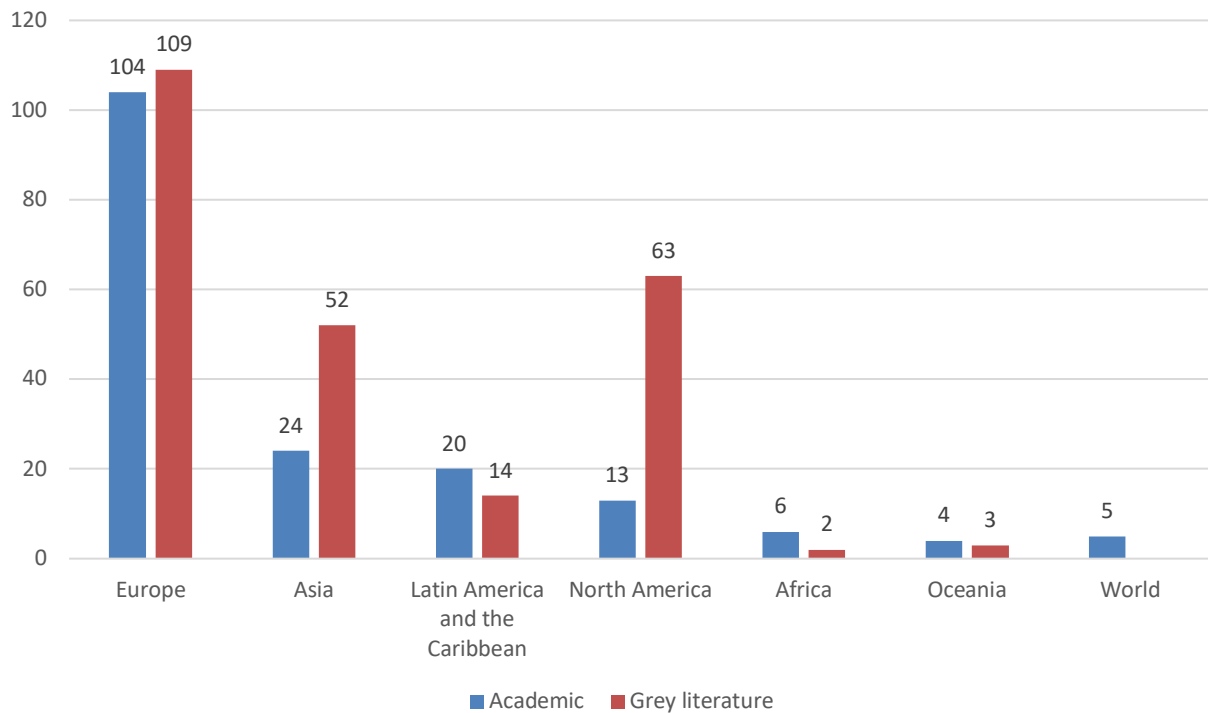


**Figure 18.** Distribution of best practices per region – academic vs grey literature. Own development.

Lastly, from figure 17, it can be inferred that *Outreach* is an area of important influence for HEIs as per the total number of documents being 72 (45 from grey literature and 27 from academic articles), which are equivalent to roughly 18% for grey literature and 15% for academic articles.

Finally, in the figure 19 it can be seen that the regions where most of the advancement of science, from academic articles and grey literature, are congruent in most cases. First, Europe region presents the largest number of publications from both perspectives. Likewise, results from the Latin America and the Caribbean region are also consistent, showing that the academic and grey literature discourse go hand in hand. Similarly, the same behavior can be seen in the African and Oceania regions, with similar results.

On the contrary, the results from the Asian and the North American regions show that, for both, the results of the grey literature present larger numbers than the academic articles. This could be correlated with the large number of HEIs in each of these regions and the fact that most of the best practices belong to these places.



**Figure 19.** Distribution of best practices per region – academic vs grey literature. Own development.

As it can be seen, literature review shows that all areas on which HEIs have influence are represented in both types of literature, academic and grey literature. As expected, *teaching* plays a highly relevant role for HEIs, evident from both perspectives, given the importance of topics related to CE and sustainability being taught. However, it is surprising to see that *research* on CE is still under development, considering that this area is a cornerstone for HEIs, meaning that there is a need to continue working from multidisciplinary perspectives to identify and test solutions for the diverse problems related to sustainability and circularity. Additionally, it is inspiring to see that *outreach* has a large impact in the local communities, which speaks volumes of the role that HEIs have within the population by providing applied solutions through education and research. Finally, it is evident that HEIs are concerned with their *campus management*, identifying and applying best practices to improve their sustainability indicators and demonstrate their commitment to the topic.

## 2.4. Mind the gap

As it can be seen from the literature review, a myriad of connections can be formed between different topics, ranging from urban mining to game-based learnings with

the main focus in the circular economy applied in HEIs aiming for the sustainable development through the different areas of influence of the HEIs, as presented in the figure 20 below. This figure presents the current state of the literature and the existing links between the different topics up to the date on which this PhD thesis was completed.

Therefore, one significant finding that provides relevant opportunities for development is the large number of topics covered by the connection between CE and HEIs, as these can be grouped within six main clusters: economic aspects of the public-private interaction within sustainable development (in light blue), frameworks to develop sustainable business models (in dark blue), economic and social aspects of sustainability (in red), topics related to waste management (in purple), general topics around education for sustainable development (in green), and topics linked to circular economy (in yellow).

However, it must be pointed out that the clusters are not without interaction with others, given the multidisciplinary nature of the sustainable development and circular economy within the higher education institutions. For example, figure 21 below shows how understanding the economic aspects of waste management requires also reviewing what are the impacts from different perspectives (social and environmental) and how these should be analyzed as well from the educational point of view. Therefore, this provides avenues for transdisciplinary collaborations, bridging gaps between different disciplines and areas of knowledge, through partnership and work with different stakeholders to address the different CE challenges. Thus, it is necessary to address one critical gap which is the lack of transdisciplinary *research* which could also impact external stakeholders, generating *outreach* positive outcomes, as well as promoting educational projects enhancing the *teaching* section.

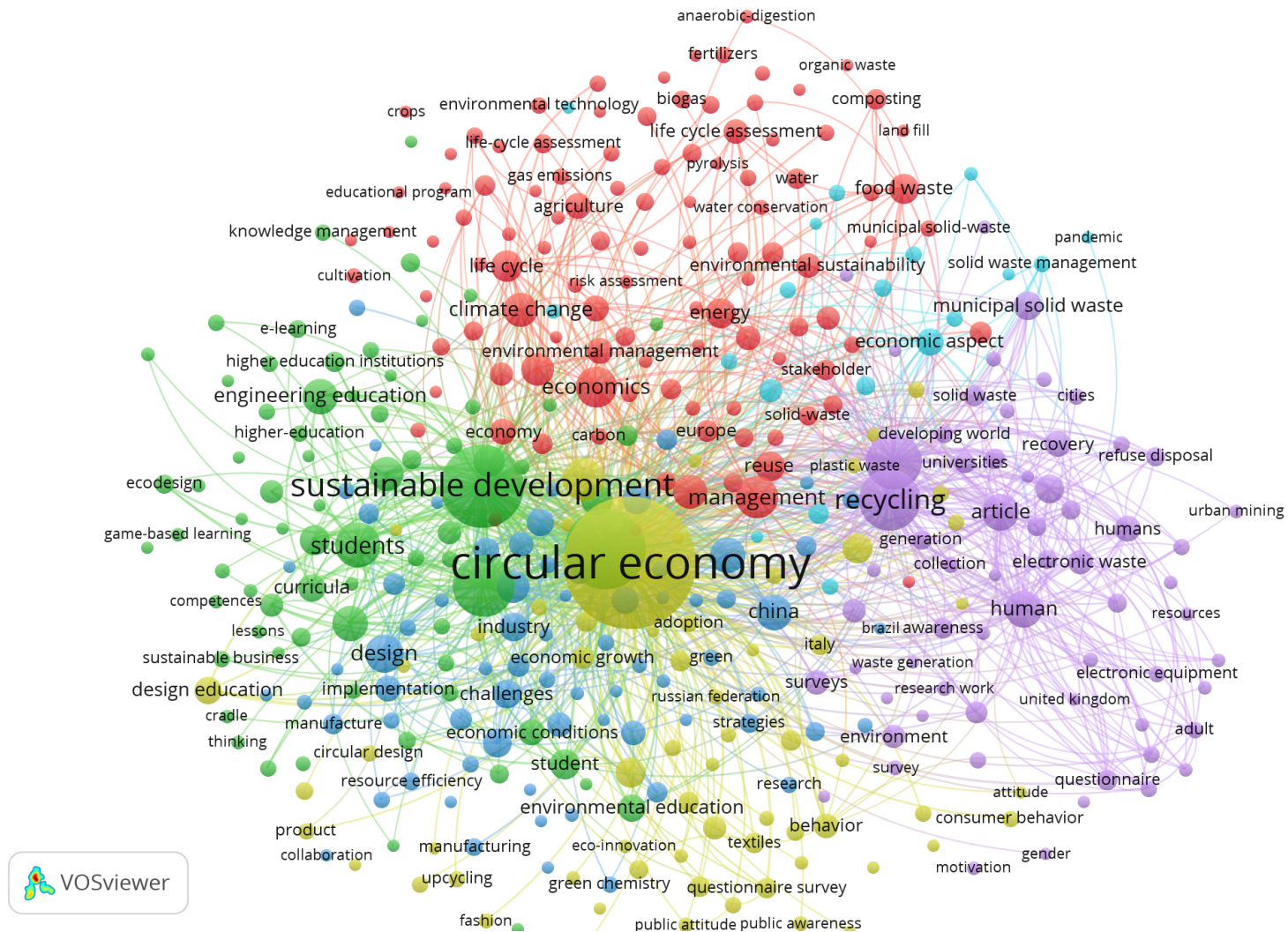


Figure 20. Topics connecting CE and HEIs from six main themes. Own development using VOSviewer version 1.6.18.

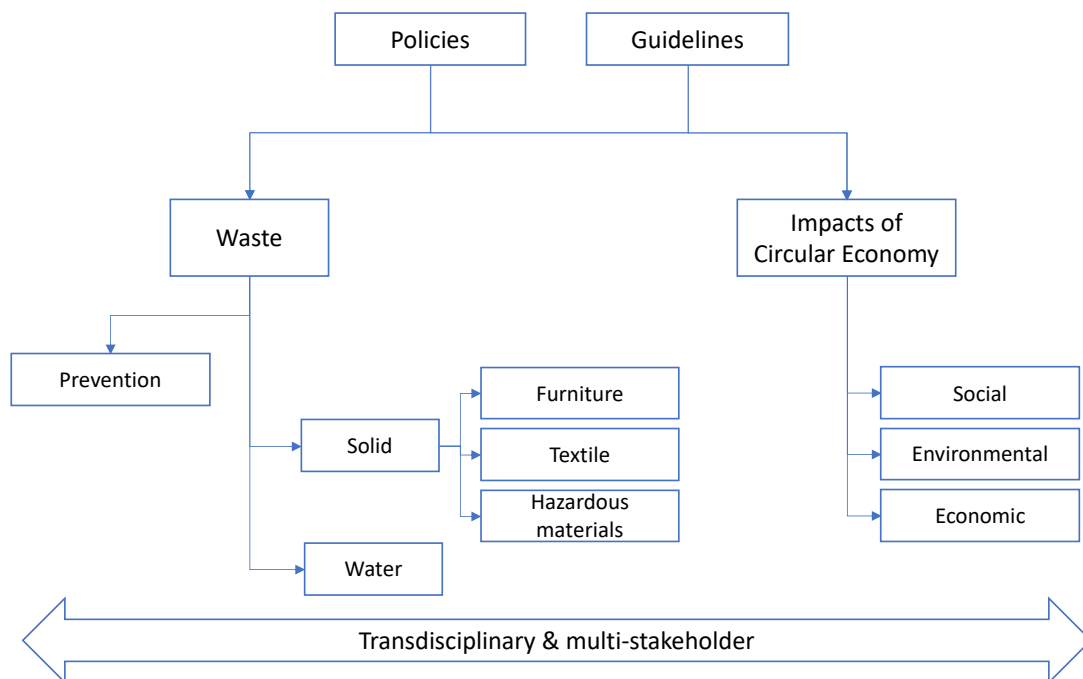




focusing on developing policies and guidelines, generating and expanding preventive measures and innovative waste reduction strategies.

Given that higher education institutions play a key role for the communities where these are embedded, there are minor efforts to fully engage with the local community, specifically researching the impacts and outcomes of the different projects. Studying the long-term impacts of HEI-community collaborations need further development, mainly focusing on understanding and measuring the effects from the social, economic and environmental points of view.

The figure 22 below summarizes the areas on which there is an opportunity to develop research avenues based on transdisciplinary and multi-stakeholder point of view.



**Figure 22.** Most relevant gaps identified in the literature on CE in HEIs. Own development.

## 2.5. Conclusions

In this chapter an ample exploration of the literature has been presented. First, investigating the interconnectedness between the concepts of circular economy (CE), higher education institutions (HEIs), living labs (LL), and action learning and action research (ALAR), shedding light on their individual contributions and synergies. It briefly highlights the importance of integrating these approaches to

cultivate well-rounded sustainability mindsets, necessary to deliver meaningful and truthful progress towards a circular future within HEIs and beyond.

Second, and thanks to the review of academic and grey literature, it is possible to understand the progress being made by different institutions through their engagement with the principles of CE, particularly in the areas of education and campus management, these are still done from an individual discipline perspective, not taking full advantage of the multidisciplinary approach that CE offers. Additionally, the review reveals a myriad of topics and themes which can be used to develop impactful tools for education and research, thanks to the interdisciplinary connections. Moreover, this can enhance collaboration with a variety of stakeholders, aiming to develop applied solutions for local communities.

Finally, it can be determined that this chapter supports further understanding the ever changing landscape of CE principles and the implications of applying these in HEIs from their different core areas, presenting areas for future research and action related to sustainable practices.

## 3. Research problem positioning and methodological approach

*“I am just a child who has never grown up. I still keep asking these 'how' and 'why' questions. Occasionally, I find an answer”. Stephen Hawking*

### 3.1. Introduction

The goal of this chapter is twofold: on the one hand, understand and position the research problem addressed in this thesis and, on the other hand, properly define the research methodology applied to tackle the research problem. The two parts are necessary to clearly understand the relevance of the topic, what is the problem and how the methodology presented in this thesis adequately addresses it.

The review presented on Chapter 2 introduces the state-of-the-art from the literature perspective (academic and grey) and identifies the research gaps intended to be addressed in this dissertation. While chapter 2 serves as an introduction to the latent problem, this chapter intends to position the research problem within the scope of sustainability in higher education, outlining a methodological approach aligning and integrating diverse concepts under a specific context. By integrating these concepts, this thesis presents a comprehensive framework that contributes to sustainable development by advancing academic knowledge and proposing tangible practices which promote changes and progress. This multidimensional approach ensures that the research here presented is of relevance, grounded in practical application of the theoretical concepts, advancing both, with a focus on sustainable practices in higher education.

In this chapter, section 3.2 introduces the scope under which the thesis is developed, section 3.3 presents the diverse research methodologies which can be applied to address the issue, and section 3.4 introduces the reader to the selected methodological approach, highlighting its importance.

### 3.2. Thesis scope and research problem positioning

The literature review presented in Chapter 2 introduced the key concepts for this thesis, Circular Economy (CE), Living Lab (LL), Higher Education Institutions (HEIs) and Action Learning and Action Research (ALAR), as well as the importance of the topic for HEIs and its application within their four core areas: teaching, research, campus management and outreach.

This section introduces an exploration to the innovative application of a LL within a HEI, under the context of implementing CE concepts. This thesis intends to investigate how integrating these concepts support enhancing sustainable practices through experiential learning while driving systematic change within the academic nature and institutional settings of HEIs. Additionally, it takes advantage of ALAR methodologies to generate insights into the effectiveness and potential of combining these concepts under the educational umbrella (teaching and research), with the goal to produce a framework which allows theoretical foundations and practical implementations to be combined, being able to be replicated and scaled across diverse educational environments, creating practical results that can be useful for HEIs and the communities on which these are entangled.

While LL provides a platform for experimentation and co-creation, largely explored from the industry perspective, its application within HEIs using CE concepts remains underexplored, particularly regarding the use of ALAR methodologies to support continuous learning and improvement, while recognizing the dual role that HEI have as educators and operational entities. Moreover, to properly position the research problem, it is important understanding the imperative need to solve global sustainability challenges through innovative approaches within HEIs to ensure developing the adequate educational knowledge and practical skills necessary for future leaders to develop practical solutions to said challenges. This is necessary as usually the different educational models have fallen short in properly bridging the gap between theory and its application within real-world context, specially under the topic of sustainability.

Therefore, this thesis positions itself at the intersection of innovation in education, sustainability concepts, and hands-on implementation, with the main purpose of addressing the question of HEIs can successfully integrate CE principles into their daily operations and academic programs and research avenues. To enhance the integration among the different topics, this thesis explores their methodological

integration through a comprehensive model which ensures that both, the educational and operational dimensions of HEIs, are properly aligned with sustainability goals, creating a living example of CE in action.

The next section presents and defines the methodological approach used to tackle the described research problem.

### **3.3. Research methodology**

As mentioned in the previous chapter of this dissertation, integrating different key elements is necessary to generate a comprehensive understanding of how Circular Economy (CE) concepts should be integrated throughout the entirety of Higher Education Institutions (HEIs) activities.

Only a few methodologies can be discussed as a way to attempt linking together these concepts, with a strong emphasis in the importance of real-world contexts, connection of multiple stakeholders, creating iterative processes, and addressing complex and multifaceted problems, from a multidisciplinary approach. In this section, a brief description of the different methodologies is presented.

#### **3.3.1. Real-world context methodologies**

##### **3.3.1.1. Living labs (LL)**

A promising research methodology which intends to facilitate experiential learning and innovation is presented in the Living Lab (LL) approach. As a methodology, it offers a dynamic, collaborative environment, which allows different stakeholders to engage in co-creation processes to develop and test new solutions in context that closely mimic real-life situations (Carrasco-Gallego et al., 2020), through iterative learning activities. The key elements of this methodology are: user-centric approach, co-creation, iterative process, experimental flexibility, holistic perspective, sustainable approach and scalability (Følstad, 2008).

##### **3.3.1.2. Participatory design (PD)**

This is a research methodology which involves all stakeholders (e.g., employees, consumers, citizens, end-users, etc.) during the design process, ensuring that the

end result meets all stakeholders' needs and is really of use. This approach underlines the importance of involving users in co-creation processes (Schuler & Namioka, 1993).

### **3.3.1.3. Action Learning (AL)**

Briefly defined, this research methodology allows small groups to work collectively on complex problems to intend provide a solution through action and learn based on the different outcomes. The most important part of this methodology is on the learning experience of the participants (stakeholders) involved in the collaborative process (Revans, 1982).

### **3.3.1.4. Action Research (AR)**

In short, this is a participatory research methodology under which researchers work with different stakeholders, develop and implement a solution, and reflect in an iterative manner on which it will improve the results over time. This method highlights collaboration and iterative cycles of reflection to identify suitable solutions (Lewin, 1946).

### **3.3.1.5. Design thinking (DT)**

This methodology is focused on problem-solving by understanding the user's needs, challenging current assumptions about the product, redefining problems, and generating innovative approaches to develop different prototypes that provide solutions through testing. It is largely based around developing a human-centered design through iterative testing, and further refinement after receiving feedback from the user (Brown, 2008).

### **3.3.1.6. Community-Based Participatory Research (CBPR)**

As per its name, this methodology presents itself as a collaborative approach involving diverse community members along the design and implementation of research projects, ensuring that the results from the research properly address the needs inherent to the specific community. It is based on active participation of different stakeholders to offer practical insights to identify solutions (Israel et al., 2010)

### **3.3.1.7. Living case studies**

This is an innovative research method under which applied and real-world cases are analyzed over an extended period of time, intending that the researchers get involved with the subject through continuous observation. This methodology provides deep understanding of the context, the subject and their interactions, over a longer period of time (Yin, 2018).

### **3.3.1.8. User Innovation Networks**

A non-traditional research approach under which networks of different users collaborate to generate new products or services, based on the particular needs from a specific company. This could be compared to a focus group type of approach. This methodology is highly focused on encouraging user-driven innovation through a collaborative environment to identify precise solutions (Von Hippel, 2005).

### **3.3.1.9. Field experiments**

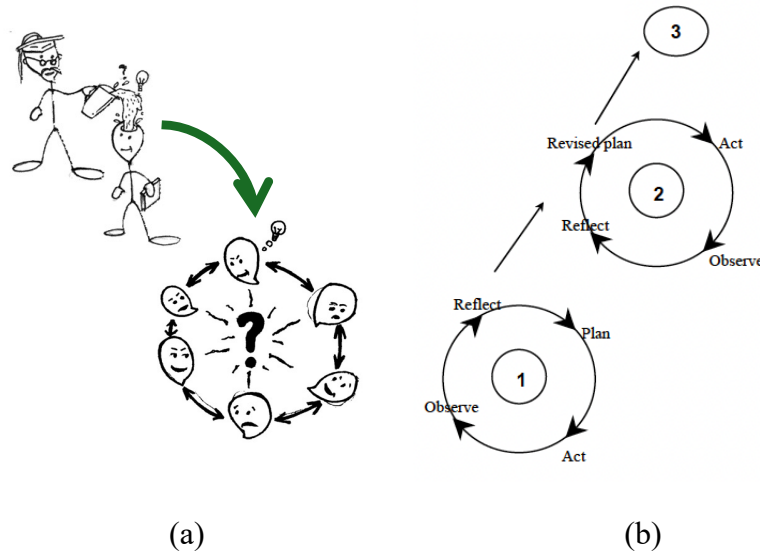
One of the most used methodologies to identify solutions to applied and complex problems, based on observing natural behaviors and outcomes, resulting of experiments conducted under real-world conditions, meaning that the experiments face uncontrolled conditions. These experiments emphasize the observation under natural settings while developing real-world solutions (Harrison & List, 2004).

## **3.4. Methodological approach used in this thesis**

The core research goal of this dissertation is framed within the intersection between the main four concepts explained in section 2.2. As argued in that section, the concepts of HEIs and ALAR have been largely discussed on the literature, including their interaction and impacts. Additionally, it has been argued that given the novelty of the other two concepts, CE and LL, the interaction between these two is still nascent. Therefore, integrating the four elements form a robust framework for advancing sustainable practices while fostering innovative educational environments.

The pivotal role of ALAR in facilitating the implementation of CE concepts through LL frameworks within HEIs, can be highlighted by the iteratives cycles of action, reflection, and adaptation (as presented in figure 28, which actively engage

stakeholders in problem-solving perspectives, co-creating knowledge and innovative solutions which drive systematic changes towards circularity.



**Figure 23.** (a) Action learning cycle, and (b) Action research spiral of research cycles. Adapted from (Coughlan & Coughlan, 2002; Zuber-Skerritt, 2001).

The proposed methodology, connecting the four concepts, presents an evolutionary approach by incorporating each concept as follows.

First, connecting HEIs and ALAR, enables enhancing educational and research capabilities, through the continuous improvement resulting from combining problem-solving focus with collaborative and experiential opportunities, towards solving real-world complex problems.

Second, connecting the previous two concepts with CE offers an opportunity to develop and test sustainable solutions for complex problems, by engaging different stakeholders (i.e., students, researchers, community members) in theoretical and applied projects that explore CE principles.

Third, incorporating LL as experimental spaces, complements perfectly the previous three concepts. LLs offer a controlled yet flexible setting to co-create, test, refine and implement real-world solutions. This user-centered approach ensures that the identified solutions are effective, scalable, practical, and capable of closing the gap between theory and practice.

Finally, by implementing the approach combining ALAR, CE, HEI and LL, it is possible to create a synergistic methodology aimed to enhance educational outcomes and promoting sustainable innovation. This integrated methodology presented in this dissertation not only supports bridging the gap between theory

and practice, but also advancing academic and practical knowledge, while at the same time, preparing students to solve complex sustainability challenges through development of additional practical professional skills.

Therefore, in the research trajectory developed through the implementation of a LL focused on CE within a HEI, which will be described in the next chapters, the results demonstrate that multidisciplinary collaboration is necessary to develop successful sustainable solutions to a myriad of problems. The quantitative and qualitative results presented in the next chapters, demonstrate the versatility and strength of the methodology presented in this dissertation.

## 4. The Circular Economy Living Lab: the setup

*“If you think you're too small to make a difference... Consider the size of a mosquito”. African Proverb.*

### 4.1. Introduction

In this chapter the reader will be introduced to the process followed to develop a living lab (LL) focused on circular economy in the campus of the Polytechnic University of Madrid (UPM, Universidad Politécnica de Madrid), in Madrid, Spain. Establishing this type of LL presents an opportunity to propose and adopt innovative and applied solutions to issues related to sustainability from a multidisciplinary point of view. Moreover, through collaboration with both, academic partners and local community stakeholders, it is possible to enhance the educational and research activities, through hands-on activities.

Additionally, given the intricate nature of the circular economy (CE) and its inherent multidisciplinary approach, it can be considered that the development of the circular economy living lab (CELL) can be compared to the complex mechanisms of a biological cell. Therefore, the reader is introduced to the idea of CELL serving as a fundamental unit within the HEI ecosystem, similarly to its biological counterpart, which incorporates several processes to maintain homeostasis and support the organism's unit of life.

### 4.2. Understanding the university context

The Polytechnic University of Madrid (UPM – *Universidad Politécnica de Madrid*) was created in 1971 through the joint effort of the different Higher Technical Schools (*Escuela Técnica Superior*) and University Schools of Technical Engineering (*Escuela Universitaria de Ingeniería Técnica*) existing in the city of Madrid, many of them already centuries-old institutions with a long tradition of training and research in engineering and architecture. As a consequence of the context under which the university was created, it does not have a single campus,

but rather several Schools scattered around the city and its surroundings. To alleviate the complex management of the university, a network of four campuses was created: Ciudad Universitaria campus (shared with Complutense University of Madrid), Madrid Centro campus, South campus and the Montegancedo campus. The Madrid Centro campus is probably the most particular one as it is constituted by four independent schools located within relatively close distance from each other. Each school then could be considered as a “mini campus” as it is deeply entrenched in the urban network of their surroundings.

Within the Madrid Centro campus, the Higher Technical School of Industrial Engineering (ETSII – *Escuela Técnica Superior de Ingenieros Industriales*) decided to develop an initiative under the paradigm that university campuses are encouraging spaces for multidisciplinary experimentation and to promote interaction between different interest groups within the university and the city. The Living Lab initiative named “*CircularizatE*” was born to demonstrate that the principles of Education for Sustainable Development (ESD), although complex and fuzzy (C. D. Jensen, 2016), can be brought into practice to identify solutions applicable at university campuses.

### **4.3. Developing the Circular Economy Living Lab (CELL)**

The main objective of *CircularizatE* is to demonstrate that the principles of circular economy are applicable, technically viable, economically profitable, socially inclusive, and environmentally responsible by using first, the Higher Technical School of Industrial Engineering (ETSII), part of Madrid Centro campus, as a test-bench, and then expanding its footprint to the rest of UPM university campus. The project seeks to establish the entire UPM campus as a testing ground “of practices and policies which bring into line the principles of the circular and regenerative economy, creating (and not extracting) value, and industrial symbiosis: the waste from a node of the network serves as an entry point for another node, seeking a closed industrial ‘metabolism’ through collaborations and alliances between the different schools, the UPM campus and external partners such as city councils, companies, organizations, and local communities” (Carrasco-Gallego et al., 2020). Additionally, it aspires to create innovative solutions to complex problems through applied research and knowledge sharing.

From *CircularizatE* at ETSII as a starting point, the first expansion was made to three additional Technical Schools (Industrial Design – ETSIDI, Architecture – ETSAM, Agronomics, Food and Biosystems – ETSIAAB) and impacting two campuses (Madrid Centro and Ciudad Universitaria), creating the **Circular Economy Living Lab (CELL)**. This expansion was also supported and funded with a seed capital from UPM, while receiving support and funding from five private entities: Ford Community Challenge – Apadrina la Ciencia, Plastics Europe, Acciona and Fundación Vodafone.

### 4.3.1. The CELL from a biology (counterpart) perspective

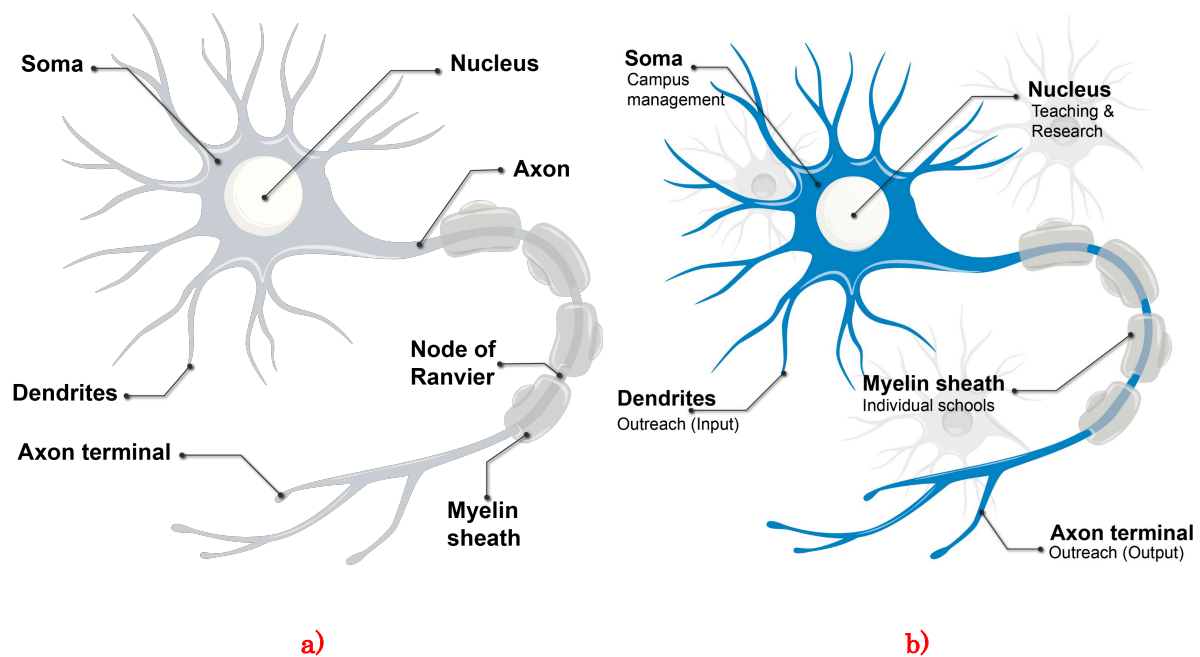
Analogous to its biology counterpart, on which a cell is defined as “the basic structural and functional unit of all forms of life” (O’Connor & Adams, 2010), CELL is portrayed as the basic unit at UPM where CE is embedded in its DNA since its conception, and will perform its basic functions (development, functioning, growth and reproduction) in the HEI system. In the following paragraphs we elaborate this parallel between the biological cell and the technical interpretation.

A basic cell structure contains three main components: plasma membrane, cytoplasm, and nucleus. The *membrane* acts as a barrier, maintaining its structure and integrity. The *cytoplasm* provides the environment on which the organelles operate inside the cell. The *nucleus* contains the genetic material and controls the activities carried by the cell (O’Connor & Adams, 2010). Depending on the specialized functions of a cell, its type and characteristics will change. In this case, for the sake of argument, we define that HEIs function as neurons, given their significance for cognitive development and brain’s functioning. On one hand, education has a lifelong positive influence in brain development and health, even as the brain ages (Goldberg, 2022). On the other hand, brain architecture encompasses connections between billion of individual neurons, transmitting signals and enabling action potentials.

Additionally, it can be argued that neurons and HEIs have a distinctive shape, receive information from the external world, process it and create impulses that react to the external stimuli and are transmitted to other cells (Stevens, 1979). Likewise, although not two neurons (or HEIs) are identical in form, they all have similar general structural features. In the following paragraph we’ll explore first, the structure of the neuron and second, the interpretation of HEIs as neurons.

According to Stevens (Stevens, 1979), the basic structure of the neuron distinguishes three main parts: the cell body, the axon, and the dendrites. The *cell body* (also called *soma*) contains the *nucleus* and all the biochemical machinery to preserve the cell's life. The *dendrites* provide the main surface to receive incoming signals and tend to branch out, meaning that these are 'the arms of the cell'. The *axon* is the largest structure and provides the pathway where signals travel from the cell body to other cells farther away by extending its branches in different directions. Additionally, to be able to support signal transmission, axons have supplementary components which play key roles: *Oligodendrocyte* which support unions along the axon and are responsible for covering it with myelin; *Myelin* which form sheaths around neuronal axons to protect, isolate and speed up the transmission of the potential for action; *Node of Ranvier* which is a space between each myelin sheath, essential to optimize impulse transmission and safeguard its arrival; and *Axon terminals*, or *synaptic boutons*, in charge to link with other neurons and transmit impulses. The structure of the neuron cell is presented in figure e24 (a) below.

Comparable to the neuron, HEIs also have components and specific functions. For this, the four crucial areas for HEIs (university management, teaching, research and community outreach) (Figueiró et al., 2022) are considered as the key elements assigned to the neuron parts.



**Figure 24.** a) Structure of a neuron cell; b) interpretation of HEI as a neuron cell.

Adapted from Betts et al (*Betts et al., 2013*).

First, the *Nucleus*, which is the central part of the neuron, would be the core purpose of HEIs. Their main role can be summarized as creating an educational platform to develop innovation, new learning experience and educational outcomes (United Nations, 2022). Therefore, *teaching and research* activities are the key element to achieve their core purpose.

Second, the *Soma*, where all the parts reside, enables the existence of the cell by performing all necessary activities to ensure its life. The physical space where the parts reside would be the equivalent of the *campus* at the HEI, and the actions necessary to preserve its existence would be all the *campus management* activities.

Third, the *Dendrites*, which receive the signal from the environment outside can be compared to the *outreach* activities that HEIs carry when reaching out for diverse members of the community (people and companies) with particular needs. Furthermore, these activities allow HEI to receive information (*input*), allowing them to learn and understand about the problems outside of their boundaries, creating action potentials to propose solutions to these issues.

Finally, the *Axon*, responsible for transmitting electrical signals from the soma of the neuron to the terminal buttons, plays a key role as it includes additional elements of the neuron. It supports the connection and collaboration between the *Myelin sheaths*, which are the different individual schools that shape the entire HEI and increase the strength of the signal by inducing additional knowledge. As it is also possible that, over time, new programs and schools are created or become part of the HEI, the axon enables this connection to the rest of the neuron. The *Axon terminals* would be the *outreach* activities carried by HEIs to share their knowledge with the external world (*output*) in different spaces (e.g., conferences, workshops, academic journals, case studies, books, social debates, open-spaces, academic and company reports, interviews, etc.), aiming to reach diverse audiences and maximize the exchange of information. The interpretation of HEI as a neuron is summarized in figure 24 (b).

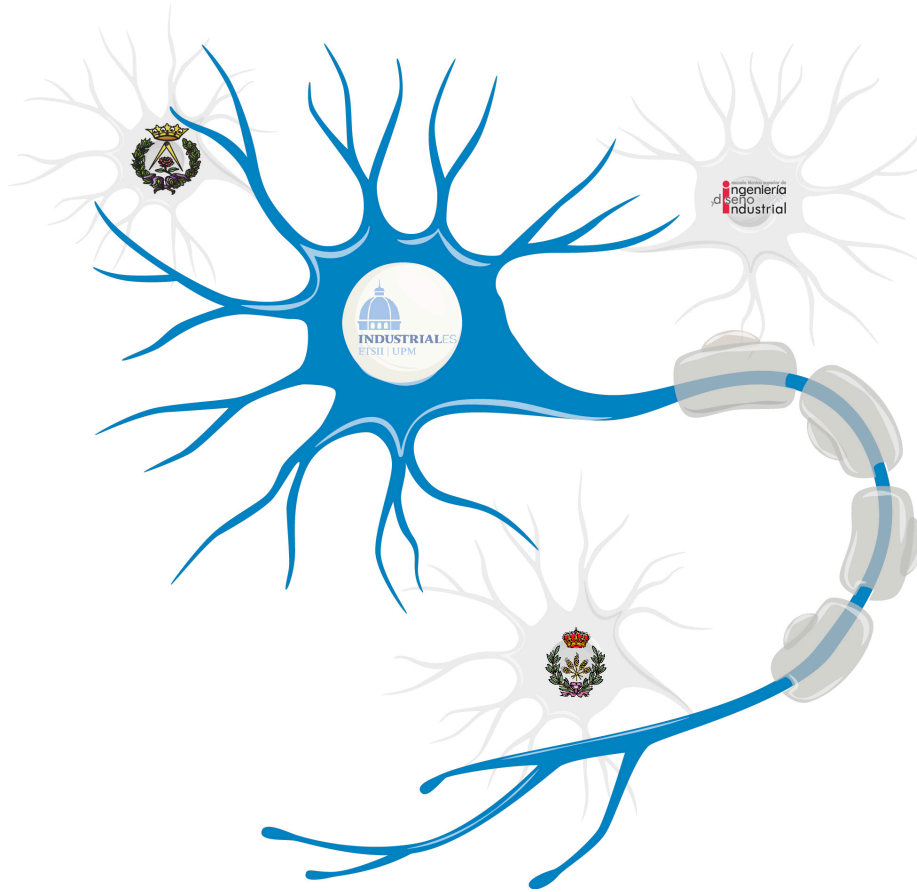
Based on the discussion presented in the previous paragraphs, it makes sense to represent the CELL based on the neuron, under two main assumptions: on the one hand, we consider the four crucial areas for HEIs, namely CORT (campus management, community outreach, research and teaching) (Figueiró et al., 2022) and parallel these at HEIs as entities where the brain is exercised (research and

teaching), stimulating its cells to achieve results which are transmitted to other cells (outreach) while preserving itself (campus management) over time. Moreover, its structure allows for growth and supports communication via longer connections. On the other hand, the neurons create neural circuits (or networks) which enable fast communication among them, providing quick responses to activation signals. Comparably, HEIs create collaboration networks as a result of information exchange (research and teaching) and can respond to internal or external incentives (activation signals) to foster their participation in a project.

Furthermore, it could be argued that stem-cells are precursor cells from which different type of cells with specialized functions are generated (Chagastelles & Nardi, 2011) after specific DNA has been embedded. Likewise, HEIs can implant a broad variety of DNA depending on the specific research needs of the particular cell; therefore, HEIs have the ability to create STE(A)M cells, which is, to all intents and purposes, a happy coincidence.

#### **4.3.2. Expansion of the CELL**

Afterwards, CELL's progressive expansion to other schools and campuses of the university was possible thanks to the collaboration with sustainability offices at the different schools around the university campus. The *SGD Nodes* (Universidad Politécnica de Madrid, 2023) initiative has been fundamental for this as it designates a working group comprised by faculty and students at each of the 15 schools at UPM, collaborating to generate different synergies within and between schools with focus on actions aiming to fulfill the Sustainable Development Goals (SDGs) at UPM level. Along the support of the Vice-rectorate for Research, Innovation and Doctorate, the SDG Nodes and a network of researchers and faculty interested in further developing the initiative, an innovation community funded by the Vice-rectorate of Research on the topic Circular Campus was created: UPM Circular Campus (*Campus UPM Circulares*). Thanks to this collaboration, the initiative permeated three additional Technical Schools (Forest Engineering and Natural Resources – ETSIM, Telecommunication Systems – ETSIST, Computer Engineering - ETSIinf), adding two additional campuses to its current footprint (South Campus and Montegancedo campus), reaching an impact in all four UPM campuses. This expansion is presented in figure 25.



**Figure 25.** The Circular and Regenerative Campus community at UPM, showing its expansion to other schools. Own development.

Additionally, the UPM Circular Campus community was able to continue developing research and applied innovation by engaging nine additional private and public partners: Ayuntamiento de Madrid, Mercados de Madrid, Coronavirus Makers de Madrid, Ecoembes, Repacar, Plataforma Tecnológica Española de Construcción (PTEC), Plataforma Tecnológica Ferroviaria Española (PTFE), Fundación de los Ferrocarriles Españoles (FFE) and Fundación Plastic Sense.

This community allows diverse areas of engineering (mechanical engineering, chemical engineering, organizational engineering, agronomic engineering, and materials engineering) and architecture, to actively participate and work together to transform the entire university campus. Moreover, this community brings together UPM researchers working in CE, providing visibility, encouraging debate and strategic reflection around this area, and interlacing the network between academia and external actors (companies and public administrations), to enhance synergies and encourage participation in research and innovation projects (European projects, NEXT funds, among others) within and outside the region.

Additionally, collaboration with external institutions has also been planned since the conception of the CELL. As HEIs create collaboration networks with other HEIs and non-academic institutions within and outside the country, it is important to understand the potential growth and impact that CELL could have. In the following paragraphs, we'll explain CELL's footprint outside UPM in academic and non-academic institutions.

#### 4.3.2.1. Academic expansion

At academic level, UPM is a founder member and a partner of the European Engineering Learning Innovation and Science Alliance (EELISA) initiative, which is a group of 10 universities distributed around 8 countries in Europe, with the common purpose to strengthen engineering skills on students and foster common practices and education tools around Europe, with a rooted understanding of society and the environment (EELISA, 2020). The HEI members of the initiative, represented in the figure 26 below, are Budapesti Műszaki és Gazdaságtudományi Egyetem (BME) from Hungary, École des Ponts ParisTech and Université Paris Sciences et Lettres (PSL) from France, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) from Germany, Scuola Normale Superiore (SNS) and Scuola Superiore Sant'Anna (SSSUP) from Italy, Universitatea Politehnica din București (UPB) from Romania, İstanbul Teknik Üniversitesi (ITU) from Turkey, Zürcher Hochschule für Angewandte Wissenschaften (ZHAW) from Switzerland, and Universidad Politécnica de Madrid (UPM) from Spain.



**Figure 26.** EELISA network. Source: (*EELISA, 2020*).

The EELISA initiative is one of the 50+ initiatives funded by the European Commission under the program Erasmus+, which aims to “establish alliances between higher institutions from all across Europe, for the benefit of their students, staff and society” (European Commission, 2020b) and ambitioning to expand to 60 European Universities alliances involving over 500 HEIs. Within each of these initiatives, collaboration among the different HEIs is a cornerstone to improve international competitiveness, and support creation of knowledge through multidisciplinary approaches. This is possible through different communities within the alliances, which allow for collaborative learning and research, achieving innovation, academic excellence with social impact.

In the specific case of the EELISA alliance, almost 50 communities have been established, aiming to solve diverse challenges aligned with the 17 SDGs, with the inclusion and active participation of different stakeholders. An EELISA Community serves as a platform which encourages the use of knowledge, research, and innovation to solve complex problems, such as those framed in the 2030 Agenda or the European Green Deal, through collaboration and cooperation. These communities generate a vital environment which acts as an incubator for collaboration and as a magnet to attract and cluster existing talent, projects and activities within the Alliance and the regions where the challenges are set.

One of these communities has been originated as a result of the efforts of CELL to share its knowledge and increase its impact within the network. The EELISA Circular and Regenerative Campus (CRC) Community involves stakeholders (academics, researchers, students, faculty and staff members, and external partners) who share a common vision of the role that HEIs play in addressing sustainability challenges. This EELISA community aspires to leverage the potential of HEIs’ campuses to become a proof-of-concept / demo-sites of the circular economy in our local communities. Moreover, EELISA CRC intends to serve as a test bed for business models and new production and consumption models that close materials loops, with a strong educational dimension for the future engineers that will lead the transition to a more resource-efficient economy, contributing to the change in mindsets required to move from linearity to a circularity. Although the focus of this community is on materials flows, we fully

recognize the importance of water and energy flows and their interaction with the circular economy, and we are actively exploring this connection.

#### **4.3.2.2. Non-academic expansion**

On the non-academic level, CELL has served as a test-bench for the local community in the city of Madrid, not only because of its influence as an education and research center embedded in the city fabric, but as a point of connection and exploration for different public and private entities. A key example of this collaboration between different stakeholders, where CELL has participated, is presented in the following paragraphs.

The City of Madrid has developed a policy that supports the economic fabric and job creation with a vision based on innovation and joint work between the government and companies, promoting, on the one hand, a cluster policy which supports the development of strategic economic sectors and, on the other, the creation of a set of innovation hubs. For the City Council of Madrid, circular economy is a strategic sector for the competitiveness and sustainable development of the city, given its capacity to generate new companies and quality employment, as well as to ensure an adequate ecosystem to thrive in. Through the Government Area of Economy, Innovation and Employment of the City Council of Madrid (*Consejería de Economía, Innovación y Empleo del Ayuntamiento de Madrid*), an initiative to promote innovation and experimentation of solutions based on sustainability and circularity in the capital was born: The Circular Economy Innovation Center (*CIEC - Centro de Innovación en Economía Circular*) of Madrid.

The CIEC Madrid serves as a node of innovation, knowledge, and networking around CE, which aims to create an ecosystem of leading companies – and communities – in innovation and experimentation of solutions aligned with the principles of CE, act as an incubator for companies and startups, and design collaboration formulas between the private sector and CIEC (CIEC, 2023). It also functions as a public training facility for citizens in general through mentoring programs, training, events, and free open workshops.

Additionally, CIEC Madrid also incorporates a broad program of dissemination and awareness activities on waste prevention and the importance of undertaking, at all levels and by all citizens, actions to recycle, reuse, recover or seek second uses to our products, while generating new resources. For this purpose, CIEC offers two unique spaces: the *Digital Manufacturing Laboratory (FabLab)*, which is a

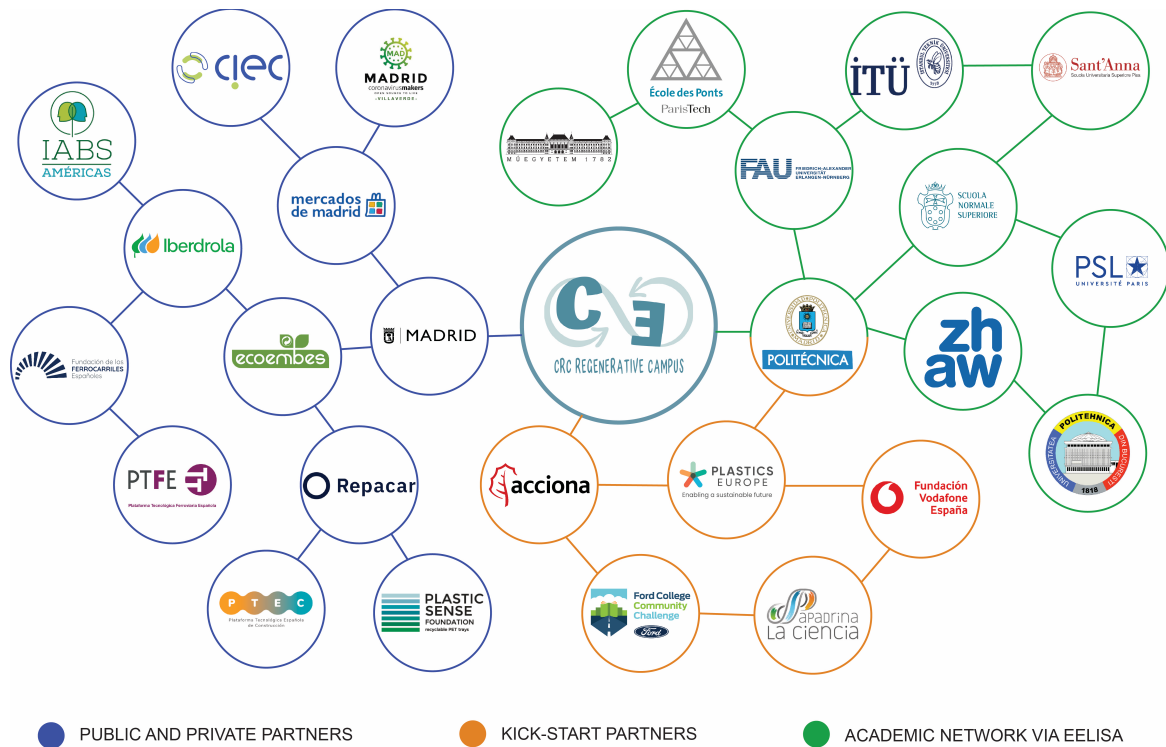
space open to the public intending to stimulate local innovative experimentation in ecodesign, digital manufacturing and maker culture; and the *Nature-Based Solutions Laboratory (SBN)*, which seeks to include more vulnerable groups or those at risk of exclusion in the transition to circular models of production and sustainability.

### 4.3.3. Creating networks

The essential function of a biological cell is to survive, replicate and become part of more complex structures. As the organic neuron cells create networks with cells with similar functions, their technical equivalents, the HEIs, also seek to be part of networks with other entities sharing mutual interests. Moreover, the higher the number of nodes included in the network, the largest its impact and the knowledge that can be extracted from it.

Following the approach of an artificial [academic and non-academic] neural network ([A]NN) (McCulloch & Pitts, 1943), on which the net of neurons share similar characteristics, require interaction and generate impulses to propagate a message, we argue that, in the extended sense, HEIs and the entities who make part of the network need to share similar characteristics and/or interests.

As presented in the previous section, CELL has generated different types of connections and networks with a myriad of entities, academic and non-academic, with common interests. Moreover, CELL has played a key role in two fronts: one, by serving as a connection point to link together different entities and, two, by showcasing the LL work methodology and sharing the know-how to support transitioning from linear to circular models. On the one hand, CELL been able to link together the government (City Council of Madrid), as a public entity, with an educational entity (Universidad Politécnica de Madrid), three private entities (Barrabés, Sacyr and Eurostar Mediagroup) and an NGO (Fundación Juan XXIII) to create public-private synergies, with their particular knowledge and know-how, that accelerate the process of transforming the economy and society towards a circular model in the city. On the other hand, CELL has shared its knowledge and learnings in the different areas presented by Carrasco-Gallego et al (Carrasco-Gallego et al., 2020), supporting CIEC creating their own circular roadmap and ensuring collaboration between both entities. The neural network created by CELL with the different partners is presented in the figure 27 below.



**Figure 27.** Academic and non-academic network of partners involved with CELL. Own development.

As it can be seen, CELL has come a long way from a concept within one school at UPM, to expand its impact in four schools within UPM, to disseminate its influence across all UPM campuses and majority of its schools thanks to the *UPM Circular Campus community*, to multiply its presence and magnify its impact outside of the UPM educational borders within the city of Madrid to work along public-private entities via the *CIEC Madrid*, and finally, beyond the national borders of the country to enlarge its footprint across the European region through the *EELISA CRC community*. This confirms that results obtained in a LL can have strong influence in different areas (research, education, management, and outreach) within and outside its borders.

Considering the multiple actors involved in the *CELL*, the *UPM Circular Campus community* and the *EELISA Circular and Regenerative Campus (CRC) community*, it is important to highlight that each of the stakeholders play a vital role to its success. Researchers and teachers are a key driving force as they detect real needs and emerging challenges by applying their research and training experience to transfer high impact solutions into the real world. Similarly, students involved in the project contribute to improve and evolve the lab through

their vision, ideas, knowledge, and orientation to innovation, and are able to share its evolution with the local and external community. In return, they enhance their technical competences in the field of circular economy and acquire valuable transversal skills for their subsequent professional development. Finally, external partners have “legitimized” the need to implement CE concepts to move from linear to circular models, promoting new avenues for research, and demonstrating that CE is, indeed, a technically viable, economically feasible and socially inclusive solution.

### 4.3.3.1. The numbers

*CELL* was conceptualized in early 2019 as an idea from four faculty members with diverse research interests at the Industrial Technical School (ETSII) at UPM, aspiring to expand its footprint to include students and other researchers across the School and, hopefully, the entire UPM campus. By the end of 2019, *CELL* included a committed team of about 20 students (undergraduate and graduate) and staff from the School actively working on the project, which was the first step to broaden the project’s impact. During the span of four years, since 2019 and until today, *CELL* has kept a steady stream of about 35 active students supporting the different projects developed in the lab, which is remarkable considering that students *pass through* the institution, since joining as newcomers and to completion of their studies. Moreover, the project has been able to include 11 new researchers encouraging novel research avenues. Although the numbers might seem small, it is important to highlight that this figure includes only students directly involved and actively working in *CELL* and does not include students who are indirectly impacted by *CELL* through teaching and research activities.

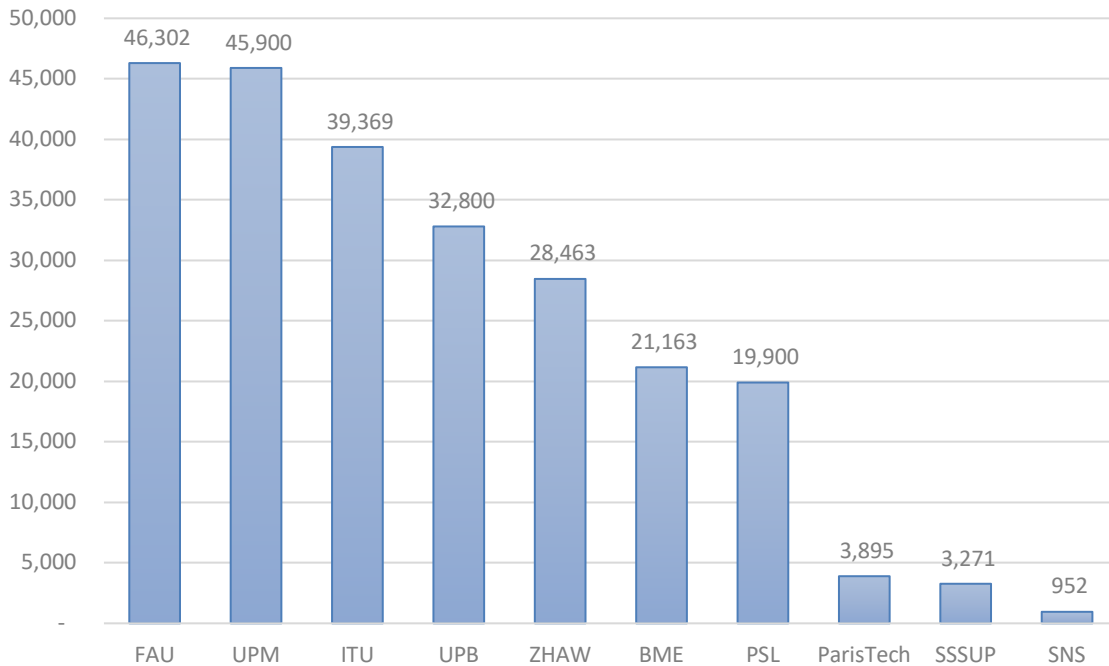
Therefore, *CELL* has impacted, directly and indirectly, the entire population at ETSII, consisting of roughly 5,000 people (4,500 students, 300 faculty members and 200 staff members) attending the school every day. In perspective, this number is not small as it is similar to the population of a minor town or village (e.g., Fregenal de la Sierra, Borja and Garachico in Spain, Oberammergau in Germany, Lauterbrunnen in Switzerland, Korcula in Croatia, Guichon in Uruguay, Ain Leuh in Morocco, among others) concentrated in a small area within the city center of Madrid.

Through the *UPM Circular Campus community* covering all UPM Schools and campuses and its entire population, the total number of people impacted, directly and indirectly, by the initiative rises to 45,000 people (40,000 students, 3,900

faculty members and 2,000 staff members). This number is significant as it represents 1.4% of the entire population of the City of Madrid, 15% of the total number of HEI' students in Madrid and is comparable to the total population of a medium town (e.g., Tres Cantos, Manacor and Denia in Spain, Nordhausen in Germany, Châteauroux in France, Paternò in Italy, Santa Elena in Ecuador, Chiquinquirá in Colombia, Albury in Australia, among others).

In addition to the academic community impacted by the initiative, it is worth highlighting that the *CELL* and *UPM Circular Campus* currently involve 13 partners in Spain who actively work with the community in diverse projects: Ayuntamiento de Madrid, Ecoembes, Mercados de Madrid, Repacar, Plataforma Tecnológica Española de Construcción (PTEC), Plastics Europe, Fundación Plastic Sense, Plataforma Tecnológica Ferroviaria Española (PTFE), Fundación Ford – College Community Challenge, Acciona, Fundación de los Ferrocarriles Españoles (FFE), Fundación Vodafone España, and Coronavirus Makers de Madrid.

Moreover, considering the *EELISA Circular and Regenerative Campus (CRC) community*, the total figure grows exponentially. Adding all the population from the 10 HEIs, we can account for a total of 242,015 people (214,040 students, 18,951 faculty members and 9,024 staff members), information discriminated per institution is visible in figure 28 below. This number becomes very significative as it can be compared to the population of a medium-size urban area (e.g., A Coruña or Granada in Spain, Chemnitz in Germany, Eindhoven in the Netherlands, Porto in Portugal, Reno in United States of America, Neuquén in Argentina, Fuji in Japan, and so forth) or a portion of a country's population (e.g., 105% of Samoa, 85% of Barbados, 64% of Iceland, 45% of Malta or 37% of Luxembourg, among others).



**Figure 28.** EELISA CRC community’ total population, discriminated per HEI. Own development.

These numbers show the potential impact that projects and research initiatives incubated through *CELL*, and spread through the university via *UPM Circular Campus* and across national borders thanks to *EELISA Circular and Regenerative Campus community*, can have a major impact by supporting the development of circular models involving academic and non-academic entities, with the common goal of transforming communities for the benefit of its inhabitants.

#### 4.3.3.2. Applying the United Nations Sustainable Development Goals (SDG)

The *CELL*, *UPM Circular Campus* and *CRC Community* contributes directly and indirectly to different goals of the United Nations’ 2030 Agenda for Sustainable Development. In this section, we succinctly present the specific SDGs and indicators on which the project has influence, given its transdisciplinary nature.

On the one hand, the following SGDs and indicators are directly impacted by the project.

- **SDG 4.** Quality education

Due to the nature of *CELL* and the projects developed within the university, it has a direct and positive impact on target 4.7, through indicator 4.7.1, consistent with indicators 12.8.1. and 13.3.1.

- **SDG 8. Decent Work and Economic Growth**

CELL contributes directly to target 8.4 by seeking to decouple economic growth from resource extraction and the subsequent degradation of the environment, measured through indicators 8.4.1 and 8.4.2, which are consistent with indicators 12.2.1 and 12.2. .2, respectively.

- **SDG 9. Industry, Innovation, and Infrastructure**

An increase in the number of full-time researchers and students working at CELL creates a direct and positive impact on target 9.5, through indicator 9.5.2 Number of researchers (in full-time equivalent) per million population.

- **SDG 11. Sustainable cities and communities.**

Current projections show that over 68% of the world's population will live in urban areas by 2050, therefore it is important to reduce inequalities in the cities, ensuring air quality and guaranteeing proper waste management. CELL contributes directly to target 11.6, through indicator 11.6.1. Proportion of municipal solid waste collected and managed in controlled facilities in relation to the total municipal waste generated, broken down by city.

- **SDG 12. Responsible consumption and production.**

Considering the current consumption pattern, it can be forecasted that in the medium term the planet will run out of resources while population continues growing. This particular goal supports the transition from traditional consumption habits to more sustainable ones. CELL directly and positively impacts targets 12.2, 12.5 and 12.8, through the following indicators:

- 12.2.1. Material footprint, material footprint per capita, and material footprint per GDP
- 12.2.2. Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
- 12.5.1 National recycling rate, tons of material recycled.
- 12.8.1. Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment.

- **SDG 13. Climate action**

There is a direct contribution by CELL to target 13.3, which seeks to improve education and awareness on climate change mitigation, adaptation, and impact

reduction through indicator 13.3.1, generating a globally educated citizen, aware of sustainable development.

- **SDG 14.** Life below water

Considering current ocean pollution rates, it is vital to act towards reducing the amount of plastic disposed on the ocean. CELL has a direct and positive impact on target 14.1, through indicator 14.1.1 Coastal Eutrophication Index (ICEP) and density of floating plastic waste.

- **SDG 15.** Life on land

CELL contributes directly to target 15.2, which seeks to promote the implementation of sustainable management of all types of forests, promoting afforestation and reforestation globally, measured through indicator 15.2.1.

- **SDG 17.** Partnership for the goals

Creating collaboration networks and partnerships between public sector, private sector and civil society is vital to achieve the goals. CELL has a direct and positive impact on targets 17.16 and 17.17 as it has demonstrated that multistakeholder collaboration is achievable.

On the other hand, the SDGs indirectly impacted by the project are:

- **SDG 3.** Good health and Well-being

Education and research developed at CELL have an indirect impact on target 3.9 and its indicators 3.9.1 and 3.9.2 as the project supports guaranteeing safe environmental (air and water) conditions for all, reducing the unhealthy environments.

- **SDG 5.** Gender equality

Although STEM HEIs are spaces where females could feel discriminated against their male counterparts based on the ratio 1:3, we encourage all kind of students to take part in the project, disregarding their gender. CELL provides a learning space without discrimination, supporting the development of target 5.1.

- **SDG 6.** Clean water and sanitation

CELL supports as well clean water availability by reducing the amount of water necessary to extract raw materials, reducing the need for virgin materials by

improving recycling rates, which aligns with target 6.4 and its indicator 6.4.1 (Change in the efficient use of hybrid resources over time).

- **SDG 7. Affordable and clean energy**

The distributed recycling performed at CELL is less energy intensive than a linear model based on extract-produce-consume-dispose. In this way, target 7.3 and its indicator 7.3.1 (Energy intensity measured based on primary energy and gross domestic product (GDP)) is impacted.

As it has been presented in this section, CELL is a multidisciplinary project with a transverse influence across almost all SDGs, which are directly and/or indirectly impacted. SDGs 4, 12, 14 and 17 are impacted in depth due to the nature of the project, while SDGs 8, 9, 11, 13 and 15 are positively influenced in a narrow way. Additionally, SDGs 3, 5, 6 and 7, are indirectly impacted by the project. It is worth mentioning that, although the SDGs cover a broad range of topics through the 17 individual goals, with 169 targets and 232 indicators, it is important to understand that these cannot provide a unique understanding of reality based on an individual interpretation, but rather require to look at the big picture to understand how these are interconnected.

## 4.4. Conclusions

In this chapter the initial setup and posterior evolution of the Circular Economy Living Lab (CELL) at the Polytechnic University of Madrid (UPM) were introduced, marking a significant milestone in integrating sustainable development principles into higher education institutions (HEIs). After its conceptualization and gestation as a pilot at ETSII, CELL has progressively extended its impact across multiple schools and campuses within UPM, driven by the commitment of different stakeholders (faculty, students and external partners) interested in applying the principles of circular economy.

Through the living lab (LL) multidisciplinary approach, CELL is able to demonstrate the feasibility, profitability, and inclusivity of the circular and regenerative solutions, and be able to support the transformation of the UPM campuses thanks to its ability to promote multidisciplinary interaction and

experimentation, generating applied and actionable insights extending beyond the HEI's boundaries.

Finally, understanding CELLS impact within the HEI and its comparison with the biological cell, supports the orchestration of a myriad of activities thanks to its function as critical element to the entire organism. Moreover, CELL serves as a point of connection between different stakeholders (i.e., students, researchers, industry partners, public entities, and community members), supporting its work in harmony, like organelles within the biological cell, to reach solutions for circularity. This approach not only enriches learning and research processes, but also supports the sustainable development of the HEI, similarly to a biological cell which supports the organism's life.



## 5. The Circular Economy Living Lab: the framework and results

*“The idea is to write it so that people hear it, and it slides through the brain and goes straight to the heart”. Maya Angelou*

### 5.1. Introduction

In this chapter the reader will be introduced to CELL’s framework of reference and the work areas under which the different activities will be carried. By linking academic learning and solving real-world problems, CELL offers students the opportunity to contribute to applied research projects, collaborating with diverse stakeholders within and beyond the university campus, and enhancing their learning experience from a multidisciplinary perspective. Furthermore, this multidimensional approach to understand and apply CE principles at a HEI not only advances the academic and research frontiers, but also contribute to the community engagement and the HEI’s role as a referent in sustainable practices.

Additionally, for better exemplifying and understanding the intricate connections between the different work areas, these are paired to the structure and function of the human brain, considering its unique contribution to a particular purpose without omitting the fact that one cannot work properly without the other. Through this parallelism, the multifaceted nature of CE principles is drawn, demonstrating that CELL offers a well-structured approach to address the complexities of interdisciplinary collaboration and innovation.

### 5.2. Setting up the framework

The CELL initiative generates opportunities for different stakeholders within the university campus (i.e., faculty, students, and the institution) and outside campus (i.e., investors, industry, and citizens) by providing hands-on experience through education and practice. The way in which the initiative is intended, allows

students to develop applied research projects in which they combine their knowledge acquired in their classes with the additional skills they can obtain through discussion with peers and professors and practical learning, moving away from the purely technical engineering problem-solving (EPS) (Jonassen et al., 2006) strategy towards the Engineering Education for Sustainable Development (EESD) (Halbe et al., 2015; Kamp, 2006) education strategy. Through this model, understood as a cyclical process, new knowledge is generated through active participation (Coughlan & Coughlan, 2002).

As part of the methodology to set up CELL's framework, the authors served as active participants in the project, being largely and directly, involved with its strategic development at ETSII-UPM, working along with key stakeholders (faculty and students). The roles of the author and his advisor within the university have also played an important role in the success of the project. On the one hand, Dr. Ruth Carrasco-Gallego, the advisor, serves as part of the Vice-Chancellor's office for SDGs at ETSII-UPM, has been part of the project since its ideation in early 2019 and has supported the expansion of the CELL outside the borders of the university campus by identifying different companies to work with. On the other hand, David A. Hidalgo-Carvajal, the author, has been engaged with the project since late 2019, served as an instructor of the CELL interacting directly with students and researchers on applied projects, and as "facilitator" to support fostering an environment where different researchers can generate projects from different angles and backgrounds.

To properly setup the framework, it is necessary to understand the different waste flows in the university campus, focusing mainly at ETSII, and then to identify possible ways to improve these flows. The starting point (baseline) of the project allows evaluating the impact of the introduction of the circular perspective in the centers (Leclerc & Badami, 2022; Smyth et al., 2010; Tangwanichagapong et al., 2017; Zhang et al., 2011) while better understanding what can be improved in different areas (i.e., reduce, recover, reconnect, re-naturalize, re-experiment) (Carrasco-Gallego et al., 2020) and considering diverse timeframes.

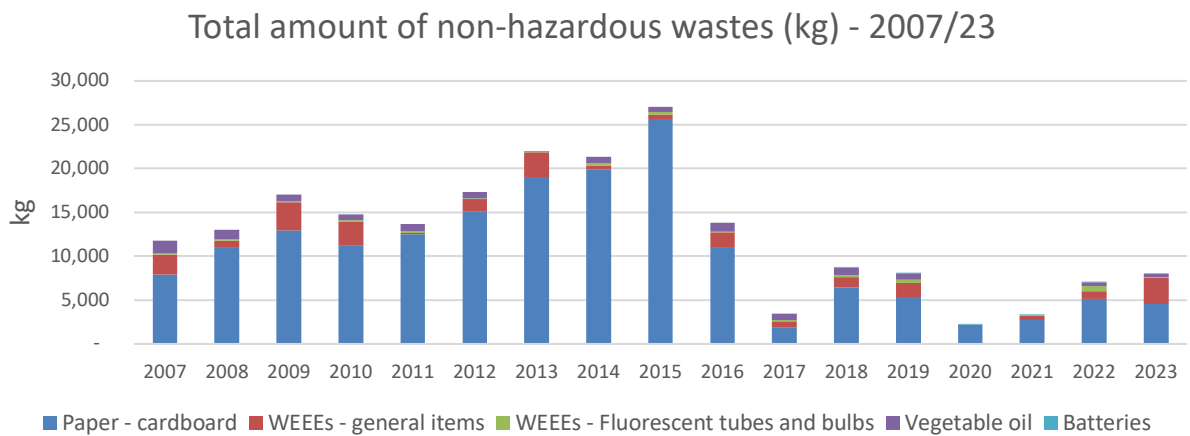
Finally, it should be pointed out that the framework presented in the following sections of this chapter use the document "*Circularizate: Un living lab de Economía Circular real en el ámbito universitario*" by Carrasco-Gallego et al (Carrasco-Gallego et al., 2020) as starting point to develop and complement the initial approach presented in 2020. The new framework enriches the initial proposition by updating some research lines and generating new research areas after reflecting

on the initial findings and facing different challenges, ensuring that the final framework encompasses the diverse angles necessary to successfully implement CE concepts within the four core areas at HEIs.

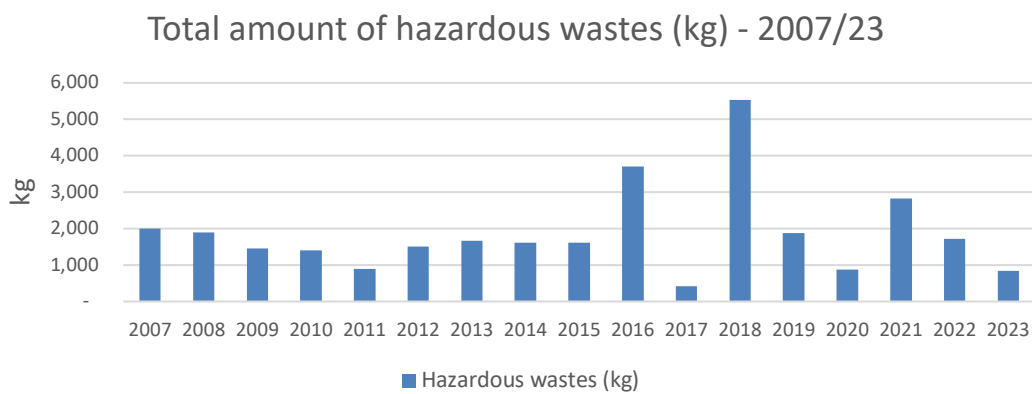
### 5.3. Defining the framework and work areas at CELL

The main objective of CELL is to demonstrate that circular [and regenerative] economy is technically viable, economically profitable, and socially inclusive. For this, it is necessary establishing the HEI campus as a test bench of practices and policies aligned with the principles of the regenerative economy and industrial symbiosis. Furthermore, through the scope and goal of the CELL, it is intended to showcase that it is possible to create a system under which the waste from a node of the network serves as raw material for another node, pursuing a “closed ‘industrial metabolism’(Ayres, 1998)” thanks to collaborations and alliances between different academic and non-academic partners, such as other HEIs, city councils, companies, and local communities. Consequently, the baseline needs to describe the current practices regarding waste generated across the UPM to transform it into a closed industrial metabolism (CIM) system. Lastly, understanding the CIM as a system enables segmenting the complex problem into smaller, yet interconnected, problems which can be solved through complementary projects.

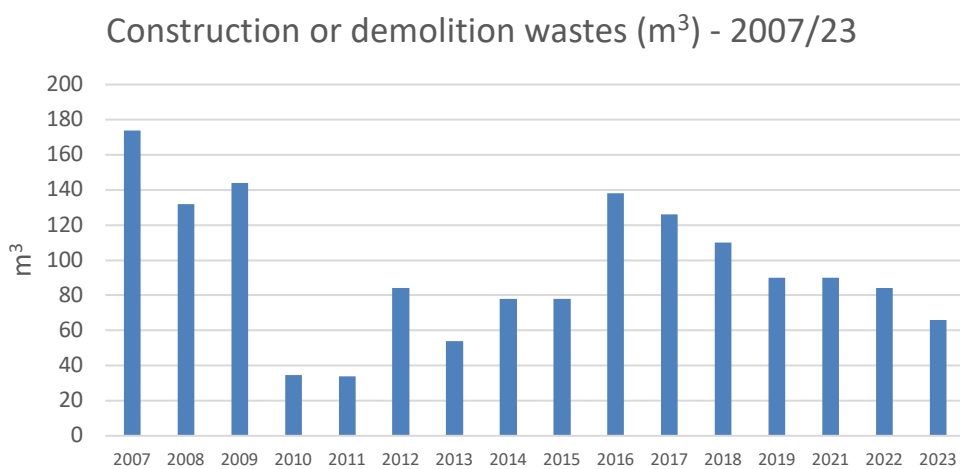
Ideally, we would consider as a baseline the inventory of waste generated at the different schools involved in CELL, following the sustainability report approach methodology (Yáñez et al., 2019). Unfortunately, this is not possible given that only one of the schools (ETSII) has actively reported their waste through their Social Responsibility Reports since 2007. Therefore, we set CELL’s baseline through the five published ETSII-UPM social responsibility reports (2007-2017) (ETSII-UPM, 2009, 2011, 2014, 2016, 2018) and with the internal information available at ETSII, which will be available in the upcoming reports (2018-2023) in the near future, and the most recent data reports from 2023. In figure 29 we can see the total waste of non-hazardous materials (paper-cardboard, WEEE, vegetable oil), while figure 30 shows the total waste of hazardous materials (chemical products, fuel oil, paint and others). Additionally, construction and demolition waste (CDW) are presented in figure 31; although CDW is not present at large at ETSII, it includes significant quantities of waste that is not of stone origin, such as wood, plaster, textiles and most metals.



**Figure 29.** Waste of non-hazardous materials at ETSII-UPM (2007-2023). Own development.



**Figure 30.** Waste of hazardous materials at ETSII-UPM (2007-2023). Own development.

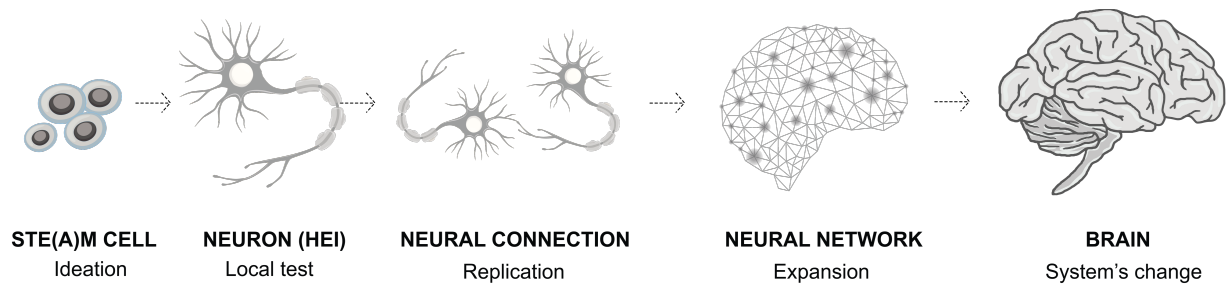


**Figure 31.** Waste of construction and demolition at ETSII-UPM (2007-2023). Own development.

Establishing a baseline serves two main principles: First one, as previously mentioned, having a baseline data allows evaluating the impact of introducing the circular perspective in the different schools. Second one, understanding the type of waste generated, its quantities and the waste management practices, supports identifying the work areas for the framework. Through these two principles, we propose the six work areas related to specific questions aiming to solve a part of the problem. These are presented as follow:

1. *Re-think* – is it possible to change the way on which we understand waste, how we manage it and our relationship with it?
2. *Re-naturalize* – can we return this residue into the 'biosphere' in addition to the techno-sphere?
3. *Re-duce* – can we eliminate this residue?
4. *Re-experiment* – can we incorporate this waste into the UPM's circular experimentation spaces and extend its life through repair, refurbishment, remanufacturing, or recycling?
5. *Re-generate* – is it possible to create value with the residue, through the network of partners, to avoid extracting virgin material?
6. *Re-connect* – could this residue become a “raw material” for another node in the UPM network (internal and external partners)?

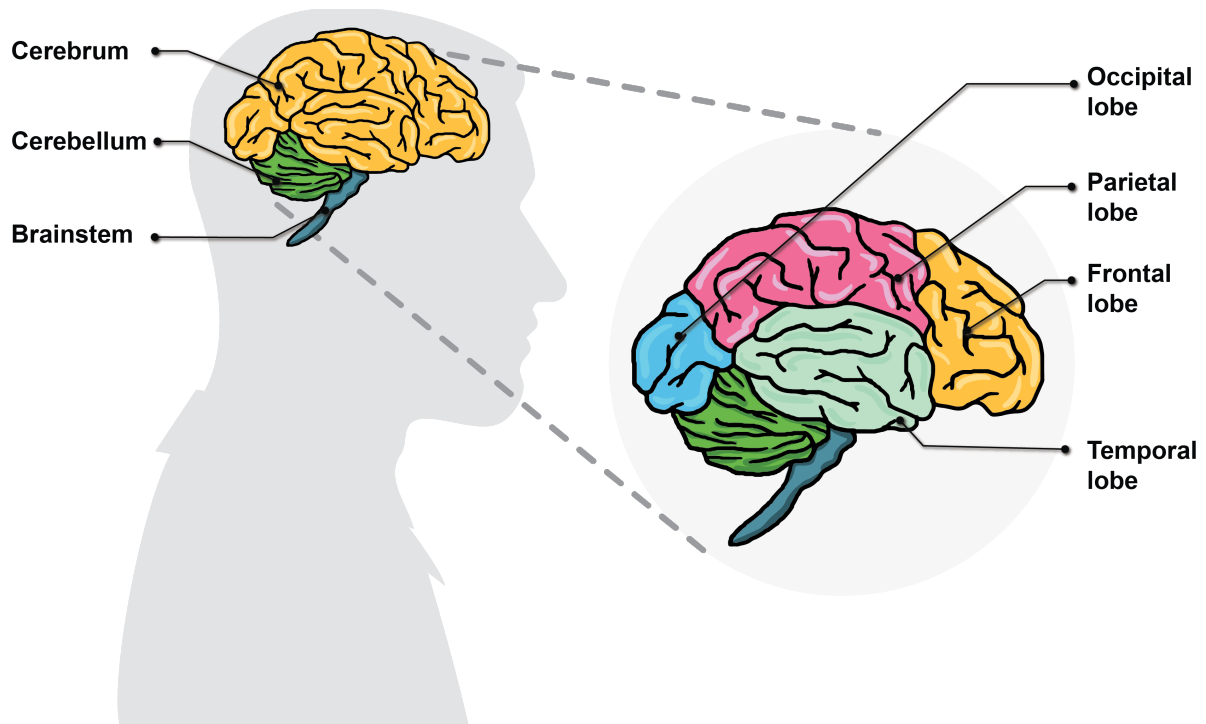
The above-mentioned work areas help establishing CELL's framework. Subsequently, following the interpretation of the growth of the living lab since its conception, from the technical (STE[A]M) CELL, through the neuron (HEI), ending in the [academic and non-academic] Neural Network ([A]NN), the logical next step in the chain would be depicting the framework as a brain, as can be seen in figure 32. Therefore, in this section we use the different parts of the brain to portray the diverse work areas that make part of CELL's framework.



**Figure 32.** Expansion from idea to change in the system. Own development.

The brain is not only an indispensable organ for the human body but also the most complex one. It receives, processes and interprets information, controls thought, touch, memory and emotions, commands motor function, balance and coordination, and coordinates the automatic function of several systems in the body such as breathing, sleep, heart rate, temperature control and every other process which regulates the human body (Carter et al., 2009).

As stated by Nauta & Feirtag (Nauta & Feirtag, 1979) and Carter et al (Carter et al., 2009), the brain is split in three main elements: cerebrum, cerebellum and brainstem. The *cerebellum* is located in the base of the brain and represents about 11% of the brain; it manages motor skills and posture, and is associated with some cognitive functions that require trial and error, such as language. The *brainstem* makes up for about 9% of the brain, connects the brain to the spinal cord, and regulates many of the automatic functions of the body not consciously controlled. Finally, the *cerebrum* is the largest part, accounting for the 80% of the brain and is in charge of reasoning and learning, regulating emotions and interactions with the different senses, controlling body temperature, and coordinating movement. This myriad of functions is performed by four different areas, named the lobules: the *frontal lobes*, located in the front part of the brain, are involved in speech, intellect, and movement; the *parietal lobes*, situated in the middle part of the brain, participate in identifying objects, spatial awareness and understanding the environment and the body; the *occipital lobes*, in the back of the brain, concerned with visual information, helps the brain interpreting shapes, colors and movement; the *temporal lobes* positioned near the ears are involved in memory development, recalling words and places, recognizing people and interpreting other's emotions. The structure of the brain is presented in figure 33 below.



**Figure 33.** Structure the brain. Adapted from Nauta & Feirtag (*Nauta & Feirtag, 1979*) and Carter et al (*Carter et al., 2009*).

Analogously to the six main areas in the brain mentioned above, our framework interprets and links these areas to the six work areas developed in the CELL. Here we present a succinct description of the work areas and the connection with the parts of the brain.

First, as the *frontal lobes* control voluntary movement, speech, and intellect, we correlate it to the *Re-think* work area given its direct relation with the learning scope at HEIs.

Second, we consider that the *parietal lobes* receive and interpret information to understand the environment and the body; therefore, we link this to *Re-naturalize* work area as it allows to link bio-sphere and techno-sphere, to make sure that the environment and the body (planet) are properly taken care.

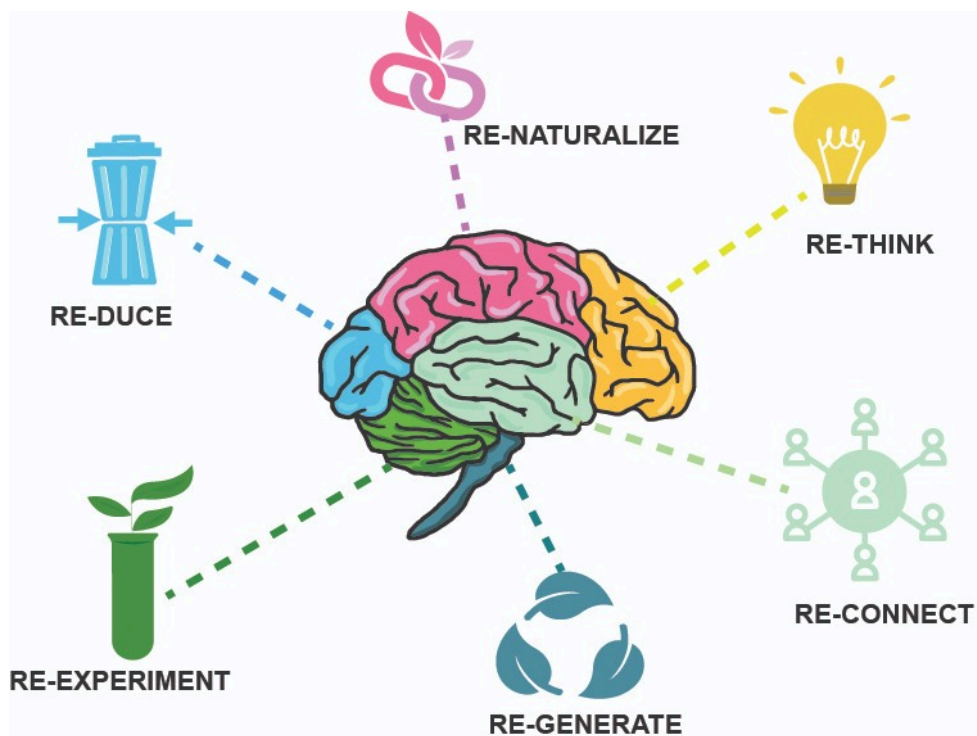
Third, as the *temporal lobes* is linked to recognizing people, words and places, and understanding other people's emotions, we parallel it to the *Re-connect* work area given the different connections that can be formed to create and expand the Neural Network.

Fourth, given that the *occipital lobes* allow detection and interpretation of visual information, processing shapes, colors and movement, we connect it to the *Re-duce* work area as recognizing the materials already in the system is fundamental to take actions to avoid unnecessary waste.

Fifth, since the *cerebellum* (also named “little brain” in Latin) plays a key role in motor coordination and balance, and additionally, contributes to learning, we match it with the *Re-experiment* work area given that experimentation plays a key role in learning activities in the HEIs.

Finally, considering that the *brainstem* is responsible for regulating basic body functions that are not under conscious control, we align it to the *Re-generate* work area as the planet (system) generates its own pulse and an uncontrolled interference would generate negative consequences. Therefore, recovering all materials already in the system would have a positive impact by reducing the need to extract new materials and avoiding overshooting the planet’s capacity.

The proposed framework is represented in the figure 34 below.



**Figure 34.** The six work areas of CELL. Own development.

These work areas allow defining a methodology for the identification of waste streams and their potential for circularity, not only at UPM or in HEIs in general, but also in other institutions (e.g. hospitals, corporate headquarters, and public administration entities) or industrial parks, and constitute the main contribution of this work (c.f., (Hopff et al., 2019; Mendoza et al., 2019a)).

## 5.4. Understanding the work areas at CELL

As previously mentioned, this framework has been updated from Carrasco-Gallego et al (Carrasco-Gallego et al., 2020), incorporating one additional research area and supplementing 3 additional lines for research. This updated framework enriches the baseline, ensuring that the four core HEIs' areas are covered, guaranteeing that UPM is truly leading by example to incorporate CE concepts all across. The six work areas presented in figure 34 are described in detail in the following section, including the work lines within each of the work areas.

### 1. *RE-THINK work area.*

Despite the growing urgency to reduce the use (and abuse) of non-renewable materials, the transition towards a system with virtually no waste can be seen from a daunting prospect. Therefore, the first thing we need to do is RE-THINK our relationship with waste and see it from the perspective of what it really is: resources ready to be used in other parts of the manufacturing system. Here, we propose two lines to change this linear mindset deeply rooted in our environment.

#### a. *Line 1. Incorporating sustainability into classrooms.*

The main mission of a HEI is to educate and train the future (and current) professionals. By including sustainability and SDG topics in the curriculum taught in the classroom, the future decision-makers will have the right tools to guarantee positive and meaningful changes. Therefore, it is necessary to embed these concepts through action learning activities with multidisciplinary perspectives. Such efforts have already been developed at UPM in ETSII via different subjects, theses (undergrad and graduate level), and projects which implement these concepts by design.

#### b. *Line 2. Inspiring society.*

Inspiring civil and corporate society is essential to generate sustainable changes. While corporate society has an impact in the way products and services are

developed, civil society makes the final decision on how these changes are adopted. Thus, it is important to encourage both to rethink our current approach.

On the one hand, corporate society can be inspired to rethink their businesses and decouple growth from resource consumption via training and direct experimentation. With the support of external entities, is possible to establish a set of courses intended to stimulate disruptive thinking in product and process design at corporate level. On the other hand, civil society can have access to diverse information and be inspired at several levels through conferences, forums and public open conversations around circular economy.

*c. Line 3. Sustainable procurement.*

This line of research includes public procurement in HEIs, as a proposition to integrate CE principles focusing on reducing waste and promoting the reuse and recycling of materials through suppliers, who retain the ownership of the product and ensure that the service is delivered. Thus, servitization plays a key role here as it can transform the traditional procurement models, enabling HEIs to access high-quality services while minimizing waste and enhancing resource efficiency.

*2. RE-NATURALIZE work area.*

In most projects related to CE the reduction of the techno-sphere waste (i.e., technology already in the system) is contemplated as a fundamental part. However, the part related to the bio-sphere is largely overlooked. In CELL, we include both spheres (techno- and bio-) to properly understand their respective cycles and minimize interference in the system. For this, we consider two lines of action.

*a. Line 1. Local composting.*

The green waste (organic waste) generated in cafeterias and landscaping at UPM facilities can be collected selectively to be composted directly at the different schools, eliminating the need to purchase fertilizers for gardening activities. In this sense, the maintenance and gardening personnel at UPM will receive the necessary training, provided by teachers and staff from the ETSIAAB and in alliance with local authorities of the Council of Madrid. In case of compost surplus, it could be donated to other Schools, HEIs or other institutions that may need it.

*b. Line 2. Increase in vertical green (from waste generated in the centers).*

The circular experimentation spaces proposed in the previous section must convey an image of sustainability and be an example of the ideas they advocate. For this reason, it would be appropriate to invest in vertical gardens and urban nature tools in these spaces, which in addition to transmitting image and comfort, act as thermal regulators in the proposed experimental spaces. Both, ETSAM and ETSIAAB have extensive experience in this line. Additionally, CELL can take advantage of the networking with other HEIs with experience in greening urban sustainability (e.g. (Villalba et al., 2023)) to implement these practices in our campus.

### *3. RE-DUCE work area.*

One of the pillars of CE is that materials never become waste as these are kept in the system through several process, reducing to a minimum the amount of waste generated, thus conserving the matter and energy already incorporated in the product. Consequently, HEIs must set “Environmental, Health & Safety policies and procedures” intending to reduce and avoid waste, as a prerequisite for the university to legitimately engage in CE principles. These policies are procedures, which can be interpreted as a minimum requirement, are also an essential for students since the contents taught in classrooms (sustainability and SDGs in the curriculum) are reinforced in a crucial way if the students perceive an “institutional alignment” to said contents. The “RE-DUCE” work area includes three specific lines of work.

#### *a. Line 1. Reduction of single-use containers in cafeterias and introduction of deposit-refund systems.*

Previous studies at ETSII show that students identify the cafeterias at the university as spaces that generate a large amount of waste, on which current waste management negatively impacts the aforementioned “institutional alignment”. However, it is important noting that canteens are not the only waste-generating spaces within the schools, but rather one where waste is highly visible.

In the case of single-use plastic products and packaging, UPM has already successful initiatives such as *Caminos Sin Plástico* (ETS Civil Engineering School without plastics) or *Montes Sin Plástico* (ETSIM without plastics), intended to reduce the amount of plastic in use at these schools. Additionally, there are supplementary initiatives in other HEIs such as Complutense University of Madrid (UCM), which shares a campus with the UPM in Ciudad Universitaria, on

which its management declared the need to eliminate single-use plastics at its schools in 2020. For this to succeed, it is necessary to work closely with the catering service suppliers to ensure successful implementation, because as academic literature (Hahn et al., 1990; Yawar & Seuring, 2018) and practical experience prove, the merely regulatory approach is not usually effective as the suppliers require support in this process of change.

Nevertheless, it is necessary to clarify that our focus is on reducing the use of the disposable products and packaging, rather than just a change of material. Just by replacing plastic packaging with paper (probably covered with a plastic film to resist moisture) does not reduce the environmental impact of such packaging.

*b. Line 2. Events.*

In many of our centers, different types of events are held, such as: (i) student parties (e.g. San Pepe in Industriales, San Cemento in Ciudad Universitaria); (ii) job fairs, business conferences, academic conferences (e.g. Induempleo); (iii) other events. It is necessary to seek the alignment of all these events with the circular campus initiatives. For example, at student events, through student representatives and associations, it is possible to promote initiatives to reduce waste and introduce durable glass tumblers through companies that facilitate the rental and cleaning of these glasses.

Additionally, in business and academic events at the different schools it is necessary to analyze the specific waste that they generate (e.g. fair carpet, attendee accreditations) which have high potential to be addressed from a circular perspective.

*c. Line 3. Prevent food waste and connect with healthy campus initiatives.*

Quality menus in the canteens of the university prevent food waste (Ferreira et al., 2013; Nordic Council of Ministers et al., 2012). With this line of work, we intend to promote healthier menus, with local and seasonal products that reduce the distance from the farmer to the university dining room table, ensuring high quality products. The cafeterias at the schools can also become a demonstrator of a sustainable agronomic system, aligned with the work carried out by ETSIAAB within the framework of the project “*La red Natura 2000: alimentando el campus* (Natura 2020 Network: feeding the campus)”, a pilot project carried out in 2018 aiming to promote consumption of local, seasonal and/or organic foods in collective university catering, through the incorporation of foods produced in municipalities

of the Natura 2000 Network of the bioregion of Madrid (Community of Madrid, province of Ávila and province of Toledo) (Comunidad de Madrid, 2014; Observatorio para una cultura del territorio, 2017).

Additionally, other measures to reduce or prevent food waste in the canteens are providing reusable and returnable plastic containers (Accorsi et al., 2014) so users can take leftover food, or including different portion sizes with different prices (Boschini et al., 2020; Visschers et al., 2020).

*d. Line 4. Identify and encourage existing internal recovery channels.*

The initiative “recycling furniture” and “electronic consumables” at ETSII encourages communication between the different areas to achieve synergies in the use of resources. Thanks to it, materials that are no longer going to be used in one area of the school (e.g., tables, chairs, drawers, printers, ink cartridges, etc.) are made available for use at other departments and units of the school. This prevents these from becoming waste before the end of their useful life and satisfies the needs of the staff without incurring financial expenses or time to manage the purchase.

*4. RE-EXPERIMENT work area.*

This axis of the demonstrator addresses the creation of spaces for experimentation where the university community (students, teachers, staff) and citizens can experience the principles of CE. These types of spaces contribute to the change of mentality necessary in engineering professionals for the transition from linear systems to circular and regenerative systems where "waste" does not exist as such but are valuable sources. In these spaces, the aim is to “short-circuit” the traditional linear flows of materials, promoting closed cycles as short as possible: first, reuse; second, repair, reconditioning, or remanufacturing; finally, recycling, in order to give value to the waste generated whenever possible within the university campus itself.

An example of these spaces for experimentation has been carried out since 2020 at ETSII through the initiative “CircularizatE”, the starting point of CELL presented in this dissertation. The experimentation space, namely *CircuLab* (see figure 35 (a) and (b)), is inspired by several initiatives that emerged in the Netherlands around the valorization and closing the loop of plastic materials: Precious Plastics (Eindhoven), Better Future Factory and its Perpetual Plastics Project, or the Refil initiative (Rotterdam). Inside the *CircuLab*, we designed a process to recycle the

plastic waste generated at ETSII, in order to produce valuable objects that can be used within the center. At the moment, the space is equipped with a shredder, a plastic pellet dryer, an extruder and spooling machine for 3D printing filament, as well as several 3D printers available in various locations within ETSII (see figure 35 (c) and (d)). Additionally, the School's *FabLab* (Fabrication Lab), located only few meters away from the *CircuLab* experimentation space, is used for repair, reconditioning, and remanufacturing activities, and is equipped with a laser cutter, milling machines, a cutting plotter, as well as various utensils and tools. Furthermore, for more complex processes requiring additional machinery, other UPM facilities and laboratories can be used.

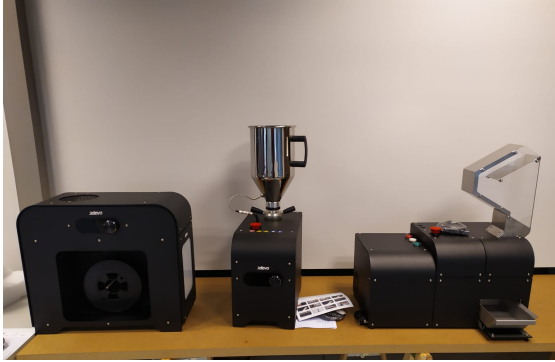
This line of experimentation has great research potential (publications in materials, polymers and additive manufacturing journals, c.f. (Moretti et al., 2021; Schirmeister et al., 2019)), as well as a driver to search for funding opportunities calls for research and transfer to the productive sector. There is growing interest in obtaining 3D printing filament from widely available waste materials, but the production process is not yet well developed. Hence, CELL serves as a test-bench for these processes.



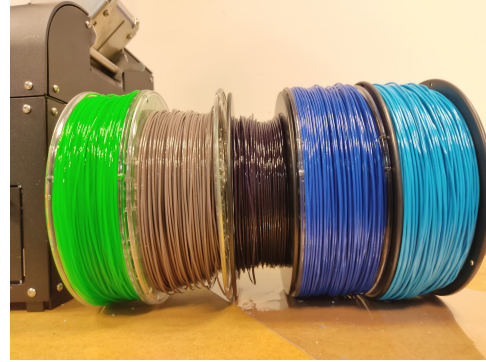
a) CircuLab logo



b) CircuLab facility at ETSII



c) From right to left: shredder machine, airdryer machine, extruder and spooling machine.



d) Resulting filaments from 3D waste

**Figure 35.** CircuLab facility and machinery. Own development.

Through the work carried in both labs (*CircuLab* and *FabLab*) we implement other circular initiatives, incorporating recycling, remanufacturing, reconditioning, and repair processes, as well as circular design tools (*design thinking*), and demonstrate that the Lab's value lies not only in providing objects with a second life to be further used within the university, but also in the action learning and research that our students experience through hands-on experience.

### 5. *RE-GENERATE* work area.

In this work area, the hidden value of the "waste" generated in the university environment is examined, recovering materials for which we can close the loop directly at the university itself or through alliances with third parties. Instead of continuously degrading nature, we support building and preserving natural capital.

#### a. *Line 1. Transforming waste into economic resources.*

At UPM we identify certain waste streams (i.e., paper, aluminum cans, electronic waste) which cannot be recycled within the university campus as we currently do not have the capacity or the machinery to do so. However, these materials have a high value in the market and can become an income source for different projects at the university, given the volume of waste produced at the university. Depending on the prices of the raw materials in the market it could be attractive to negotiate directly with interested recyclers to obtain economic value through its sale, taking advantage of economies of scale of the waste generated at the university.

*b. Line 2. PLA [Poly (lactic acid)] recovery node.*

In many UPM schools, 3D printing is used for teaching and research activities. PLA filament' spools and other polymers used for additive manufacturing are expensive and production rejects (i.e., misprints) are easily recyclable. We can close the 3D printing loop and guarantee that the material can be returned to the biosphere later. Additionally, we take advantage of an existent inter-school transportation system to deal with the logistic issue, so that schools can send their used PLA and receive recycled PLA spools in exchange at no additional cost, with consequent cost savings for schools and research groups.

*c. Line 3. Revalorization of agro-food waste.*

As mentioned in the RE-NATURALIZE work area, agro-food waste is a highly valuable type of waste available in the canteens at UPM. In addition to the composting proposition, it could be possible to take advantage of this available resource to create bio-based polymers or use it as additives (i.e., micro- and nano particles, active agents, among others) (Balart et al., 2021), to propose solutions to the increasing demand for sustainable plastics in several areas of interest, such as food packaging, clothing, medical devices, among others.

*6. RE-CONNECT work area.*

The principles of industrial symbiosis require connecting the nodes within an ecosystem, so that the waste from one node serves as raw material to another node in the system. Without these connections the circular economy on campus could not work, since no school, not even the entire university, can function as a self-sufficient system. It is necessary to establish connections within and outside the university. To promote these interactions and relationships, the following lines are proposed in the demonstrator.

*a. Line 1. Alliances between schools and industrial symbiosis.*

The living lab investigates whether it is possible that the waste (output) from one school can become a raw material (input) for other schools at UPM, aside from composting mentioned as part of RE-NATURALIZE work area. For example, industrial waste from the electricity sector, such as graphite, improves the mechanical characteristics of construction materials, such as gypsum. Connecting seemingly disconnected research areas would allow university to expand its

research and educational impact and, at the same time, reduce its total amount of waste.

*b. Line 2. Expand the circular economy living lab to other centers and campuses.*

Although this initiative was born in ETSII, one school in the Madrid center campus, it is intended to gradually involve the entire UPM university community, to expand the concept of circularity and replicate successful actions, as well as collect “circularization” experiences from other institutions and tailor these to meet our particular needs. This reconnection is enabled by the SDG nodes at UPM and makes possible connecting people from different specialized areas with different resources (materials and people), with the objective to solve a sustainability challenge. This also allows multidisciplinary collaboration and synergy of resources to promote innovation and co-creation, as well as tackling new challenges in the field of CE, such as closing the loop in the textile-sector, an area with large potential for innovation.

*c. Line 3. Connection with campus decarbonization and energy transition initiatives.*

Moving from the traditional linear manufacturing system towards a new paradigm requires also moving away from the use of fossil sources. Consequently, this initiative is aligned with the commitment to decarbonize UPM campuses, which has taken a huge step by guaranteeing that the energy provider is certified as of renewable origin. Additionally, experimentation spaces such as CircuLab, should also implement the use of renewable sources in a self-consumption mode.

The UPM Declaration on the Occasion of the 2019 United Nations Climate Change Conference in Madrid (COP25) (Universidad Politécnica de Madrid, 2019) is a commitment by UPM to action against climate change through work with its personnel and training people (staff and students) to understand the impact of greenhouse gases and propose solutions to the challenges of the future. In addition, it commits to cancel the net direct emissions of greenhouse gases by 2030 in order to reach the climate neutrality of the UPM by 2040. CELL supports the latest directly by mitigating the carbon footprint of the campuses by reducing the amount of waste they produce and, therefore, the CO<sub>2</sub> equivalent linked to said waste.

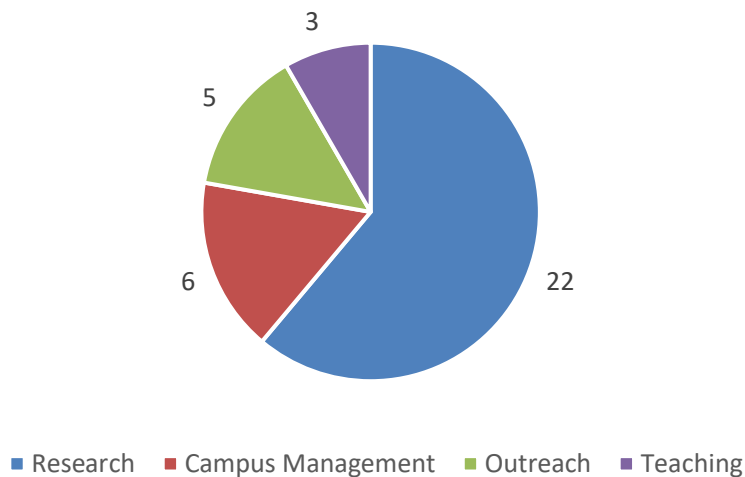
*d. Line 4. Connection with the city, the country, and the world.*

Thanks to the network involved in CELL (see figure 34), it is possible to have a multi-stakeholder view of actors involved in the supply chain (i.e., suppliers of raw materials and intermediate products, producers, consumers, recyclers, and waste managers) of various products. The different connections between CELL and its environment at different levels (i.e., government, educational institutions, public and private companies) guarantees a larger impact through different initiatives and projects with a broader network of actors connected to individual actors along the network. This systemic vision makes it easier to find innovative and feasible solutions to several challenges.

Additionally, one of the pillars of the university is to achieve social impact through outreach, hence, it is possible to engage other actors from civil society and carry out dissemination work. The networking within Spain and the world will be carried out through different national networks, such as Spanish Network for Sustainable Development (SDSN Spain / REDS Red Española para el Desarrollo Sostenible) and international networks, such as SDSN (Sustainable Development Solutions Network) and the International Sustainable Campus Network (ISCN).

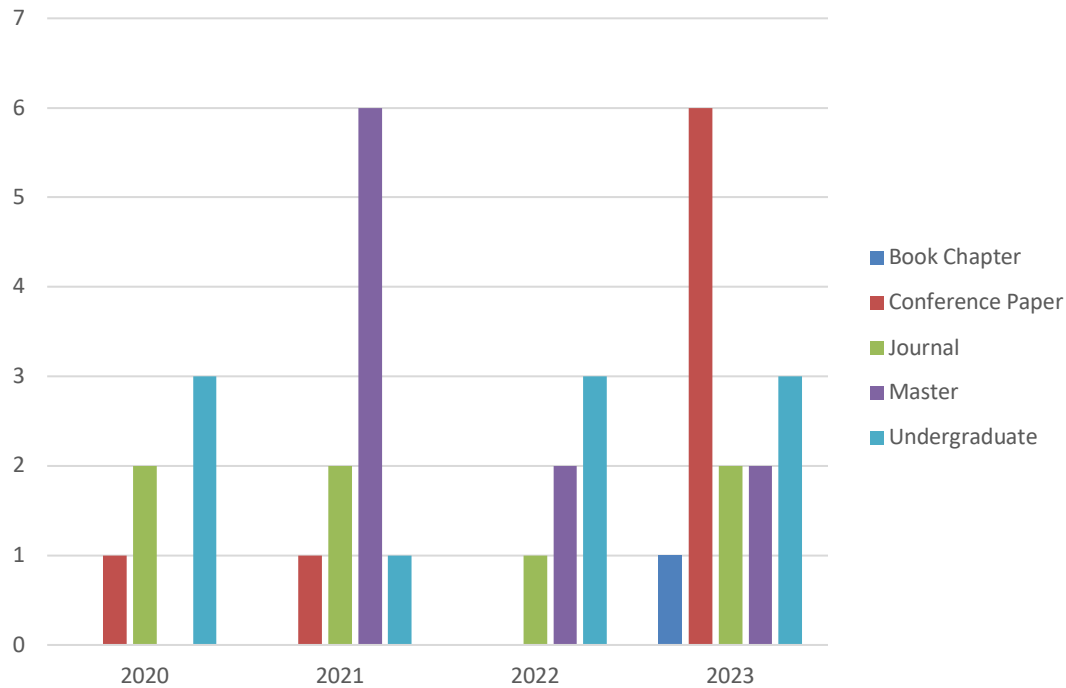
## 5.5. Results obtained under CELL's framework

The results of CELL can also be allocated within the four core HEI's areas as the projects conducted within the laboratory have been focused on supporting introducing CE concepts to the academic community. A total of 36 documents demonstrating the importance of CE at HEIs were created, from which 61% have a large impact from the *research* perspective, followed by 17% focusing on *campus management*, 14% have proven to provide *outreach* impact and just 8% were related solely to *teaching*, as presented in figure 36 below.



**Figure 36.** Academic results achieved at CELL (2020-2023) allocated to the four influence areas at HEIs. Own development.

Through the ALAR methodology conducted at the CELL, different projects have been developed, achieving academic (i.e., undergraduate and master theses, and formal research publications in conference papers, journal papers and book chapters) and industry/government results (i.e., applied research), as well as having an impact in the formal education programs with a few lectures incorporating the X-BL approach. Although only a small sample of the documents detail *teaching* approaches, the ALAR methodology shows that the students are interested not only in receiving a formal instruction but rather into putting this learning into practice, therefore, the methodology is a solid tool to generate applied results. Nevertheless, it is important to consider that the results here presented are only related to published documents and do not necessarily consider the changes in the *teaching* methodologies currently being implemented. Figure 37 below summarizes the academic contributions since the conception of the project and its development during the last four years (2019-2023).



**Figure 37.** Academic results achieved at CELL (2020-2023). Own development.

Table 8 categorizes the abundant results obtained within the myriads of topics covered at CELL during the 4-year period, and groups them into eight main categories.

Topics	2020	2021	2022	2023
Waste management system	1U	2M		
Plastic waste management	2U, 1C, 1J	1U, 1M, 1J	1U	1C, 1J
Electric and electronic waste		2M, 1C	1J	
Paper and cardboard waste			1U	1J
Food waste				1U, 2C
Construction and demolition waste				1U
Changes in the system		1M, 1J	2M	1U, 1M, 1C, 1BC
Circular economy (general)	1J		1U	1M, 2C

Abbreviations: Undergrad Thesis (U), Master Thesis (M), Conference paper (C), Journal paper (J), Book Chapter (BC)

**Table 3** - Academic results achieved at CELL allocated into the main categories. Own development.

The achieved results at CELL are detailed within each of the six work areas mentioned in section 5.2 and 5.3, where we present the results as general (i.e., results not necessarily available at grey literature) and formal (i.e., results that can be found in academic literature), although these are not necessarily split in that way in each of the sections.

### 1. *RE-THINK* work area

Within this work area, although the number of achieved results might look small, these contribute significantly to the transformation of the education at the HEI.

Among the general results, we have contributed to including sustainability into the activities in classrooms through the ALAR approach with the following cases:

- INGENIA is a teaching initiative where students need to identify solutions to a real-world problem through a project. Taking advantage of design thinking approach and circular design tools, students of the Master program in Industrial Engineering were able to propose solutions to different needs, such as developing “low-cost” products for vulnerable communities (2018), designing “low-cost” furniture for an academic fair (2019), design modular products (2020), and developing circular solutions to the latent problems in Mercados de Madrid (Madrid’s food markets) (2020).
- Following the Challenge-based learning approach, undergrad and master students were presented with different problems and asked to propose innovative solutions. The students had the support of advisors and lecturers who combined their knowledge and teaching at their respective subjects, to propose the most applicable, yet disruptive solutions. Closing the loop of construction and demolition waste (2021), food waste challenge in UPM canteens (2022) and identifying future uses for wind blades from aerogenerators (2023), have been the topics of the challenges, and have met with a myriad of applicable solutions.
- Lastly, UPM currently offers a wide variety of subjects related to sustainability and circular economy, available at its different schools.

Moreover, thanks to the interest in the subject, and as proof of this multidisciplinary approach, UPM has developed a Master Program in Circular Economy in which four schools collaborate.

Additionally, our approach to inspire society has been focused on engaging with external entities, establishing set of courses intended to stimulate disruptive thinking in product and process design at corporate level. Examples of collaboration with external entities include:

- First, in collaboration with Ecoembes and its “Circular campus” initiative (Ecoembes, 2024), we have been able to create educational courses around sustainability and circular economy topics, which have been made accessible for different companies.
- Second, several open conversation spaces have been crafted thanks to the collaboration with CIEC, creating the “Open Labs” series (CIEC, 2024) on which CE has been discussed from different approaches on its 15 editions, up to date. CELL community has been actively engaged in the series thanks to its expertise.

The formal contributions are described briefly. For instance, Agüero et al (Agüero Rodríguez et al., 2023) present an approach to engage students in a set of activities aiming to introduce the SGDs and CE concepts through plastic recycling activities. Yáñez et al (Yáñez et al., 2023) combined the “design thinking” approach with the challenge-based learning methodology to address the food waste problem at HEI. This was part of a four-month project developed in class, and which has been replicated three years in a row now with different focus each year. Carrasco-Gallego et al (Carrasco-Gallego et al., 2020) proposed the idea of the living lab focused on circular economy, which was the baseline for the development of CELL.

Finally, it should be considered that it is necessary to rethink the HEI’s system regarding procurement as it could enable sustainable practices by developing servitized practices, which would extend product lifecycles, reducing resources’ consumption and lowering the overall environmental impact. In this case, Torres García (Torres García, 2023) presents a first proposal to develop circularity calculators to include sustainable procurement metrics for catering service suppliers within the “contract clauses” at ETSII.

### 2. *RE-NATURALIZE* work area.

Integrating both spheres (techno- and bio-) is not an easy task. Despite this layer of complexity, we have contributed to the transformation of the campus through the following activities.

To deal with the green waste (organic waste) generated in cafeterias and landscaping at UPM facilities, a “food-waste challenge” has been developed as part of a transversal engineering subject for students in their first year. This approach has followed an ALAR approach and provided interesting results from the student’s perspective and imagination. Moreover, while the work presented by Yáñez et al (Yáñez et al., 2023) identifies ideas for food waste composting at the HEI, the work by Agüero et al (Agüero Rodríguez et al., 2023) proves that PLA can be safely re-naturalized upon reaching its end-of-life.

Finally, to take advantage of a plastic waste available at HEI, we have developed a few experiments to transform polypropylene covers (from student’s old homework) to plastic pots, by thermoforming these and making them available for planting.

### 3. *RE-DUCE* work area.

As waste is the most visible part of the misuse of resources it is necessary to provide solutions that tackle (and prevent) its generation, by keeping the materials in the system as long as possible. In this work area we have achieved the following results.

As a top priority to reduce the diverse kinds of waste, it is necessary to characterize the types of waste available at UPM to propose changes to the system to reduce its generation. Villa Bueno (Villa Bueno, 2020) and Cuetos (Cuetos González, 2021) analyzed and quantified the types of waste generated at ETSII, identifying potential solutions for it.

Regarding the reduction of single-use plastics, and based on the good practices detected at UCM and *Caminos Sin Plástico*, along with the schools’ management

at UPM, we have proposed including clauses in the contracts of UPM's catering services and vending machines that allow users to either bring their own containers or, if they do not have one at hand, offer them a reusable packaging service managed with a deposit system (also called DRS – deposit-refund system (Calabrese et al., 2021)). For this, students proposed a DRS system as part of the solutions for the Food waste challenge at the HEI (Yáñez et al., 2023). Additionally, food waste prevention requires that customers are aware how their eating behavior's impact and incur in practices to avoid unnecessary leftovers (Hidalgo-Carvajal, Mejia-Argueta, et al., 2023).

Although outer packaging contributes to the waste generation at HEIs as paper and cardboard have been identified as a significative waste generated at ETSII, these cardboard boxes are still being discarded without considering keeping them in the loop. Hidalgo-Carvajal et al (Hidalgo-Carvajal, Gutierrez-Franco, et al., 2023) studied their returnability to suppliers and identified that customers (i.e., nanostores) have no incentives to do so. Unfortunately, the issue seems to be the same with some procurement activities (including canteens and office' materials) at HEI level. As a way to reduce this waste, we are currently working on initiatives at the *FabLab* to upcycle the material and use it in other spaces as support structures (and even ornaments), reuse the material and avoid directly becoming a waste.

Finally, to reduce the amount of discarded electronic equipment (WEEE) and, additional to the “recycling furniture and electronic consumables” initiative at ETSII, applied research focused on this type of waste has been developed. De Myttenaere (De Myttenaere, 2021) explored sustainable business model to extend the life of smartphones, Soriano González (Soriano González, 2021) analyzed the second life for electric vehicles and their batteries, Hidalgo-Carvajal & Carrasco-Gallego (Hidalgo-Carvajal & Carrasco Gallego, 2021; Hidalgo-Carvajal & Carrasco-Gallego, 2022) studied the future e-waste from photovoltaic modules and provided insights on how the informal recyclers could be included in the system to maximize its recovery.

#### 4. *RE-EXPERIMENT work area.*

The *CircuLab* is intended as an experimentation and connection space where ALAR takes place linking together the community (students, teachers, researchers, staff, and citizens) under the principles of CE.

Thanks to the infrastructure and machines available at the *CircuLab* and *FabLab*, the expertise from researchers and academic community, and the hard work by students from diverse disciplines (e.g., chemical engineering, industrial engineering, mechanical engineering, etc.) and different education levels (i.e., undergraduate and graduate), we have been able to produce a myriad of results in different areas. We summarize these briefly below.

In the plastic waste management area, extensive work has been developed around the plastic from non-renewable origin as well as bioplastics.

- In the non-renewable plastics, Ramírez Arenas (Ramírez Arenas, 2022) devised a low-cost method of classification and separation of polyolefin plastics waste, which can be later transformed to different pieces through injection process.
- Regarding the bioplastics, work related to evaluating the technical viability of PLA mechanical recycling (Beltrán et al., 2021; Moreno et al., 2020; Moreno Escribano, 2020) and its circularity (Gil Muñoz et al., 2020) through different extrusion cycles (Hidalgo-Carvajal, Muñoz, et al., 2023; Hortal Muñoz, 2021) has been performed. Furthermore, thanks to the ALAR approach at CELL, students have been able to experience first-hand the circular processes by using recycled PLA materials to manufacture new 3D printed parts for different applications (Agüero et al., 2023; Hidalgo-Carvajal, Carrasco-Gallego, et al., 2023). Thanks to the established protocol to process the waste material (i.e., misprints, 3D-printing support structures, discarded PLA products) (Gil Muñoz et al., 2020) available at UPM we can continue experimenting with different types of polymers, mixtures, and additives for the production of 3D printing filaments from used materials.

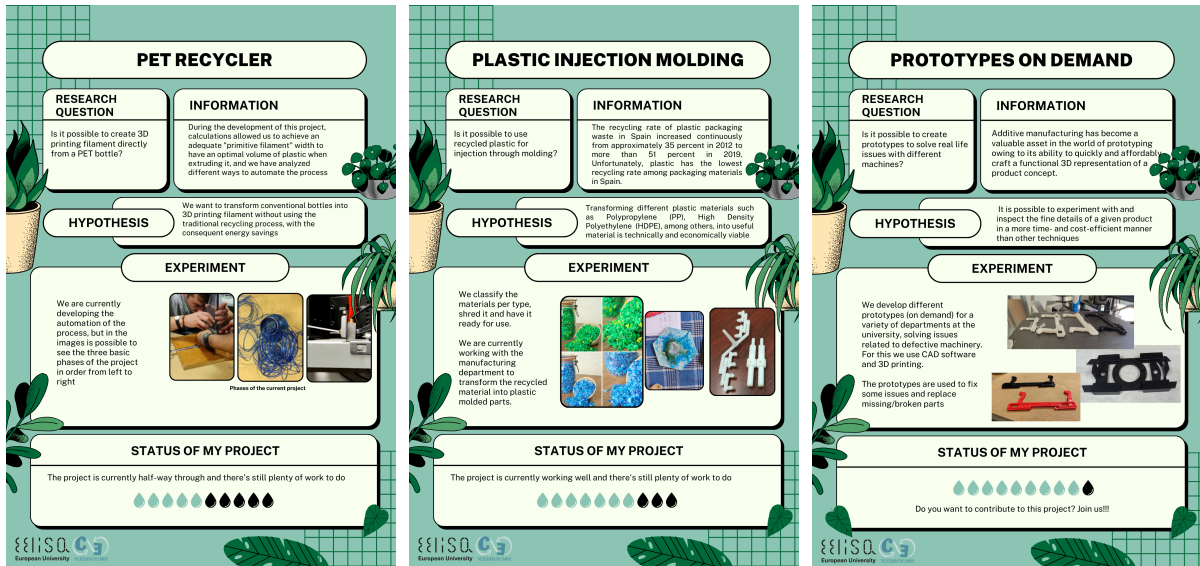
As paper waste is also a valuable resource widely available at the entire UPM, Serrano Gamir (Serrano Gámir, 2022) has been developed a process related to the recovery and upcycling of the material at ETSAM, in which the discarded architecture models have been collected, their materials sorted and the paper and

cardboard has been used to manufacture sound-proof panels to be installed in different classrooms.

Another type of “low-value” waste used to experiment has been the concrete, part of the CDW. Novellón Coloma (Novellón Coloma, 2023) has proposed a project on which the concrete has been used as an input in the jewelry manufacturing process, thanks to some of its mechanical and chemical properties.

Given the diversity of waste available at HEIs and considering that CE calls for imagination to integrate different processes to avoid waste generation, we take advantage of the machines available at the *CircuLab* and *FabLab* to generate a home-made machine. Chapon (Chapon, 2023) developed a human-powered shredding machine, namely “*La Recicleta*” (the recycling bicycle), which combines a bicycle, old pallets, rubber, metal parts and other materials, to create an alternative method for plastic recycling.

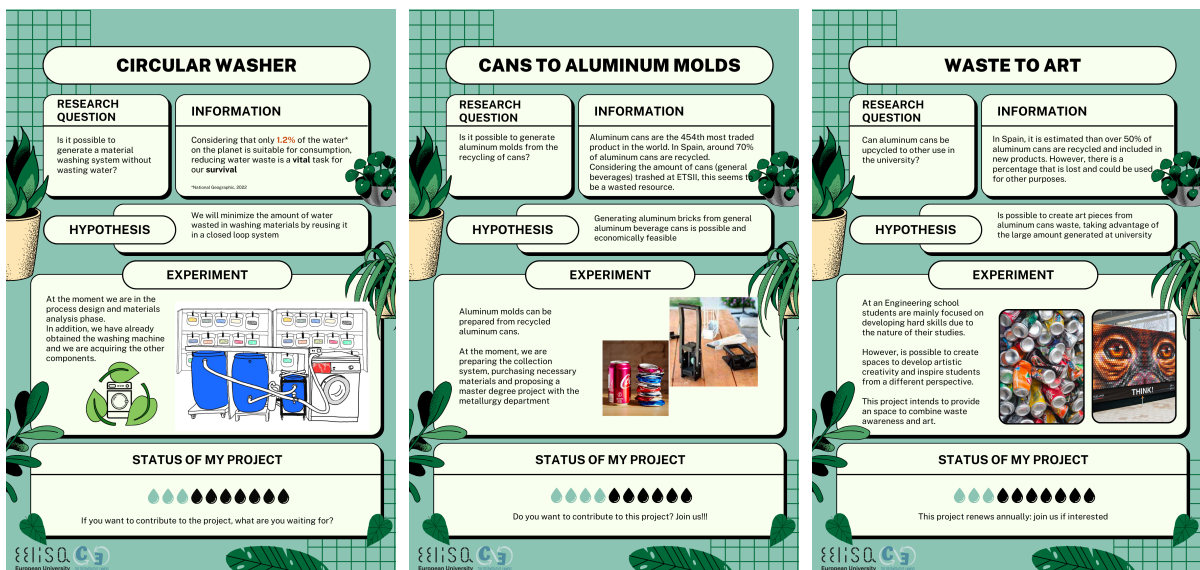
Through ALAR approach, students and researchers propose different projects and initiatives incorporating circular processes, which intend to continue experimentation to reduce waste generation at UPM. In the figure 38, we present the projects currently under development, among which are included: **a)** a recycled PET filament production line, transforming the bottles directly to useful PET 3D printing filament, **b)** classifying and shredding PP and PE materials, to have them ready for plastic molding extrusion, **c)** generating 3D printed prototypes upon request, taking advantage of our recycled materials, **d)** creating a zero-waste (water) washing machine to clean the plastic materials while keeping the water for several cycles, **e)** collecting the aluminum cans and melting them to create different molds which can be later used for other processes, and **f)** using the aluminum cans to create art murals.



a) Pet bottle to filament

b) plastic injection molding

c) prototyping



d) closed-loop washer

e) aluminum molding

f) waste to art

Figure 38. Projects currently under development at CircuLab. Own development.

As it can be seen, *CircuLab* has become not only a space where the machines and university projects are housed but also an area for reflection, dialogue and experimentation for the university community and the citizens of Madrid around the circular economy.

5. *RE-GENERATE* work area.

Identifying the hidden value of the waste in HEI to further close the loop through reduce, reuse, recycle and regenerate activities is essential to support building and preserving natural capital. Here we present results achieved on this area.

Among the waste available at HEIs, as previously mentioned plastic waste is an important material that can be recovered and transformed for reuse. Moreno Escribano (Moreno Escribano, 2020) proved the viability of recycling PLA waste, Agüero et al (Agüero et al., 2023) showed that the resulting material can be used to manufacture customized lab elements and equipment, Hortal Muñoz (Hortal Muñoz, 2021) verified the number of cycles that the material can be recycled, Hidalgo-Carvajal et al (Hidalgo-Carvajal, Muñoz, et al., 2023) proposed a traceability process to maximize the number of cycles the material can be recycled, and Agüero et al (Agüero Rodríguez et al., 2023) corroborated the compostability of the material at the end of life. The overall process demonstrates that the material can be extracted, used in the technosphere for several cycles and safely returned to the biosphere. Furthermore, Palacios Rodríguez (Palacios Rodríguez, 2021) analyzed the recovery of PLA waste from food packaging and food trays from a nearby store, expanding the footprint that the project has in the community outside of the HEI campus.

The use of food waste to generate value has also been explored. For example, Solís Lorente (Solís Lorente, 2023) investigated the process to manufacture bioplastic films for food packaging from Kombucha, which is a probiotic drink that can be prepared from tea (or coffee) waste, fermented with sucrose and yeast (SCOBY). The bacterial cellulose films are a by-product of the resulting beverage.

As mentioned in the RE-EXPERIMENT section, “low-value” waste can be upcycled, repurposed, and/or introduced as raw materials in other industries. As proof, Serrano Gamir (Serrano Gámir, 2022) use paper waste from architecture models to create sound-proof panels, Novellón Coloma (Novellón Coloma, 2023) employ the concrete from CDW as an input in the jewelry manufacturing process, and Chapon (Chapon, 2023) combines different types of waste to develop “*La Recicleta*” (the recycling bicycle).

As it can be seen from the different results, there's currently applied research at laboratory/local level, however, scaling to the industrial sector still requires further development.

### *6. RE-CONNECT work area.*

Finally, to be able to expand the impact that CELL can have through industrial symbiosis, it is necessary to connect with other nodes in the system. Here we present the achieved results.

First of all, it is important to highlight that since the conception of CELL, a total of 17 non-academic partners and 10 academic partners (see Figure 27), have joined the initiative, contributing to the research and learning activities of the academic community. Thanks to this network, CELL has been able to accomplish academic and socially impactful outcomes at different levels: within the HEI and its surroundings, extended local community, and the system in general.

The following results illustrate the influence that RE-CONNECT lines have at the HEI and its surroundings level. Gil Cordero (Gil Cordero, 2022) contributes to the campus decarbonization and energy transition initiative by carefully evaluating the environmentally relevant impacts related to replacing non-renewable sources with renewable technologies through a Life Cycle Analysis (LCA) performed at the Renewable Energy Resources Laboratory of the University of Bucharest where the previous heating and cooling system supplied by natural gas (fossil fuels) was upgraded to include renewable technologies (i.e., geothermal heat pumps, and hybrid solar panels). Chillón Bartol (Chillón Bartol, 2023) studied how waste is currently being managed at the different facilities of the Spanish Superior Council of Scientific Investigations (CSIC, for its acronyms in Spanish) campus, and proposed creating a Sustainability Office to develop guidelines to standardize their practices and design centralized waste management systems that enable industrial symbiosis.

Among the results, we highlight the contributions that the applied research and outreach generated in the extended local community. For instance, Amo Garcia (Amo García, 2020) proposes implementing a Pay-as-you-throw (PAYT) system for the city of Madrid, aiming to identify a viable solution to improve waste

management and treatment in the city of Madrid, by maximizing the recollection and recycling rates, and limiting the amount of waste generated by users as these are charged a rate based on how much waste they present for collection to the municipality. Gordillo Alcalá (Gordillo Alcalá, 2021) analyzed the composition of the waste generated at Chamberí municipal market, one of Madrid's food markets, identifying great potential for material recovery and later reintroduction in the production system, through selective collection and compaction. Campos Molina (Campos Molina, 2022) assessed circular economy metrics for the Line 11 project by Metro de Madrid, analyzing its environmental impacts from a people-oriented service point of view and creating a set of indicators for its successful implementation, and lastly, recommending developing guidelines for similar projects. Finally, Conejero et al (Conejero et al., 2022) propose changes in the current waste management regulations in the city of Madrid and test this regulatory innovation in the development of the Madrid Nuevo Norte project (which includes two main districts in the city) to implement circular economy practices to give a “second life” to roughly 90% of the materials already present in the project area.

Moreover, changes in the system require active participation of several parties and collaboration between them. Changes can be approached from different points of view in the system. For example, from the manufacturer point of view, it is possible to change the way that companies approach the customer by offering services instead of pure products was studied by Hidalgo-Carvajal et al (Hidalgo-Carvajal et al., 2021), where they highlighted the role that servitization plays in the shift from linear production systems towards circular systems, described the challenges and drivers that companies face when embracing this transition, and suggested that collaboration enables an effective change.

From the product's end of life point of view, Hidalgo-Carvajal & Carrasco-Gallego (Hidalgo-Carvajal & Carrasco Gallego, 2021) emphasize the need to minimize the waste inherent to the material losses of discarded products and maximize material recovery rates by complementing the formal recycling system through including the informal recyclers in the system, given their experience with second hand markets and other informal marketplaces, and knowing that they are already part of the system despite not being officially recognized.

Another perspective usually “unintentionally” omitted are the social aspects ingrained in the manufacturing of any product. Fernández Aguirre et al (Fernández Aguirre, 2021) and Hidalgo-Carvajal et al (Hidalgo-Carvajal, De Stefano, et al., 2023) studied the Social Life Cycle Analysis (S-LCA) and identified the lack of standardized methods to analyze the social impacts of products and services. Given the key role that these social issues play along supply chains and, with the growing trend towards circular supply chains, Hidalgo-Carvajal et al (Hidalgo-Carvajal, Picanço-Rodrigues, et al., 2023) conceptualized social issues as complex systems due to their high levels of interconnectedness among intricate variables, and proposed a classification scheme for the social performance measurement of circular supply chains based on the concept of system’s leverage points and their effect on the many actors and stakeholders across supply chains, from companies and non-governmental organizations to communities and public agencies.

Additionally, as one of the pillars of the HEI is achieving social impact through outreach, we have engaged other actors from civil society to share the generated knowledge. In the RE-THINK area, we described the results achieved with private (Ecoembes) and public (CIEC) entities thanks to the collaboration and connection with these entities. However, the dissemination work with other educational entities was not mentioned in that section. Consequently, we would like to mention that CELL has been actively engaged in educational processes directed to elementary, middle and high-school students, taking part in several academic tours at ETSII (2021-2023), engaged in the activities of “Semana de la ciencia” (Science week) organized by the Ministerio de Ciencia e Innovación (The Ministry of Science and Innovation) and the City Council of Madrid (2021-2023), participated in La Noche Europea de los Investigadores de Madrid (The European Night of Researchers in Madrid) (2020-2022) and several activities for the UPM community.

Finally, it is important to highlight that, thanks to the proven impact achieved by the academic community (i.e., students, researchers, and staff) actively participating in the project, we have received the following awards which validate our efforts and show the impact that CELL has: **a)** First prize of the university competition “*Project Lab Youth4Good*” from Fundación Vodafone España in 2020, **b)** Runner-up prize at the *II BASF Circular Economy Awards* (II Premios BASF a la mayor práctica de Economía Circular en España) in 2020, **c)** First prize at the

First edition of the *Ford College Community Challenge* by Apadrina la Ciencia and Ford Foundation in 2019, **d)** Runner-up prize at the Second edition of the *Ford College Community Challenge* by Apadrina la Ciencia and Ford Foundation in 2021, **e)** First prize at the Third edition of the *Ford College Community Challenge* by Apadrina la Ciencia and Ford Foundation in 2022.

## 5.6. Conclusions

The main conclusion of this chapter is that the CELL initiative developed at ETSII-UPM demonstrates that it is possible to create an innovative approach to integrate the four core HEIs' areas to promote the principles of a circular and regenerative economy. It is also key to highlight that this is possible thanks to the collaboration with a wide range of stakeholders (internal and external), which facilitates generating hands-on learning environments where students can apply the knowledge acquired in the classroom. Thanks to the active participation approach inherent at CELL, different models of collaboration are possible, fostering ecosystems for applied and impactful research for different members of the community.

Developing CELL's framework was possible through a comprehensive analysis of the different waste flows and management practices currently in practice, generating a baseline to propose specific work areas (i.e., Re-think, Re-naturalize, Re-duce, Re-experiment, Re-generate, and Re-connect) aimed to tackle the complex challenges of implementing the principles of circular economy. The proposed work areas, compared to the functions of the brain, highlight the interconnected nature of CELL, which should be fully considered to achieve a closed industrial metabolism.

The obtained results demonstrate CELL's contribution to advancing CE concepts within HEIs, not only from a research perspective but also in implementing these within the teaching, outreach and campus management activities. Implementing ALAR methodology has been fundamental to engage students and researchers in practical projects addressing real-world issues, and enhancing their educational background and professional training as future leaders in sustainable practices.

Aligning CELL with global and local sustainable goals (i.e., UPM's decarbonization goals and SDG nodes) demonstrate the importance of the initiative to implement the different CE principles into the HEIs' four core areas. Moreover, this approach

not only demonstrates UPM's commitment to sustainability but positions the institution as a leader in implementing CE practices, generating more sustainable and resource-efficient campuses, which can be replicated by other HEIs. Furthermore, this framework can serve as a model for other institutions and sectors interested in implementing sustainable and circular practices.



## 6. The Circular Economy Living Lab from a Circular Supply Chain perspective

*“Supply chain is like nature; it is all around us”. Dave Waters*

### 6.1. Introduction

In this chapter, the reader will be introduced to a point of view under which higher education institutions (HEIs) are understood from a supply chain (SC) point of view. Although, due to their nature, HEIs are not mainly manufacturers of physical products, they do generate two main “products”: Knowledge (through teaching and research) and well-trained professionals. Then, HEIs serve as nodes for innovation and knowledge dissemination, and can become test-benches for testing and validating theoretical concepts in real-world scenarios. Furthermore, HEI campuses offer a unique opportunity to integrate research and education, through hands-on experiences, to test different projects that involve resource recovery, material reuse and waste minimization, generating empirical insights which can provide tangible benefits for different entities along the supply chain.

### 6.2. Understanding HEIs from a Supply Chain perspective

We can define HEIs as “public (or private) organizations” as they have customers, stakeholders, costs, competitors and generate “products”. Furthermore, HEIs face fluctuating challenges in the environment (Lichy & Enstroem, 2015) and in the customer behavior (Emiliani, 2004). This broad set of characteristics could be equivalent to the definition given to a “commercial organization”, where the organization is “a person or entity engaged in the buying, selling, or production of goods and/or services for profit, or not, regardless of being publicly or privately owned” (Investopedia, 2022; LawInsider, 2023).

Additionally, considering the production process where the inputs and outputs can be tangible (i.e., financial, and physical assets) (Ombaka et al., 2015) or intangible (i.e., knowledge, experience and skills, brand name and reputation, and all related organizational processes) (Rockwell, 2019), it is possible to understand the direct correlation between commercial entities and HEIs through the value chain approach with the value stream based on primary and secondary activities (Groves et al., 1997; Pathak & Pathak, 2010), later redefined as the primary and support activities (Hutaibat, 2011). The value chain approach, adapted from Porter (Porter, 1985) for the HEI, contemplates the tangible and intangible streams in the system following the supply chain (SC) structure, making it possible to identify the education processes analogous to general supply chain management (SCM) processes, considering operations related to product development and its inherent waste. In general, HEI's value chains perform a wide range of activities to meet a myriad of objectives with the ultimate goal to add value to society (Hutaibat, 2011; Morien, 2019; Pathak & Pathak, 2010).

In the case of ETSII-UPM, a value chain approach for the HEI has been developed and presented previously the Social Responsibility Report 2014 (ETSII-UPM, 2014) and updated later in the Social Responsibility Report of 2016 (ETSII-UPM, 2016), which included additional processes. The value chain is presented in the figure 39 below.

Following the supply chain perspective within the value chain approach, we can further identify two main flows in the HEI system: material flow (tangibles) and information flow (intangibles). In the case of the material flow, we refer to the different tangible products necessary to develop the main activities within the system, such as teaching materials (i.e., books, teaching notes, etc.), laboratory products, furniture, Information and Technology (IT) infrastructure and computer supplies, general office supplies, maintenance supplies, non-essential materials (i.e., packaging, general disposable waste), among other products. In the case of the information flow, we mention the intangible materials that are needed for the system to work, such as the general administration information (i.e., staff and student information, payrolls, budgeting, etc.) and the education administration (research and teaching) information (i.e., curriculum design, teaching timetables, course and subject enrolments and allocation, grading, feedback from students, research results, etc.). Finally, both types of flow take part in the "*pedagogical production line*" (Morien, 2019) with incoming students (raw materials) who go

## The Circular Economy Living Lab from a Circular Supply Chain perspective

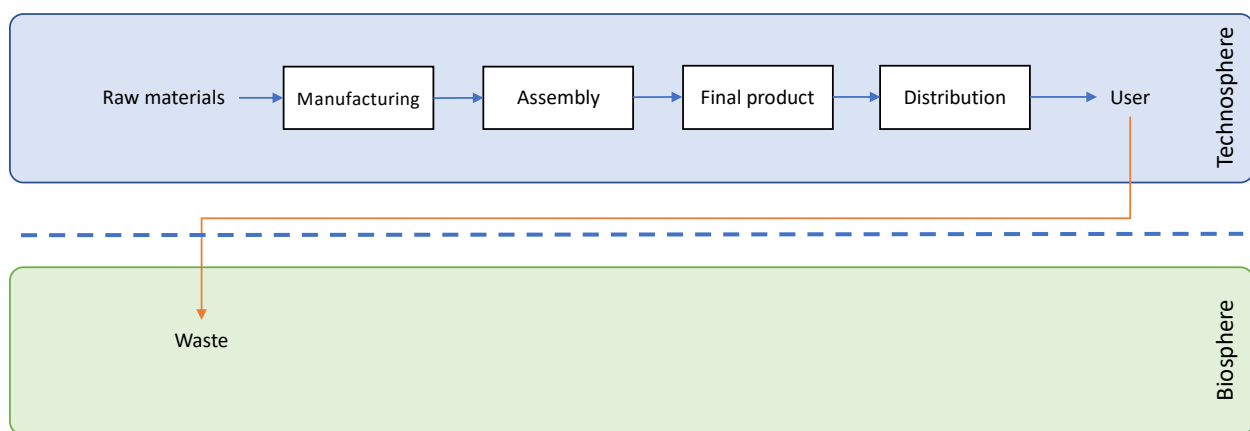
through their educational section of the system (production line) until satisfactory completion of their studies (finished product) and return to the system (society), and at the same time envision to follow “*leagility*” (Rahiminezhad Galankashi & Helmi, 2016) principles, combining lean thinking principles and agile education practices, while avoiding unnecessary educational wastes.

<b>University infrastructure</b>		Needs' identification and satisfaction; Infrastructure and service management; Economic Management; Environmental management			
<b>Academic administration</b>		Policies, communication & marketing; Strategic planning; Social Responsibility; Government; Alliances; Competitor surveillance; Communication & awareness; Code of ethics; Internal Guarantee Indicators (GI) Management: active participation and commitment to improvement processes; Creation of collaborative environments; Teaching support processes; Research support processes; Management support processes			
<b>Human Resource Management</b>		Selection and admissions; Training; Recognition and motivation; Work environment management; Promotion and professional development; Occupational Risks; Equality; HR Policy; Risk prevention			
<b>Technology Development</b>		Identification of technological needs (teaching and research); Implementation of new technological resources			
<b>Procurement</b>		Sustainable purchasing management; Including responsible practices in the outsourcing of services			
	<b>Inbound logistics</b>	<b>Operations</b>	<b>Outbound logistics</b>	<b>Marketing and sales</b>	<b>Service</b>
<b>Teaching</b>	<b>Student arrival</b>	<b>Knowledge transfer</b>	<b>Student / work environment relationship</b>		<b>Feedback and alumni management</b>
	* Selection * Student Admission * Reception processes * Relationship with potential students	* Teaching support processes * Preparation, teaching and evaluation of subjects * Promote comprehensive training * Quality learning * International exchanges * Innovation in education * Teaching improvement	* Advising Bachelor/Master theses * Internships in companies * Job insertion * Entrepreneurship * Training results	* Relationship with contractors (private companies, NGOs and public administrations) * Competitor surveillance	* Alumni management
<b>Research</b>	<b>New researchers</b>	<b>Generating new knowledge</b>	<b>Knowledge transfer to society</b>		<b>Feedback and relationships with external organizations</b>
	* Selection * Admission of researchers * Onboarding process * Tutoring new researchers	* Research support processes * Resource and knowledge management * Basic and applied research * Researcher training * Research seminars * Research and society * Research resources * International mobility of researchers * Interdepartment collaborations	* Transfer of new techniques * Technology transfer * Knowledge transfer * Research results	* Collaboration mechanisms with Relationship with other companies (private companies, NGOs and public administrations) * Competitor surveillance	* Relationship with external stakeholders and other organizations
<b>Impact</b>	<b>Relationship with society</b>	<b>Connecting University &amp; Society</b>	<b>Scientific outreach</b>		<b>Feedback and relationship with society</b>
	* Selection of strategic external stakeholders	* Increase in technological vocations * Increase in relations of external stakeholders with the university	* Promotion of scientific and cultural dissemination events * Communication and awareness * Volunteering	* Communication and social networks	* Relationship with general society

**Figure 39.** HEI's value chain – adapted from (ETSII-UPM, 2014, 2016, 2018; Groves et al., 1997; Pathak & Pathak, 2010; Hutaibat, 2011; Morien, 2019)

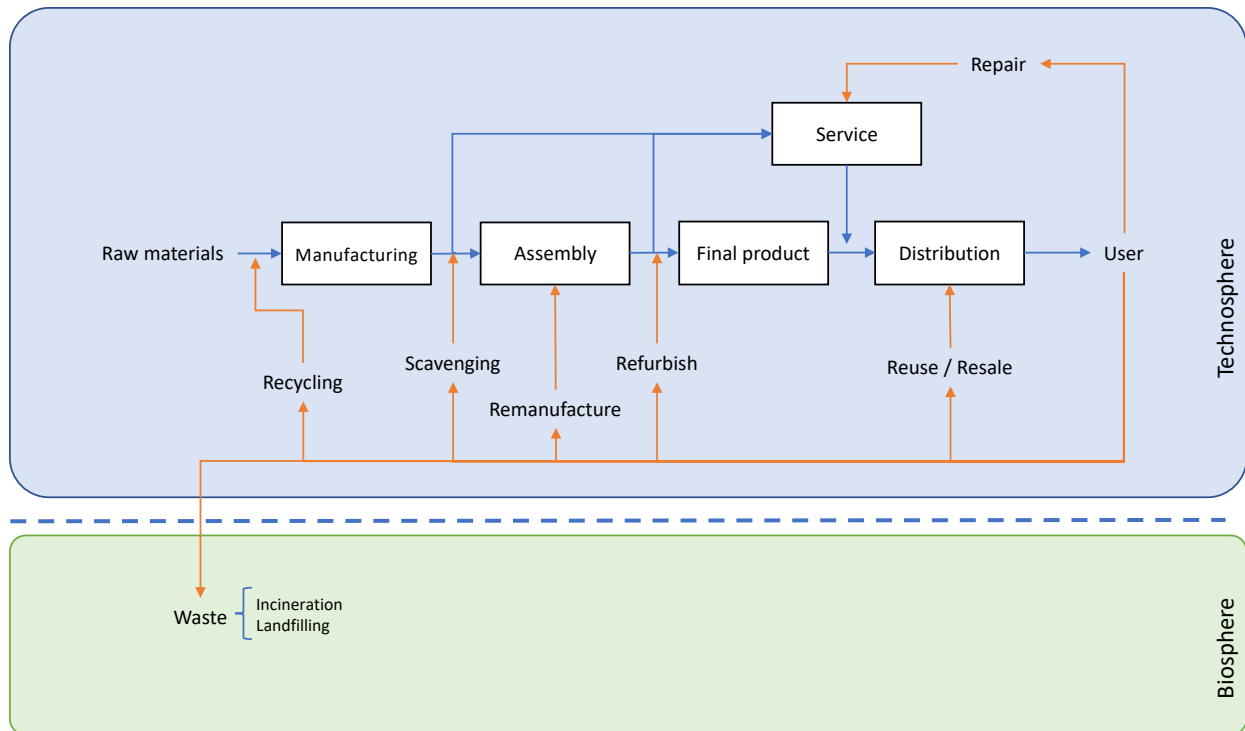
In the tangibles side, HEIs are considered to follow a multi-commodity supply chain strategy as their material flow structure behaves like a linear-system: receive inputs from the outside which could be considered as raw materials (i.e.,

materials and people), the user experiences/uses the product (i.e., material flow – facilities, educational material, experimentation materials, among others) or service (i.e., education and research) and finally the material is returned to the system (i.e., trained professionals and physical material waste). As it can be seen from a SCM point of view of material flow, HEIs have a direct influence in the techno- and bio- spheres, as presented in the figure 40 below, where the blue line represents the linear manufacturing system allocated in the techno-sphere (in blue), while the orange line represents the waste disposed in the bio-sphere (in green).



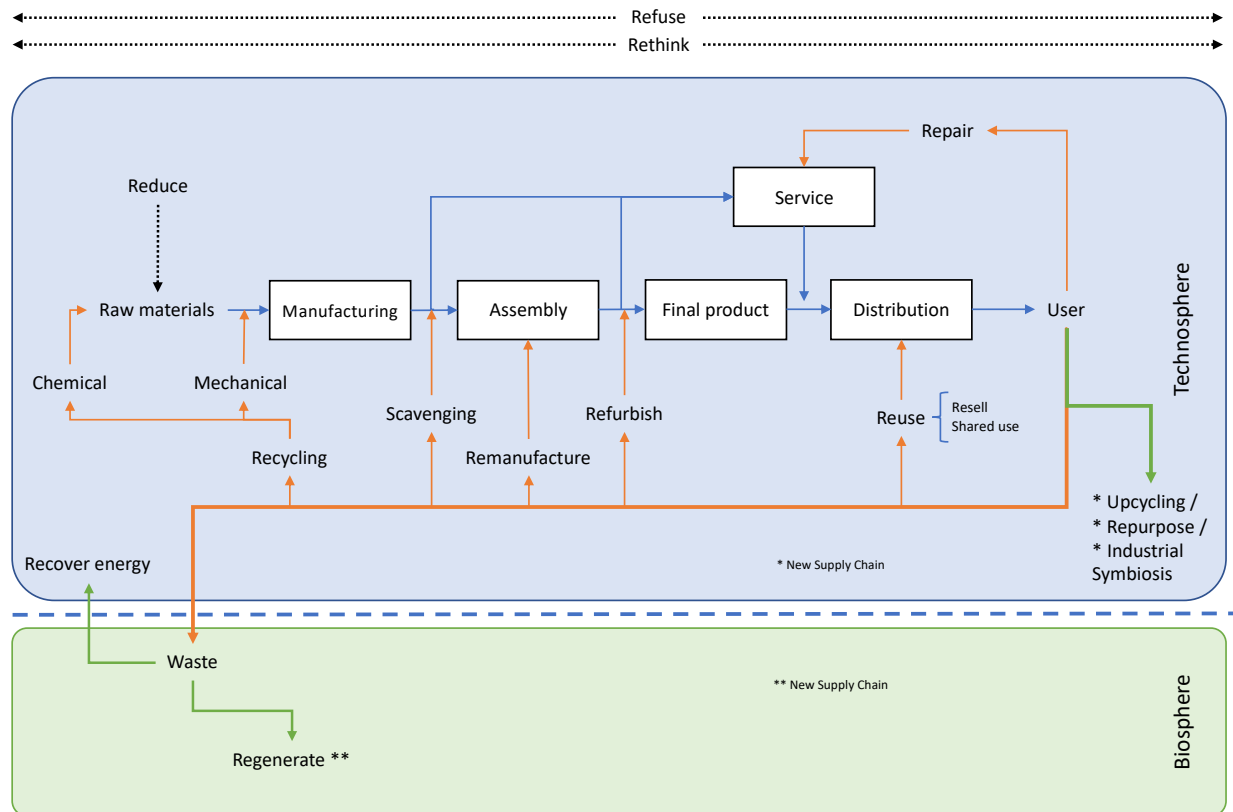
**Figure 40.** HEI's material flow as a linear system – adapted from (*Ellen MacArthur Foundation, 2015; McDonough & Braungart, 2002; Thierry et al., 1995*)

Furthermore, given the changing needs of society and the fluctuating environment, it is important that HEIs adapt to updated concepts which impact society in general, changing the way on which they currently operate. One of these concepts with high traction over the last decades is sustainability (Velazquez et al., 2005), through the development of the different “R” frameworks, and more recently, the circular economy (Mendoza et al., 2019b). The processes presented in the product recovery management (PRM) strategy proposed by Thierry et al (Thierry et al., 1995) should be included in the HEI management system, along with additional strategies to supplement the current state of the linear system to make it more circular. In the figure 41 below, we present the adapted model by Thierry et al (Thierry et al., 1995), including the product recovery strategies and which of the spheres (bio and techno) these influence the most.



**Figure 41.** HEI's material flow following a product recovery management strategy – adapted from (*Ellen MacArthur Foundation, 2015; McDonough & Braungart, 2002; Thierry et al., 1995*).

Under this consideration, we present a proposition of how the supply chain for tangibles within HEIs can be improved to move from a traditional linear system towards a circular system where the different tangibles can be returned to the system. Through the different “R’s frameworks” (from 3R to  $n^{th}$ R) in sustainability and, considering the triple bottom line (Alhaddi, 2015; Elkington, 1998; Tseng et al., 2020) as cornerstone, it is possible to update the model proposed by Thierry et al (Thierry et al., 1995) to include additional circular initiatives, as presented in the figure 42 below.



**Figure 42.** HEI's material flow as a circular supply chain system. *Own development.*

The figure 42 presents an updated approach to the supply chain, and includes the different practices commonly conceptualized under diverse “R-frameworks”, aiming to maximize recovery of materials and shift the traditional linear supply chains towards more circular supply chains (CSC) (Kirchherr et al., 2017; Reike et al., 2018). Additionally, the proposed approach also facilitates evaluating different key criteria in the sustainability rankings intended to improve campus sustainability.

### 6.3. Allocating the academic literature within the CSC framework

In addition to categorizing the different academic articles within the four core HEI areas, it is also important to catalogue them following a supply chain approach, considering the different stages on which products (and services) are developed, from the design stage to the final disposition of the product.

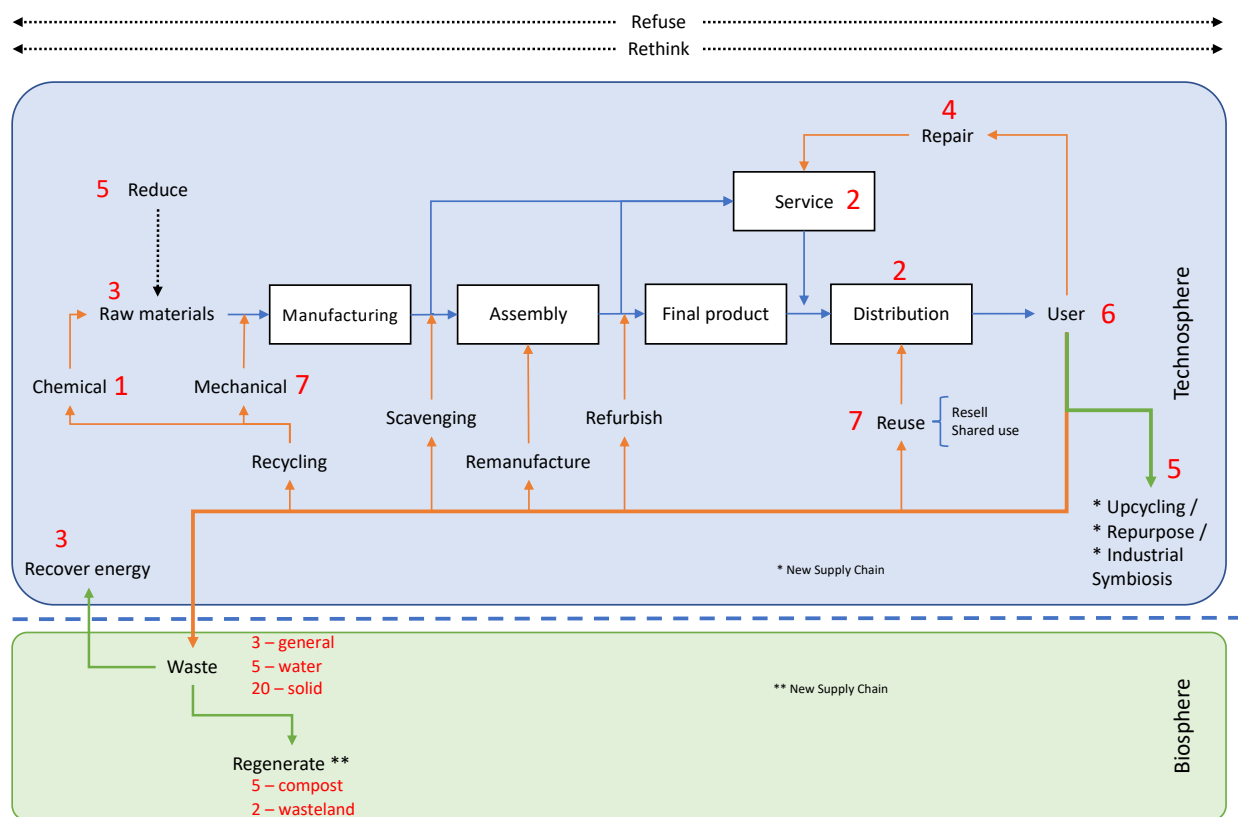
Thanks to the SC approach presented in section 6.2, we were able to identify that out of the 176 documents it was possible to allocate 80 directly into the CSC

## The Circular Economy Living Lab from a Circular Supply Chain perspective

approach, while 96 cover more general topics which cannot be allocated to one specific section of the approach.

In the figure 43 below, it is possible to see allocated academic topics according to the different areas pertaining to the CSC strategy. It is important to highlight that the academic documents are part of the four core areas of HEIs and are not exclusively from one of these.

Following the supply chain flow from the beginning, we can identify documents focusing on reducing the need for new products by using materials intending to improve the user's comfort within the HEIs. This aims to reducing the need for fossil fuels to improve the lighting conditions (Behi et al., 2021; Beu et al., 2018; Ciugudeanu et al., 2019) and the climatization (Bakos & Schiano-Phan, 2021; Díaz-López et al., 2022) of the institution. Then, the advance of sustainable raw materials has been identified by 3 documents (Blok et al., 2019; Iuorio et al., 2019; Vuylsteke et al., 2022) which suggest the importance of developing this type of materials for a consistent CE strategy.



**Figure 43.** Number of academic documents allocated per topic, following the proposed Circular Supply Chain approach at HEIs. Own development.

Then, after a final product can take two roads to reach the user: a service approach, or directly reaching the user. From the service approach, understood as having a renting and/or leasing option for the user to enjoy the product, the documents by (Sánchez-Carracedo & López, 2021; Sumter et al., 2018) suggest that this approach presents benefits for the user and the manufacturer. From the second perspective, the product can reach the user directly through a variety of suppliers, therefore sustainable procurement (Gutierrez et al., 2020; Zaidi et al., 2019) is key to ensure that the user is receiving the products in the most sustainable manner.

After that, the user is responsible for the proper use of the product and its maintenance and, ultimately, its disposal. The user's responsibility in supporting adequate waste management is highlighted by 6 documents (Ebrahimi & North, 2017; Ferronato et al., 2020; Gallo et al., 2017; Gherheş et al., 2022; Smyth et al., 2010; Stephan et al., 2020), focusing on how the waste should be collected, properly sorted and measured, and furthermore, create strategies to prevent and reduce the waste generation.

Regarding the cycles of circular economy (Ellen MacArthur Foundation, 2021), it is possible to identify how the CSC approach is directly linked with the different processes to ensure the product is retained in the system for the longest time, from the shorter cycles to the largest ones, and considering its end of life.

Repairing would be the first option for a user as demonstrated by (Bigerna et al., 2021; Bonoli et al., 2018, 2021; Terzioğlu & Wever, 2021), which show the benefits for the user of keeping the product, and for the system, to eliminate the need for new materials to create new products.

As second option, the reuse of products considers other processes as shared products, resell and re-gifting of products is presented. As a result, 7 documents were identified from which (Leclerc & Badami, 2022; Shittu et al., 2021) deal specifically with EEE, (Kumdokrub et al., 2023; Rizzo et al., 2017; Sacco & Cerreta, 2020; I. Williams & Powell, 2019) with reuse of products in general and (Cerreta et al., 2020) mentions the reuse of a building.

Fortunately, the following cycles consisting of refurbish and remanufacture of products have been also considered within previous strategies (Leclerc & Badami, 2022; Sánchez-Carracedo & López, 2021; Sumter et al., 2018).

The next cycle would include the recycling perspective which can be split into two main topics: downcycling and upcycling.

From the downcycling perspective, eight documents were identified from three main areas: solids, plastics and WEEE. The documents regarding solid waste are related to general materials (i.e., cardboard, glass and fabrics) (Christensen, 2021; Mbama et al., 2023; Moustairas et al., 2022). In the plastics area, three documents were identified from which (Gil Muñoz et al., 2020; Hidalgo-Carvajal, Muñoz, et al., 2023) are related to biopolymers and (Park et al., 2023) to traditional polymers. Finally, (Pierron et al., 2017; Saldaña-Durán & Messina-Fernández, 2021) focus on recycling WEEE to maximize material recovery.

On the upcycling perspective, under which the repurposing and the industrial symbiosis are also considered, five documents present solutions to transform waste into useful products that can be used in a different supply chain (James & Kent, 2019; Leblanc, 2020; Mahdi et al., 2021; Mansour et al., 2020; Matrapazi & Zabaniotou, 2020).

Finally, once the product has reached its end of life, a proper management of the waste it is necessary and, as literature shows, a large focus has been put here with a total of 28 documents related to the *waste* management. A total of three documents (Fleischmann, 2019; Nolasco et al., 2021; O. M. Owojori et al., 2022) present propositions on how HEIs should manage their waste to avoid landfilling and reduce environmental impacts. Specific solutions for general solid waste (i.e., glass, cardboard, organic) are proposed in seven documents (Bringsken et al., 2018; Jaglan et al., 2022; Merchán-Sanmartin et al., 2021; O. Owojori et al., 2020; Rada et al., 2020; Tangwanichagapong et al., 2017; Virsta et al., 2020), solutions for plastic waste in four documents (Bianchini & Rossi, 2021; Galati et al., 2022; Maruyama et al., 2019; Mottese et al., 2021), and propositions to solve food waste issues in nine documents (Bas-Bellver et al., 2020; Börühan & Ozbiltekin-Pala, 2022; Brenes-Peralta et al., 2020; Klammsteiner et al., 2021; Kooduvalli et al., 2020; Leal Filho et al., 2023; Liang et al., 2022; Maçin et al., 2023; Yeo et al., 2019). Additionally, five documents mention the importance of considering an adequate water waste management (Colares et al., 2019; Mannina et al., 2021; Merchán-Sanmartín et al., 2022; Weissbrodt et al., 2020; I. D. Williams et al., 2018).

Finally, to avoid losing the inherent properties of the material, it is important to consider recovery strategies to avoid discarding the materials without taking full advantage. Next to the waste management we can identify two recovery strategies in action. On one side, seven documents focus on regenerating the waste, with five documents focusing on composting and returning the material to nature (Erälinna & Szymoniuk, 2021; Jakimiuk et al., 2023; Keng et al., 2020; Kumble, 2019;

Torrijos et al., 2021), while two documents focus on wasteland regeneration (Mateus et al., 2020; Rigillo et al., 2018). On the other side, we identify three documents focusing on the energy recovery and generation from waste (de Sousa et al., 2022; Kılıkış & Kılıkış, 2017; Vaskalis et al., 2019).

The 96 documents that were not allocated directly within the circular supply chain flow, can be considered as of support to the development of circular economy and have been allocated within the table 4 below per topic.

Topic	Campus management	Outreach	Teaching	Research
Life cycle analysis		(Piekarski et al., 2019)	(Duane et al., 2020; Gomes et al., 2022; Reichmanis & Sabahi, 2017)	
Product design		(Bakırhoğlu et al., 2021; Hall & Velez-Colby, 2018)	(Baeza & Quinn, 2021; Leube & Walcher, 2017; Neto, 2019; Predan, 2020; Ryńska, 2020; Sadowski, 2021; Sumter et al., 2020, 2021; Villalobos et al., 2021; Watkins et al., 2021; Widera, 2021)	(Vink, 2020)
Collaboration		(Bakırhoğlu & McMahon, 2021; De Medici et al., 2018; Koprina, 2021a; Newton & Frantzeskaki, 2021; Raeva et al., 2021; Wandl et al., 2019; Whitehill et al., 2022)	(Janssens et al., 2021; Wolf et al., 2022)	(Hart et al., 2021)
Sustainable campus development	(Amenta & Qu, 2020; Ares-Pernas et al., 2020; Fortes et al., 2021; Hopff et al., 2019; Lee et al., 2022; Mendoza et al., 2019a, 2019b; Nunes et al., 2018; Omazic & Zunk, 2021; Ottoni et al., 2022; Ozdemir et al., 2020; Qu et al., 2021; Ramakrishna et al., 2020; Salas et al., 2021; Salguero-	(Gao et al., 2006)	(Bugallo-Rodríguez & Vega-Marcote, 2020; Soto-Solier et al., 2023)	(Korance, 2021)

## The Circular Economy Living Lab from a Circular Supply Chain perspective

	Puerta et al., 2019; Sawalkar et al., 2023; Valls-Val et al., 2023)			
Developing business models		(Fernandes et al., 2021)	(Atalay Onur, 2020; Del Vecchio et al., 2021)	
Competences and skills			(Baptista et al., 2021; Burger et al., 2019; Giannoccaro et al., 2021; Hudima & Malolitneva, 2020; Qu et al., 2020; Spreafico & Landi, 2022; Vera-Puerto et al., 2020)	
Gamification and new tools			(de la Torre et al., 2021; Deda et al., 2022; Fraccascia et al., 2021; Jääskä et al., 2021; Kioupi et al., 2022; Manshoven & Gillabel, 2021; O'Grady et al., 2021; Sierra & Suárez-Collado, 2021; Whalen et al., 2018)	
Innovation in curriculum		(Sukiennik et al., 2021)	(Alonso-Calero et al., 2021; Faludi et al., 2023; Geng et al., 2009; González-Domínguez et al., 2020; Hoffman et al., 2021; Ibelli-Bianco et al., 2022; Kirchherr & Piscicelli, 2019; Kopnina, 2014, 2018, 2019a, 2019b, 2020, 2021b; Kowasch, 2022; Landrum, 2021; Liu & Côté, 2021; Loste et al., 2020; Manieson et al., 2021; Obrecht et al., 2022; Prieto-Sandoval et al., 2022; Qu et al., 2022; Rodríguez-Chueca et al., 2020; Sánchez-Carracedo et al., 2020; Senthil, 2022; Summerton et al., 2019; Venugopal & Kour, 2021)	

**Table 4.** Topics covered by the academic text that cannot be directly allocated within the CSC model. Own development.

## **6.4. Allocating CELL's results within the CSC framework**

Likewise, the same methodology was applied to the results obtained at CELL, being able to allocate 23 out of 36 directly within the CSC approach, while 13 are related to general topics that support the CE initiatives at UPM, as it can be seen in figure 44 below.

It was interesting to identify that following the CSC flow, the first area on which the academic documents have an impact is the user's responsibility on supporting the development of recovery strategies for the different materials within the HEI campus, as demonstrated by (Cuetos González, 2021; De Myttenaere, 2021; Hidalgo-Carvajal, Gutierrez-Franco, et al., 2023; Villa Bueno, 2020).

Then, the recycling is the area on which most of the development has taken place. Downcycling considers most of the work conducted in the lab, with the results being reported in eight academic documents (Agüero et al., 2023; Beltrán et al., 2021; Gil Muñoz et al., 2020; Hidalgo-Carvajal, Muñoz, et al., 2023; Hortal Muñoz, 2021; Moreno et al., 2020; Moreno Escribano, 2020; Palacios Rodríguez, 2021). On the upcycling side, it was also interesting to identify that five academic documents (Chapon, 2023; Chillón Bartol, 2023; Novellón Coloma, 2023; Serrano Gámir, 2022; Solís Lorente, 2023) focus in repurposing waste materials to create new products by extending the product's life cycle.

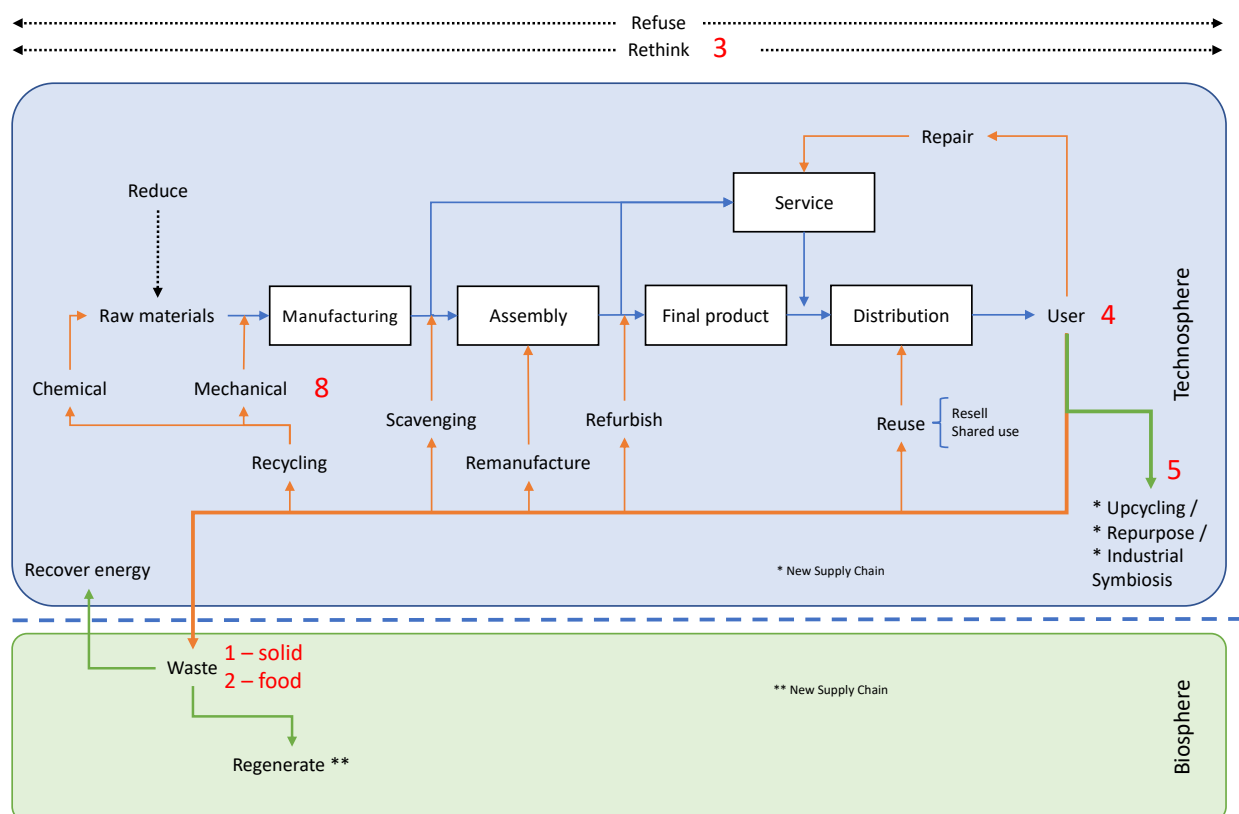
On the waste management section, three documents (Hidalgo-Carvajal, Mejia-Argueta, et al., 2023; Ramírez Arenas, 2022; Yáñez et al., 2023) focus on how the waste could be recovered or properly discarded. Two of the documents pay attention on food waste and how it could be recovered through different options, while the third one explores the potential for composting a biopolymer.

It must be highlighted that three documents have a scope related to changes in the system to improve the circularity strategy of the HEI. These include the development of the circularity initiative at UPM (Carrasco-Gallego et al., 2020), including the informal recycles in the system to maximize the potential of recovery of materials (Hidalgo-Carvajal & Carrasco Gallego, 2021), and proposing changing

## The Circular Economy Living Lab from a Circular Supply Chain perspective

from product ownership to servicing (Hidalgo-Carvajal et al., 2021) and what are the challenges and drivers for the transition.

As it can be seen, most of the documents focus into recycling (downcycling and upcycling) of different materials available at HEIs, which is reasonable to consider understanding that the HEI campus mostly receives material from the outside and, the material it generates, its mostly for academic purposes. This is also correlated to the number of documents proposing initiatives for users to improve their waste management skills to support maximizing the recovery of the materials by proper allocation and finally, once the waste has been fully taken advantage of through the processes mentioned before, how the waste can be properly recovered or discarded.



**Figure 44.** Number of projects allocated following the proposed Circular Supply Chain approach at HEIs. Own development.

Considering the design phase of products and systems, proposals have been allocated ranging from reducing WEEE by design (Hidalgo-Carvajal & Carrasco-

Gallego, 2022; Soriano González, 2021), improving local transportation system (Campos Molina, 2022), creating a food market with a circular focus (Gordillo Alcalá, 2021), proposing regulatory systems (Amo García, 2020; Conejero et al., 2022; Torres García, 2023) and educational techniques for circularity (Agüero Rodríguez et al., 2023; Hidalgo-Carvajal, Carrasco-Gallego, et al., 2023) and analyze the life cycle of products (Fernández Aguirre, 2021; Gil Cordero, 2022; Hidalgo-Carvajal, De Stefano, et al., 2023; Hidalgo-Carvajal, Picanço-Rodrigues, et al., 2023).

## 6.5. Conclusions

Circular supply chains (CSC) are critical for continuing developing sustainability and resilience within the current economy scheme as these focus on minimizing waste flows while maximizing resource efficiency by keeping the different materials and products in use in the long term. Under this context, Higher Education Institutions (HEIs) can contribute to improve environmental impact through an educational framework for students and researchers, serving as living labs under which the principles of circular economy (CE) can be tested. By adopting a CSC educational framework, HEIs can enhance their curriculum and academic (and research) offer, providing hands-on experiences intending to better prepare students for future careers in sustainability. Additionally, adopting a CSC approach supports implementing sustainable development goals (SDGs) at HEIs, improving their environmental commitments.

Moreover, this approach provides an avenue for multidisciplinary research and collaboration with industry and government agencies which can support developing innovative technologies and policies that improve current economic schemes, reducing environmental impacts and improving social conditions for different social groups. Furthermore, the resulting academic studies can validate the proposed models through on-field data collection, providing a robust foundation for policy recommendations and practical applications.

Finally, it must be highlighted that different projects developed under the scope of the *CircularizatE Lab (CircuLab)* initiative have produced several academic results such as undergraduate and master thesis, conference and journal publications, as well as applied research with external partners. Additionally, academic courses have been redesigned considering CE concepts, interacting with the CELL through direct contact with the researchers aiming to identify solutions

to complex problems. Nevertheless, it is important to stress that the successful implementation of the project presented in this study has been possible due to the contribution of key stakeholders (faculty, students, and external partners) and does not guarantee that the process can be applied directly in other contexts.



## 7. Academic pillars of the Circular Economy Living Lab

*“Do, or do not. There is no ‘try’”. Yoda*

### 7.1. Introduction

In this chapter, the reader will be introduced to the main contributions to science developed by the author. The goal of this section is to provide a summary of the academic papers published in journals developed by the author. The papers here presented provide rigorous, peer-reviewed research, that help understanding the role that each individual paper provides to the circular economy (CE) principles, from a circular supply chain (CSC) perspective, and the implications these have for Higher Education Institutions (HEIs), not only from a theoretical point of view but rather from an applied approach. Moreover, the body of work here presented not only enriches the knowledge base but also demonstrates the importance of multidisciplinary collaboration, serving as a bridge to connect apparently disconnected research areas under the scope of the CE concept.

### 7.2. The contributions under the CSC framework

Following the CSC approach presented in the previous chapter, the main contributions are related to the results linked with CELL and within the CSC framework. Although not all 33 academic documents and results developed in CELL have been directly influenced by the author, it is worth mentioning that the author has contributed to a large number of the different initiatives regarding ALAR implementation within the CELL. As a proof, it can be mentioned that the author has authored, co-authored, advised or co-advised a total of 20 academic documents.

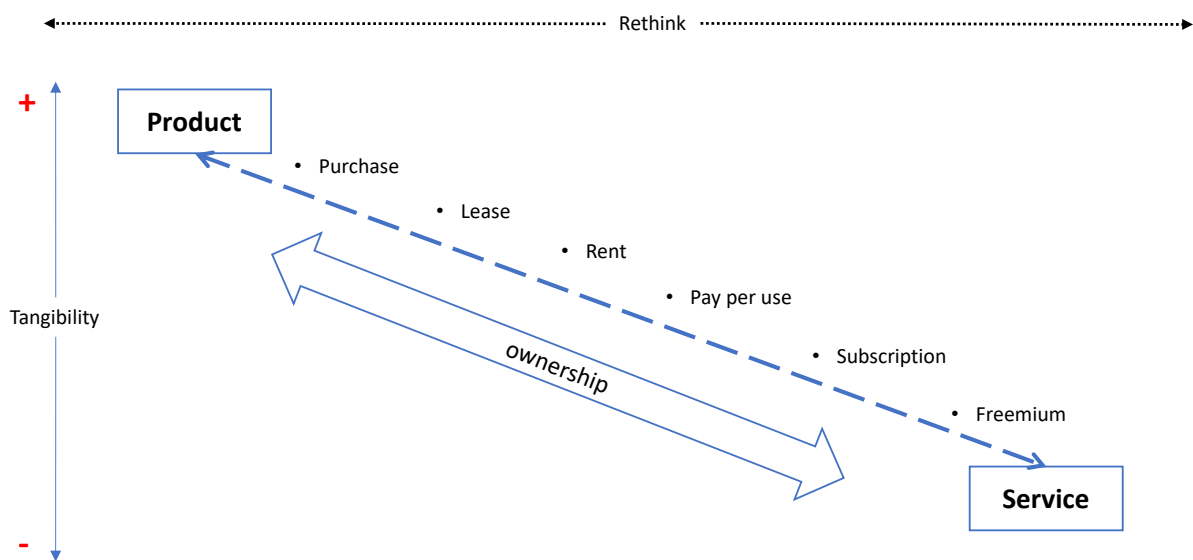
In this section, a summary of the published documents in academic journals on which the author has contributed as first author is presented. Each of the

documents here presented are allocated within the context of the circular supply chain approach proposed in chapter 6, section 6.2.

### 7.2.1. First contribution - on rethinking the system

Hidalgo-Carvajal, D.; Carrasco-Gallego, R. & Morales-Alonso, G. (2021), *From Goods to Services and from Linear to Circular: The Role of Servitization's Challenges and Drivers in the Shifting Process*, *Sustainability*, 13(8), 4539.

This paper presents an approach to the shift from merely sale of products towards business models including added valuable features to the products in the form of services, transitioning from product ownership to service provision. This can be seen in the figure 45 on which the product ownership vs service provision is presented as an alternative to reach the final user of the product. This approach invites to rethink the system to ensure continued prosperity while preserving natural and social capital.



**Figure 45.** Examples of servitization options from ownership perspective. Adapted from (Tauqeer & Bang, 2018).

The shift towards servitization, while beneficial for advancing circular business models, presents several challenges. Companies must develop new capabilities

such as designing durable products and processes for repair and refurbishment, and establishing long-term customer relationships. Organizational changes are necessary to accommodate the shift from transactional to relational approaches, impacting product design, supply chains, ICT, and ownership models. Despite these challenges, drivers such as environmental regulations, material scarcity, and the potential for stable income flows support this transition.

The study intends to distinguish between challenges and drivers in servitization, identifying that these terms are often used interchangeably in literature through an analysis involving 59 academic documents (46 journal articles and 13 conference papers) to classify challenges and drivers into "hard" and "soft" categories.

Among the hard challenges and drivers three main categories were identified (technical, economic, and market readiness), while for the soft challenges and drivers also three categories (regulations, managerial, and socio-cultural values) were recognized. These categories were introduced within a matrix framework, proposing specific groups within each "hard" and "soft" classification, finding that there are more terms identified as challenges (106 hard and 81 soft) than drivers (82 hard and 64 soft).

One key finding is related to the lack of standardization as many terms in literature are used indiscriminately within various context, leading to inconsistencies across the literature. Therefore, it is highlighted the need for broader and standardized approaches to understand the challenges and drivers to incorporate servitization as a business practice. Moreover, a cautionary attitude should be taken against drawing conclusions from a limited sample of papers.

As key insight, this study advocates for a complete approach involving collaboration across departments within the company to effectively implement the servitization strategy. Furthermore, it suggests that traditional business tools may not fully capture the complexities of servitization, considering also the coexistence of physical and digital aspects in servitization, urging companies to adapt their service offerings while recognizing the importance of physical products.

Additionally, servitization must be introduced as a way to transform the traditional procurement models, enabling HEIs to access high-quality services while minimizing waste and enhancing resource efficiency, while avoiding unnecessary ownership, when it applies. This requires further research, although there have been some initiatives on the matter.

Finally, the study proposes exploring emerging trends such as the shift towards rental models and the extension of product lifecycles, as well as addressing identified gaps in understanding challenges and drivers in servitization. This is one of the flagships of circular economy which needs to be explored in further detail to avoid overflowing the market with products with limited lifecycles, shifting from the linear economy.

#### **7.2.1.1. Implications for HEIs**

As servitization represents a significant shift in how industries operate and deliver value to customers, understanding its challenges and drivers is key for HEIs.

First, as teaching is part of HEIs main core activities, properly preparing students for the changing demands of the job market is key. Introducing the students to the latest concepts through the curriculum helps developing the necessary skills (service operations, customer relationships, innovating service-based solutions) and expertise to support industries in the different transition processes.

Additionally, thanks to research and outreach activities, HEIs can provide valuable insights to the challenges and drivers proposed by servitization, not only enriching the academic discourse but also driving real-world applications to support development of industries intending to take a servitization approach.

Moreover, HEIs can incorporate servitization practices among their practices, exploring new revenue streams beyond traditional educational services, such as partnerships with industry for research collaborations, technology transfer, or consultancy services.

Furthermore, servitization can be applied to enhance their campus management, adopting service-oriented strategies aiming to improve campus operations. For example, transitioning from traditional facility management to integrated service solutions by implementing smart campus technologies, such as IoT devices for energy management and predictive maintenance, can lead to cost reduction, better maintenance practices and improve the campus infrastructure.

### 7.2.2. Second contribution – on (e-)waste management

Hidalgo-Carvajal & Carrasco-Gallego (2022), *Preparing for future e-waste from photovoltaic modules: a circular economy approach*, **International Journal of Production Management and Engineering**, 10(2), 131-141

This document presents a proposition on how to maximize the collection rates for e-waste from photovoltaic modules by supplementing the current formal recycling system through the inclusion of the informal recyclers in the system, thus benefitting social groups and material recovery along different streams in the supply chain.

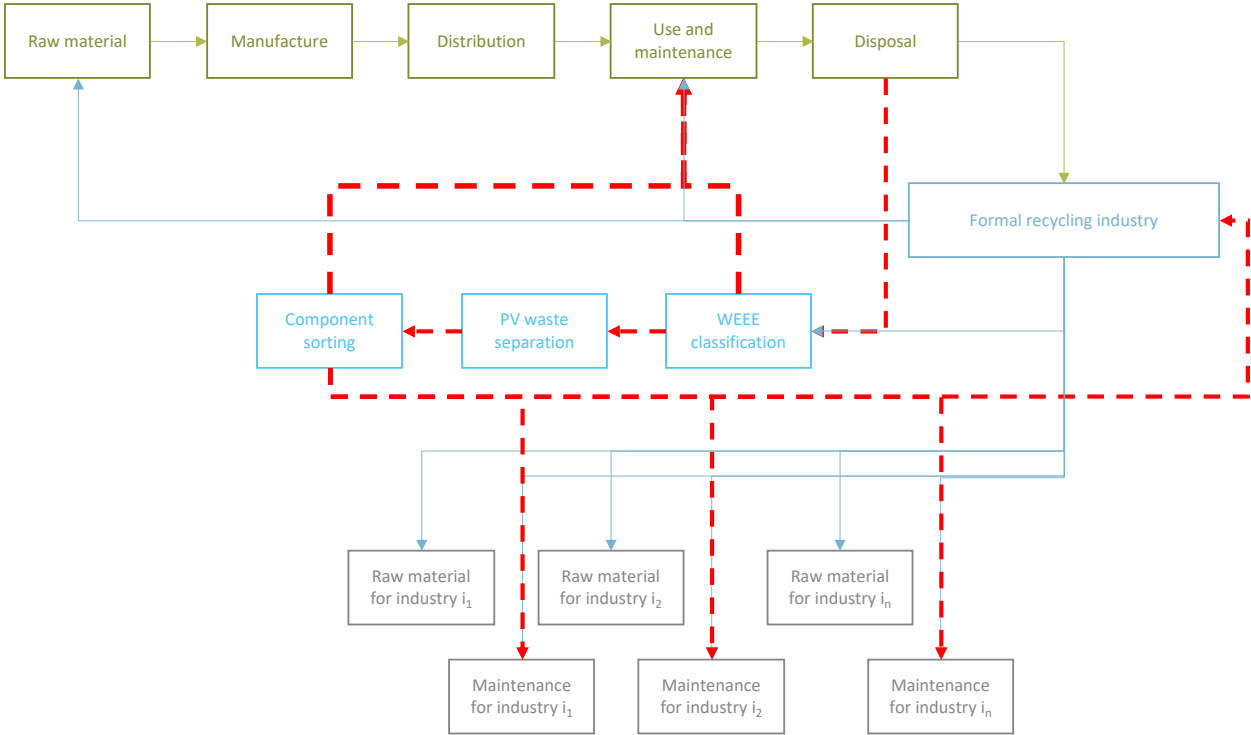
It can be seen in the figure 46 on which the processes related to the formal recycling system are depicted in light-blue lines while the ones from informal recyclers are shown in red-slashed lines. This approach invites to rethink the system to ensure maximizing material recovery through inclusion of the “invisible” informal recycling system, impacting both, natural and social capitals.

As the world's population continues to growth, the demand for electric and electronic equipment (EEE) grows as well, from smartphones and computers to household appliances and industrial equipment. At the same time, the demand of energy rises, motivating the adoption of clean and/or renewable energy sources, such as solar power, leading to an important increase in the installation of photovoltaic (PV) panels. This increase in population, EEE and need for clean energy, has a direct and significant impact on the proliferation of e-waste, or Waste of Electrical and Electronic Equipment (WEEE).

It is important to highlight that, while the increase in use of clean energy supports mitigating climate change, it should be considered that the materials will inevitably age, and it is necessary to prepare for the future disposal of the PV modules and its e-waste. The materials used in the modules, such as silicon, cadmium, telluride, aluminium, among others, pose different processing challenges and environmental risks if these are not properly managed. Thus, there is an urgent need for robust recycling infrastructures, innovative waste management strategies, and sustainable production practices to handle this complex issue effectively.

The research employs a qualitative methodology, focusing on a multivocal literature review to examine both academic and grey literature. The 39 documents

reviewed demonstrate that while WEEE management is expected to improve with increased waste generation, this is not always the case depending on the different regions of the world where the e-waste management is taking place, identifying good and bad practices in WEEE management.



**Figure 46.** Including informal recyclers within the Circular Supply Chain approach. Own development and available at (Hidalgo-Carvajal & Carrasco-Gallego, 2022).

On the one hand, good practices involve socially and environmentally responsible initiatives, often seen in developed markets, such as e-waste policies, social enterprises, education programs, and advanced recycling processes. On the other hand, bad practices were also identified and are, unfortunately, prevalent in developing countries, due to poor regulation and management. These practices lead to significant environmental and social impacts, such as hazardous material mishandling and adverse health effects on informal recyclers. Addressing these issues requires improved regulations and better integration of the informal recycling sector into formal systems.

From the findings, a proposition to include the informal recycling sector (IRS) in WEEE management is developed, leveraging their expertise as waste pre-

collectors and segregation experts, supporting different processes such as reuse or sale, thus supplying materials back to Formal Recycling Industries (FRI).

The model in figure 46 presents different benefits in the three areas of sustainability: a) economic, by reducing the need for virgin raw materials, reducing manufacturing costs and boosting domestic economy; b) environmental, by avoiding unnecessary risks related to mismanagement of potentially hazardous materials and disposal of e-waste; and c) social, by generating job opportunities and improving the economic and social conditions of the marginalized groups which are usually the base of IRS.

Proper WEEE management can prevent harmful chemical disposal, recover valuable materials, and support sustainable development goals. By combining the strengths of both formal and informal recycling sectors, a more effective and inclusive waste management system can be developed, contributing to reduced waste and a more sustainable future.

Finally, the document recommends continuing developing indicators to measure the combined contributions of IRS and FRI, addressing the specific needs of e-waste related to solar technology from a multidisciplinary perspective, and validating and contrasting the findings with data from different stakeholders involved in waste management.

### **7.2.2.1. Implications for HEIs**

The integration of the informal recycling sector (IRS) into Waste Electrical and Electronic Equipment (WEEE) management presents a unique opportunity for higher education institutions to contribute to sustainable development and social equity.

First, HEIs must take advantage of their teaching nature to educate future leaders about sustainable waste management practices by integrating concepts related to WEEE management and circular economy into their curricula, supporting students' commitment to tackle e-waste challenges. This could take two approaches: first, offering courses and seminars on the different concepts and the environmental impacts of e-waste to ensure educating students on the importance of responsible disposal of EEE. Second, educational programs which include practices that recognize the value of IRS, through community engagement and service-learning projects, can promote a fairer approach to understand waste

management and highlight the importance of all parties, and for students, earning firsthand experience on the issue and promoting the social responsibility aspects, which are usually left-out in sustainability analysis. Embedding these two approached into the academic curricula, HEIs can provide students with the necessary knowledge and competences to address WEEE challenges both during their studies and in their future careers, creating a culture of sustainability that extends beyond the campus boundaries.

Moreover, the research area can benefit from conducting studies on the lifecycle of electronic products, the efficiency of different recycling methods, and the socioeconomic impacts of e-waste, universities can contribute valuable insights to the broader field of waste management. This provides an avenue for multidisciplinary research and collaboration with industry and government agencies which can support developing innovative technologies and policies that improve WEEE recycling and disposal. The resulting academic studies can validate the proposed models through on-field data collection, providing a robust foundation for policy recommendations and practical applications.

Furthermore, higher education institutions (HEIs) generate considerable amounts of e-waste from different sources, such as outdated computers and electronic devices, labs and canteens' equipment, and spare parts from other EEE. Therefore, it is necessary to address this issue from within the campus, developing efficient collection systems, partnering with certified recyclers, and ensuring that the WEEE is properly disposed, avoiding unexpected and unnecessary contamination. This is paramount for HEIs to demonstrate their commitment to sustainability, inspiring the community (academic and external) and reducing their ecological footprint.

Finally, HEIs can use their campuses as living labs to experiment with different e-waste management strategies, providing a real-world testing ground for innovative solutions, thanks to partnerships between academia, industry and government (Tripple Helix), while also enhancing the sustainability of their own operations. Moreover, taking advantage of the outreach area, HEIs can host conferences, workshops, and seminars to disseminate research findings and best practices, promoting a global dialogue on sustainable waste management.

### 7.2.3. Third contribution – on (bio-)plastic waste management

Hidalgo-Carvajal, D; Hortal Muñoz, A.; Garrido-González, J.J.; Carrasco-Gallego, R.; & Alcázar, V. (2023), *Recycled PLA for 3D Printing: A Comparison of Recycled PLA Filaments from Waste of Different Origins after Repeated Cycles of Extrusion*, *Polymers*, 15(17), 3651.

This document analyzes how many cycles is possible to mechanically recycle the waste from poly(lactic acid) (PLA), widely used for 3D-printing. For this analysis, two types of PLA-waste are used to compare the number of recycling cycles that can undergo depending on their origin: known and unknown origin. It must be pointed out that the research presented on this document is a continuation of the work developed during the collaboration on three previous papers, from which the author was also part of.

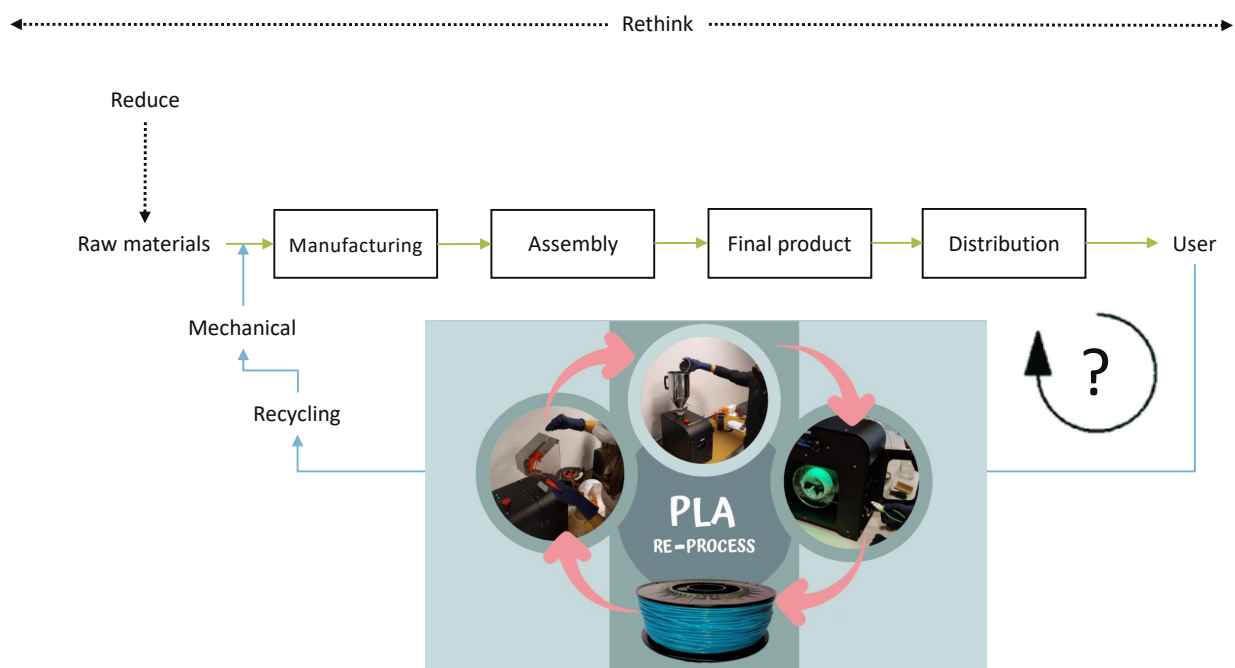
This work takes advantage of the relevance of PLA material and the large amount of PLA-waste resulting of a growing trend of prosumers (producers-consumers) with 3D printing machines at home. Additionally, during the COVID-19 crisis, a large amount of PLA-waste was generated as a result of people developing personal protective equipment (PPE), and other materials, at home intending to support medical professionals and other health workers during those difficult moments. As previously mentioned, two PLA 3D-printing wastes were used: waste coming from a well-known PLA grade and originated within the university laboratories, and a mixture of PLA 3D-printing residues of unknown grade (and origin) coming from an association of coronamakers in Madrid. For context, during the framework of the COVID-19 crisis, CELL established an alliance with the CoronaMakers movement (EsPlásticos, 2020; Martínez-Campos, 2020) in Madrid for the recovery of the PLA-waste generated as production errors (i.e., misprints and supportive structures) while manufacturing visors and other PPE for medical professionals, and these can be recycled at CELL's experimentation space. The CoronaMakers network in Madrid donated around 14.5kg of PLA-waste and 120 polystyrene coil holders in which the PLA is spooled.

The first paper, Gil-Muñoz et al (Gil Muñoz et al., 2020) evaluated the technical viability of mechanical recycling the PLA 3D-printing waste, demonstrating the benefits of the recycling process established within CELL and analyzing the material circularity indicator (MCI) for the resulting material.

The second paper, Moreno et al (Moreno et al., 2020) characterized the PLA-waste and evaluated the effect of their heterogeneity on the technical feasibility of mechanical recycling, identifying better properties (higher viscosity values, lower crystallization and higher transparency) on the resulting materials from known origin compared to those from unknown origin.

The third paper, Beltrán et al (Beltrán et al., 2021) follows a melt-extrusion reprocessing process, which is different from the presented in Gil-Muñoz et al (Gil Muñoz et al., 2020). The optical, structural, thermal and crystallization behaviors of the resulting 3D-printed films obtained were characterized. Additionally, to improve the intrinsic viscosity values for both types of PLA-waste, a solid-state polymerization process was followed, observing better results in the waste from known origin.

The document here presented explores the number of mechanical recycling cycles that the material can undergo until it is no longer possible to continue recycling it as its mechanical properties (density, crystallization and transparency) are not any longer suitable for 3D-printing. As it can be seen in the figure 47, this paper supports the proposed framework from three points of view: first, by recycling waste and reintroducing it to the productive system during not only one cycle; second, by reducing the need for virgin bio-plastic materials; and third, by rethinking the system to include these processes under the circular supply chain approach.



**Figure 47.** Cycles of mechanical recycling for PLA-waste within the Circular Supply Chain approach. Own development.

Using biodegradable materials like PLA for 3D printing presents itself as an opportunity to comply with the 3Rs (reduce, reuse, and recycle), as PLA is biodegradable, biocompatible, recyclable, and compostable, making it suitable for various applications, including medical and agricultural tools. However, the expected growth in 3D printing, given the lowering cost and easiness for technology adoption, could lead to future waste management challenges, necessitating effective recycling methods. Previous studies have shown that while recycled PLA can be used in 3D-printers, the quality of the printed parts can decline with each recycling cycle. Similarly, research on closed-loop recycling of PLA, including the conversion of waste into new filaments and films, indicates that careful sorting and processing are crucial for maintaining material properties.

The study used two types of PLA wastes: commercial-grade black PLA (PLA-C) and white PLA from a mix of coronamakers' PPE material (PLA-M). The PLA wastes were processed following the process described in Gil-Muñoz et al (Gil Muñoz et al., 2020), then characterized and subjected to multiple recycling cycles. Fourier-transform infrared spectroscopy (FTIR) and viscometry were used to analyze the molecular structure and viscosity of the PLA samples. Mechanical properties were assessed via tensile testing. Additionally, the study proposed two mechanical recycling models: one with full traceability of PLA from known sources and another using a mix of PLA from unknown sources, examining the material's degradation and the feasibility of multiple recycling cycles. The first model emphasizes maximizing recycling cycles through full traceability, while the second model involves quality sorting and assumes some materials may be recycled multiple times without precise tracking.

The results show that intrinsic viscosity and molecular weight measurements showed substantial reductions after multiple cycles, with PLA-C maintaining better molecular weight properties during initial cycles. FTIR analysis confirmed no significant contamination in both types. Diffusion-Ordered NMR spectroscopy (DOSY) confirmed the correlation between diffusion coefficients and molecular weights. And mechanical tests indicated stable elastic modulus but decreased tensile strength and elongation with reprocessing. As overall results, it was found

that mechanical recycling was feasible up to three cycles for PLA-C and two for PLA-M, beyond which substantial degradation occurred. The latest raises the question of whether recycling should be limited to single-source waste (full traceability) or include mixed sources (unprecise traceability), as the performance difference was minimal, highlighting economic and collection advantages of mixed sources.

### **7.2.3.1. Implications for HEIs**

From the teaching perspective, HEIs with a focus in engineering and materials science, can benefit from using PLA 3D printing waste for recycling as it supports hands-on learning about sustainable practices and circular economy. Furthermore, the learnings can be integrated into the curriculum through lab sessions focusing on the process of mechanical recycling of PLA 3D printing waste, analyzing its properties through various reprocessing cycles, and understanding its impact on mechanical and chemical characteristics, thus promoting experiential learning and reinforcing theoretical concepts with practical application by presenting practical applications for students to engage with real-world environmental challenges, while developing competences involving innovative recycling techniques.

For the HEIs, implementing a PLA recycling program can benefit the campus management area by reducing costs associated to responsible purchase and acquisition of new filament for 3D printing for the different activities on their labs, minimizing cost related to waste disposal, and, at the same time, potentially creating revenue streams from the sale of recycled filaments. The latest can be done through establishing standard operating procedures for collection, cleaning and reprocessing of PLA-waste. This aligns with the sustainability plans and goals of HEIs, by reducing waste and lowering the environmental footprint of their operations, positioning themselves as models for other institutions and the wider community.

Additionally, the research area could also benefit from grant applications and funding opportunities centered around sustainability and innovation in polymer recycling. Furthermore, this could foster collaborations between academia, industry, and government, driving innovation and influencing policy-making to support sustainable practices.

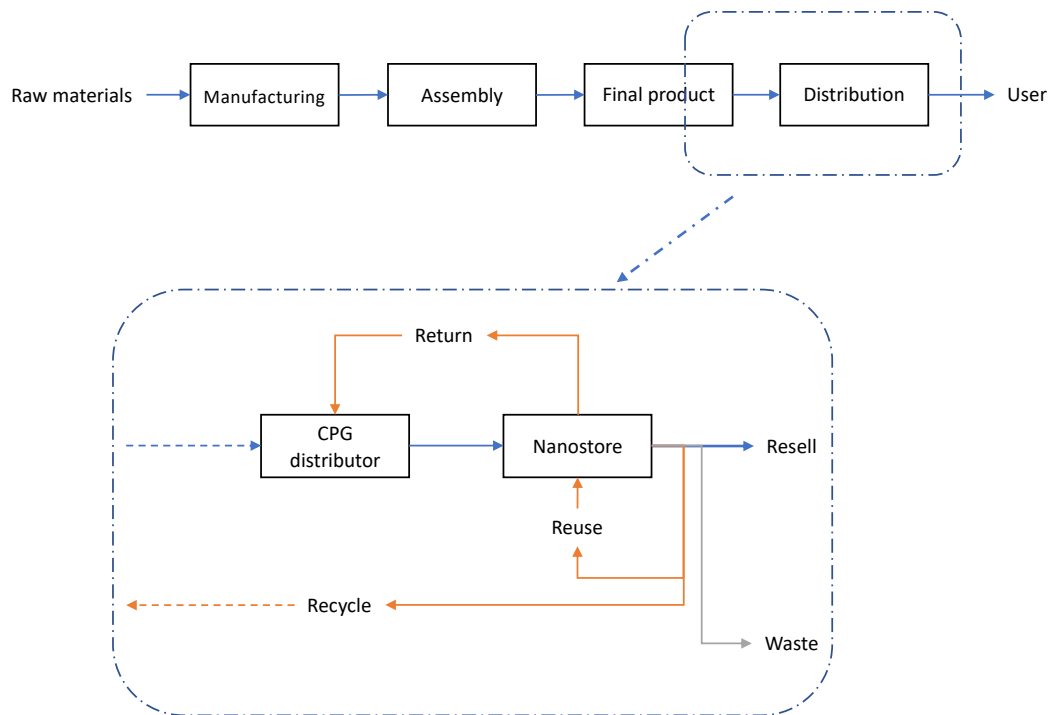
#### 7.2.4. Fourth contribution – on cardboard waste management

Hidalgo-Carvajal, D.; Gutierrez-Franco, E.; Mejia-Argueta, C. & Suntura Escobar, H. (2023), *Out of the Box: Exploring Cardboard Returnability in Nanostore Supply Chains*, *Sustainability*, 15(10), 7804.

This document examines the role that nanostores play to influence the return of cardboard packaging and their willingness to support a closed-loop supply chain system for cardboard boxes. This has a direct influence on the CSC framework from the user (nanostore) perspective and the different routes the product (cardboard boxes) can take to be kept in the system, as can be seen in [figure 48](#), with the goal to ensure preserving natural capital within the techno-sphere.

Nowadays companies face increasing pressure from different stakeholders to adopt sustainable practices and reduce waste, particularly from packaging. Despite different strategies proposed to minimize packaging waste, issues inherent an inadequate recovery structure hinders collection rates, especially for materials like cardboard and glass. Among the main contributors to this problem, the food and beverage industries are identified as these use large amounts of transport packaging, highlighting the need for retailers to adopt circular economy models. It could also serve as a model to support other industries where large amount of waste is generated, such as fashion (De-Juan-Vigaray & Seguí, 2019).

Considering the growing trend in adoption of e-commerce, accelerated by COVID-19 pandemic, it is possible to understand the significant increase in the demand for cardboard packaging, which calls for urgent action to promote reuse and recycling of said materials, understanding consumer behavior and willingness to support these initiatives. However, the companies don't reach directly the end consumer as some intermediaries, such as distributors and retailers, play a key role connecting these two parties, despite the different challenges they face. In the particular case of emerging markets, distributors face challenges like urbanization, traffic congestion, and economic uncertainty while serving nanostores, which are small family-operated shops, crucial for daily essentials. Nanostores are key players in supporting packaging reuse and reduction initiatives.



**Figure 48.** Five R-“routes” for cardboard boxes from the “user’s” perspective within the Circular Supply Chain approach. Own development and available at (Hidalgo-Carvajal, Gutierrez-Franco, et al., 2023)

This research aims to understand and demonstrate how nanostores can actively participate in the return and reuse of cardboard packaging, supporting circular supply chain initiatives, filling a significant gap in the literature on circular economy models in emerging markets. For this, an exploratory methodology was used through interviews and surveys with a statistically significant sample of shopkeepers to represent the estimated 15,388 nanostores in two cities in Bolivia: La Paz and El Alto. The survey was designed to maximize data collection and minimize bias, was conducted by a group of 15 data collectors, and covered five dimensions for circular supply chains: reuse, return, resell, recycling, and waste.

The findings highlight that suppliers frequently deliver products in cardboard boxes, leading to significant amounts of packaging material that shopkeepers must manage. It was interesting to identify that shopkeepers prefer to reuse, recycle or resell the cardboard boxes instead of directly disposing these as waste. Additionally, an argument for the reusing being the first choice is due to limited return options offered by the suppliers, demonstrating that for shopkeepers would be interested in returning the material if offered effective intervention schemes,

such as monetary rewards for returning packages, supporting social impact initiatives or even contributing to environmental reduction programs. Despite the proactive practices of most shopkeepers, a significant percentage of cardboard boxes are discarded due to poor quality, highlighting the need for better more durable packaging.

This study highlights the willingness of the user to contribute to sustainable practices, however, they need clear environmental programs and financial incentives to become actively engaged. Moreover, developing partnerships with recycling facilities and offering education and training to shopkeepers can further encourage the adoption of sustainable practices. Additionally, this also emphasizes the need for collaborative efforts between retailers, distributors, and policymakers to promote sustainable practices along the entire retail supply chains, to make them more circular and promote practices which allow the material to be kept within the system as long as possible. Finally, it must be pointed out that although the study is region-specific, the findings highlight the importance of strategic decision-making in logistics operations and the potential for broader application in other regions.

### **7.2.4.1. Implications for HEIs**

From the teaching point of view, HEIs can incorporate cardboard box returnability practices into the educational framework, through lectures and practical projects focusing on designing and optimizing circular systems. Students can benefit from hands-on activities aimed to reinforce their learnings, such as analyzing lifecycle of packaging materials, conducting waste audits, developing different solutions for material reuse and recycling, and propose different circular practices. Moreover, this approach provides students with competences and practical skills to implement sustainable practices in their future careers. A wide variety of academic programs can benefit from this practical knowledge, particularly those focused on environmental science, business, and supply chain management.

As HEIs are often large consumers of goods delivered in cardboard packaging, it is necessary to adopt robust strategies to manage this type of waste efficiently, through reuse, recycling and reselling programs. Incorporating said practices into the campus management operations can lead to environmental footprint reduction and reduction of costs associated with the management of this type of waste. For example, used cardboard boxes can be reused for storage of different material,

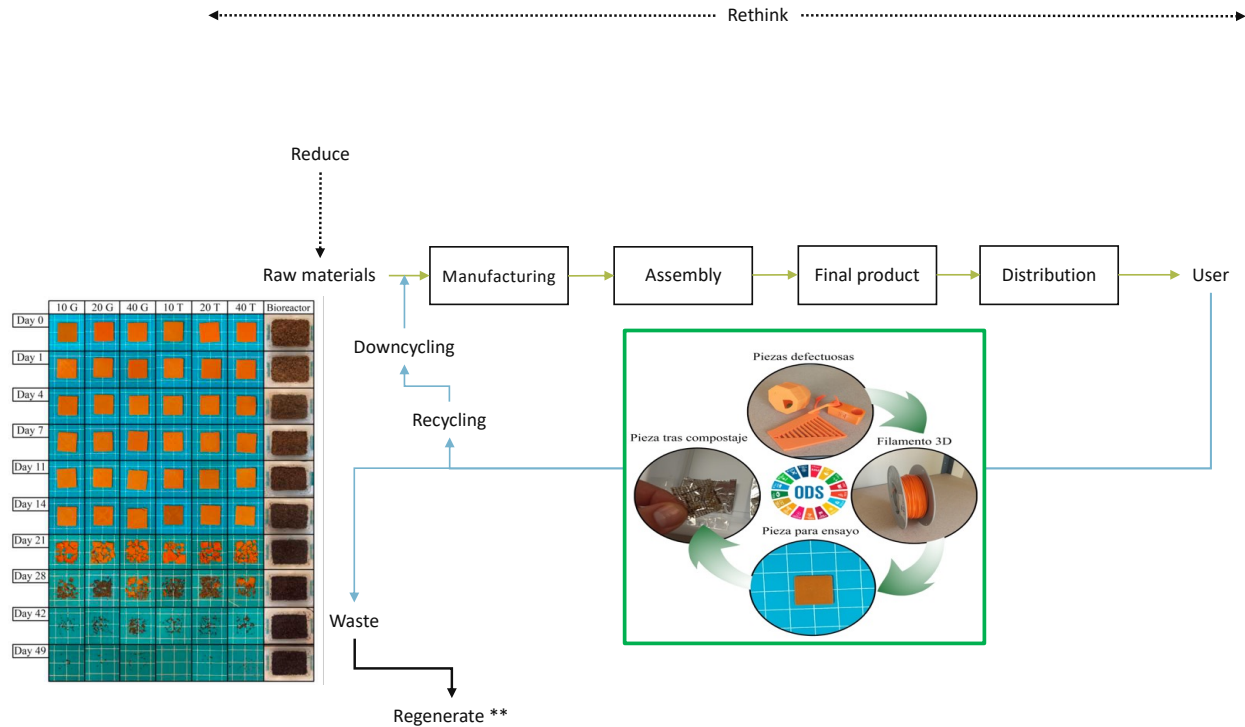
redistributed to students or staff for moving purposes, resold to recycling companies, recycled for different projects and even returned to the supplier as part of better purchasing terms, thus, keeping the material in circulation and reducing the need for virgin raw materials. Furthermore, it is possible to include students and researchers in these practices, serving as supplementary educational tools which support raising awareness about sustainable waste management. Therefore, by fostering a culture of sustainability through both operations and education, HEIs can lead by example, demonstrating the practical benefits of circular economy principles within and beyond the campus community.

Finally, collaborating with local recyclers and different sustainability-focused organization can support establishing comprehensive recycling systems for the community, thanks to the outreach approach. Additionally, partnerships with different stakeholders (i.e., startups and industry experts) can lead to innovative and improved material recovery methodologies and technologies, following the circular supply chain approach. Implementing such a system requires effective coordination and communication with all stakeholders, ensuring that everyone is aware of the procedures and benefits.

### **7.2.5. Fifth contribution – on regenerating biopolymers**

*Under review:* Hidalgo-Carvajal, D; Agüero Rodríguez, A.; Lascano, D; Muneta, M.L.M.; Balart, R.; Arrieta, M.P. & Carrasco-Gallego, R. (202X), *Using a closed-loop perspective to evaluate the life cycle of recycled PLA of 3D-Printing waste*, **Discovery Sustainability**, xx(xx)

This document presents the collection model employed at UPM as a HEI for PLA-waste around the four campuses using the internal transportation system and proposes regeneration scheme through composting of known sourcing material, considering different printing patterns to compare if that has an impact on the compostability rate, while also addressing a life cycle assessment for the entire system. This can be seen in figure 49, where one cycle has been considered for compostability after mechanical recycling. Furthermore, the LCA results demonstrate that is more beneficial to recover a material than generate a virgin one.



**Figure 49.** Composting the PLA-waste after recycling within the Circular Supply Chain approach. Own development.

Plastic pollution, encompassing both macroplastics and microplastics, is a critical environmental concern which calls for urgent and effective management and minimization strategies. Despite the increasing use of biobased plastics, most of plastic production is still related to non-renewable petrochemical sources, leading to significant waste accumulation. However, biopolymers present themselves as an opportunity for some processes and products to reduce manufacturing costs, and, at the same time, reduce the inherent environmental footprint.

In the case of biopolymers, mechanical recycling process intends to efficiently recover polymers, although it faces different challenges like contamination and material degradation, as previously discussed. For effective polymer recycling, large volumes, standardized processes, and incentives for waste generators are essential, alongside tailored waste management systems to maximize material recovery and quality.

This academic document presents a contribution to science in two main areas. First, the collection of material section presents a “tailored” system at UPM to gather PLA-waste from its various schools using an internal delivery system and the recycling process already introduced in Gil Muñoz et al (Gil Muñoz et al., 2020).

This system demonstrates that, collaboration between different entities is possible and can produce significant results. Second, the Life Cycle Assessment (LCA) employed to compare new versus recycled PLA filaments, demonstrates the importance of understanding the entire life cycle of a product.

The study investigates the environmental benefits of recycling PLA-waste following a LCA approach, which allows comparison between recycled PLA and virgin PLA. On the one hand, results show that producing virgin PLA has more significant environmental impacts, particularly due to electricity use and natural gas combustion, compared to recycled PLA. On the other hand, mechanically recycled PLA demonstrate that lower environmental impacts in categories such as ecotoxicity and carcinogens are possible.

When analyzing the properties of recycled PLA, it was observed that thermal transitions such as glass transition temperature, cold crystallization temperature, and melting temperature remain relatively stable through recycling processes for the recycled material from known source. Additionally, we could argue that mechanical recycling leads to changes in the crystallinity and molecular weight of the PLA, impacting its thermal behavior and mechanical properties. However, and despite these changes, recycled PLA filaments were functional for 3D printing, maintaining similar dynamic-mechanical properties and compostability similarly to a virgin PLA material. Finally, we conclude that mechanically recycled PLA not only retains suitable material properties but also offers significant environmental benefits, aligning with sustainable production goals.

#### **7.2.5.1. Implications for HEIs**

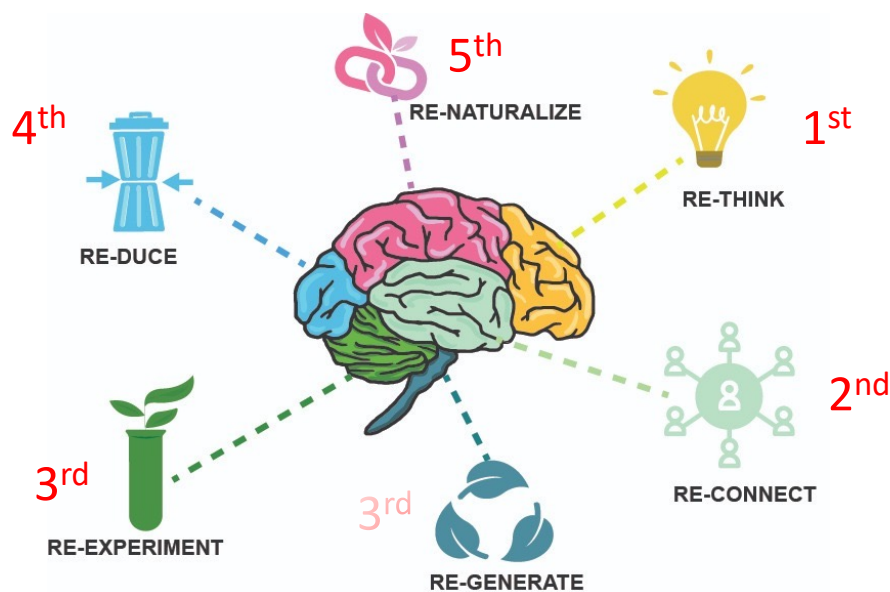
Once again, the educational role for HEIs is key in this section. HEIs are uniquely positioned to serve as incubators for innovative waste management solutions, creating a closed-loop system where PLA waste from a known origin is collected, recycled, and reintroduced into the system until its final disposal, and significantly reducing the environmental footprint.

The positive environmental outcomes demonstrated through the Life Cycle Assessment (LCA) approach, show that HEIs can lead by example in sustainable practices, reducing the need for virgin materials and promoting circular approaches. By rethinking waste as a valuable resource rather than a disposable byproduct, is it possible for HEIs to contribute to environmental sustainability and campus circularity, through hands-on experiences.

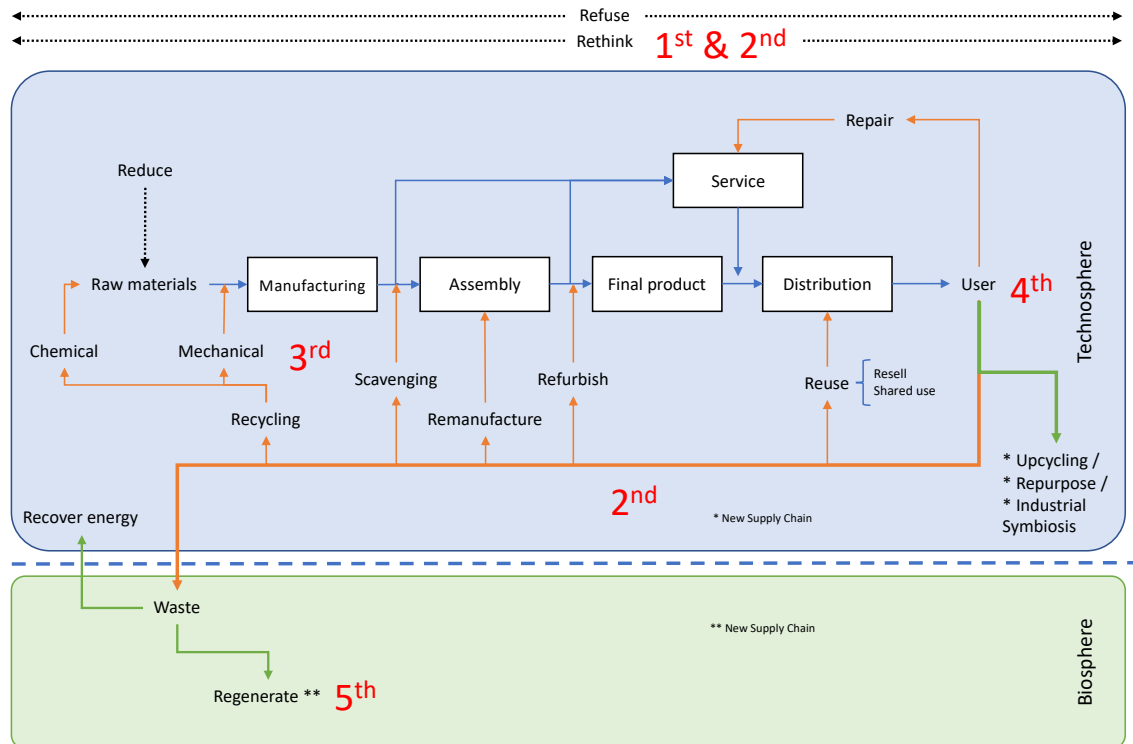
Furthermore, non-discarded materials can be integrated into various educational and research initiatives within HEIs, providing hands-on learning opportunities for students across disciplines, by actively participating in the lifecycle of materials. This not only benefits the environment as it also enriches the educational experience, furthermore, positioning HEIs as leaders in the global movement towards a sustainable and regenerative economy.

### 7.3. Summarizing the contributions under the frameworks

As demonstrated by the author within the five academic papers described in section 7.2, CE principles are broad and require a multidisciplinary approach to significantly contribute to the advancement of science and to applied results rather than merely theoretical contributions. Figure 50 presents the described contributions under CELL's framework. Likewise, Figure 51 positions the described contributions under the CSC framework.



**Figure 50.** Allocating the contribution of the five papers under the CELL's framework.  
Own development.



**Figure 51.** Allocating the contribution of the five papers under the Circular Supply Chain approach. Own development.

As it can be seen, the 1<sup>st</sup> and 2<sup>nd</sup> papers contribute mainly to rethinking the system to make sure that products last longer and the need for new virgin materials is lowered. Additionally, 2<sup>nd</sup> paper contributes to include an “invisible” social group in the system as their expertise can contribute to maximize material’s recovery through different loops in the system.

The 3<sup>rd</sup> paper contributes to recovering the material through mechanical recycling of the PLA-waste and analyzing the number of cycles it could be reintroduced to the system. Moreover, demonstrates the need for proper material recovery schemes to optimize the material recovery.

The 4<sup>th</sup> paper explores the user’s perspective to contribute to returnability of the material to the system through different schemes, and analyze the incentives required to enhance the returnability.

Lastly, the 5<sup>th</sup> paper investigates the compostability of the PLA-waste material after repeated recycling cycles and presents a life cycle assessment to evaluate the environmental impacts of recycled materials versus virgin materials.

Finally, on the table 5 below, the academic papers on which the author has been the first author are presented. The numbering below (paper number) is according to the one previously presented in this chapter under section 7.2.

<b>Paper Number</b>	<b>Journal</b>	<b>Area of knowledge</b>	<b>Ranking</b>	<b>Position</b>	<b>Source</b>
1 <sup>st</sup>	Sustainability	Environmental Sciences	Q2	114/275	JCR
		Environmental Studies	Q2	48/128	JCR
		Renewable energy, sustainability and the environment	Q2	48/128	SJR
2 <sup>nd</sup>	International Journal of Production Management and Engineering	Industrial and manufacturing engineering	Q2	62/180	SJR
3 <sup>rd</sup>	Polymers	Polymer science	Q1	17/94	JCR
		Chemistry (miscellaneous)	Q1	18/94	SJR
		Polymers and plastics	Q1	18/94	SJR
4 <sup>th</sup>	Sustainability	Environmental Sciences	Q2	114/275	JCR
		Environmental Studies	Q2	48/128	JCR
		Renewable energy, sustainability and the environment	Q2	48/128	SJR
5 <sup>th</sup>	Discover Sustainability	Environmental science (miscellaneous)	Q2	50/91	SJR

**Table 5.** Summary of the academic papers, journal, area of knowledge and raking. Own development.

Additionally, the table 6 below presents other papers published in academic journals on which the author has been part of the academic team although not being the first author.

Paper	Journal	Area of knowledge	Ranking	Position	Source
Gil Muñoz et al, 2020	Applied Sciences	Engineering (multidisciplinary)	Q2	64/180	JCR
		Chemistry (multidisciplinary)	Q2	100/231	JCR
		Material Sciences	Q2	215/438	SJR
Beltrán et al, 2021	Polymers	Polymer science	Q1	17/94	JCR
		Chemistry (miscellaneous)	Q1	18/94	SJR
		Polymers and plastics	Q1	18/94	SJR

**Table 6.** Summary of the academic papers, journal, area of knowledge and ranking. Own development.

## 7.4. Conclusions

The academic papers presented in this chapter contribute to the body of knowledge around Circular Economy (CE) from an interdisciplinary approach by exploring applied solutions to diverse topics such as efficient use of resources, waste reduction, sustainable production and responsible consumption patterns.

The methodology used in the papers follows the Circular Supply Chains (CSC) approach, which encourages both, theoretical explorations and empirical analysis to translate the concepts into actionable strategies for different types of industries, with a focus on Higher Education Institutions (HEIs) serving as living labs to test the principles of CE.

Furthermore, through dissemination of the findings to different audiences, including students and other researchers, practitioners, and public interested in the topics, the academic papers support education initiatives and research agendas in HEIs. Moreover, publications serve two additional purposes: first, as facilitators for internal and external collaboration allowing researchers to share their insights with academic pairs worldwide, and second, enriching the credibility of the CE initiatives, contributing to the development of policies around the topic and investment in CE technologies and practices.

## 8. Conclusions, original contributions and future research lines

*“The sea is always the same and yet, every day it is new”. Viking proverb*

*“The trail is dark and dusty, the road is kinda rough, but the good road is awaitin', and boys, it ain't far off”. Paths of victory. Bob Dylan*

*“Auch aus Steinen, die einem in den Weg gelegt werden, kann man Schönes bauen”  
– Even from stones places on one's path, one can build something beautiful –  
Goethe.*

In this final chapter, the overall contributions of this dissertations are presented. The general conclusions of this thesis are introduced in section 8.1, demonstrating the key learnings from the overall research objective, along with a brief discussion about specific conclusions for each of the objectives. Then, in section 8.2, the original contributions to the body of knowledge are summarized. Finally, in section 8.3 the future lines of research resulting from this thesis are discussed.

### 8.1. Conclusions of this PhD dissertation

The implementation of the Circular Economy Living Lab (CELL) within the context of a Higher Education Institution (HEI), in this case Universidad Politécnica de Madrid (UPM), represents a significant step towards integrating sustainability and circular economy concepts into the HEI's main areas of influence and action, following an action learning and action research (ALAR) methodology.

The insights identified through this thesis have been fundamental on concluding that implementing CE concepts within HEIs is possible thanks to the combination of LL and ALAR methodologies, which support learning and research activities and enhance multidisciplinary collaboration achieving high value results, bridging the gap between theoretical knowledge and applied solutions.

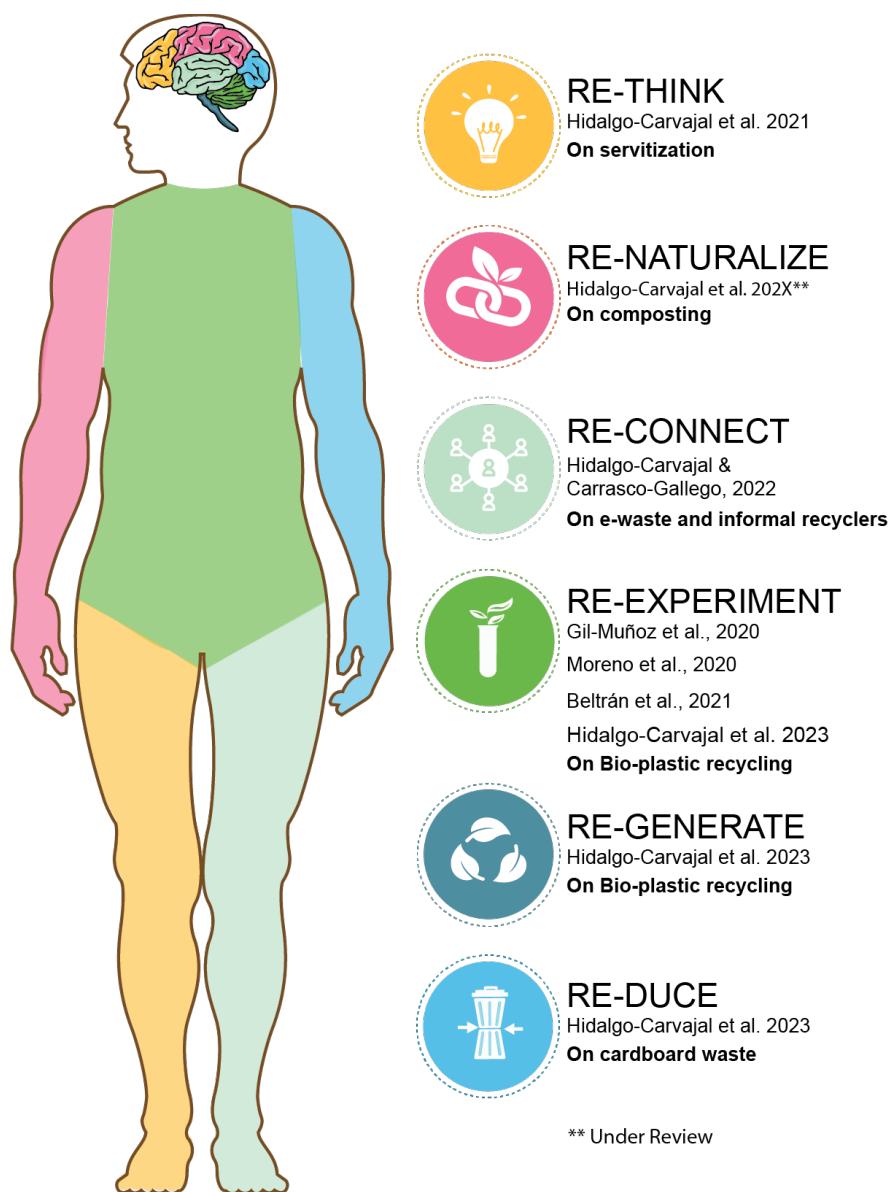
First, this dissertation offers a comprehensive review of both, academic and grey literature, to understand how CE principles are being integrated within HEIs. On one hand, the results from the academic literature demonstrate that the CE principles are being included in educational settings under the HEI's four core areas of influence. On the other hand, analyzing the reports from the International Sustainable Campus Network (ISCN) supported understanding how CE principles are being applied in practice, highlighting the contributions and the common challenges faced by HEIs. This twofold approach ensures an ample understanding of the topic, bridging the gap between theory and practice. Furthermore, this contribution to the body of knowledge enhances the relevance and applicability of this research, becoming a useful tool for different stakeholders (i.e., academics and practitioners, as well as policymakers) to promote sustainable practices in HEI.

Second, this thesis highlights the importance of developing continuous review and critical assessment processes, which are key elements of the ALAR methodologies. Through this approach, HEIs can engage in a repetitive cycle of improvement in the four core areas, ensuring that their sustainable and circular initiatives remain effective and current, as well as innovative and adaptable.

Third, incorporating practical, hands-on projects into the curriculum, enhance learning processes and ensure that students gain deeper understanding of sustainable and CE concepts, while developing additional skills and knowledge necessary to address complex environmental challenges.

Fourth, it can be concluded that the framework proposed here facilitates interdisciplinary collaboration and multiple stakeholder engagement. The methodology and framework presented in this thesis promote a solid and sound approach to problem-solving, by bringing together students, faculty, and researchers from diverse disciplines, and connecting them with local communities and public and private entities, to work together in collaborative projects. This multilayered and interconnected environment support collaborative action towards sustainability.

Finally, the academic results presented in Chapter 7 show the contribution to the academic body of knowledge of CE, demonstrating the validity of interdisciplinary collaboration to provide applied solutions to real-world issues. All the results can be seen in the [figure 52](#) below.



**Figure 52.** A complete framework model (brain and academic work) for the CELL at UPM. Own development.

After presenting the general conclusions for this thesis, the next step is to introduce the key learnings and insights from each of the specific objectives of this thesis.

**Objective 1. To develop a comprehensive model for LL in HEIs which allow implementing CE principles, serving as a blueprint for other institutions.**

One of the cornerstone achievements of this thesis has been the creation of detailed and adaptable model for implementing LLs in HEIs. The model serves as a layout

for other institutions interested in integrating CE principles into their operations, ensuring that they can replicate the success seen in this lab, promoting adoption of sustainable practices in academia. Additionally, the model can be customized to fit the unique context of different institutions, maximizing its impact across diverse educational settings.

Furthermore, this model incorporates feedback mechanisms through iterative processes, enabling continuous improvement in such way that its effectiveness remains relevant to addressing sustainability challenges. Additionally, the model facilitates long-term sustainability and scalability of LL initiatives.

**Objective 2. To promote experiential learning and student engagement, demonstrating the usefulness of ALAR methodologies for continuous reflection and improvement.**

The thesis has proven that ALAR methodology is effective in promoting experiential learning and commitment from different internal stakeholders (i.e., students, researchers and staff), enhancing practical learning, and developing new skills and knowledge. The engagement of students in real-world problem-solving activities has enhanced their critical thinking, collaboration, and innovation skills, preparing them for future roles as sustainability leaders within their companies.

Moreover, applying ALAR methodologies has advanced continuous learning and adaptation processes among students and faculty alike. Thanks to this dynamic learning environment, participants engage in challenging current suppositions, exploring new ideas, and developing innovative solutions to address the diverse and complex sustainability issues.

**Objective 3. To evaluate the impact that CE concepts have within the curriculum and research settings under both, the LL and ALAR methodologies.**

Integrating CE concepts within the curriculum and research settings has provided critical insights into their effectiveness. Both LL and ALAR methodologies have shown positive impacts, enhancing the learning experience and encouraging the integration of sustainable practices in research activities from a multidisciplinary perspective. Moreover, these findings highlight the value of incorporating CE principles into academic programs and identifying areas for further development. This approach identifies key factors for the successful integration of CE concepts,

such as interdisciplinary collaboration, stakeholder engagement, and institutional support.

Furthermore, embedding CE principles into the curriculum allows HEIs not only to enrich the educational experience but also promote a campus-wide culture of sustainability. This has resulted in increased awareness and commitment to sustainable practices among students, faculty, and staff, leading to tangible improvements in resource efficiency, waste reduction, and overall environmental performance.

**Objective 4. To document and disseminate the different academic findings in diverse forums, contributing to the global body of knowledge.**

Documenting and disseminating research findings in various academic and professional forums have significantly contributed to the global body of knowledge on CE and sustainability in education. This objective ensures that the insights and innovations developed through this research can reach broader audiences, supporting developing practices and policies beyond the HEI campus. The dissemination efforts include publications in peer-reviewed journals, presentations at conferences, developing undergraduate and master theses, sharing the results in other academic and non-academic forums, thus maximizing the impact and visibility of the research.

Additionally, the active dissemination of findings has facilitated knowledge exchange and collaboration with other stakeholders, such as industry and other HEIs. This collaborative approach has strengthened the collective capacity to address sustainability challenges and promote the adoption of CE principles across different sectors.

**Objective 5. To facilitate interdisciplinary collaboration which enhance sustainable practices within HEIs.**

This thesis has demonstrated that interdisciplinary collaboration is not only possible but necessary to enhance sustainable practices within HEIs. Bringing together diverse perspectives and expertise from various academic disciplines, support developing more innovative and effective solutions. Moreover, the collaborative efforts have extended beyond academia, involving external stakeholders such as industry partners, government agencies, and community

organizations. This multi-stakeholder engagement has enriched the research process and outcomes, ensuring that the developed solutions are practical, scalable, and aligned with real-world needs.

**Objective 6. To generate external and internal alliances, creating stronger networks which allow further engaging local community in different projects.**

The creation of strong external and internal alliances has been essential in expanding the reach and impact of CELL's projects. Thanks to these alliances, a deeper engagement with the local community has been possible, generating opportunities to develop collaborative projects with real-world applications of CE principles. Additionally, this network of partnerships has strengthened UPM's existent commitments to sustainability. Furthermore, the internal alliances within UPM have promoted a collective action among students, faculty, and staff. Finally, the development of strong alliances has also facilitated the exchange of knowledge and best practices, contributing to the continuous evolution and enhancement of CE initiatives under HEI's context.

**Objective 7. To increase awareness and advocacy for sustainable practices by becoming a living proof of implementation of CE concepts.**

The implementation of CELL has served as a living example of how CE concepts can be implemented under a HEI context, significantly increasing awareness of sustainable practices and engaging in further commitments within and beyond the university campus. This demonstrates the practical benefits of adopting CE principles, inspiring other institutions and communities to adopt similar approaches, thanks to the visibility and success of the different projects.

Moreover, the increased awareness efforts have had a ripple effect, promoting sustainable behaviors and practices among a wider audience, as well as facilitating a triple helix approach, becoming a tangible proof of the positive impacts of CE on different contexts. This thesis demonstrates that HEIs should lead by example, playing a key role in driving change towards advancing sustainability.

## 8.2. Original contributions

In this section the contributions to the academic body of knowledge achieved through this thesis are listed and briefly explained. These contributions have been largely explained in under each of the objective conclusions, as well as the specific academic documents have been summarized in chapter 7.

The first contribution is on the advancement and unification of academic and grey literature, demonstrating the relevance and applicability of the topic from both perspectives. By integrating peer-reviewed research with real-world insights from case studies in academic reports, this thesis closes the gap between theory and practice. This approach presents a twofold benefit, by first, enriching the academic discourse around the implementation on circular economy principles in HEIs, and second, validating the real-world applications of sustainable practices within HEIs, highlighting the tangible benefits and challenges for their implementation. Furthermore, the findings are grounded on scientific and practical contributions, ensuring their credibility and utility for scholars and practitioners, and moreover, these could be used by different stakeholders, including policy makers, to promote the adoption of sustainable practices within and outside HEIs borders.

The second and most important original contribution is on the development of a comprehensive model for circular economy living labs (CELL) in HEIs, which addresses the unique challenges and opportunities for implementing CE concepts within the HEI environments, including understanding the impacts along the HEIs' four core areas of influence. The proposed model serves as a strategic framework tailored to the particular dynamics of HEIs, serving as a blueprint to integrate CE principles and facilitating their measurements and evaluation, supporting the transition towards circular and regenerative campus systems.

The third contribution is directly linked with the CELL model as it promotes interdisciplinary collaboration within HEIs, involving diverse academic actors and external stakeholders, including industry partners and local communities. This provides a blueprint for other institutions interested in promoting collaboration environments from different perspectives, which demonstrate that innovative and comprehensive solutions can be developed to solve real-world problems. Furthermore, this collaboration support creating strong networks and alliances within and outside the institution, fostering community engagement and support for developing sustainable efforts. Therefore, this contribution directly addresses objectives 5 and 6 under the framework umbrella.

The fourth contribution generated in this thesis is linked to the results obtained at the CELL thanks to the implementation of ALAR methodologies, which emphasize continuous learning, reflection, and iterative problem-solving attitudes in students and researchers, enhancing educational experiences and contributing to the development of evidence-based sustainable practices. Thanks to this methodology, it is possible to assess how the CE principles can be embedded in educational curriculum and research agendas into HEIs, effectively preparing students to address current and future real-world environmental challenges and, at the same time, pushing the frontier of knowledge on CE. Additionally, this approach has improved documenting and disseminating academic findings in various formal academic (e.g., academic conferences and journals, theses) and informal (e.g., community meetings) forums, advancing the global discourse on CE concepts, influencing academicians and practitioners. Finally, and overall, the combined effect of these lines of work demonstrates the increased awareness around CE principles, providing empirical evidence of the benefits of creating a culture of sustainability and the impacts it could have within and beyond the institution, thus contributing to the global movement towards a CE. Therefore, this contribution directly addresses objectives 2, 3, 4 and 7, under the CELL framework umbrella.

The fifth contribution is on the advancement of the CE body of knowledge through developing practical implementation of CE principles under CELL's framework. The empirical results and outcomes presented in section 5.5, section 6.4 and in chapter 7 demonstrate the effectiveness of CELL's framework to add to the academic and practical understanding of CE concepts and principles, and how these can not only effectively work within educational environments but also the impact these can have by transcending the HEI's borders.

### **8.3. Future research lines**

As a result of the research developed during this PhD dissertation, a few opportunities for further research have been identified. These research avenues are presented in this section.

The first research opportunity is related to assessing **what are the impacts resulting of implementing circular initiatives in HEIs?** This question proposes avenues for analyzing the impacts from a comprehensive perspective, including

social, economic and environmental assessments. From the social perspective, future research could investigate students' engagement and community partnerships during the implementation of the circular initiatives, analyzing the role of HEIs in changing social behaviors. On the economic viewpoint, further research could enable exploring the cost-benefit analysis of the implemented circular initiatives, pinpointing potential savings from waste reduction and resource optimization, and additionally, exploring future funding opportunities for research and to develop circular businesses. Regarding the environmental standpoint it could explore environmental impact assessment to quantify the potential benefits of implementing circular initiatives, validating their effectiveness and supporting sustainability reports by providing tangible metrics which can enhance transparency in HEI operations. Finally, it is important to evaluate the long-term impacts of implementing CE initiatives in HEIs, which can help identifying benefits and challenges, generating continuous improvement strategies for said CE initiatives in HEIs.

A second research line is related to **how can digital technologies enhance implementing circular initiatives from a multidisciplinary approach?** This area of research proposes taking advantage of digital tools (i.e., Internet of Things – IoT, blockchain, data analytics) to boost collaboration between different stakeholders from a transdisciplinary approach, to improve the efficiency and effectiveness of CE initiatives. For example, with IoT is it possible to monitor the use of resources in real time, which can enable optimization on use of said resources (i.e., materials, energy and water), and tackle the issue from a multidisciplinary (i.e., engineering, environmental sciences, economics, social sciences, etc.) methodology. This collaboration should include not only academicians, but also external stakeholders using the triple helix approach, facilitating environments to co-create innovative solutions, enriching not only the educational experience within HEIs but also supporting the generation of data-driven decision-making, facilitating transparent circular processes, thus further advancing sustainability goals.

A third research avenue includes understanding **which are the adequate metrics necessary to develop governance frameworks to enhance transparency and accountability of CE initiatives in HEIs?** This area proposes developing evaluation metrics and indicators that would enable a continuous assessment of the effectiveness of the initiatives, identifying areas for improvement and supporting HEIs assessing their progress towards sustainability goals. Moreover, by establishing robust metrics, HEIs can develop guidelines and regulations which

support integrating CE principles within the institutional structure and all decision-making processes. The governance frameworks would ensure that the sustainability efforts are aligned with institutional objectives, facilitating transitioning HEIs' campuses towards regenerative systems.

A fourth research line is linked to analyzing **which educational innovations are most effective on promoting CE principles on different institutions?** On this research line it is possible to evaluate the diverse educational innovations and outcomes through a comparison across multiple institutions, assessing the effectiveness of different teaching methodologies and their impact on the students' engagement in CE initiatives. Moreover, this comparison offers practical guidance for institutions seeking to implement CE programs, understanding the challenges faced by other institutions, and the requirements for successful implementation.

Finally, it should be noted that these proposed lines of research are broad given the interconnectedness of the diverse topics and its inherent characteristics. Nevertheless, it should be mentioned that the authors intend to continue working from a multidisciplinary approach to assess the implementation of CE principles across the HEI's four core areas of influence and assessing the results outside of the campus. Furthermore, another area of interest for the researchers is analyzing the implementation of CE initiatives in other institutional contexts, such as industrial parks.

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