ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO DI RICERCA IN

Scienze e Tecnologie Agrarie, Ambientali e Alimentari

Ciclo **XXXVII**

Settore Concorsuale: 7/A1- ECONOMIA AGRARIA ED ESTIMO

Settore Scientifico Disciplinare: AGR/01 – ECONOMIA ED ESTIMO RURALE

TITOLO TESI

"Unveiling Food Systems Impacts with Systemic Approaches: The Role of Life Cycle Thinking to Support Evidence-Based Policymaking"

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Esame finale anno 2025

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Abstract

The current food system confronts multiple sustainability challenges, including environmental degradation, food insecurity, and socioeconomic inequalities, which are driving humanity beyond a safe operational space. Tackling the complexity of these interconnected issues necessitates a systemic approach to identify key entry points for transformative change within food systems. This research investigates how systemic approaches can contribute to sustainable food systems transformation in Europe and the Mediterranean, focusing on the interaction between policy, science, and society. A systematic scoping review underscores the crucial role of science-policy interfaces in guiding food systems towards global sustainability goals while emphasising the need for a unified vision of sustainability. A sustainability assessment of carbon farming practices in the Mediterranean, employing Life Cycle Assessment, environmental Life Cycle Costing, and social Life Cycle Assessment, demonstrates these practices' potential to enhance soil quality, biodiversity, and farmers' profitability, but also the necessity of policy support for adoption and equitable benefit distribution. Finally, a Life Cycle Assessment and environmental Life Cycle Costing combined with a policy foresight analysis on the future uptake of non-conventional water resources in the Mediterranean suggests that water reuse can alleviate water scarcity; yet its effective adoption requires technological improvements, financial incentives and targeted communication to raise public awareness and address perceived risks. This research contributes to advancing a systemic approach to the transformation of sustainable food systems, accentuating the need for integrated policy, scientific, and societal actions to achieve a more sustainable and equitable food system.

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List of Abbreviations

ACW	Aerated Constructed Wetlands
AS	Activated Sludge
BAU	Business as usual
CA	Conservation Agriculture
CC	Climate Change
CF	Characterisation Factor
CPI	Consumer Price Index
CW	Constructed Wetlands
ECO_{tox}	Freshwater Ecotoxicity
EGD	European Green Deal
eLCC	Environmental Life Cycle Costing
EPD	Environmental Product Declaration
ET_f	Eutrophication, freshwater
ET_m	Eutrophication, marine
F2F	Farm To Fork
FU	Functional Unit
GAC	Granular Activated Carbon
GHG	Greenhouse gas
GW	Groundwater
IC	Impact Categories
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LU	Land Use
MIPs	Molecularly Imprinted Polymers
P.E.	Person Equivalent
PEF	Product Environmental Footprint
SOC	Soil Organic Carbon
SDG	Sustainable Development Goals
SFS	Sustainable Food Systems
sLCA	Social Life Cycle Assessment
UASB	Upflow Anaerobic Sludge Blanket Reactor
WR	Water Reuse
WU	Water Use
WW	Wastewater
WWTP	Wastewater Treatment Plants

Introduction

Transforming food systems is crucial for advancing sustainable development (Rockström et al., 2020). Given their extensive interconnections with social, economic, health, political, and environmental systems, food systems constitute a crucial pathway for advancing multiple Sustainable Development Goals (SDG) and have the potential to drive substantial societal change (TWI2050, 2018). Furthermore, transforming these systems can support long-term sustainability transitions, making them vital for tackling global challenges such as climate change, poverty, and inequality (Sachs et al., 2019).

Food Systems Complexity

Currently, food production and consumption generate complex, intertwined environmental impacts. Food systems are responsible for approximately one-third of global greenhouse gas emissions (Crippa et al., 2021) and account for over 90% of scarcity-weighted water usage (Poore and Nemecek, 2018). In Europe, food systems exceed planetary boundaries in critical areas, including climate change, particulate matter, and freshwater ecotoxicity (Sala and Sanye Mengual, 2022). For instance, the biogeochemical flows of nitrogen and phosphorus have surpassed safe limits, further degrading ecosystems (EEA, 2020). While agrochemical inputs have contributed to increased food production and stable yields, the discharge of significant quantities of pesticides, nutrients, sediments, and organic matter into water bodies compromises water quality, exacerbates water scarcity and drives habitat destruction (Bernhardt et al., 2017; Stevens, 2019).

Agriculture represents one of the main drivers of biodiversity loss (Benton et al., 2021; IPBES, 2019), and land-use changes and agricultural management affect soil quality and health by depleting soil organic carbon (Ramankutty et al., 2018). Biodiversity loss is not limited to natural environments; it also affects domesticated species. The overexploitation of fish stocks beyond sustainable limits has led to evolutionary changes, resulting in smaller maturation sizes, reduced growth rates, and diminished genetic diversity (Schenk et al., 2023). Similarly, livestock systems raise ethical concerns related to animal welfare due to practices such as animal mistreatment, intensive genetic selection and over-use of antibiotics, which represent a risk to public health and safety (Björn and Christina, 2014).

Despite the significant resources invested in food systems, approximately 20% of food produced in Europe is wasted, reflecting inefficiencies within food supply chains (Stenmarck et al., 2016), exacerbating environmental degradation, contributing to nutritional losses, and worsening food insecurity (Gatto and Chepeliev, 2024; Scherhaufer et al., 2018).

On the other hand, the complex interconnections among natural resources, human health, and well-being expose food systems to vulnerabilities arising from climate change, ecosystem degradation, biodiversity loss, and aggravating resource scarcity. Climate change is expected to increase pressure on the ecosystems that support food systems, ultimately impacting yields and food availability (IPCC, 2023).

Disruptions in supply chains due to extreme weather events are anticipated to significantly affect food security, prices, and nutrition among vulnerable groups who are already adversely impacted by current market distortions (Cutter, 2017). In addition, food systems are embedded in global trade patterns that render them susceptible to disruptions or shocks (e.g., COVID-19, wars), with repercussions at both local and global levels (Garnett et al., 2020; Zhang et al., 2023).

The negative impacts of food production and consumption are inadequately reflected in food prices, which tend to favour environmentally unsustainable and unhealthy products and diets (FAO, 2023; Hendriks et al., 2023). Diets generate considerable adverse health outcomes, including rising obesity rates and the prevalence of non-communicable diseases (Afshin et al., 2019). Current dynamics and power relations within food systems contribute to socio-economic inequalities and the creation of unethical value chains (Moragues-Faus et al., 2017), often characterised by unfair wages and the violation of workers' rights and labour conditions. As a result, the agricultural sector contains a significant proportion of the global working poor (World Bank, 2016). The degradation of rural areas, driven by increasingly globalised supply chains, urbanisation and environmental changes, marginalises farming communities and displaces rural poor (de Sherbinin et al., 2008; Liu et al., 2022; Salerno et al., 2024). At the same time, existing incentives remain largely focused on economic factors, neglecting environmental, social, and health externalities, thereby discouraging stakeholders from adopting sustainable production and consumption practices (Kortleve et al., 2024; Pe'er et al., 2020).

Navigating Sustainability Complexity: The Need for Systemic Approaches

This intricate web of relationships within food systems poses wicked sustainability challenges that complicate effective governance. Food systems impact several areas, involving many actors connected by diverse interests with different decision-making power (Díaz-Méndez and Lozano-Cabedo, 2020). As a result, the transformation of food systems is prone to trade-offs across interventions. For instance, limited land creates conflicts between biodiversity conservation, bioenergy, and food production (Gjerris et al., 2016; Kopainsky et al., 2015; Moragues-Faus et al., 2017; Vicente-Vicente et al., 2022). Reducing fertilisers and pesticides may lower yields, threatening food security (Béné et al., 2019a; Gjerris et al., 2016; Kopainsky et al., 2015). Healthy diet shifts could compromise food affordability and cultural preferences (Nicholls and Drewnowski, 2021; Pires et al., 2020). While plant-based diets benefit health and sustainability, they may reduce access to high-quality proteins (Pires et al., 2020), the biodiversity benefits of grazing and potentially threaten farmers' livelihoods (Cué Rio et al., 2022).

Synergies, trade-offs, and spillover effects necessitate integrated and systemic approaches to operationalise food system transformation (De Schutter et al., 2020; Schmidt-Traub et al., 2019). In 2015, the UN's 2030 Agenda aimed to establish a concrete sustainability framework by introducing 17 goals, 169 targets, and 233 indicators to promote the interconnectedness of sustainability, with food systems addressed from multiple perspectives. However, advancing these goals requires a systemic analysis of potential impacts across different governance and geographical levels to identify transboundary effects of policy strategies in various political and territorial contexts (Fuchs et al., 2020; Xiao et al., 2024).

In Europe, the SDG framework has been translated into systemic initiatives such as the European Green Deal [COM (2019) 640, final] and its Farm to Fork (F2F) Strategy [COM (2020) 381, final], designed to enhance policy coherence and address longstanding inconsistencies in the agricultural and food sectors (Brooks, 2014; Candel and Biesbroek, 2016; F. Galli et al., 2020; Matthews, 2008). Examples of misaligned objectives in Europe concern existing environmental policies (*e.g.*, Water Framework Directive, Nitrates Directive) and policy frameworks that promote large-scale commodity production (*e.g.*, CAP or biofuel incentives under Renewable Energy Directive) (IPES-Food, 2019) or incoherencies within the same policy, for instance CAP income support logic (Pillar I) in contrast to the provision of public good (Pillar II) (De Schutter et al., 2020). Hence, moving from isolated approaches to systemic perspectives in science and policy opens avenues to foster better policy integration within the food system domain (OECD, 2021).

While the scientific community has increasingly recognised the role of systemic approaches, shifting from sectorial to food systems research (Béné et al., 2019b; Brouwer et al., 2020; Eakin et al., 2017), the multiple impacts of food systems and entry-points for their transformation remains still understudied. This requires tools and methodologies capable of unveiling environmental, social and economic hotspots as well as their synergies and trade-offs to support integrated strategies and evidence-based decision-making (Zhao et al., 2024). Additionally, it is essential to understand the potential consequences and impact pathways of innovation strategies by considering the perspectives of multiple stakeholders (Herrero et al., 2021). This includes exploring the interactions within socio-ecological systems (Leach et al., 2018) and examining future scenarios and the long-term impacts of policy strategies to facilitate informed decision-making (Wiebe et al., 2018)

Thesis Aim

This thesis aims to explore potential transition pathways toward sustainable food systems by analysing the economic, environmental and social impacts of introducing sustainable resource management practices in farming systems while exploring their synergies and trade-offs. Further, this work investigates how systemic approaches and sustainability assessment can support decision-making by utilising a set of tools grounded in food supply chain analysis (Life Cycle Thinking), sustainability science, future scenario planning, and participatory approaches to support the design of evidence-based policies in the food system domain.

To this purpose, the thesis answers the following research questions:

RQ1. *How does academic literature conceptualise potential systemic pathways for transitioning to sustainable food systems in Europe after the UN Agenda 2030?*

RQ2. *How can systemic sustainability assessment framework unveil the environmental, economic, and social performances of introducing carbon farming practices in the Mediterranean?*

RQ3. *How can systemic sustainability assessment identify policy actions to enhance the diffusion of water reuse for agricultural irrigation in the Mediterranean?*

Thesis Structure

The thesis is organised as follows: first, it introduces the **theoretical and methodological foundations** of the research. The main body is then divided into three chapters. **Chapter 1** employs a PRISMA systematic scoping review to explore academic perspectives on systemic pathways for transitioning to sustainable food systems in Europe post-Agenda 2030, establishing the theoretical foundation for subsequent analyses. **Chapter 2** applies a sustainability assessment framework based on Life Cycle Thinking to evaluate hotspots and trade-offs in the introduction of sustainable soil management practices across eight typical Mediterranean crop rotations. **Chapter 3** combines the sustainability assessment framework with a policy foresight exercise to assess the impacts of adopting water reuse practices for agricultural irrigation and explores potential future applications. Finally, the thesis draws general **conclusions** by discussing the results, outlining limitations, and presenting potential policy and research implications.

Theoretical Background

A system is defined as an interconnected set of elements organised to achieve a specific purpose (Meadows, 2008). The first definition of the food system concept dates to 1994 when it was described as "*the way human beings organise themselves across space and time to access and consume their food*" (Malassis, 1994). This definition has since evolved with the integration of environmental and social dimensions and being understood as "*a coupled social-ecological system, in which efforts to achieve food security both influence and are influenced by environmental outcomes and broader aspects of social welfare and livelihood security*" (Ericksen, 2008). In 2017, the High-Level Panel of Experts (HLPE) on Food Security and Nutrition expanded the definition, describing food systems as encompassing "*all elements and activities related to the production, processing, distribution, preparation, and consumption of food, as well as the market and institutional networks governing these processes, and the socio-economic and environmental outcomes of these activities*."

The definition of sustainability of those outcomes in food systems has similarly evolved, with various international organisations proposing frameworks and conceptualisations (Bock et al., 2022; SAPEA, 2020; FAO, 2018). These frameworks aim to set a common vision for the transition towards sustainable food systems and to assist policymakers in establishing concrete targets to operationalise these definitions. For instance, sustainable food systems have been defined as those that "*ensure food security and nutrition for all, without compromising the socio-economic, environmental, and social bases for current and future generations*" (HLPE, 2017). Nonetheless, the practical implementation of these definitions and frameworks often encounters challenges, including trade-offs and actors' competing interests inherent within food systems. This necessitates the development of strategies to promote policy coherence and integration in support of a shared transformative agenda (Deconinck et al., 2022).

Achieving policy coherence in the food systems domain is particularly challenging due to several factors. Firstly, stakeholders often lack sufficient information on the potential trade-offs and synergies between sustainability objectives. This underscores the need for scientific tools capable of not only assessing the impacts of food production and consumption but also understanding these impacts across multiple dimensions, timeframes, and geographical scales (Fanzo et al., 2021). Tools such as Life Cycle Assessment (LCA) can offer insights into the socio-economic and environmental footprints of food products, thereby helping policymakers and stakeholders identify sustainability hotspots across food supply chains (Sala et al., 2016; Sanyé-Mengual and Sala, 2022). Furthermore, approaches like true cost accounting can reveal the hidden costs associated with certain products (e.g., meat or high-sugar foods), increasing consumer awareness and potentially shifting demand towards more sustainable alternatives (de Adelhart Toorop et al., 2021; Michalke et al., 2023).

The use of single or mixed policy instruments may lead to varying degrees of policy coherence. Understanding how interventions in the food system can generate systemic change necessitates innovative approaches in sustainability science to identify both lock-ins and leverage points. Leverage points, as defined by Meadows

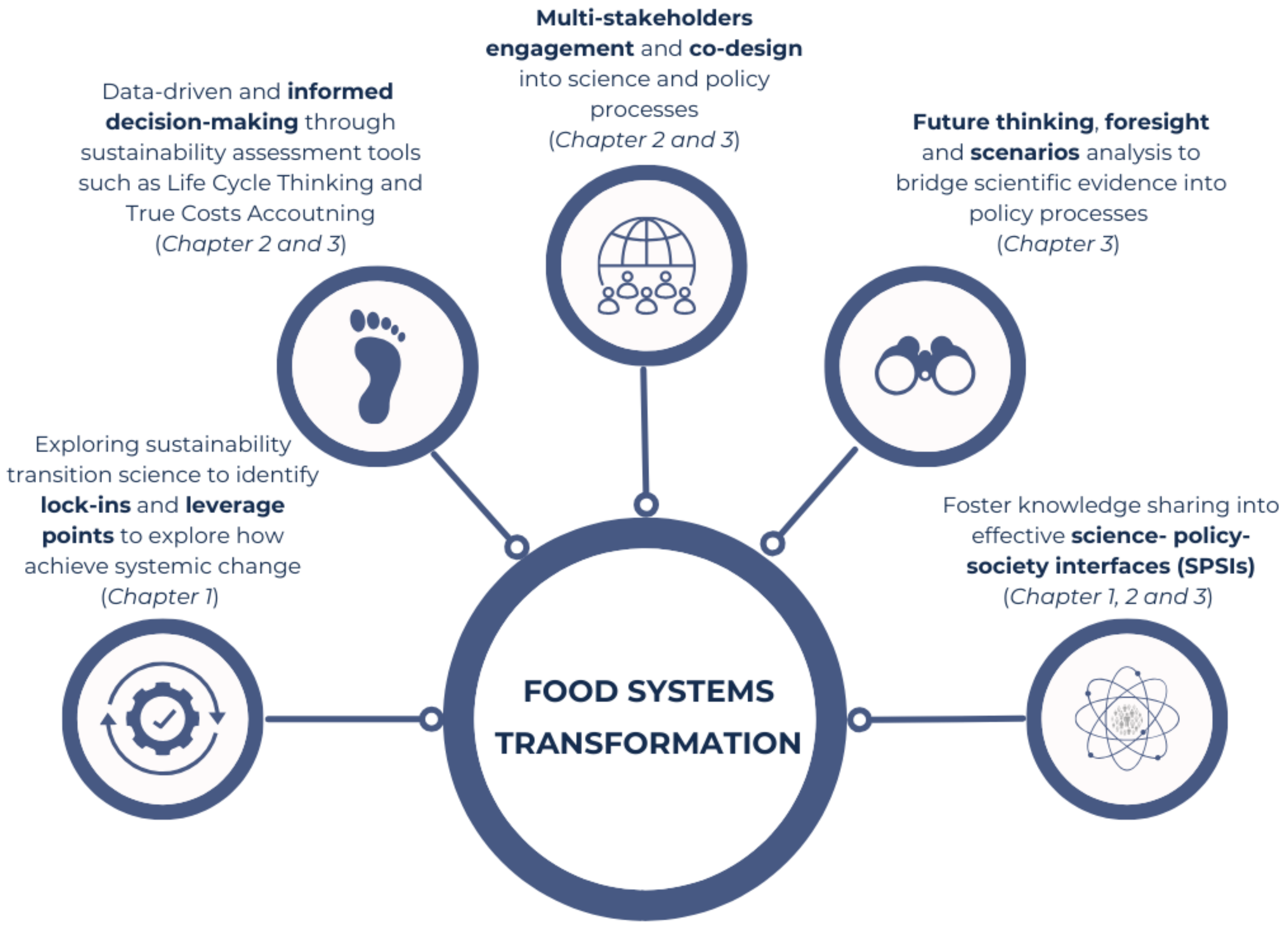
(1999), represent areas in a system where a small change can yield significant impacts. For instance, Meadows identified 12 leverage points, each with varying capacities for transformation, offering a framework to evaluate potential solutions based on their ability to drive systemic change. In contrast, lock-ins are self-reinforcing mechanisms that prevent transformation and maintain the status quo, requiring targeted actions to "unlock" systemic inertia. This approach in food systems research helped to understand economic, technical, behavioural and political barriers preventing food systems transformation as well as to identify entry points for policy actions (Geels, 2019; Klein Woolthuis et al., 2005; Weber and Rohracher, 2012; Weituschat et al., 2022).

Moreover, resolving trade-offs within food systems requires an understanding of societal preferences. For example, consumers may prioritise different values, such as adopting healthy diets, purchasing cheaper food, or protecting animal rights and welfare (Gjerris et al., 2016). Sustainability challenges are interpreted through lenses of morality, knowledge, and power dynamics (Leach et al., 2018). Therefore, engaging multiple stakeholders in the co-design of science and policy processes is crucial for transforming food systems (European Commission, 2022). Such engagement helps identify perceived trade-offs, ensures the technical feasibility of long-term pathways, and raises awareness of sustainability issues (Sachs et al., 2019). Involving stakeholders from different sectors is essential for fostering innovation, knowledge exchange, and sustainable development (*e.g.*, as in the Quintuple Helix proposed by (Carayannis and Campbell, 2012), ensuring also the engagement of vulnerable and traditionally excluded groups.

Finally, the rapid pace of social and environmental change necessitates future-oriented thinking to anticipate trends and drivers of transformation within food systems. Foresight, a systematic and participatory process for exploring long-term futures, can help anticipate and prepare for emerging challenges and opportunities (Wiebe et al., 2018). This approach allows for navigation through the complexities of food systems, supporting present-day decision-making by providing insights into potential futures and highlighting the need for proactive policy interventions (Störmer et al., 2020). In doing so, foresight helps to bridge the gap between scientific evidence and policy discussions (OECD, 2024), ensuring that future-oriented thinking is embedded in efforts to promote sustainable food systems.

The interface between science, policy, and society is expected to play an increasingly critical role in shaping food policy and advancing food system transformations grounded in scientific knowledge and evidence (SAPEA, 2020). These interfaces are essential for framing stakeholder dialogue and creating inclusive science–policy–society interfaces (SPSIs) (European Commission, 2022). This calls for the development of research tools and methods that promote collaboration and facilitate effective knowledge sharing and communication across these domains. This thesis builds upon these principles (summarised in **Figure A**), forming the rationale for the methodological framework and the research hypotheses presented in the subsequent chapters.

Figure A. Principles of the theoretical background behind the research objectives addressed in the chapters.



Source: Authors own elaborations

Methodological Background

This thesis employs a systematic scoping review to identify systemic pathways for food system transformation by leveraging the knowledge established in academic literature. Such studies have proven effective in synthesising knowledge, contextualising policy, and mapping literature on broad topics to identify future research areas and gaps, using a standardised framework to minimise author bias or preferences (Anderson et al., 2008; Barrett et al., 2021). In **Chapter 1**, this study performs a systematic scoping review following the PRISMA guidelines (Tricco et al., 2018), exploring the topic of sustainable food systems in Europe to establish the theoretical framework for the subsequent chapters.

Secondly, this thesis developed and tested a methodological framework based on Life Cycle Thinking, applied to sustainable soil and water management practices within the food systems domain. Life Cycle Assessment (LCA) is a standardised methodology used to quantify environmental impacts across the entire product life cycle (ISO, 2006a, 2006b). This methodology considers interconnected impacts, avoids burden shifting, and informs stakeholders about product footprints and resource allocation. It is central to the development of a harmonised methodology for calculating the Product Environmental Footprint (PEF) within the European Union (Commission Recommendation (EU) 2021/2279). Listed as a tool for analysing impacts in impact assessment, evaluations and fitness checks in the Better Regulation Toolbox[1] (Tool #66), LCA is adopted by policymakers, businesses, and consumers, underscoring its utility in promoting sustainable production and consumption patterns (Notarnicola et al., 2017). It proved it can support the whole policy cycle from the identification of emerging issues, the definition of policy options, their comparison, implementation and evaluation of possible policy impacts (Sala et al., 2016).

Despite the PEF efforts to develop a harmonised method, this methodology faces several challenges as several environmental labels and certification frameworks (e.g., EPD) ground in LCA, generating concerns about product comparability, methodological harmonisations and divergent results (Hélias et al., 2022; Konradsen et al., 2023; Minkov et al., 2020). In addition, the efficacy of LCA in capturing the multifunctionality of agriculture has been questioned, arguing that the LCA product-based approach may not fully encapsulate the diverse array of benefits provided by sustainable farming systems (*e.g.*, ecosystem services provision) and penalise extensive agroecological systems (van der Werf et al., 2020) Further, LCA faced several critiques on regionalisation of impact categories and the need to integrate environmental analysis into broader sustainability assessment (Hellweg and Milà i Canals, 2014).

For these reasons, in **Chapter 2** this work integrates LCA into a broader sustainability assessment framework. Life Cycle Costing (LCC) aims to complement environmental analysis by assessing the costs of a product or process over its entire life cycle. This method follows the guidelines of ISO (2017) and is expanded to include the monetisation of environmental costs, as suggested by Hunkeler et al. (2008) and Swarr et al. (2011). Social

[1] The Better Regulation Toolbox presents guidance, tips and best practices to complement the Better Regulation Guidelines presented in SWD (2021) 305. These guidelines set out the principles that the European Commission follows when preparing new initiatives and proposals and when managing and evaluating existing legislation.

Life Cycle Assessment (sLCA) seeks to uncover the social impacts of products and processes, integrating into the overall sustainability framework by adhering to the guidelines of UNEP- SETAC (2020) and recent ISO (2024). LCA, LCC and sLCA are grounded in the four phases, which are outlined in the subsequent chapters: 1) Goal and scope definition; 2) Life cycle inventory; 3) Impact assessment; and 4) Results interpretation.

To facilitate communication of results to policymakers, sustainability assessment frameworks need to be integrated with policy decision tools. Foresight is a systematic, participatory process designed to inform present decision-making by anticipating future challenges and opportunities, thus enabling joint actions that support policymaking (Cook et al., 2014). As suggested in the Better Regulation Toolbox[1] (Tool #20), its goal is to explore a range of plausible future developments and prevent the creation of ineffective or counterproductive policies that fail to account for emerging changes (OECD, 2024). Various methodologies can be employed, including horizon scanning, megatrend analysis, scenario planning, and backcasting (Störmer et al., 2020). In this work, a combination of megatrend analysis, scenario planning, and structured expert methodologies, such as the Delphi method and focus groups, was utilised. The foresight process generally involves six key steps: defining the scope, collecting inputs, analysing signals, interpreting information, determining actions, and implementing those actions (Cook et al., 2014; Hines, 2016). In **Chapter 3**, sustainability assessment was employed to identify drivers of change that were subsequently explored in the foresight exercise. Through expert consultation and analysis of megatrends identified by the *Joint Research Centre Megatrends Hub,* the process focused on understanding the potential developments of these drivers and devising interventions to address them.

Hence, in line with the theoretical and methodological foundations outlined in these sections, this thesis applies the following methodologies in the subsequent chapters:

M1. *Systematic scoping review of academic literature combined with content analysis and mapping of concepts with sustainability science frameworks (lock-ins and leverage points)*

M2. *Sustainability assessment framework based on Life Cycle Assessment, environmental Life Cycle Costing and social Life Cycle Assessment*

M3. *Sustainability assessment framework based on Life Cycle Assessment and environmental Life Cycle Costing combined with a Policy Foresight for scenarios development*

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Chapter 1

Time to transform? Sustainability narratives for European Food Systems

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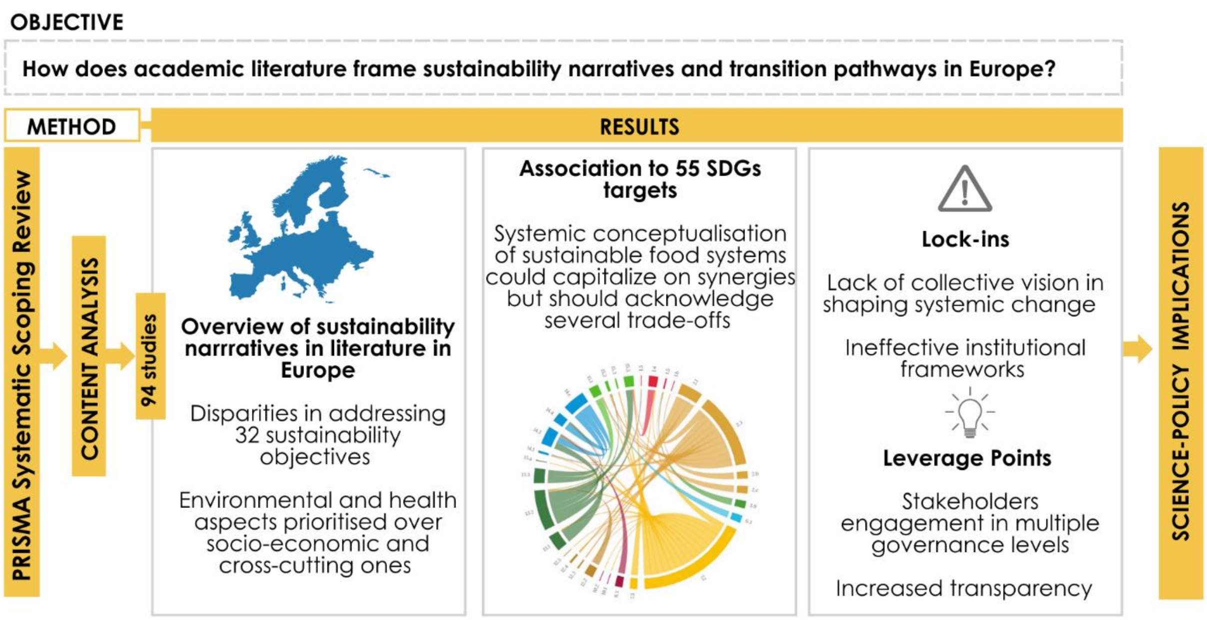


Chapter 1

Time to Transform? Sustainability Narratives for European Food Systems

Published as: Guerrieri, V., Borchardt, S., Listorti, G., Marelli, L., & Vittuari, M. (2025). Time to transform? Sustainability narratives for European food systems. Global Food Security, 44, 100831. https://doi.org/10.1016/j.gfs.2025.100831.

Abstract

The unsustainable nature of prevailing food systems contributes to drive humanity out of a safe operating space. Despite recognising the need for food systems transformation, its direction diverges into different sustainability narratives and conflicting objectives resulting in disjoint policy agendas and problem definitions. While few studies compared and identified gaps and trade-offs in food systems frameworks, systematic reviews for conceptualising sustainable food systems remain scarce. Focusing on the European context, we investigated how academics framed sustainability narratives and their role in advancing Sustainable Development Goals targets, exploring lock-ins and leverage points for transformation. By conducting a PRISMA systematic scoping review and analysing 94 documents, we found disparities in current research with socio-economic and cross-cutting aspects comparatively overlooked to environmental and health ones. Linking sustainability objectives to 55 SDG targets we demonstrated their potential contributions to sustainable development by addressing systemic conceptualisations and acknowledging trade-offs. We identified the lack of vision and coordination among stakeholders and institutional framework shortcomings as barriers to change. Analysis of leverage points suggested stakeholder engagement and system transparency as pivotal for transformation. Lastly, we provide concrete policy recommendations to shape a food system transformation grounded in a shared sustainability paradigm forged through collaborative efforts among scientific, policy, and societal domains.

Keywords

Sustainable food systems; Food system transformation; SDG; Systematic scoping review; Systems thinking

1.1 Introduction

Advancing the United Nations Sustainable Development Goals (SDG) requires a transformation of food systems (Rockström et al., 2020). Indeed, the current food production and consumption patterns create complex sustainability challenges that are driving humanity out of a safe operating space (HLPE, 2020; SAPEA, 2020). These challenges include environmental degradation, food insecurity, socio-economic inequalities, and diet-related health problems (Moragues-Faus et al., 2017; Notarnicola et al., 2017; Penne and Goedemé, 2021; Yumuk et al., 2015).

Effectively addressing the wicked nature of those challenges requires integrated and systemic policy approaches (Rittel & Webber, 1973) . In 2015, the UN 2030 Agenda pursued building a tangible sustainability agenda by proposing 17 goals with 169 targets and 233 indicators to advance the interconnectedness of sustainability and touching food systems from multiple perspectives. Attempts to better operationalise such a global sustainable development framework even translated food systems into a transformational pathway through which multiple SDG can be effectively advanced in an integrated way (Sachs et al., 2019; TWI2050, 2018).

In Europe, the attempt to respond to cross-cutting societal challenges turned into systemic initiatives such as the European Green Deal (EGD) and its Farm to Fork Strategy (F2F) with the aim of strengthening the coherence in policy design, addressing those inconsistencies having accompanied the agricultural and food sectors for years (Brooks, 2014; Candel and Biesbroek, 2016; F. Galli et al., 2020; Matthews, 2008). Nonetheless, their effectiveness is challenged by food systems complex dynamics in which multiple actors are voluntarily and involuntarily involved and connected through composite relationships shaped by different social, environmental, and economic interests and goals, varying access to resources and diverging degrees of decision-making power (Díaz-Méndez and Lozano-Cabedo, 2020). Further, being food systems embedded in global trade patterns, these relationships encompass not only European but also global dynamics in which policy strategies can create spillover effects outside the EU political and territorial context (Fuchs et al., 2020).

Rooted in the agricultural and ecological sciences perspectives, the food system concept was introduced several decades ago (Getz and Gutierrez, 1982; Knee, 1989) and evolved over time increasingly recognising its interactions with global environmental changes affecting societal outcomes (Ericksen, 2008) and its determinant role for achieving sustainable development (Rockström et al., 2016). First attempts to describe food systems concept date to 1994, when it is defined as "*the way human beings organise themselves across space and time to access and consume their food*" (Malassis, 1994). This definition has since evolved into more comprehensive descriptions, as the one provided by HLPE (2017) which describes food systems as: "*elements and activities that relate to the production, processing, distribution, preparation, consumption and disposal of food, and the outcomes of these activities, including nutritional, food security but also socio-economic and environmental outcomes*". Nonetheless, when defining the sustainability of these outcomes, the food systems narratives depend on the scale of analysis, actors' perspectives, and values (Allen, 2014; Béné et al., 2019a; Eakin et al., 2017; Kanter et al., 2018) resulting in a lack of a comprehensive and agreed-upon definition and conceptualisation of what should be considered 'sustainable'. This plurality of definitions reflects into incoherent policy agendas and hinders efforts to set concrete targets and action plans to operationalise terms such as 'resilient', 'safe' or 'inclusive' (Smaal et al., 2021).

Investigating diverse conceptualisations of food systems dynamics can contribute to prevent miscommunication, inaccurate problem identification (Kelly et al., 2019; Stock and Burton, 2011) and diverging agendas-setting (Kugelberg et al., 2021). The reinvigorated experts' interest in understanding sustainable food systems resulted in an increasing number of conceptual frameworks proposed by international organisations (Bock et al., 2022; SAPEA, 2020; FAO, 2018), experts' panel (HLPE, 2017; IPES-Food, 2019) and academics (Eakin et al., 2017; Hebinck et al., 2021; Kugelberg et al., 2021; Stefanovic et al., 2020; von Braun et al., 2021). Nonetheless, food systems conceptualisations tend to overlook the dynamics, encompassing feedback loops, nonlinear relationships, and time-dependent behaviours within the system, resulting in static narratives that could misrepresent their real complexity.

While Brouwer et al. (2020) compared different food systems frameworks emerging from grey literature, Zou et al. (2022) explored their gaps and limitations focusing on urban food systems. Béné et al. (2019a) explored how sustainability is included in food systems narratives linking to the questions of healthy diets and focusing on a time frame from 2000-2017. However, there still remains a necessity to conduct studies aimed at systematically explore how these sustainable food systems visions and conceptualisations emerge and reflect in academic literature, especially after the publication of UN Agenda 2030. Further, the existing literature lacks a recent thorough review of the existing academic knowledge that attempt to investigate multiple and systemic aspects of food system transformation existing in scientific documents (**Table 1.1**).

To fill this gap, this paper aims to understand how academic literature envisages possible systemic pathways for transitioning to sustainable food systems (SFS) in Europe after the UN Agenda 2030. By adopting a systematic scoping approach, it analyses how the academic literature addresses not only reported food systems sustainability objectives but also their intrinsic trade-offs. Then, it operationalises these outcomes: *a)* by analysing the transformative potential of these aspects in achieving SDG targets and *b)* by identifying the obstacles (lock-ins) and the multipliers (leverage points) that can hamper or boost this transformation. Ultimately, based on the findings of the analysis, it attempts to draw some science-policy implications to shape the food systems transformation.

This article is organised as follow. **Section 1.2** provides the methodological background for the selection of eligible documents, content analysis and SDG mapping. **Section 1.3** reports the sustainability objectives and trade-offs identified in the scientific documents' narratives, their contribution and interactions with SDG targets, and the lock-ins and leverage points for their achievement. **Section 1.4** discusses results and limitations and lists potential implications for the science-policy agendas.

Table 1.1 Existing reviews addressing the conceptualisation of food system frameworks.

Author	Time horizon	Scope	Nr. of documents	Sources
Béné et al. (2019a)	2000 - 2017	To explore how sustainability is included in different food system narratives and the link to the question of healthy diets	More than 70	Science Direct, Google Scholar and Grey Literature
Brouwer et al. (2020)	2016 - 2019	To identify and compare differences in the frameworks used for food systems analysis, and discrepancies in the procedures to identify strategies for and performances of food system transformation	32	Grey Literature
Zou et al. (2022)	N.S.	To discover the current limitation in existing FS frameworks to enhance the development of a new FS/urban food system framework that can tackle the triple burdens of malnutrition and FS unsustainability	50	Web of Science
This review	2015 – 2023	To investigate how academic literature envisages sustainability objective, dynamics, and systemic pathways for transitioning to sustainable food systems	94	Scopus and Web of Science

1.2 Method

We employed a scoping review methodology, which is recognised for its systematic synthesis of diverse findings to address broad topics and has proved being effective for knowledge synthesis and policy contextualisation (Anderson et al., 2008; Tricco et al., 2018). Indeed, the breadth and heterogeneity of the investigated concepts, definitions and methods hinders a quantitative analysis of empirical findings, as well the quantitative assessment of the risk of bias, as in the case of systematic reviews and meta-analysis.

1.2.1 Search Strategy and Data Sources

Adhering to PRISMA extension guidelines, the study adopts a systematic search on two of the most widely used scientific databases for bibliometric analysis (V.K. Singh et al., 2021) - Web of Science and Scopus databases- utilising the following keywords: 'sustainable food systems' or 'food systems' near 'sustainability' and 'concept*', 'element*', 'defin*' and 'framework' (See *Table 1.A, Supplementary Materials I*). Running searches in January 2023 and updating in January 2024, the review focuses on articles, reviews, book chapters and notes published post-2015, assuming increased relevance after the launch of the UN Agenda 2030.

1.2.2 Eligibility Criteria and Screening Process

Obtained records were screened by two independent researchers, reviewing title and abstract for each publication with respect to the eligibility criteria (presented in **Table 1.2**), to ensure a consistent and topic-focused set of publications for the content analysis. The eligibility Criteria 1 was defined to narrow down the geographical scope to the European context, stemming on the consideration that food systems outside and within Europe may present different characteristics and dynamics. Secondly, the eligibility Criteria 2, 3 and 4 were defined to limit the analysis to studies that propose overarching and systemic approach to analyse different elements of sustainability, expanding to food systems related aspects, and identified transition pathways. Mendeley Reference Manager facilitated screening and data extraction processes. Documents that did not meet Criteria 1 and Criteria 2 or 3 or 4 were excluded.

Table 1.2 Inclusion and exclusion criteria for studies' eligibility.

<table>
<tr><th>Number</th><th>Inclusion</th><th>Exclusion</th></tr>
<tr><td>Criteria 1</td><td>1a. Address the European context or include a case study in the European area (including Switzerland and the UK).
1b. Address the conceptualisation of sustainable food systems without targeting a specific geographical context and without reporting results from a specific case study application</td><td>Address or include a case study outside the European context and area (excluding Switzerland and the UK)</td></tr>
<tr><td rowspan="3">Criteria 2
OR
Criteria 3
OR
Criteria 4</td><td>2. Attempt to or propose a framework to conceptualise food systems sustainability by proposing an overarching and systemic approach (e.g., SFS frameworks) and analysing different elements of sustainability</td><td rowspan="3">Address specific solutions or interventions (e.g., insects, school canteens), methodological frameworks for sustainability assessments (LCA, indicators), specific food systems (e.g., fisheries, livestock), elements of food systems (e.g., soils, waters) or responses to external shocks (e.g., wars, COVID-19)</td></tr>
<tr><td>Apply an integrated perspective on food systems-related aspects from different conceptual entry points:
3a. Address the conceptualisation of Alternative Food Networks (AFNs) as the term covers emerging networks of food systems' actors that propose alternatives (concepts) to the standardised food supply
3b. Address concepts related to food system governance (e.g., food democracy) to address the institutional and political context governing food systems and their mechanisms and interconnectedness with the other elements of the systems
3c. Address concepts related to elements affecting food environments (e.g., physical, and economic access to food, food safety and quality) and food system outcomes (e.g., healthy diets)[1]</td></tr>
<tr><td>4. Analyse transition pathways towards food system sustainability advantaging from the sustainability transition science. This sub-criterion envisages the conceptualisation of barriers and solutions towards SFS</td></tr>
</table>

Source*: Authors own elaboration*

1. As illustrated by the food system framewrks proposed by HLPE (2020)

1.2.3 Data Extraction and Content Analysis

To systematically analyse the message characteristics in the documents, we performed a content analysis (Neuendorf, 2020) by using Microsoft Excel and elaborating graphics with Python and Tableau Software.

Concepts Coding

Based on frameworks grounded in food systems and sustainable diets conceptualisations (Ericksen, 2008; HLPE, 2017; Ingram, 2011) we extracted the individual text lines and coded qualitative data from the whole text of the eligible documents. The framework (*Supplementary Materials, Figure 1.B*) captured bibliometric details, geographical scope, methodology and sustainability definitions. Secondly, it attempted to extract the sustainability objectives reported in academic literature, considering the food environment, the food system environmental, social and economic impacts, their nutritional and health outcomes and the synergies and trade-offs among these aspects.

Additionally, it coded information on lock-ins, and leverage points for food system transformation to identify transition pathways and potential feedback loops. Prior data extraction, we agreed on a glossary of terms' definitions for ensuring reproducibility and coherence (*Supplementary Materials, Table 1.D*).

Concepts Categorisation

Extracted text lines on food systems impacts, outcomes and environment were grouped in keywords and qualitatively clustered over dimensions and objectives of food system sustainability. Coherently with the paper's objective, this process followed a mixture of inductive, drawing on existing frameworks (Béné et al., 2019a; Bock et al., 2022), and deductive approaches, due to the divergence of values and interests that generated a lack of a shared vision in food systems domain. As the sustainability objectives identified entailed overlapping concepts, each text line was matched to multiple objectives.

On the other hand, an inductive approach was adopted for lock-ins classifications following the systematisation of Geels (2019), as it explains several dimensions of their mechanisms (Weituschat et al., 2022) and includes comprehensive groups that fitted the collected data. Further, we deepened the analysis by complementing lock-ins explanation with system failures classification following Woolthuis et al. (2005) and Weber and Rohracher (2012).

Further, identified solutions were qualitatively mapped to the 12 leverage points for system interventions proposed by Meadows (1999) and systematised by Abson et al. (2017) to identify possible entry points to intervene in different parts of a system (parameters, feedback, design and intent) and the transformational process needed to change the system. Building on this approach, each text line was univocally matched with a type of lock-in, system failure and leverage point.

Finally, having categorised the text lines, results were expressed as frequencies counting the number of scientific documents reporting the specific objectives, lock-in, failure and leverage point identified. Data extraction, coding and classification processes are detailed in the *Supplementary Material I*.

1.2.4 Mapping of SDG Target and Interlinkages

We explored the transformative potential of sustainable food systems by qualitatively associating coded elements with the United Nations' 17 Sustainable Development Goals (SDG). The mapping was independently conducted by first and second authors (VG and SB) and validated by the rest of the research team. Each SDG encompasses targets addressing social, economic, environmental, and governance dimensions, forming a comprehensive framework for global well-being planet (United Nations, 2015). Depending on the level of granularity of the coded elements, we associated one or multiple SDG targets to them.

Adopting an interlinkages perspective, the analysis draws from a database of over 23,724 records (Fronza et al., 2023) examining directed and undirected interlinkages, positive synergies, and negative trade-offs at the goal, target, and indicator levels. To the authors' knowledge, this is to date the most comprehensive database on SDG interactions, synthesising findings of 92 of studies that analysed and revealed interlinkages in various geographical contexts by applying a broad range of diverse methods on different analytical scales and governance levels. Based on the outcomes of the SDG mapping, interlinkages between associated SDG targets were extracted from the database to capture and better understand internal interactions between the system elements.

1.3 Results

Out of 579 initially identified documents, 94 studies meeting the inclusion criteria were integrated into the analysis (*Supplementary Materials*, *Figure 1.A*).

1.3.1 Extent and Range of the Collected Evidence

The database includes mainly scientific articles (n=71) integrated with reviews (n=12), book chapters (n=10) and notes (n=1). The database covered mainly the European area, while 36% of the studies investigate sustainability concepts without targeting a specific geographical area. Among the studies addressing the European context (n=60), case studies focused mostly on Western (30%) and Southern Europe (12%), while less documents targeted specifically Northern (7%) and Central and Eastern (5%) Europe.

1.3.2 Nature of the Collected Evidence

Qualitative studies prevailed over quantitative ones. Indeed, almost half of the studies (n=40) employed literature and content analysis to investigate concepts, while one third made use of qualitative methods such as structured and semi-structured interviews, focus groups, workshops (n=18), and analysis of laws, policy, and strategies (n=13). The number of studies employing quantitative methods (n=7) was lower and includes footprinting and modelling approaches. Other methods included Multi-Criteria Decision-Making Analysis (MCDA) (n =2), Socio-Ecological System (SES) frameworks (n=2), foresight (n=1), and participatory spatial planning assessment (n=1).

1.3.3 How Does the Academic Literature Address the Sustainability Objectives for Transforming EU Food Systems?

The scientific production trend of the selected studies proves the increasing efforts in investigating sustainable food system frameworks after 2015. The number of scientific documents produced increased steadily from 2015 to 2022 with the highest annual growth rate (+ 200%) in 2017 (*Supplementary Materials*, *Figure 1.C*).

Only one-third (n=32) of the studies examined in this analysis offer explicit definitions of the concepts under investigation. Consensus among scholars is relatively high regarding the definition of food security (n=7) as established by the World Food Summit in 1996, and sustainable diets (n=7) as defined by FAO (2012). Higher heterogeneity characterises the definition of sustainable food systems with nine studies reporting six distinct definitions of sustainable food systems. Among these, three studies reference the definition outlined by HLPE (2017). Indeed, there is a broader spectrum of perspectives evident in the literature, with eight studies reporting four different definitions for food systems cited as Ericksen (2008); FAO (2018, 2014); HLPE, (2017) that draw on other existing definitions (e.g., HLPE, 2014; Ingram, 2011). Additionally, the discourse encompasses other terms connected to various aspects of the food systems sustainability such as 'sustainable bioeconomy systems', 'food governance', 'local food systems', 'alternative food networks', 'food justice', 'food democracy', and 'food sovereignty'.

Drawing on these definitions and investigating recurring narratives in the set of scientific documents, results show a pattern of disparities in the sustainability objectives addressed. Resulting from the deductive categorisation, the analysis identified 974 text lines containing sustainability objectives in the narratives of the 94 studies, grouped into 32 categories, 9 sub-dimensions and 5 dimensions of sustainability. The studies were grouped according to the 5 main scopes of the conceptualisation they presented, to coherently reflect the criteria 2, 3, and 4 outlined in **Table 1.2**. The heatmap (**Figure 1.1**) illustrates the percentage of the 974 objectives occurring over the 32 categories. Narratives related to the environmental management of natural resources and food environment prevail over socio-economic and cross-cutting (*e.g.,* democracy, sovereignty) aspects. Indeed, seven of these objectives recurred more frequently (more than 5%) and entail food security, quality and healthy diets delivery, protection and restoration of biodiversity, climate change mitigation and adaptation, management of natural resources use, and equity guarantee.

Despite different studies' objectives, the pattern showed in **Figure 1.1** replicates across the groups of scientific documents with slight differences in studies conceptualising Alternative Food Networks (AFN) and sustainable governance mechanisms. While narratives in food and nutrition studies remain concentrated around objectives that pursuit sustainable food environment and environmental aspects, guaranteeing food democracy was more frequently addressed (6%) in the set of objectives identified in AFN studies. On the other hand, studies focusing on governance aspects show a focus on equity, equality, and cultural and social acceptability aspects.

Trade-offs Identified in the set of Documents

Only a small number of these studies highlights trade-offs and synergies among the sustainability categories they identify. According to those studies, several trade-offs occur among food security and other sustainability aspects especially in terms of land use. Due to limited amount of land, conflicting objectives occur between biodiversity, bioenergy, and food production exacerbated by a potential shift to plant-based diets (Gjerris et al., 2016; Kopainsky et al., 2015; Moragues-Faus et al., 2017; Vicente-Vicente et al., 2022). Further, several studies point out the trade-off in reducing fertilisers and pesticides use which generate lower yields threatening food security and self-sufficiency (Béné et al., 2019a; Gjerris et al., 2016; Kopainsky et al., 2015).

Many of these studies illustrate how shifting to healthy diets generate further trade-offs among healthy food, affordability (*e.g.,* higher costs of diets) but also food safety (*e.g.,* nuts that could be rich in aflatoxins) and cultural acceptability (*e.g.,* cultural accepted diets with high number of calories) (Nicholls and Drewnowski, 2021; Pires et al., 2020). Also, while shifting to plant-based diets could significantly benefit human health and environmental sustainability, reducing meat consumption implies reducing high sources of high-quality protein (Pires et al., 2020) and renouncing the grazing benefits on biodiversity and threatening farmers livelihood (Cué Rio et al., 2022).

Figure 1.1 The percentage of the 974 objectives over 32 categories identified in the sustainability narratives of 94 studies through keywords clustering grouped over the 5 main scopes of their conceptualisation. The intensity of colours shows the frequency of the objectives across the sustainability categories and studies' aim (color should be used for this figure in print).

Dimensions, sub-dimensions, and categories

Dimension	Sub-dimension	Categories of Sustainability Objectives		Total	Overarching Framework	Sustainable Governance	Alternative Food Networks	Sustainability Transition	Food and Nutrition
ENVIRONMENTAL	Management of Natural Resources	Adapt and mitigate	Climate Change	5.75	5.79	4.81	4.06	5.58	7.19
		Protect and restore	Natural Resources Quality (air, water, soil)	5.44	5.79	3.85	4.57	5.08	6.59
			Natural Resources Use (water, land)	4.41	4.25	2.88	3.05	4.57	6.59
			Biodiversity State	6.67	7.34	3.85	6.60	6.09	7.78
			Ecosystems Extent and Condition	3.70	2.70	3.37	2.03	4.57	5.39
			Agricultural Landscape	0.92	0.39	0.48	2.03	1.02	0.60
	Food Supply Chain Optimisation	Reduce	Pesticide, Fertilisers and Antimicrobial Use	2.87	2.70	2.40	2.03	3.05	3.59
			Food Losses and Waste	3.29	4.63	1.92	3.55	2.54	2.40
		Improve	Circularity of Resources	1.13	1.54	1.44	0.00	1.52	0.60
			Waste Management	0.62	0.39	1.44	0.00	0.00	1.20
ECONOMIC	Distribution	Ensure fair and just	Income/Salary for food workers	4.41	5.02	4.81	2.54	4.06	4.19
			Added value distribution in the value chain	1.64	1.16	1.92	2.54	1.02	1.20
			Trade	0.72	0.77	0.96	0.51	0.00	1.20
	Development	Boost	Local Economy	2.05	1.54	4.33	2.03	0.51	1.20
		Generate	Employment	1.13	1.93	0.00	1.02	1.52	0.60
SOCIAL	Welfare and well-being	Guarantee	Equality	4.11	3.09	5.29	4.06	3.55	3.59
			Equity	5.95	6.56	5.29	7.11	3.05	5.99
			Cultural and Social Acceptability	4.00	4.63	4.33	4.06	1.52	4.19
		Boost	Rural Development	1.44	1.54	1.92	0.51	1.52	1.20
		Protect	Worker rights and conditions	1.23	1.16	1.92	2.03	0.00	0.60
		Ensure	Social well-being	1.33	1.16	2.88	0.51	1.02	0.60
			Animal welfare	1.75	1.54	0.96	2.54	1.02	2.40
	Connectedness	Strengthen	Community engagement	3.29	4.25	4.33	3.55	2.03	0.60
			Connectedness of consumers and producers	1.44	0.77	3.85	1.52	0.51	0.00
HEALTH & NUTRITION	Food environment	Deliver	Food Security	6.78	6.95	5.77	8.63	3.05	7.78
			Food Safety	3.18	3.09	2.88	2.54	1.02	5.99
			Food Quality	5.44	5.79	5.29	5.08	3.05	6.59
			Healthy Diets	5.13	5.41	3.37	7.11	3.05	5.39
CROSS-CUTTING	Governance	Guarantee	Food Democracy	2.87	1.16	3.85	6.09	1.52	1.20
			Food Literacy and transparency	2.26	1.54	3.37	4.06	1.02	0.60
			Food Sovereignty	2.05	1.93	3.85	1.52	2.03	0.00
	Resilience	Increase	Resilience	2.98	3.47	2.40	2.54	2.54	2.99

Percentage of sustainability objectives identified (%) grouped over the main scope of the conceptualisation.

Source: *Authors own elaboration*

Not only environmental concerns incur in trade-offs, but authors also highlight the dilemma of supporting local economy or encouraging small producers (especially in low- and middle-income countries) to gain access to a profitable global market, which can risk imposing unfair trading rules (Boylan et al., 2020; Gjerris et al., 2016). Finally, the identified trade-offs concerned not only system goals but also conflicts among stakeholders' interests and values occurring in the food systems (F. Galli et al., 2020; Scaramuzzi et al., 2021).

1.3.4 Leveraging a Sustainable Food System Transformation to Advance the SDG

Sustainability Objectives and SDG Target

A transformational pathway towards a sustainable food system provides an operational perspective to advance multiple SDG in an integrated way. This is also emphasised by the numerous links between the sustainability objectives categories identified and the SDG targets of the 2030 Agenda (**Figure 1.2a**). By having qualitatively mapped the 32 sustainability objectives categories to SDG targets, the analysis led to 55 unique targets spanning across all 17 SDG and corresponding to major social, economic, and environmental aspects of sustainable development as envisioned in the 2030 Agenda. Results show that the sustainable food system conceptualisation presented alludes to aspects that are absent in the SDG framework, like animal welfare as well as cultural and social acceptability. SDG 2 on Zero Hunger emerged as the most frequently addressed goal with all its targets being linked to the sustainability objectives. Other frequently addressed goals are SDG 12 on sustainable production and consumption as well as SDG 15 on life on land, but also social (SDG 1 and 10) and economic (SDG 8) goals are well addressed (See *Table 1.K, Supplementary Material I* for further details on the specific targets and sustainability objectives linked).

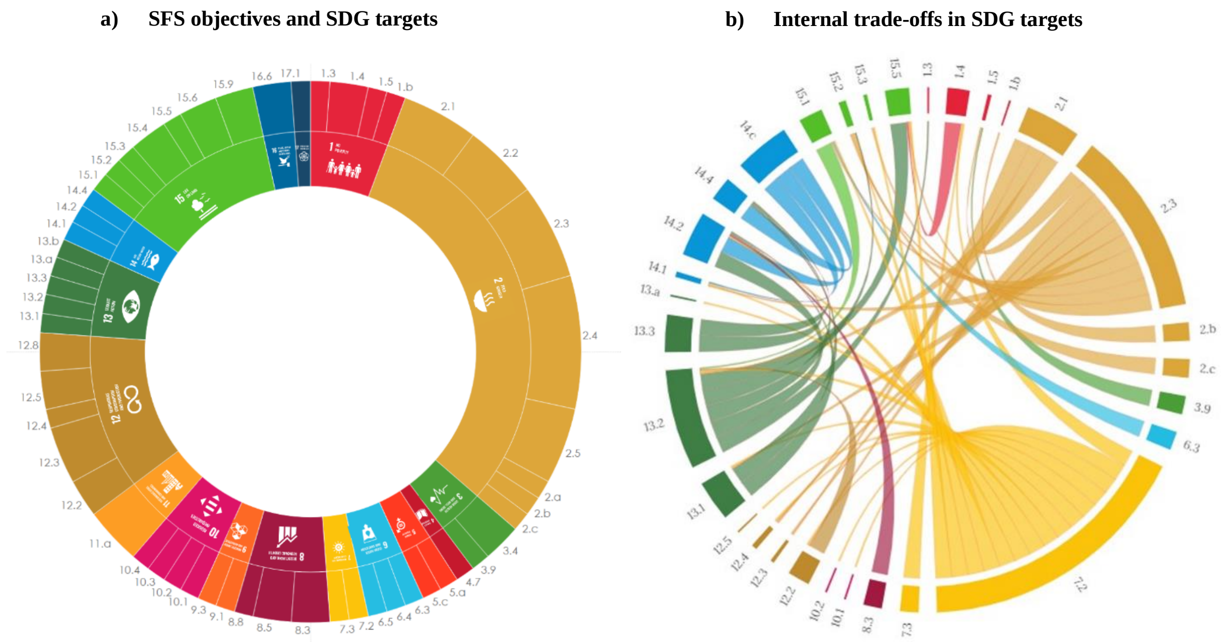
SDG Interlinkages

While the numerous links with the SDG framework well reflect the multi-dimensional nature of a sustainable food system, its interconnectedness is strongly underlined when looking at the interlinkages between the associated SDG targets that correspond to the sustainability objectives (**Figure 1.2a)**.

Though most interactions tend to be positive, trade-offs need to be considered to carefully manage possible internal conflicts between different sustainable food system objectives when attempting to govern the transition. Capitalising on a database of SDG interlinkages (Fronza et al., 2023) and considering only directed interlinkages between SDG targets associated with the 32 sustainability objectives the analysis reveals a total of 615 relevant interlinkages between the selected SDG targets, out of which 534 interlinkages are considered positive and 81 negative links.

Figure 1.2b focuses on the internal trade-offs between the selected SDG targets, highlighting targets belonging to SDG 2 (zero hunger), 7 (clean energy) and 13 (climate change) and environmental goals (14 on life below water, 15 on life on land) as main sources for trade-offs. Concrete examples concern for instance SDG target 7.2 on substantially increasing the share of renewable energy in the global energy mix and its potential negative implications for environmental targets like 15.5 on halting environmental degradation and biodiversity loss, 15.2 on sustainable forest management or 14.1 on marine pollution due to the expansion of renewable energy infrastructures and its possible impacts on the environment which indicates a possible area of friction between a sustainable food system's climate change and adaptation objectives and sustainable resource use and biodiversity protection objectives. Food security objectives as outlined in SDG target 2.3 which envisions a doubling in agricultural productivity may create trade-offs with many other SDG targets, particularly those related to environmental aspects like target 12.2 on sustainable natural resource management or target 15.3 on combatting soil and land degradation and to climate change objectives (*e.g.*, target 13.1 on strengthening climate resilience). These trade-offs also well-reflect and underline the trade-offs identified by the reviewed studies between the identified sustainability categories (*e.g.*, in the context of land use conflicts).

Figure 1.2 (2a) Mapping of SDG goals and targets with the 32 objectives for sustainable food systems identified in the scoping review process. (2b) Trade-offs among identified targets as identified by literature (Fronza et al., 2023). The width of the arches indicates the number of targets connected to the 32 objectives and of trade-offs among them (color should be used for this figure in print).



Source: *Authors own elaboration*

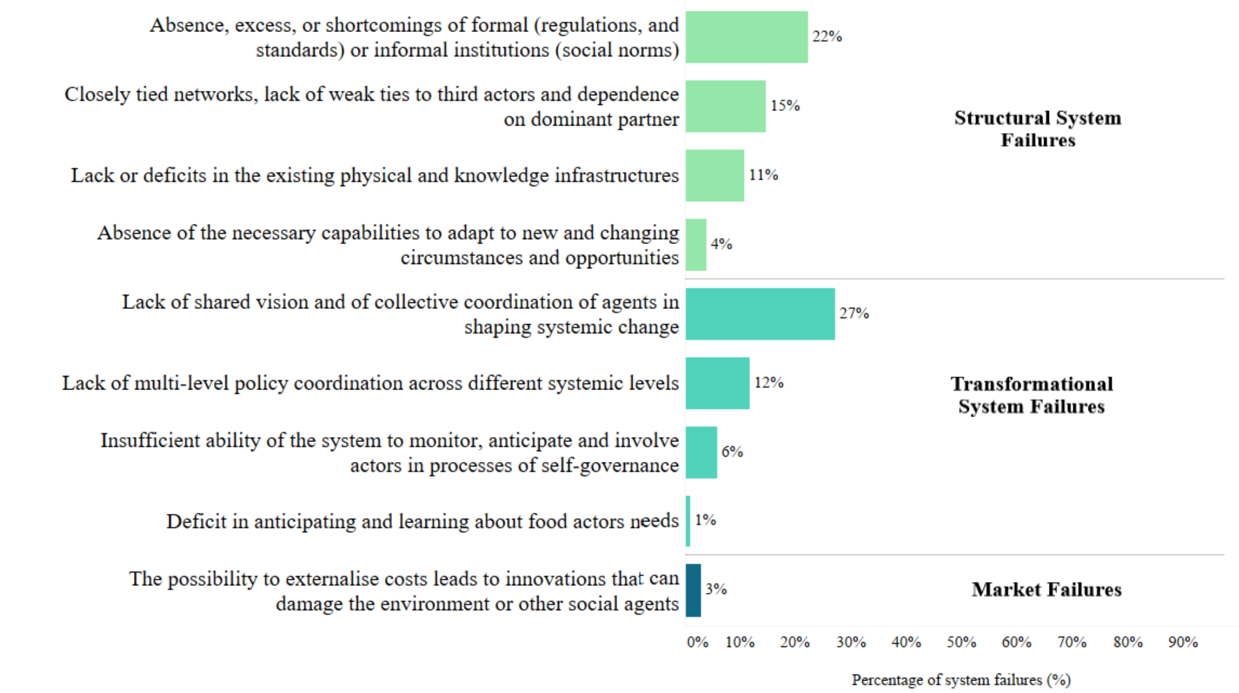
For what concerns synergies, many interlinkages emerge between SDG related to the environmental dimension, for instance between SDG 12 on sustainable production and consumption and SDG 13 and 15 and more specifically between target 12.2 on sustainable resource use and targets 13.1 and 13.2 or 12.8 on promoting and fostering sustainable lifestyles that positively interacts with targets under SDG 13, 14 and 15. When considering the number of interactions with other targets, target 13.1, 14.1, 14.2 (sustainable management and protection of marine ecosystems) as well as 15.5 and 7.2 emerge as those with the highest number of interlinkages (see *Supplementary Material, Figure 1.D* for full matrix of interactions).

1.3.5 Which are the Lock-ins Impeding the Transition to Sustainable Food Systems?

While enabling a food system transformation could lead to the achievement of multiple and interconnected goals, around 60% of the studies (n=54) report the existence of self-reinforcing mechanisms that reproduce status quo (lock-ins) and impede the transition to sustainable food systems.

The nature of these lock-ins revealed multifaceted, hiding systemic failures not only at structural level due to inefficacies in formal and informal institutions, but also at transformational level where a lack of directionality for the food system transformation impede change. Starting from the set of 54 studies reporting the lock-ins, we identified 103 barriers in the set of studies grouping them by nine types of failures (as identified by Weber and Rohracher (2012)). **Figure 1.3** shows the percentage of the 103 barriers over the nine types of failures grouped in transformational, structural and market failures. These failures originate at structural level due to the shortcomings of current institutional frameworks (22%) (*e.g.,* existence/absence of taxes, subsidies, or regulations) and due to the presence of closely tied networks (15%) that disconnect marginalised actors and reinforce reliance on dominant partners. The lack of physical and knowledge infrastructures (11%) and capabilities to adapt to new circumstances (4%) reinforces these mechanisms. While when transformation occur, the lack of a shared vision (27%) and the consequent policy coordination failures (12%) send conflicting and changing messages to food system actors, whose engagement result disadvantaged by the inability of system to monitor and involve actors in the process of self-governance (6%) and the deficit in anticipating actors' needs (1%). Market failures (3%) related to the externalisation of costs contribute to these failures by leading to innovation that damage the environment and the society.

Figure 1.3 Percentage of market and structural and transformational system failures identified in the scientific documents. Based on Woolthuis et al. (2005) and Weber and Rohracher (2012) (color should be used for this figure in print).



Source: *Authors own elaboration*

The systems failures contribute to different extents to generate systemic lock-ins that impede food system transformation. **Table 1.3** groups the nine types of systemic failures by 3 different types of lock-ins proposed by Geels (2019) by providing concrete textual examples from the set of analysed documents. Approximately 50% of the identified barriers, totalling over 103, pertain to institutional and political lock-ins stemming from prevailing regulations, standards, and policy networks. Roughly 30% are attributed to techno-economic lock-ins resulting from inefficient investments and established economies of scale, while the remaining 20% are associated with social-cognitive lock-ins linked to the attitudes, behaviours, and alignments within social groups.

1.3.6 Which are the Leverage Points and Feedback Loops that can Boost the Transition to Sustainable Food Systems?

To unlock self-reinforcing mechanisms, changing the social structures and institutions governing food systems could leverage a shift to a systemic transformation. Starting from the set of studies reporting a solution for system transformation (n=71), we have identified 146 solutions grouped by the 12 leverage points identified by Meadows (1999) placed in order of increasing effectiveness and systemic resistance (from 12 to 1) and the associated four system's characteristics identified by Abson et al. (2017). The bar plot in **Figure 1.4** illustrates the percentage frequency of 146 solutions over the 12 leverage points. **Table 1.4** exemplifies and contextualises the leverage points for transformation in the food systems domain reporting solutions identified in the set of analysed papers.

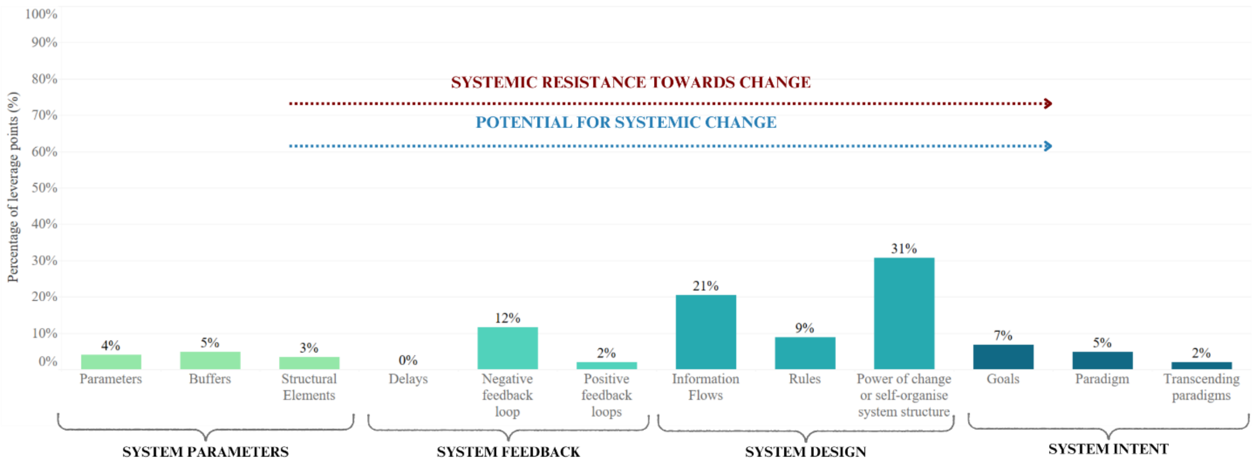
The majority of solutions identified in the set of scientific documents leverage on changing the social structures and institutions that manage food systems interactions and parameters (design). These solutions include the restoring information flows and leveraging the power of system actors of changing and self-organising to achieve systemic change, which scientific studies recognise as a powerful solution, despite the high systemic resistance towards targeting this leverage point (e.g., due to power relations dynamics). Solutions leveraging on self-organisation, the more frequently addressed in the set (31%), include stakeholders' engagement at multiple governance levels, multi-stakeholders' approach, proactive participation for reflexive and polycentric governance systems, democratisation of food system processes, creation of policy assemblages based on bottom-up approaches. Further, literature report knowledge exchange tools, education, awareness campaigns, labels, or certification and quality schemes (21%) as possible solutions to achieve systemic change by restructuring information flows. In the set of documents, solutions targeting weaker leverage points tend to be less documented – presumably due to their lower potential for systemic change. Similarly, solutions targeting high leverage points with stronger potential for systemic change were also less documented – most likely due to the higher systemic resistance associated with targeting them which also makes it challenging to even identify, design and implement them effectively. In the first case, these solutions target the mechanistic and physical elements (*parameters*) of the systems (*e.g.*, taxes, infrastructures) and range from 3 to 5% of the whole set; in the second case, they target the underpinning values and goals of actors that shape the system orientation (*e.g.*, shift from the productivist paradigm, shift in beliefs) and range from 2 to 7% of the whole set.

Table 1.3 Lock-ins mechanisms and associated failures based on Geels (2019), Woolthuis et al. (2005) and Weber and Rohracher (2012).

Lock-ins /System Failures			Examples	Source
Institutional/Political (50)	Structural	**Institutional**	**Labelling, standards and regulatory barriers** (*e.g.,* seeds, safety regulations) marginalising small-scale producers**; Lack of monitoring and control** of measures effectiveness; Inefficacy of voluntary initiatives; Monitoring frameworks often **lack standardised indicators** covering the whole food system; **Lack of financial and temporal resources** for collaboration and **excessive bureaucracy**; **Historical regulatory frameworks** locking farmers in the dependency from retail and catering corporates and EU subsidies; Unfavourable trade policies (EU trade agreement with duty free protein based imports).	Anderson et al., 2019; Báldi et al., 2023; Baldy and Kruse, 2019; Blumberg et al., 2020; Cifuentes and Gugerell, 2021; Connolly et al., 2022; F. Galli et al., 2020; Gliessman et al., 2019; Jarzebowski et al., 2020; Kugelberg et al., 2021; Lang and Mason, 2018; Marsden et al., 2018; Scaramuzzi et al., 2021; Triboulet et al., 2019; Weituschat et al., 2022; Zawalińska et al., 2022
		Capabilities	**Capacity gaps** of the local institutions to implement their responsibility; **Lacking** progressive **dynamic change** in administration settings; **Slow adaptation** of institutions to new opportunities; Low institutional **capacity** to solve **wicked problems**;	A. Galli et al., 2020; Moragues-Faus et al., 2017; Säumel et al., 2022; Zawalińska et al., 2022
		Interaction/ Network	Local production and supply networks **are not integrated into the corporate food regime,** building relationships that depart from the **hegemonic socio-technical script** and its institutional framework;	Báldi et al., 2023; González De Molina and Lopez-Garcia, 2021; Scaramuzzi et al., 2021
	Transformational	**Policy Coordination**	**Sectorial policies** creating silos between different approaches and actor groups; EU and national policies sending **conflicting objectives** to promote health and to support sustainable development objectives; CAP income support logic (Pillar 1) in contrast to the provision of public good (Pillar 2); Exclusion of local food system and urban based initiatives from CAP support; **Lack of food policy councils** and urban food policy planning; **Lack of integration** among trade-offs of sustainability outcomes which hinder reflexive thinking among current and detrimental practices; **Lack of coordination** among municipal, national and European food security goals and actions.	Anderson et al., 2019; De Schutter et al., 2020; de Vries et al., 2021; De Vries et al., 2022123AD; Fesenfeld et al., 2023; A. Galli et al., 2020; F. Galli et al., 2020; Kennedy et al., 2020; Kugelberg et al., 2021; Minotti et al., 2022; Moragues-Faus et al., 2017; Moragues-Faus and Carroll, 2018; Säumel et al., 2022
		Directionality	Historic **focus on mass production** for food security (historic prioritisation of EU policies on cereals lead to marginalisation of legumes); Policies that tend to **support the status quo** of largely specialised, animal-based and export-oriented primary production; Unbalanced geometries of power inside the food chain and in the broader political spheres which **impose a dominant discourse on consumerism, free trade and neoliberalism**; Agenda setting of food security policies focuses **on quantity of production** and crops and less attention to food availability, access, utilisation and stability; The **lack of agreement over a shared vision** at the provincial level.	Biesbroek et al., 2023; Cué Rio et al., 2022; De Schutter et al., 2020; F. Galli et al., 2020; Kugelberg et al., 2021; Maughan et al., 2020; Minotti et al., 2022; Moragues-Faus et al., 2017; Moragues-Faus and Carroll, 2018; Säumel et al., 2022; Venn and Burbi, 2023; Weituschat et al., 2022; Zollet and Maharjan, 2021
		Reflexivity	The **heterogeneity of groups negatively affected** by dynamics in food systems (especially food workers, migrant labour, and the urban and rural poor) is **underrepresented** in policy processes.	Maughan et al., 2020; Minotti et al., 2022
Techno-economic (30)	Market	**Externalisation Costs**	**Nutrient rich food is costly than more energy dense ultra-processed food** with lower nutritional value; The intensification and specialisation efforts are linked to attempts to compensate falls in agricultural income and employment creating a disproportionate increase in the technical means of production and deterioration of the land's environmental quality and its associated resources.	Biesbroek et al., 2023; Fanzo et al., 2020; González De Molina and Lopez-Garcia, 2021
	Structural	**Institutional**	Lack of **subsidies** (previously effective); Investment on cereals and red meat (even if their supply exceeds the global need); Tools that aim to **sustainability performance** (*e.g.,* direct payments); Food **taxation only at national level** and contested; C**omplexity of certification schemes** for organic product; Economic viability with **low financial incentives** (*e.g.,* lock-ins contracts); **Lack of public funds** invested for supporting the organisational structure; The dominant regime's interrelated **market incentives** and policies lock many farmers into individual path-dependencies towards large scale, high-external input dependent agriculture.	Anderson et al., 2019; Béné et al., 2019a; De Schutter et al., 2020; Díaz-Méndez and Lozano-Cabedo, 2020; F. Galli et al., 2020; Weituschat et al., 2022; Zawalińska et al., 2022

Lock-ins /System Failures			Examples	Source
		Infrastructural	Lack/inadequacy of risk management tools; Vulnerabilities of food assistance systems; Poor access to standardisation and global value chains for small farmers; Knowledge barriers (*e.g.,* unequal access to intellectual property); Weak infrastructure of farming or food systems; Lack of human capital (*e.g.,* skills required for a new technique); Cost of technology adoption, lack of IT and accountancy skills, lack of expertise in branding; Lack of knowledge on how persuading consumers to buy more nutritious food; **Agro-industrial monoculture systems** disrupting resource cycles, making farmers dependent on external inputs, undermining their knowledge and distancing consumers from agri-production.	Anderson et al., 2019; Boylan et al., 2020; Díaz-Méndez and Lozano-Cabedo, 2020; Fanzo et al., 2020; F. Galli et al., 2020; Gliessman et al., 2019; Jarzebowski et al., 2020; Küchler and Herzig, 2021; Levidow, 2015; Weituschat et al., 2022; Zawalińska et al., 2022
		Interaction/ Network	**By imposing certain criteria** on the upstream part of the food chain (*e.g.,* homogeneity standards) **corporate retailers exclude** a significant part of the foods that are most **sustainably produced** and **force farmers to use more chemical inputs**; **Primary producers and manufacturers are put under commercial pressure** to reduce prices **by a highly concentrated retail sector,** which is expanding aggressively. **Power of corporations** is now deeply embedded in the debt cycle that locks in farmers and governments to vicious cycles of debt, chemical dependence, and unequal diets.	Biesbroek et al., 2023; Bui et al., 2019; Gliessman et al., 2019; Paloviita, 2017
	Transformational	**Directionality**	Lack of agricultural production diversity due to **region's focus on monocultural livestock production**; Retailers want to manage local food production as a **niche market** separated from the conventional supply chain and favour the reproduction of the incumbent system. 'Bioeconomy' and 'sustainable intensification' **agendas reinforce corporate power** to extract more market value from agri-food value chains.	Bui et al., 2019; Díaz-Méndez and Lozano-Cabedo, 2020; Levidow, 2015; Moragues-Faus and Carroll, 2018
		Demand articulation	**Expensive for consumers** as exclude less affluent consumers and, as consequence, these SFSCs may remain **niches** in the food market.	Vittersø et al., 2019
Social/Cognitive (23)	**Structural**	**Interaction/ Network**	Dichotomy between corporate industry and local/trans-local alternative food networks create **fragmented food landscapes**; Marginalisation of Food Self-Provisioning in the research debate respect to Alternative Food Networks which are the dominant narrative in Western Europe (mostly accessible for privileged groups); **Individualistic**, **self-enhancing orientation**; Lack of **transparency** (especially from retailers food industry and restaurateurs); Lack of **trust** due to failed past cooperative experiences and difficulties in maintaining the **actors' engagement** with the biodistrict's goals.	Anderson et al., 2019; Cifuentes and Gugerell, 2021; Daněk et al., 2022; Goszczyński, 2020; Marsden et al., 2018; Moragues-Faus et al., 2017; Scaramuzzi et al., 2021
	Transformational	**Directionality**	Lack of appropriate **knowledge** and **information** due to constantly **changing and conflicting discourses** on sustainable consumption; Divergences of actors opinion on legitimacy to participate in the process and credibility (*e.g.,* presence of hidden goals or values); Alternative Food Organisations are not united **under common and transformative goals** and share a common understanding of sustainability, **foster citizens' confusion** about what to do in light of the multiple challenges that they face; **Consumers** may in these instances face a **normative dilemma between** the ethical issue of "fair price" and the moral issue of acting economically sensible	Baldy and Kruse, 2019; Daněk et al., 2022; de Vries et al., 2022; Díaz-Méndez and Lozano-Cabedo, 2020; Fanzo et al., 2020; F. Galli et al., 2020; Gjerris et al., 2016; González and Lorenzini, 2021; Goszczyński, 2020; Moragues-Faus et al., 2017; Vittersø et al., 2019
		Reflexivity	Dominant regimes **ignore** the roles, **knowledge** and **perspectives** of **women and marginalised actors** in rural communities; Discursive frames on high-tech or reductionistic approaches that **trivialise smallholders**; **Separation of consumers/citizens from nature** that discourages positive attitude and emotions towards the environment and creates a cycle of disaffection; Lack of knowledge about the local food system that **hinders actors from participating in transformation processes.**	Anderson et al., 2019; Báldi et al., 2023; Baldy and Kruse, 2019; Mehrabi et al., 2022

Figure 1.4 Percentage of solutions identified in the database mapped against 12 leverage points for systemic change (from 1 to 12). The arrows show leverage points placed in increasing order of effectiveness (Blue arrow) and increasing order of resistance (Red arrow) in changing the system. Based on Abson et al. (2017) and Meadows (1999) (color should be used for this figure in print).



Source: *Authors own elaboration*

Finally, solutions targeting the interactions occurring between the elements (*feedback*) within the systems show higher variability. Indeed, while the 12% of solutions identified leverage on acting on negative feedback loops (*e.g.*, monitoring frameworks or mechanisms of internalisation of externalities), none of the solution identified target the delays occurring between interventions and their effectiveness in the food systems (*e.g.*, plans for long-term agricultural practices).

Table 1.4 Leverage Points description and examples extracted from the database. Based on Abson et al. (2017) and Meadows (1999).

INTENT	1. The power to **transcend paradigms**	Self-transcending sustainability, ethical system changes, shift in values and beliefs;
	2. The mindset or **paradigm** out of which the system arises	Shift from corporate-environmental food regime, 'food as a common';
	3. The **goals** of the system	Common food policy, shift to a food system perspective;
DESIGN	4. The power to add, change, evolve, or **self-organise** system structure	Multistakeholder engagement in food governance, reflexive governance;
	5. The **rules** of the system	Food public procurement strategies and programmes, legal frameworks;
	6. The structure **of information flows**	Labels, certification, education and awareness campaigns, knowledge exchange tools;
FEEDBACK	7. The gain around driving **positive feedback loops**	Sustainability rewards, investments, or progress income taxes to boost or slow multiplier effect;
	8. The strength of **negative feedback loops**, relative to the impacts they are trying to correct against	Evaluation and Monitoring frameworks, mechanisms for externalities internalisation;
	9. The lengths of **delays**, relative to the rate of system change	Plan for long-term sustainable agricultural practices;
PARAMETERS	10. The **structure** of material stocks and flows	Regional food hubs, alternative distribution chains, infrastructures;
	11. The sizes of **buffers** and other stabilising stocks, relative to their flows.	Crop diversification to increase system resilience;
	12. Constants, **parameters**, numbers	Market-based (taxes) or command and controls instruments (standards).

1.4 Discussion

1.4.1 Summary of Evidence

Although various academics attempted to investigate sustainability narratives in food system frameworks, this work represents a first attempt to provide a general overview on the status of academic research on food systems narratives, dynamics, and pathways for systemic transformation in Europe after the launch of Agenda 2030 by conducting a thorough review of academic studies.

Having identified 974 sustainability objectives in the narratives of 94 studies grouped into 32 categories, we found a pattern of disparities in the sustainability objectives addressed. In Europe, sustainability narratives in the academic field tend to focus on environmental, health and nutrition objectives while socio-economic, and crosscutting aspects related to food system governance remain marginal. This connects with the lack of indicators and data at global level on socio-economic (e.g., welfare of food systems workers beyond agriculture) and governance aspects (e.g., lack of indicators for policy coherence) evidenced by researchers (Schneider et al., 2023).This gap might suggest a possible discrepancy between the scientific agenda, shaped by reactions to negative impacts and externalities, and the political agenda, which struggles with socio-economic issues (*e.g.,* the recent protests and strikes of European farming communities). Indeed, as also underlined by Brouwer et al. 2020 who analysed 32 food systems frameworks in international studies, governance aspects and power dynamics between stakeholders tend to be overlooked, underscoring the necessity of systemic approaches that acknowledge and address the existence of competing networks with unequal resources and power (Canfield et al., 2021) in the complexity of food systems governance.

The potential contribution of these 32 sustainability categories to the achievement of 55 SDG targets further highlights the connection between scientific and political spheres. Since the adoption of the Agenda 2030 in 2015, we observed a significant increase in scientific output within food systems science and we identified 5 groups of diverse studies' aims (sustainable food systems frameworks, food system governance, sustainability transition, Alternative Food Networks, food and nutrition). These findings may suggest that the Agenda 2030 could have significantly stimulated scientific engagement with food systems research in Europe (e.g., through a stronger integration of the SDGs into the Horizon Europe Framework Programme, the EU funding programme for research and innovation) and, conversely, that food systems science has contributed to shape policy agendas, as illustrated by the sustainability objectives identified in the studies and their connection to specific SDG targets. Further, this reinforces the crucial role that scientific advancements may play in accelerating the implementation of the Agenda 2030 (Herrero et al., 2021), as well as the relevance played by current and future Science Policy Interfaces (SPIs) (e.g., HLPE, IPCC) and political initiatives mobilising science (e.g., UNFSS) in advancing food systems transformation, as highlighted by B.K. Singh et al. (2021).

The analysis of interlinkages highlights 81 negative links among the 55 SDG targets identified confirming that fostering sustainable food systems transformation requires a careful analysis of systemic trade-offs, competing objectives, and conflicting values and interests in food systems actors, as highlighted by other scholars (Béné et al., 2019b; Brouwer et al., 2020; Herrero et al., 2021). We found that most trade-offs occur in advancing SDG 2 (zero hunger), SDG 7 (clean energy) and SDG 13 (climate change), as also shown by potential incoherences existing between current EU environmental policies (*e.g.*, Water Framework Directive, Nitrates Directive) and policy frameworks that promote large-scale commodity production (*e.g.*, CAP or biofuel incentives under Renewable Energy Directive) (IPES-Food, 2019) highlighting areas of improvement to promote better policy integration in the food system domain (OECD, 2021).

Our investigation of major barriers hampering food systems transformation pointed to 103 barriers hindering transformative change that we categorised into three main types of lock-ins (according to Geels, (2019) further discussed below:

- *Institutional/political lock-ins*. Half of the studies report how ineffective institutional frameworks, policy networks and vested interests reinforce the status quo and impede food system transformation. The studies reported that these structural lock-ins are attributed to ineffective institutional framework and lack of policy coordination and directionality that leads to a lack of a common vision at institutional level. Hence, academic studies highlight the great potential residing in re-designing EU current policy instruments and institutional frameworks. For instance, several scholars argue that existing EU schemes lack sufficient incentives for a shift towards more sustainable production and consumption patterns (Kortleve et al., 2024; Pe'er et al., 2020). Indeed, while agricultural subsidies have become progressively decoupled from production, a substantial portion still takes the form of commodity-specific support measures through direct coupling or market price support (Springmann and Freund, 2022). Research suggests that repurposing these subsidies within Europe to align with environmental and health goals, by supporting sustainable production and consumption practices and acknowledging the potential trade-offs associated with different repurposing options, could significantly contribute to the transition towards sustainable food systems (FAO, UNDP and UNEP, 2021; Gautam et al., 2019).
- *Techno-economic lock-ins*. The ineffective institutional frameworks identified in the set of documents, the weak physical and knowledge infrastructures, and the market power dynamics further create barriers for food systems transformation driven by sunk investments in R&D and dominance of low costs and high-performance technologies (e.g., due to ignorance of externalities). Scholars report how grassroots and social innovations (e.g., alternative food networks) remain a niche in the market separated from conventional supply chains (Vittersø et al., 2019) which are shaped by corporate retailers' power. This gap highlights the need of incentives and investment in innovation (e.g. by introducing new support schemes as shown in Gautam et al. (2019)) by ensuring financial support and knowledge access to climate-smart or social innovations (Dinesh et al., 2021) as well to propose new business models and strategies for sustainable food systems (Long et al., 2018) that target and reshape current power relationships and dynamics.
- *Social-cognitive lock-ins.* Only 23 barriers report that routines, mindset, and social groups alignments and lifestyles impede food systems transformation due to interaction failures (e.g., fragmented foodscapes), directionality failures (e.g., consumers' confusion about sustainability choices), and to the marginalisation of certain social groups in food systems policy. The emphasis on techno-economic and political drivers in existing studies suggests a need for increased attention to the behavioural aspects influencing, for instance, dietary choices (Higgs, 2015; Hoek et al., 2017) or household food waste (Vittuari et al., 2023), as their

integration can provide a more comprehensive understanding of the factors that facilitate or hinder the transition towards sustainable food systems also at individual level.

These findings are consistent with those from similar systematic reviews. For example, Conti et al. (2021) conducted a review of 122 scientific documents to explore lock-ins that generate resistance to change within agri-food systems. Their analysis identifies several major barriers occurring due to shifts in directionality, including the entrenched nature of dominant technologies, institutional and policy frameworks that design inefficient incentives, attitudes and cultures resistant to change, existing power dynamics influencing the political economy of food systems, and misaligned sustainability narratives in the research agenda.

Having integrated the identified potential solutions for food system transformation into a framework of system intervention, our analysis identified 146 potential leverage points with varying transformational potential and systemic resistance. They encompass strategies for creating new social structures and behaviours (e.g., democratising food systems and fostering reflexive governance), enhancing information transparency, implementing effective monitoring frameworks, and developing new legal structures. While policymakers tend to target shallow leverage points like food systems' stock and flow structures or parameters of different food system elements (e.g., taxes, regulations) (Abson et al., 2017), the research agenda acknowledges the potential impacts of altering social structures and institutions that govern food systems and the interactions among elements that drive internal dynamics (*system design*) to rebuild assemblages embedded in a more reflexive governance configuration (Marsden et al., 2018). Nonetheless, the success of these reconfigurations depends on and results from power relationship dynamics in policy arrangements. Harnessing feedback loops to drive change in system's behaviour is another powerful intervention area where solutions can be deployed to foster a food system transformation like well-designed subsidies incentivising sustainable agricultural practices (Gautam et al., 2019). On the other hand, higher leverage points that could address the underlying values, goals, and perspectives of actors shaping the direction of food systems (*system intent)* are less frequently reported. This indicates that the research agenda is not adequately focused on challenging the current paradigms underpinning European food production and consumption (Béné, 2022; Jackson et al., 2021). Nonetheless, changes in parameters (e.g., agri-environmental payments) or feedback mechanisms (e.g., true price labels) may induce a shift in the mindset of food system actors and contribute to targeting higher leverage points. This highlights the need for further exploration of the interactions between different types of solutions at various systemic levels to implement effective combinations of interventions as the interplay between systemic resistance and potential for change associated with targeting different leverage points suggests that a well-balanced mix of solutions targeting different system parts and leverage points might be the most effective approach for fostering a food system transformation (Abson et al., 2017).

1.4.2 Limits and Strengths of Current Research

Although scoping reviews inherently accommodate diverse study designs (Tricco et al., 2018), we acknowledge the qualitative nature of the investigated topic as a potential limitation to the reproducibility of the selection process, emphasising the need for nuanced consideration in interpreting the findings. However, we considered the heterogeneity of the methods employed in the scientific documents analysed and their qualitative nature as enriching sources for our analysis, even if we acknowledge the weaknesses and limitations of such an approach.

The complexity and the wider systemic nature of the topic overlooked the granularity and the context specific characteristics of the diverse food systems across Europe, including the stakeholders' interaction in those systems. For instance, the interlinkages dataset (Fronza et al., 2023) contained scientific documents identifying synergies and trade-offs through different methodologies and in different geographic contexts (also outside Europe). Also, the numerous links between targets indicate some level of ambiguity in the type of interaction (either positive or negative) underlining the importance to contextualise interlinkages within the specific scope and context of such an analysis. Nonetheless, the sheer number of interlinkages emphasises the strong interconnectedness of the SDG framework in general, but also of the food system elements, which articulates a high degree of complexity for sustainable food system governance.

Despite the benefit of integrating a stronger systemic perspective through the notion of leverage points for system intervention, we acknowledge the potential biases and imperfection of this mapping due to its qualitative nature. Further, as the results are based on an analysis of scientific literature, findings interpretation should consider that academic research may overlook certain processes within food systems and may not necessarily or accurately reflect their effective processes and dynamics.

1.4.3 Science-Policy Implications

The analysis highlights the complexity inherent in food system governance, the divergent visions, values, and interests of stakeholders, and the inherently wicked nature of sustainability challenges. These factors collectively underscore the significant difficulty faced by food systems in converging on a unified vision and set of objectives. However, the findings and discussions derived from our analysis provide several key implications for both scientific research and policy agendas:

a. *Understanding and strengthening the role of Science Policy Interfaces (SPIs) in shaping food system transformation.* The analysis of scientific literature and its alignment with Agenda 2030 illustrates how the scientific and policy agendas may have affected each other in shaping their respective pathways after 2015 showing not only the pivotal role that SPIs may play in the food systems transformation, but also the role of science in shaping and framing sustainability narratives that can contribute to achieving multiple interconnected sustainability objectives **(Figure 1.2a)**. The new science-policy reconfigurations explicated in the *United Nations Food Systems Summit* (*UNFSS*) organised by UN Secretary General in which the weight given to the Scientific Group and the multi-stakeholder structure were considered unprecedented compared to other summits. The UNFSS can be considered a powerful accelerator for science-policy agendas, nonetheless, understanding the possible impacts of such an initiative and the role of power configuration in its governance architecture remains essential to achieve the food systems transformation (Canfield et al., 2021).

b. *Promote policy coherence in the food systems domain.* Our analysis highlights significant trade-offs in achieving the Agenda 2030 goals (**Figure 1.2b**), underscoring the necessity for systemic policy approaches in Europe. These approaches must recognise the synergies and trade-offs among various policy areas, as well as the diverse values and perspectives of food system stakeholders that influence political priorities. Over the past decade, the scientific agenda has prioritised environmental and nutritional challenges (as depicted in **Figure 1.1**) while in the policy arena, more systemic approaches, such as the Farm to Fork strategy, have emerged, in which an increasing influence of environmental agencies and climate activists occurred. This shift has led to discontent among farmers (Matthews, 2024), further emphasising the need to consider the side effects of food system transitions and to design political strategies that mitigate potential negative impacts of new policy configurations in Europe across all sustainability dimensions equally.

c. *Re-design policy instruments for a common objective.* To overcome the diverse types of lock-ins that impede food system transformation, new policy mixes and strategic toolkits are essential. This necessitates revisiting and repurposing some detrimental policy instruments currently in place (OECD, 2021), mobilising multiple innovations across different sectors and stakeholders, and understanding the socio-cultural drivers that influence actors' behaviour in the food environments. Furthermore, implementing 'mission-oriented policies' (Mazzucato, 2018) for food system transition can be an effective approach to achieve a common policy goal. This involves exploring inclusive narratives that reconcile various values towards shared objectives (e.g., One Health approach).

d. *Re-arrange governance structures and promote power reconfigurations*. Greater emphasis should be placed on the role of European society in the transformation of the food system. Changes in social structures and behaviours are influencing European food policy, with consumers increasingly engaging in citizenship through their consumption choices and the growing prevalence of Alternative Food Networks movements contributing to urban food policy agendas (Petruzzelli et al., 2023). Societal efforts to shape EU food policies are evidenced by the scientific agenda's recognition of the power of actors to promote reconfigurations of governance structures (**Figure 1.4**) as crucial leverage points for altering the underlying paradigms of production and consumption. These efforts open new avenues for establishing effective and inclusive science-policy-society interfaces (SPSIs). These interfaces facilitate stakeholder dialogues and participation, increase transparency and knowledge access, ensure the availability of robust data, and enhance the participation of traditionally excluded groups (European Commission, 2022; van den Hove, 2007). In this context, participation needs to move beyond the usual information and consultation processes towards co-ownership that will eventually also challenge existing power relationships and asymmetries.

1.5 Concluding Remarks

In this study we reviewed how academic studies envisaged possible systemic pathways for transitioning to sustainable food systems in Europe post-Agenda 2030. By identifying 974 sustainability objectives across 94 studies, we first showed that scientific agenda focuses on environmental, health, and nutrition goals, while comparatively overlooks socio-economic and governance aspects, emphasising the need for systemic approaches to handle governance and power dynamics that affect food systems actors. Further, we linked sustainability categories to 55 SDG targets revealing sources of major trade-offs in the achievement of sustainable food systems and illustrating potential entry points to promote better policy coherence. Future research should be focused on contextualising these synergies and trade-offs at local level to promote granular horizontal and vertical integration of European food policies.

We investigated how food system science mainly identifies institutional/political barriers as hampering factors to achieve food system sustainability, while less studies document techno-economic and behavioural drivers that can thrive the food system transformation. Among these barriers the lack of a shared vision and collective coordination, exacerbated by ineffective institutional frameworks are the most cited impediments in scientific studies. When identifying potential leverage points for transformation, our analysis illustrates that scientific studies emphasises the role of changing system design (e.g., social structures, information flows), and system feedback (e.g., negative feedback loop) as well the importance of exploring interactions between solutions at various systemic levels to identify combinations that can foster sustainable food systems transformation.

We argued how these findings illustrate the increasing mutual influence of science and policy agendas after 2015 highlighting the crucial role of SPIs in advancing food system transformation towards common global sustainability goals. Nonetheless, while scientific sustainability narratives tend to focus on environmental and health externalities, food systems governance face complex challenges due to diverging interests, goals and degrees of decision-making power impeding the construction of a common vision towards a sustainable food system and generating conflicts in food system domain (e.g, as shown by the recent farmers protests). Establishing a common vision allows to repurpose existing policy instruments (e.g., subsidies) while designing new policy mixes that could tackle lack of innovations and social/cognitive drivers of food consumption.

Finally, the emphasis on higher leverage points illustrates an increasing effort of academic studies in recognising the powerful role of changing underlying social structures in food systems domain. Although power asymmetries may challenge their effectiveness, these bottom-up policy reconfiguration (e.g., AFN) could leverage a significant systemic change and illustrate the potential impact of co-designing more inclusive and participative governance in European food policy. Hence, although this work attempted to systematise food system research in system thinking perspectives further studies are needed to explore the effects of food system interventions at different systemic level as well the factors affecting their power to change and challenge underpinning food systems paradigm.

CRediT Authorship Contribution Statement:

VG: *Conceptualisation, Methodology, Data Curation, Formal analysis, Writing - Original Draft;* SB *Conceptualisation, Methodology, Validation, Visualisation, Writing - Original Draft*; GL: *Conceptualisation,* *Validation, Supervision, Writing - Review & Editing*; LM: *Conceptualisation, Validation, Supervision, Writing - Review & Editing*; MV: *Conceptualisation, Validation, Supervision, Writing - Review & Editing, Resources*.

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements:

This research was funded by the European Union under research HORIZON-CL6-2021-FARM2FORK-01-09 project "FOOODCoST—redefining the value of food", Grant Agreement No. 101060481. We sincerely thank our colleagues at the University of Bologna and the Joint Research Centre (European Commission) for their support throughout this research. Their insights, collaboration, and technical assistance have significantly contributed to the success of this work.

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Chapter 2

Unveiling Trade-Offs in Introducing Carbon Farming Practices in the Mediterranean

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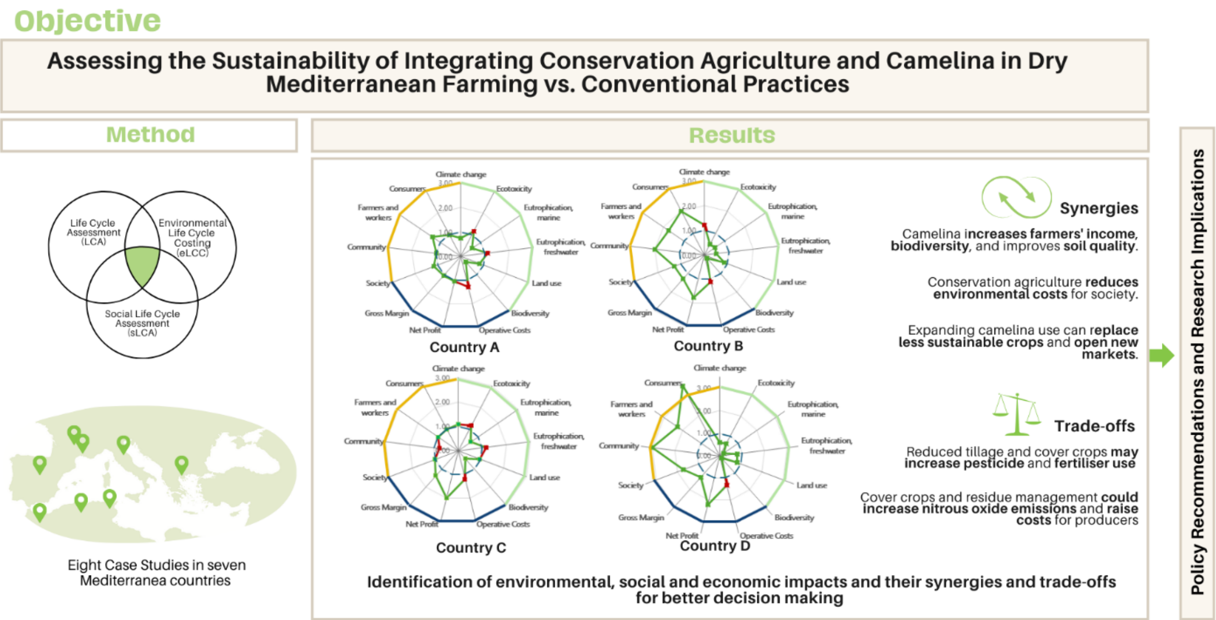


Chapter 2

Unveiling Trade-Offs in Introducing Carbon Farming Practices in the Mediterranean

Status: Under Review on Resources, Conservation & Recycling Journal

Abstract

The environmental impacts of farming practices are central to discussions on sustainable food systems, as current practices often degrade soils, water, biodiversity, and ecosystem health. Carbon farming has emerged as a promising strategy, shown to enhance soil health, increase organic carbon, and support farm profitability. While Life Cycle Assessment (LCA) is widely used to evaluate environmental impacts, its limitations in capturing agriculture's multifunctional roles encouraged approaches that integrate LCA with socio-economic analyses. This study explores the use of Life Cycle Thinking methodologies to evaluate the environmental, economic, and social dimensions of conservation agriculture, specifically testing three models involving the introduction of camelina [*Camelina Sativa* (L.) Crantz] as a cash-cover crop in Mediterranean dryland farming systems. Across eight case studies, findings indicate that conservation practices and the introduction of camelina can improve biodiversity, soil health, and farmer incomes, while potentially reducing broader environmental costs and generating sustainable market opportunities for oilseed crops. Nonetheless, certain trade-offs—such as increased input costs, reliance on fertilisers, and potential rises in nitrous oxide emissions—could impede broader adoption. Policy recommendations are provided to support sustainable agricultural practices, with LCT frameworks guiding policymakers and businesses in fostering resilient and equitable agricultural systems in the Mediterranean.

Keywords

Life Cycle Thinking, sustainability assessment, conservation agriculture, soil health, biodiversity

2.1 Introduction

The diverse and complex environmental impacts of agricultural practices are widely recognised (Benton et al., 2021; Crippa et al., 2021) and have emerged as a central focus in the global discourse surrounding sustainable food systems (Eyhorn et al., 2019; Willett et al., 2019). In the Mediterranean region, where soil degradation and water scarcity are significantly affecting agricultural systems (Ferreira et al., 2022) sustainable farming practices have the potential to provide an adequate, safe, and nutritious food supply while simultaneously reducing environmental impacts and fostering decent livelihoods for agricultural producers and rural populations (Cicek et al., 2023; Reganold and Wachter, 2016).

The role of sustainable farming practices in supporting sustainable food systems transition became central also in the political discourse. In 2020 the European Green Deal [COM (2019) 640, final] has established concrete targets (e.g., in Farm to Fork or Biodiversity Strategies) to expand their adoption in agricultural systems. The new Common Agricultural Policy (CAP) introduced stringent conditionality in Good Agricultural and Environmental Condition (GAEC) standards and supporting the implementation of voluntary eco-schemes, which reward farmers for improved environmental and climate performance. These measures include managing and storing carbon in the soil and enhancing nutrient management to improve water quality and reduce emissions (Regulation (EU) 2021/2115).

Carbon farming practices, aimed at sequestering carbon and reducing greenhouse gas emissions, are gaining attention as climate mitigation strategies (Bustamante et al., 2014; Tang et al., 2016). Conservation agriculture (CA), defined as a combination of farming practices that promote minimal soil disturbance, maintain soil organic cover (e.g., cover crops) and diversify plant species by emphasising longer crop rotations (Lal, 1997), has demonstrated benefits such as increased soil organic carbon (SOC), improved soil health (Dimassi et al., 2014; Sun et al., 2020; Tadiello et al., 2023; Wood and Bowman, 2021), water circulation (Alletto et al., 2022) and biodiversity (Wittwer et al., 2024), while sustaining farm yields (Pittelkow et al., 2015; Teng et al., 2024). Its relevance has grown, as organic methods alone cannot significantly increase SOC levels without the incorporation of appropriate soil management techniques (Nature Climate Change, 2023; Gaudaré et al., 2023).

The adoption of sustainable farming practices faces notable challenges. Farmers' protests highlight dissatisfaction (Matthews, 2024), revealing the need for socio-economic considerations and systemic approaches to address barriers. Debates persist on the unintended consequences (Freitag et al., 2024; Searchinger et al., 2018) and context-specific impacts (Seufert and Ramankutty, 2017) of transitioning to these methods, which involve trade-offs in resource management, profitability, and social acceptability within food systems (Díaz-Méndez and Lozano-Cabedo, 2020; Kanter et al., 2018). Hence, enhancing stakeholders' understanding and developing integrated models are essential to evaluate the comprehensive costs and benefits of climate mitigation for farmers and society (Tang et al., 2016).

Life Cycle Assessment (LCA) has emerged as a cornerstone methodology for evaluating the environmental impacts of agricultural systems (Boschiero et al., 2023; Meier et al., 2015) by assessing burdens across entire product life cycles (ISO, 2006a, 2006b). Its comprehensive approach helps stakeholders make informed decisions about product choices and resource use while avoiding burden shifting. LCA underpins the methodology for calculating the environmental footprint of products (PEF) in the European Union (EU Commission Recommendation 2021/2279), fostering sustainable consumption and production patterns adopted by policymakers, businesses, and consumers. Nonetheless, LCA's ability to fully represent the multifunctionality of agriculture has been questioned, arguing that the LCA product-based approach may undervalue sustainable farming benefits like ecosystem services and biodiversity, penalising extensive agroecological systems (van der Werf et al., 2020; Hélias et al., 2022). Further, LCA relies on average datasets and country-based characterisation factors, which can risk overlooking local context-dependent characteristics of agricultural systems (Hellweg and Milà i Canals, 2014).

Adopting holistic approaches to evaluate the introduction of different farming practices can contribute to unveiling unintended environmental consequences, economic hotspots, social acceptability and possible trade-offs among sustainability dimensions. Roesch et al. (2021) proposed a method for assessing farm sustainability based on the integration of a LCA methodology with a set of socio-economic and biodiversity indicators applied in the Swiss context. De Luca et al., (2018) investigated different scenarios for improving farming sustainability by using a Life Cycle Sustainability Assessment (LCSA) in Italy. Other studies were conducted to evaluate socio-economic impacts of CA practices adoption in the Mediterranean (Topp et al., 2024; Vastola et al., 2017). Nonetheless, there is still a need to holistically evaluate the multifaceted impacts of implementing sustainable farming practices by investigating hotspots and trade-offs in different contexts and countries and considering neglected social and environmental aspects (e.g., soil quality and biodiversity).

Therefore, this paper evaluates the introduction of conservation agricultural practices by applying a holistic sustainability assessment based on life cycle approach a) to compare their environmental, economic and social performances to those of conventional farming systems; b) to investigate how life cycle thinking approaches can unveil the impacts of multifunctional agricultural systems. This study aims to address the existing knowledge gap by conducting an integrated sustainability analysis. It employs the novel Product Environmental Footprint (PEF) methodology by adopting an area-based functional unit to evaluate land use and biodiversity impacts, Life Cycle Costing (LCC) as outlined by Hunkeler et al. (2008), and Social Life Cycle Assessment (sLCA) in accordance with UNEP-SETAC (2020) guidelines. The analysis spans eight case studies across seven Mediterranean countries, providing experimental primary field data on the introduction of camelina, a drought-resistant oilseed cash cover crop. The results are subsequently used to derive research implications for LCT practitioners and to formulate policy recommendations for the adoption of sustainable and climate-resilient farming practices in the Mediterranean.

This paper is organised as follows. In **Section 2.2** the integrated methodological framework, case studies and scenarios are presented. **Section 2.3** presents the results of the environmental, economic, and social assessment of conservative and conventional farming systems. **Section 2.4** by discussing results and methodological implications, presents policy recommendations, future research implications and limits of the analysis. **Section 2.5** draws general conclusions.

2.2 Method

To characterise and classify the environmental impacts of the selected farming systems, we conducted a Life Cycle Assessment (LCA) following an attributional approach, as specified by ISO14040: 2006a and ISO14044: 2006b. Additionally, we integrated LCA with Life Cycle Costing (LCC) to assess the financial and environmental costs associated with the introduction of the practices in the Mediterranean farming systems, adhering to the guidelines provided by Hunkeler et al. (2008), Swarr et al. (2011) and ISO 15686-5:2017. For the social dimension, we applied a Social Life Cycle Assessment (sLCA) to uncover the social perceptions of introducing new sustainable practices, using a reference-scale approach based on the UNEP-SETAC (2020) guidelines. LCA, LCC and sLCA ground in four phases, which are outlined in the subsequent paragraphs: 1) Goal and scope definition; 2) Life cycle inventory; 3) Impact assessment; and 4) Results interpretation.

2.2.1 Goal and Scope Definition

The study's goal was to assess the environmental, economic and social impacts of introducing conservation agriculture (CA) practices into typical Mediterranean crop rotations. We adopted an area-based (ha) and a financial (€/ha) functional unit (FU) in line with existing studies (Costa et al., 2020; Lago-Olveira et al., 2024; Nemecek et al., 2015). Specifically, the FU considered the cultivation of 1 hectare of land under both conventional and CA systems over one crop rotation cycle (ranging from two to three years). The investigation of social perceptions employed a stakeholder approach to identify potential impacts on various stakeholder categories, focusing on socially significant themes and attributes linked to inventory data and indicators (Benoit-Norris et al., 2012). We selected four of the stakeholders' categories suggested by UNEP-SETAC (2020) guidelines: workers, consumers, community, and society. Workers were complemented with the farmers' category (Brenes-Peralta et al., 2021; Goedkoop et al., 2018). Further, the environment was included in the framework (Haigh and Griffiths, 2009) to investigate stakeholders' perceptions of the benefits of CA practices to the natural environment. The system boundaries extended from cradle-to-farm gate and included the production processes from land preparation to harvesting. The system boundaries of the three analyses are detailed in **Figure 2.1**.

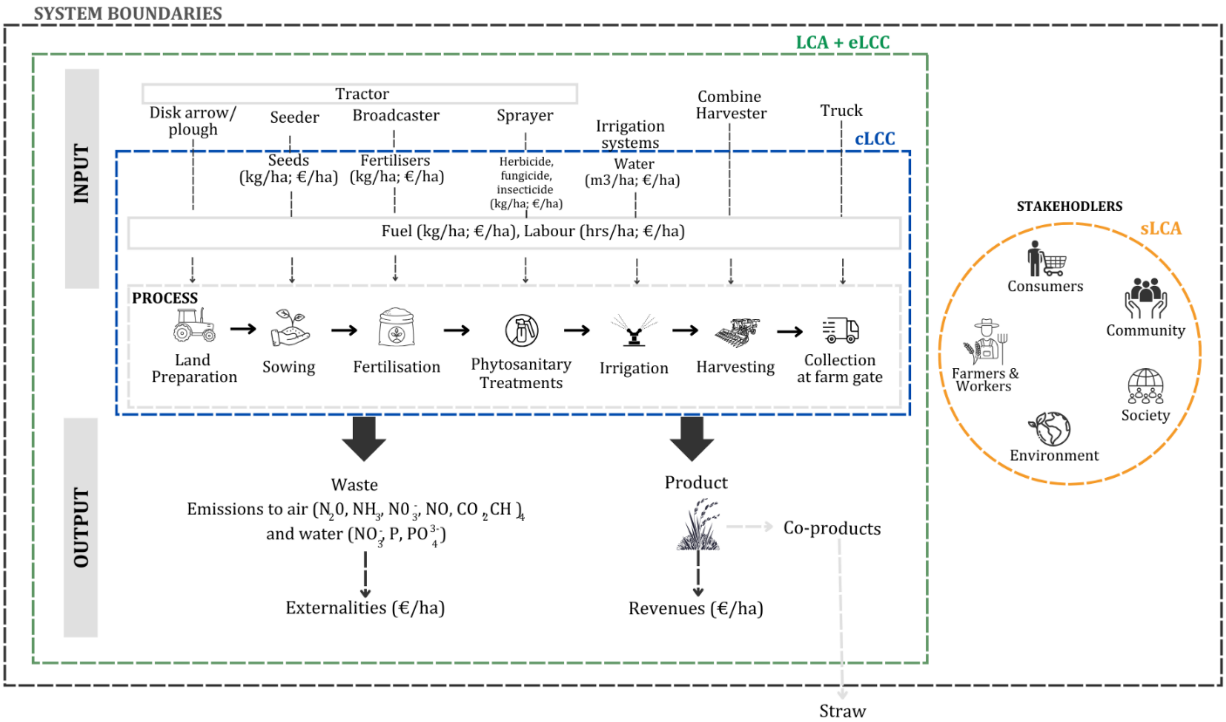
2.2.2 Data Collection and Inventories

The data were collected in the context of PRIMA Project 4CE-MED[1] in which eight research partners across the Mediterranean tested CA systems by conducting field experiments of different crop rotations (2021–2024). Data were collected by first and third author, respectively female PhD student at University of Bologna and male researcher at ARVALIS Institute which had extensive experience in data collection activities at farm

[1]The 4CE-MED project, funded by the European Union's Horizon 2020 Prima programme under Grant Agreement No. 1911, aims at developing Mediterranean innovative, diversified and resilient farming systems by introducing the cultivation of camelina, a promising oilseed crop for Europe, as a cash cover crop which might increase farmers' revenue while enhancing soil and water conservation.

level. The data collection entailed obtaining primary data with a purposive sampling selecting the eight researchers (of which 7 affiliated to research centres and 1 to university) responsible for the experimental trials and administering an Excel-based protocol (available in *Supplementary Table 2.A*) for environmental, economic, and social data, distributed by third author via email. Six bilateral meetings with partners and one collective meeting were conducted via Microsoft Teams by first and third author to validate and clarify the data collected. A second round of interviews for social data collection with partners was carried out using Microsoft Forms (October 2021–January 2022), yielding 5 responses. The missing respondents were addressed by administering the questionnaires (available in *Supplementary Table 2.B*) through 3 bilateral interviews via Microsoft Teams by first and third authors. Data were then coded by first and second authors and analysed by using Microsoft Excel and Tableau Software. When primary data were not available, we took advantage of secondary data from national and international databases and LCA databases (Ecoinvent v3.9.5).

Figure 2.1 System boundaries of the three analyses of the farming systems. Green lines indicate LCA and eLCC boundaries, blue lines of the conventional LCC, while yellow lines indicate system boundaries of sLCA (colour should be used for this figure in print).



Source: *Authors own elaboration*

We modelled nitrogen emissions from fertilisers application following IPCC (2019) guidelines (Tier 1), and EEA (2019) while phosphorus emissions following the SALCA-P framework (Prasuhn, 2006). Due to their significance (Shang et al., 2024), emissions from bare soils during fallow periods were included using default values from Schaufler et al. (2010). Pesticides emissions were modelled following the OLCA-Pest method (Nemecek et al., 2022). As novel practices affect fuel consumption in agriculture, but primary data were unavailable, country-specific fuel consumption data were sourced from academic literature (*Supplementary Table 2.D*). This data focused on land preparation and sowing phases, most impacted by soil conservation practices. The full emissions inventory is in *Supplementary Table 2.E*.

2.2.3 Impact Assessment

LCA: The Product Environmental Footprint

This study applies the EU's Product Environmental Footprint (PEF) method (EU Commission Recommendation 2021/2279) to assess the environmental impacts, using normalisation and weighting factors of 16 impact categories (Sala et al., 2017) to generate single environmental scores for the eight case studies. We investigated six agriculture-related impact categories (*Supplementary Table 2.F*), incorporating the BioMAPS method (Maier, 2023) to account for land biodiversity—recognised as a significant current gap in the PEF methodology (van der Werf et al., 2020; Hélias et al., 2022) by using SimaPro software v9.5.

LCC: Costs for Farmers and the Environment

We applied a conventional LCC which considers the direct costs incurred by farmers, alongside an environmental LCC that encompasses the costs over the product's entire life cycle, including the external (environmental) costs associated with farm operations under different management regimes (Degieter et al., 2022; Hunkeler et al., 2008). The cost analysis focused on the Operational Expenditures (OPEX) incurred by farmers from land preparation to harvest, expressed in €/ha, for implementing the novel practices. Capital expenditures (CAPEX) were assumed to be similar across the two alternative scenarios despite potential differences in machinery and their power requirements. Three profitability indicators—Net Profit, Gross Margin, and Benefit-Cost Ratio—were selected for their relevance to farm management and economic analysis. Camelina prices were estimated at €550/tonne as a cover crop in double cropping and €20/tonne lower than rapeseed price in the reference country in single cropping. Expert input, particularly from France, informed these estimates due to camelina's recent market entry (Zanetti et al., 2024).

Environmental costs associated with the introduction of farming practices were calculated by multiplying the LCA footprint indicators for PEF-compatible monetisation factors (Amadei et al., 2021; European Commission, 2020) according to the formula (**Equation 2.1**) provided by Galgani et al. (2021):

Equation 2.1 Formula for external costs calculation. Based on Galgani et al., (2021).

$$External\ costs\ = \Sigma\ (footprint\ indicator\ \times\ monetisation\ factor)\ (1)$$

Monetisation factors were adapted to 2023 prices by using country-based inflation rates and the Consumer Price Index formula (*Supplementary Materials II, Table 2.D*):

Equation 2.2 Formula for adaptation of monetisation values to 2023 prices for each country

$$Final\ value_{c,i} = Present\ value_j\ x\ \frac{CPI_{final\ c,i}}{CPI_{initial\ c,j}}\ (2)$$

Where:

Final value$_{c,i}$: represents the monetisation factor value in country *c* for the year *i* (2023) adjusted for inflation;

Present value $_{c,j}$: represents the monetisation factor value in the year *j* (2021) in country *c*;

$CPI_{final,\, c,i}$: represents the CPI value for the year *i* (2023) in country *c*;

$CPI_{initial,c,i}$: represents the CPI value for the year *j* (2021) in country *c*.

sLCA: Measuring the Social Perception

We used a Reference Scale approach for assessing social perception, focusing on activities within the product system and excluding indirect effects (UNEP-SETAC, 2020) by analysing the data collected by the 8 respondents. This method estimated the significance of social impacts from transitioning to sustainable farming practices. Having identified and selected 16 impact sub-categories and social indicators (detailed in *Supplementary Table 2.F*), the eight respondents were asked to evaluate the progresses of the social indicators when adopting CA practices for the five stakeholders' categories included in the analysis.

Given the lack of regional social data and varied Mediterranean socio-economic contexts, we used a 4-point Likert scale, inspired by Manik et al. (2013), to capture respondents' views of the current state of social aspects in conventional farming and of the potential improvements when the novel practices were adopted. This allowed for the integration of stakeholders' insights, making the assessment more locally relevant rather than relying on generalised databases. Respondents rated improvements from 1 to 4: 1–'Never' (no improvement), 2–'Slightly' (minor, inconsistent changes), 3–'Partially' (evident, though incomplete improvements), and 4–'Totally' (significant, consistent improvements) with changes scored from -3 to +3 relative to the baseline situation. The Overall Social Performance Indicator formula provided a single score (Brenes-Peralta et al., 2021). Respondents' insights collected in the 2nd round of interviews were extracted as individual text lines and coded by authors into a challenges and opportunities framework to contextualise the Likert scale ratings.

Substitution via System Expansion

Although the system boundaries extended from cradle to farm gate, multifunctional systems were compared using system expansion (*Supplementary Figure 2.A*). The analysis was broadened to encompass the end-uses of camelina, facilitating comparison with the land area required to produce an equivalent quantity of rapeseed oil and meal. This approach ensured an equitable comparison between the systems by assuming that camelina production would displace other similar oilseed crops in the market (Ahmad et al., 2022). Yield data for camelina and rapeseed oil and meal were sourced from Mondor and Hernández-Álvarez, (2022) and Nega, (2018).

2.2.4 Case Studies Application

We applied the methodological framework to three models of managing CA practices in eight countries in the Mediterranean, named Algeria, France, Greece, Italy, Morocco, Spain, and Tunisia. Based on the study of Zanetti et al. (2021) we tested the introduction of *Camelina Sativa*, an emerging oilseed crop, as a cash-cover crop in the CA farming systems. This crop proved effective in enhancing soil and water conservation in dry Mediterranean climates while increasing farmers' income and having promising market perspectives as an oilseed crop (Schillinger, 2019; Zanetti et al., 2013). *Model A* introduces camelina as a main crop in dry climates (Tunisia, Morocco, Algeria, Spain); *Model B* as a double crop before summer crops (Italy, France, Greece); *Model C* as a double crop after winter pulses/fodder cereals (France). The development and testing of the three models allowed us to investigate different crop rotation impacts in different pedo-climatic conditions in the Mediterranean region. For each case study, a Baseline scenario was established to facilitate a comparison with conventional farming techniques within the same context. Data on location, soil type, area and crop rotations tested in the experimental trials of each case study are illustrated in **Table 2.1**.

Table 2.1 Geographical and pedological characteristics of field trials in the eight case studies.

Model	Country/Region	Commune	Area (ha)	Soil Type	Baseline Scenario	CA Scenario	Growing Season (yrs)
A	Tunisia, Kef	Boulifa (36°07' N, 8°43' W)	47	Silty-Clay	Barley – Durum Wheat - Fallow	Barley – Durum Wheat - Camelina	3
	Morocco, Casablanca-Settat	Ouled Ghilane (33°7'N, 7°37'O)	1	Sandy Loam	Soft Wheat – Fallow	Soft Wheat – Camelina	2
	Algeria, Sétif	Beni-Fouda (36°09'N, 5°22'E)	66	Clay - Loam	Durum Wheat – Barley- Fallow	Durum Wheat – Barley - Camelina/pea vetch/lentil	3
	Spain, Castile-La Mancha	Carretera de Porzuna (39°1'N, 3°56'O)	40	Clay - Loam	Barley – Durum Wheat - Fallow	Barley – Durum Wheat - Camelina	3
B	Italy, Emilia Romagna	Cadriano (44° 33′ N, 11°23′ E)	2	Silty Clay Loam	Soft Wheat - Soybean	Soft Wheat - Camelina - Soybean	2
	France, Haute Garonne	Montesquieu -L (43°33'N, 3°16'E)	177	Medium Chalky Clay	Durum Wheat – Sunflower	Durum Wheat - Camelina - Sunflower	2
	Greece, Chalkidiki	Aliartos (38°22'N, 23°06'E)	7	Sandy-loam	Soft Wheat - Sunflower	Soft Wheat - Camelina - Sunflower	2
C	France, Haute Garonne	Montesquieu -L (43°33'N, 3°16'E)	177	Medium Chalky Clay	Durum Wheat – Winter Barley	Winter Barley – Camelina - Wheat	2

2.2.5 Sensitivity and Uncertainty Analysis

A sensitivity analysis identified key parameters influencing the model (*Supplementary Table K*) including emission factors for N2O and NO, fuel consumption (±25% variation), and yields of camelina (30-49%) and rapeseed oil (38-44%). Having identified minimum and maximum uncertainty ranges, we assumed a triangular distribution (Beylot et al., 2018). Monte Carlo simulations (1,000 iterations) quantified uncertainty (Huijbregts, 1998), while environmental costs variations in farming practices were assessed using low and high monetisation values (Amadei et al., 2021; European Commission, 2020).

2.3 Results

The adoption of conservation agriculture (CA) practices enhanced the sustainability performance of farming systems in most case studies, though it can generate negative impacts in some dimensions. As illustrated in **Figure 2.2**, the eight case studies generally showed positive changes in the single scores of the three sustainability dimensions, with occasional negative shifts in social and economic aspects. CA practices consistently reduced environmental impacts, achieving up to a 40% reduction in Morocco, but showed slight declines in economic benefits for Spain (13%) and France (4-5%) as well a negative perception of social impacts in Tunisia (5%). In **Figure 2.2**, green indicates positive impacts, red signifies negative impacts, and yellow denotes slight positive or negative changes.

The sustainability performance across 13 selected indicators (**Figure 2.2**) showed significant variation across case studies, highlighting the need to consider side effects. While new farming practices reduced environmental impacts, some cases (e.g., Algeria) saw increased ecotoxicity, climate change, and freshwater eutrophication. Socially, there were positive impacts on communities, though Spain and Tunisia reported neutral or negative changes. Economically, adopting CA practices raised operational costs in all cases. In North Africa, particularly when camelina replaced fallow, CA led to substantial economic benefits, while the advantages were more limited in European countries.

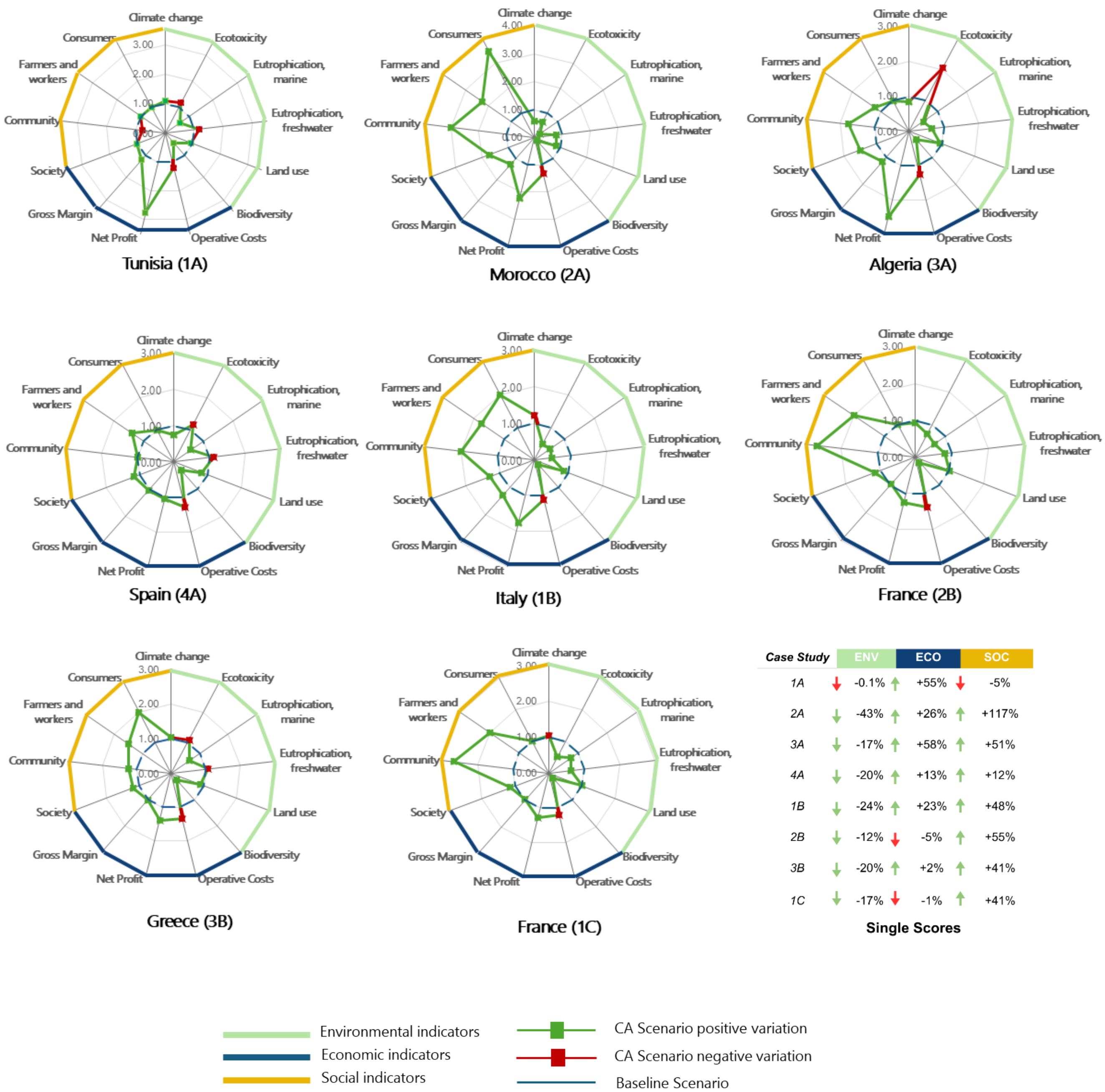
2.3.1 Environmental Impacts

The transition to CA resulted in a reduction of land use, biodiversity loss, and marine eutrophication impacts across all case studies. However, the effects on ecotoxicity, freshwater eutrophication, and climate change varied depending on the specific context of each case study. **Figure 2.3** compares the environmental impacts of different crop rotations in the eight case studies demonstrating a reduction in biodiversity impacts ranging from 50% to 87% in the CA scenarios relative to the baseline. Additionally, the adoption of new farming practices resulted in a substantial decrease in marine eutrophication, with reductions reaching up to 77% in the Moroccan case study compared to the baseline scenario.

Land use impacts were yield-dependent and influenced by the different methods of camelina integration into the agricultural systems. In single-cropping systems (**Figure 2.3**) land use improvements were modest compared to the conventional fallow baseline, with reductions ranging from 4 to 16%. In double-cropping systems, land use impacts decreased by up to 13%, except for France, where minimum changes were observed due to the lower yield of camelina compared to rapeseed. Moreover, land use impacts in the scenario where CA practices are implemented exhibit greater uncertainty, as indicated by the error bars in **Figure 2.3**.

The analysis also revealed potential side effects in certain case study contexts. CA practices reduced climate change impacts by 5 to 40% in half of the case studies. However, in the remaining cases, **Figure 2.3** shows a slight increase in climate change impacts, which can be attributed to higher nitrous oxide emissions resulting from the introduction of cover crops and crop residues (*Supplementary Table 2.E*). This increase was pronounced in Italy, where climate change impacts experienced a 22% increase due to a combination of high nitrogen application and wet climate, as for soft wheat cultivation accounting for 67% of the total impact.

Ecotoxicity impacts varied significantly across the case studies, with some experiencing reductions while others saw notable increases due to heightened phytosanitary applications. For instance, in the Algerian case studies, ecotoxicity doubled its impacts in CA scenario, primarily driven by the application of insecticides. In **Figure 2.3** error bars, expressed as Standard Error of the mean (SEM), show the uncertainty in values from Monte Carlo simulation with 95% confidence interval. They show higher degree of uncertainties in ecotoxicity parameter compared to other ICs. Also, phosphates and phosphorus emissions from P fertiliser application (*Supplementary Table 2.C*), applied for camelina cultivation too, led to higher impacts on freshwater eutrophication in some contexts (*e.g.*, Spanish case study) compared to the baseline scenario.



Source: Authors own elaboration

Figure 2.2. Percentage variations of the 13 sustainability indicators of the CA scenario over the baseline (blue line) normalised to 1 in the 8 case studies and percentage difference between their economics, environmental and social scores. Green lines and arrows show positive variations, while red lines and arrows show negative variations. Biodiversity impacts are not included in the single scores due to lack of established weighting factor.

2.3.2 Economic Impacts

Introducing a new crop into CA systems results in increased operational costs for farmers due to the additional agricultural activities required for camelina cultivation. However, when environmental costs are considered, these novel systems lead to a reduction in environmental costs. As shown in **Table 2.2**, production costs increased by 12% to 30% across all case studies. The cost of cultivating camelina ranged from €125/ha in Morocco, where no fertilisation or treatments were applied, to €516/ha in Greece, where irrigation was employed.

When environmental costs are monetised, the new practices result in a reduction in costs across all scenarios, with decreases of up to 50% in some cases, such as Morocco. However, these monetary values are sensitive to the specific monetisation factors applied, as indicated by the ranges presented in **Table 2.2**. Despite the higher operational costs, an analysis of profitability (**Table 2.2**) based on current market projections for camelina oil indicates an increase in net profit in almost all case studies, particularly in single-cropping systems in North Africa. In contrast, European countries such as Spain, Greece, and France experienced declines in gross margins and cost-benefit ratios, as the rise in costs outpaced profit growth, even though the Italian case study demonstrated a 11% increase in gross margin and a 23% improvement in the cost-benefit ratio.

2.3.3 Social Perception

Respondents perceive improvements in social impacts related to the implementation of CA practices compared to the current scenarios, albeit with some context-dependent variations. **Figure 2.4** presents the scores in the 16 impact sub-categories across the eight case studies. The score ranges on a reference scale from -3 to +3 points illustrating the change of perceptions between the two scenarios in the five stakeholder categories.

Farmers and Workers

The heatmap illustrates heterogeneous social perceptions among countries regarding farmers and workers. Most regions reported increased farmer engagement (*e.g.*, local markets, representation in public institutions), with exceptions in Tunisia and Spain, where perceptions remained unchanged. In Tunisia, farmers' engagement was perceived negatively due to delays in integration of camelina into cropping systems. Camelina’s adaptation to marginal lands improved stakeholders’ perception of profits and labour conditions in Spain, France, and Greece. However, Algeria struggled with profitability due to insufficient post-harvest operations and market opportunities. Overall, profitability varied by context.

Consumers

Improvements for consumers in terms of access to food and quality were perceived only in Morocco, with no significant changes perceived in other countries. Nonetheless, as evidenced in the semi-structured interviews, stakeholders acknowledge the opportunities related to the valorisation of camelina in oilseed markets and the improvements in cereal quality and yields in marginal areas, but they perceive no significant changes considering the lack of market of this crop in the analysed countries.

Community

Respondents perceived more positive impacts on communities compared to other stakeholders’ categories, except for Tunisia, Spain and Greece.

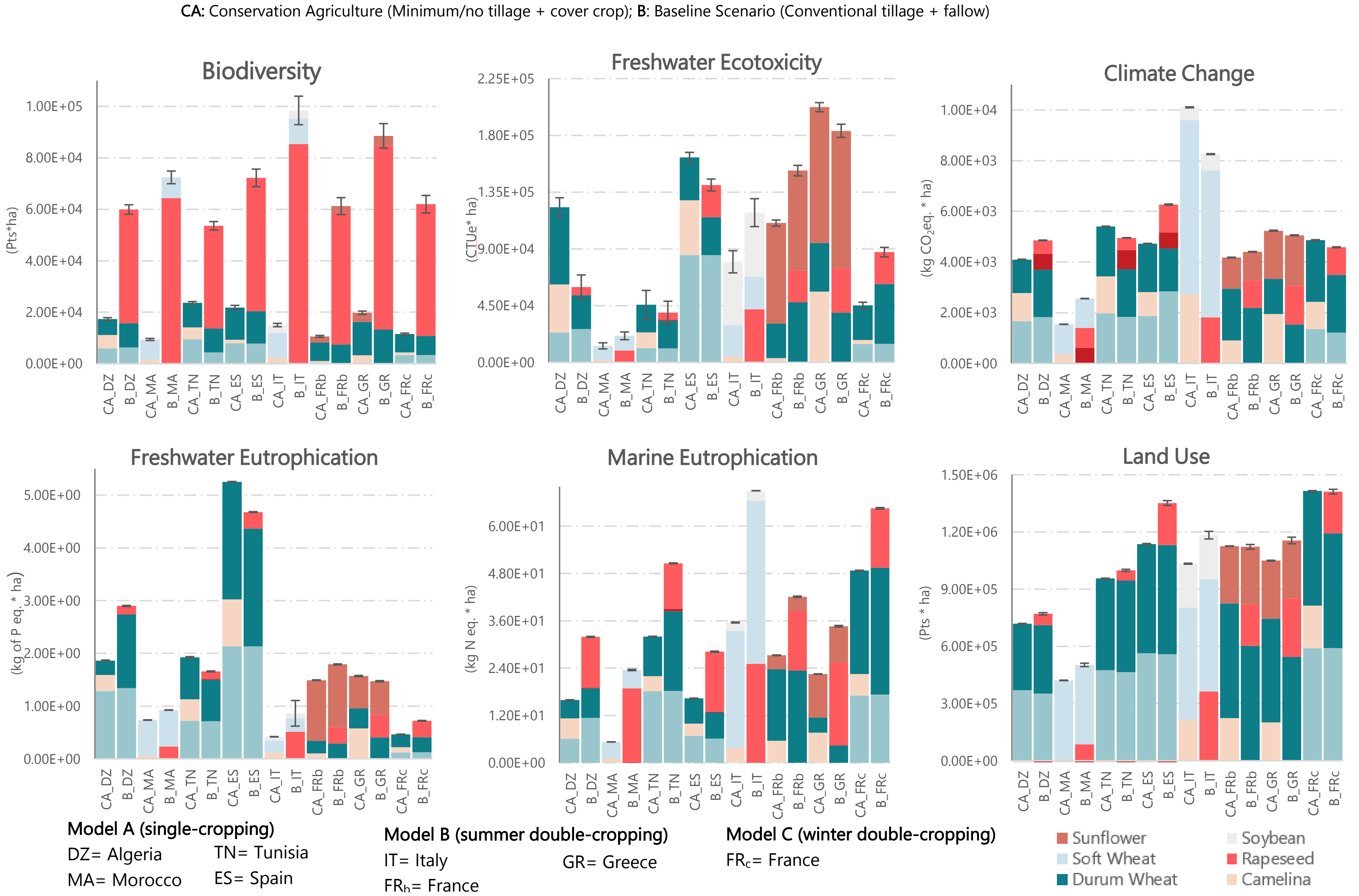


Figure 2.3. Life cycle impacts of 1 ha of land cultivated under conventional and CA practices in the eight case studies. Error bars, expressed as Standard Error of the mean (SEM), show the uncertainty in values from Monte Carlo simulation with 95% confidence interval. The reliability of the results improves as the size of the bar diminishes.

Source: *Authors own elaboration*

Table 2.2.Operative and environmental costs and profitability indicators of the eight case studies under baseline and CA scenarios.

Crop Type	Operative Costs (€/ha/y)															
	Model A										*Model B*				*Model C*	
	Tunisia		**Morocco**		**Algeria**		**Spain**		**Italy**		**France**		**Greece**		**France**	
	B	*CA*	*B*	*CA*	*B*	*CA*	*B*	*CA*	*B*	*CA*	*B*	*CA*	*B*	*CA*	*B*	*CA*
Barley	290.13	290.13	-	-	237.48	237.48	400.08	395.55	-	-	-	-	-	-	466.58	459.66
Camelina	-	164.18	-	125.00	-	183.83[a]	-	230.43	-	338.20	-	328.54	-	516.01	-	329.54
Durum Wheat	284.67	284.67	284.00	284.00	264.68	213.19	389.08	382.27	-	-	451.52	541.33	-	-	451.42	435.78
Fallow	36.38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Soft Wheat	-	-	-	-	-	-	-	-	1246.87	1177.15	-	-	733.53	717.31	-	-
Soybean	-	-	-	-	-	-	-	-	410.67	340.96	-	-	-	-	-	-
Sunflower	-	-	-	-	-	-	-	-	-	-	501.86	438.88	892.88	876.66	-	-
PC (€/ha/y)	***203.73***	***246.33***	***126.33***	***168.00***	***167.38***	***211.50***	***263.06***	***336.08***	***828.77***	***928.16***	***476.64***	***654.38***	***743.21***	***984.99***	***459.00***	***612.49***
(Share on TC%)	*24%*	*29%*	*29%*	*52%*	*31%*	*41%*	*31%*	*44%*	*42%*	*49%*	*37%*	*50%*	*44%*	*54%*	*34%*	*44%*
EC[b](€/ha/y)	***628.76***	***606.46***	***303.52***	***152.78***	***376.66***	***303.25***	***599.09***	***424.48***	***1132.53***	***983.96***	***802.60***	***647.37***	***947.12***	***824.19***	***891.86***	***770.47***
Range	*395-1594*	*371-1571*	*187-809*	*90-460*	*237-985*	*185-828*	*357-1885*	*249-1280*	*736-3169*	*606-2251*	*506-2333*	*388-1632*	*590-2902*	*492-2196*	*571-2484*	*474-1855*
(Share on TC%)	*76%*	*71%*	*71%*	*48%*	*69%*	*59%*	*69%*	*56%*	*58%*	*51%*	*63%*	*50%*	*56%*	*46%*	*66%*	*56%*
TC(€/ha/y)	***832.49***	***852.79***	***429.85***	***320.78***	***544.04***	***514.75***	***862.15***	***760.56***	***1961.30***	***1912.12***	***1279.24***	***1301.75***	***1690.33***	***1809.18***	***1350.86***	***1382.96***
	Profitability Indicators															
BCR	1.34	2.68	1.66	2.09	2.48	3.92	3.36	2.94	1.65	2.03	2.12	2.02	1.98	2.02	2.21	2.17
GM (%)	25	63	40	52	60	75	70	66	39	51	53	51	49	50	55	54
NP (€/ha/y)	148.72	414.46	249.98	83.33	247.63	618.24	620.94	650.92	536.15	956.76	535.93	670.19	725.55	1003.77	556.47	714.98

B= baseline scenario; CA= conservation agriculture scenario; Model A= single-cropping; Model B= summer double-cropping; Model C= winter double-cropping; PC= costs borne by producers; EC= costs on the environment; TC= total costs; SD= standard deviation; Ranges indicates the variation of environmental costs by using low and high values for monetisation factors as indicated in European Commission (2020); BCR: Benefit Costs Ratio; GM: Gross Margin; NP= Net Profit

[a] *Camelina is intercropped with pea vetch and lentils in this scenario;*

[b] *Environmental costs do not include costs on biodiversity due to lack of monetisation factors for the new category*

Indeed, the analysis shows that positive impacts for community development (*e.g.*, new job opportunities, % of people employed) are perceived in all countries with no significant changes for Tunisia and Spain. The potential of creating an oil-based industry was positively acknowledged for the creation of new employment, investments and companies contributing to community development and health. Nonetheless, large-scale implementation in Tunisia yielded less significant results than pilot studies, dampening initial optimism (as reported in *Supplementary Table 2.J*).

Source: *Authors own elaboration*

Figure 2.4. Variation of perceptions of the impact sub-categories from baseline to CA scenario. Red colours indicate that stakeholders perceive a deterioration of social impacts, orange indicates they perceive no changes and green indicates they perceive improvements of the impacts.

Society

The heatmap indicates that the adoption of CA practices enhanced knowledge sharing in all countries, driven by extensive training initiatives organised in the context of 4CE-MED project. However, gender and vulnerable group inclusion showed limited progress, except in Morocco and Algeria, where camelina value chain development was acknowledged as an opportunity to promote gender inclusion as women are generally more involved in transformation processes rather than field operations.

Environment

In the case of perceptions of environmental benefits, respondents noticed an improvement of soil conservation and quality, water retention capacity and landscape quality. No significant changes were observed in Tunisia, Italy and France. Indeed, environmental benefits were deemed to be more associated with context-dependent and agricultural management decisions employed in the farming systems.

The coding of the comments gathered in the 2nd round of interviews are listed in *Supplementary Table 2.J*.

2.4 Discussion

2.4.1 What are the Implications of CA on the Sustainability of Mediterranean Farming Systems?

Environmental Dimension

The introduction of cash cover crops, such as camelina, yielded notable benefits in terms of biodiversity and land use (as shown in **Figure 2.3**), confirming the ecological benefits observed in terms of plant diversity and improvements in insect communities and pollinator populations documented in experimental studies (Berti et al., 2016; Gaba et al., 2015; Groeneveld and Klein, 2014). Moreover, the results indicate that camelina has the potential to effectively substitute or complement other oilseed crops in the market (*e.g.*, rapeseed), thereby reducing their environmental impacts, if fertilisation and phytosanitary treatment practices are properly managed (Palmieri et al., 2014; Queirós et al., 2015; Tudge et al., 2021).

Nonetheless, the analysis indicates the potential for adverse side effects, specifically an increase in the impacts of climate change. This increase may arise from a combination of residues management (no removals or burning assumed), and tillage practices, which can enhance denitrification processes, leading to elevated nitrous oxide emissions (see *Supplementary Table 2.E*). This effect is well-documented and discussed in the literature. Mirzaei et al. (2022) observed increased nitrous oxide emissions resulting from crop residue management, regardless the tillage practices employed (whether conventional or no-tillage). Li et al. (2023)' s meta-analysis of three CA practices—crop rotations, cover crops, and no/reduced tillage—revealed that, under certain edaphoclimatic conditions, climate benefits might be compromised due to heightened soil nitrous oxide emissions. Furthermore, other studies indicate negative effects of no-tillage on nitrous oxide emissions, while reduced tillage exhibits non-significant effects (Guerrero et al., 2024). On the other hand, Wang et al. (2021) demonstrated a reduction in nitrous oxide emissions when reduced tillage was applied over the long term. Our emissions' model predicted an increase in N_2O emissions, particularly in wet climates, with notable rises under the CA scenario (*e.g.*, in Italy), where high fertilisation rates (ammonium nitrate: 200 kg/ha; urea: 350 kg/ha; slow-release nitrogen: 250 kg/ha) and reduced tillage practices were employed. Hence, context-specific mitigation strategies aimed at reducing denitrification processes could prevent these unintended consequences. For instance, the study of Grutzmacher et al. (2018) demonstrated that the use of biochar can reduce nitrous oxide emissions and enhance carbon sequestration. Furthermore, minimising tillage may influence the denitrification process, as its effects are dependent on soil depth (Peng et al., 2023).

The environmental impacts were largely contingent on how CA practices were implemented in the case studies. In Morocco case, the use of no tillage combined with the elimination of fertilisers and chemical inputs for camelina cultivation reduced environmental impacts. Conversely, in Algeria and Tunisia, reported increased ecotoxicity, primarily due to the use of phytosanitary products containing harmful active substances (ASs). Some of these ASs (*e.g.*, lambda-cyhalothrin and thiamethoxam) were found to exhibit acute toxicity to mammals and pose significant risks to both consumers and farmers. These were not classified as authorised

ASs in Europe but permitted under Emergency Authorisations (Carisio et al., 2024). The Characterisation Factors (CFs) of these active substances (ASs) exhibit a high order of magnitude, resulting in substantial uncertainties in the Monte Carlo simulation, as demonstrated in the contribution analysis presented in *Supplementary Figure 2.C.* Regarding land use, in the scenario involving the adoption of CA practices, the uncertainty of land use impacts is higher, as shown in **Figure 3**. This is a consequence of system expansion, where the amount of land required to substitute camelina oil and meal in the market is directly influenced by the variability in oil and meal yields.

When isolating the effects of conventional tillage and minimum or no-tillage practices on crop rotations, without accounting for cover crop cultivation, the results (*Supplementary Figure 2.B)* confirm that minimum tillage alone can enhance biodiversity and reduce land-use impacts, but sustainable management of fertilisers and pest control is essential to support these practices in achieving sustainability. In other cases, the benefits of reduced tillage were offset by prolonged sowing operations, which led to increased biodiversity and land-use impacts, suggesting context-dependent effects.

Economic Dimension

Adopting CA practices can lead to increased costs, which may pose a barrier for farmers. Although there are reductions in land preparation costs, such as decreased fuel consumption and labour in the CA scenario (as shown in *Supplementary Table 2.I*), **Table 2.2** highlights an increase in overall costs due to the introduction of cover crops into the rotation. This increase could hinder adoption, particularly in regions with widespread rural poverty, and may restrict uptake to wealthier segments of farming communities (Branca and Perelli, 2020; Makate et al., 2019). In contrast, CA practices have demonstrated a reduction in environmental costs, underscoring the necessity for alternative approaches to analyse economic benefits of sustainable farming practices. Externalities, arise when the costs are borne by individuals or groups who did not contribute to their creation (Stiglitz, 2000). Michalke et al. (2023) demonstrated that organic products generate fewer externalities by incurring lower environmental costs compared to conventional products, and in our analysis, we sought to quantify the externalities of both conventional and conservation farming practices, finding that CA can reduce the environmental costs borne by the society (as evidenced in **Table 2.2**). Furthermore, the market potential for camelina oil and meal is promising in complementing or substituting other oilseed crops (*e.g.*, rapeseed), and could enhance farmers' profitability while providing environmental benefits, as evidenced by the potential increase of net profits across all case studies (**Table 2.2**). Camelina oil can be utilised for both food and non-food applications, including biofuels, biopolymers, animal feed, and cosmetics (Berti et al., 2016; Zanetti et al., 2021).

Social Dimension

The most widely recognised positive aspect was the increase in knowledge sharing when assessing respondents’ perception (**Figure 2.4**). This finding can be attributed to the numerous training activities and participatory exchanges, that occurred during the 4CE-MED project. This is an encouraging outcome, given the critical role that knowledge assumes in the transfer of technology for the promotion of sustainable practices (Barnes et al., 2019; Garbach et al., 2012; Piñeiro et al., 2020) as well in the enforcement of food systems actors in enhancing the resilience of agriculture systems (Soriano et al., 2023)

In certain case studied, perceptions of camelina were notably positive. In Morocco, the perception of cultivating camelina was highly favourable, due to the well-established argan oil market and the absence of other oilseed crops. The positive view was further reinforced by camelina's drought resistance and adaptability to marginal soils. Gender inclusion was positively regarded in both Morocco and Algeria, as the processing of camelina products has the potential to create jobs in the transformation phase, a sector typically dominated by women. This potential was less evident in European countries, where competition with other oilseed crops is the most remarkable socioeconomic aspect (Zanetti et al., 2013).

Respondents did not perceive significant improvements in economic development, citing the lack of market opportunities and post-harvest value chains. Market development can support the establishment of these value chains exploiting the potential future uses of camelina oil and meal (Sydor et al., 2022). This was particularly evident in Tunisia, where the large-scale implementation of camelina failed to meet the initially positive expectations generated during the first round of interviews (*Supplementary Table 2.J*). In contrast, careful attention must be paid to ensuring fair prices for farmers and mitigating potential side effects of emerging value chains on the socio-economic contexts (Perry, 2020). Niche markets (e.g., cosmetics) are crucial to protect, as the increasing corporate influence in the biofuel sector poses a potential threat to small-scale farmers (Bastos Lima, 2021; Neimark, 2016).

2.4.2 Where Should Future Research Focus to Understand and Enhance the Sustainability of Farming Systems?

This study highlights the potential of camelina within conservation agriculture (CA) systems, underscoring the importance of tailoring its cultivation to diverse environments and integrating it with existing farming practices. Further research is needed to evaluate camelina’s profitability, optimal integration timelines, and environmental benefits, such as soil improvement and drought tolerance. The PEF methodology employed in this study underscores the need for a biodiversity indicator, partially addressed using BioMaps. Market analysis for camelina should incorporate LCT alongside behavioural studies, recognising its context-sensitive nature. Additionally, examining gender aspects in agriculture from a life cycle perspective is highly relevant. Challenges such as relying on Swiss data to estimate North African fuel consumption due to data limitations and uncertainties regarding straw availability must be addressed. Future research should also explore the advantages of mass-based functional units over the current reliance on hectares. Lastly, sampling for social analysis should aim to increase both the number and diversity of respondents, ensuring representation of varied stakeholder typologies to more effectively capture social impacts within the scope of the analysis.

2.4.3 What are the Policy Recommendations Derived From This Work?

This study demonstrates that CA practices, particularly those involving reduced fertiliser use, can enhance sustainability by lowering environmental and economic costs while improving soil quality and biodiversity. Practices such as crop rotation should be maintained until they achieve parity with the income levels of conventional farming. In alignment with the European Green Deal's targets, particularly regarding fertiliser reduction, these strategies have the potential to support the long-term development of African agriculture. Camelina, as a cover crop, offers significant economic and environmental benefits, making its cultivation a priority for further research and market integration. The incorporation of LCT offers systemic evaluation that can inform existing tools to promote sustainable development for Mediterranean agricultural systems, such as the new EU Carbon Removals and Carbon Farming Certification (CRCF) Regulation (EU/2024/3012). Consequently, advancing policy recommendations in this direction could play a pivotal role in fostering the transition towards food systems sustainability and climate resilience.

2.5 Concluding Remarks

Policies including the European Green Deal are directed at sustainable food systems transitions, yet there is uncertainty about practices that holistically enhance sustainability. This study assessed Mediterranean carbon and conventional farming using LCT. The analysis revealed that conservation agriculture (CA) with camelina introduction, can increase environmental sustainability, though results varied with local conditions. Socially, CA potentially offers job creation and potential for gender inclusion in African countries but faces challenges in terms of infrastructures for value chain developments. CA's success is market-dependent, highlighting the need to consider farmers access to these practices in terms of costs. Further research should focus on optimising camelina cultivation, market development, and understanding socio-economic impacts, including gender roles. The study illustrates that a detailed understanding of local conditions, research, and supportive policies are crucial for sustainable Mediterranean agriculture, as informed by the sustainability assessment.

CRediT Authorship Contribution Statement:

VG: *Conceptualisation, Methodology, Data Curation, Formal analysis, Visualisation, Writing - Original Draft;* LGH: *Conceptualisation, Methodology, Formal Analysis, Validation, Writing - Original Draft*; SM: *Data Curation, Validation, Formal Analysis, Writing - Review & Editing*; AM: *Conceptualisation, Validation, Supervision, Writing - Review & Editing, Resources*. MV: *Conceptualisation, Validation, Supervision, Resources, Writing - Review & Editing*;

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements:

The authors thank all the partners of the 4CE-MED project involved in the activities. A special thanks to Federica Zanetti, Sara Berzuini, Elena Pagani, Simone Amadori, Simone Prospero, Andrea Vicinanza and Andrea Nozzoli from University of Bologna, Louise Hermet from ARVALIS, Sripada Udupa from ICARDA, Imen Trabelsi from INRAT, Paloma León Guadaño from Camelina Company, Kyriakos Kempapidis from BIOS, Abderrahmane Hannachi from INRAA who supported data collection activities.

Ethical Approval:

The research has been conducted within 4CE-MED - *Camelina: A Cash Cover Crop Enhancing Water and Soil Conservation in Mediterranean Dry-Farming Systems*, funded by the European Union's Horizon 2020 Prima programme under Grant Agreement No. 1911. The research was approved by the project coordination and the project was subject to rigorous ethical review, as per institutional requirements and in accordance with the European Union data protection law (GDPR).

Data included in this study were collected within the 4CE-MED consortium complying with European regulation on protection (GDPR). Consortium partners provided consent to participate in the study, to use of data and to publication. All participants have been fully informed that their anonymity is assured, why the research is being conducted, how their data will be utilised, and if there are any risks to their participation.

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Chapter 3

Combining Life Cycle Thinking with Policy Foresight: A Case on Future Diffusion of Non-Conventional Water Resources

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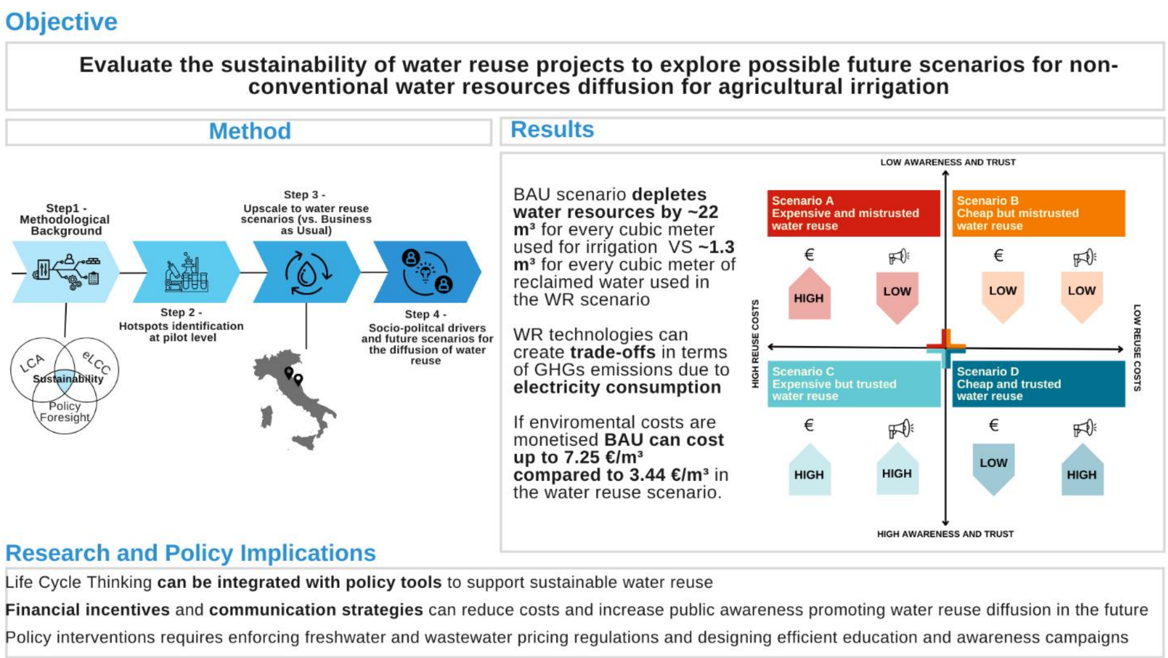

Chapter 3

Combining Life Cycle Thinking with Policy Foresight: Future Scenarios for the Diffusion of Non-Conventional Water Resources

Status: Submission to Waste Management Journal.

Abstract

Water reuse represents a promising approach to addressing water scarcity in the Mediterranean. However, its integration into mainstream water management faces challenges, including low public acceptance, high reclamation costs, and stringent safety standards. While new treatment technologies are emerging, comprehensive assessments of their environmental and socio-economic impacts are limited. This study examines the sustainability of water reuse initiatives, identifying key drivers of change and future scenarios for the use of non-conventional water resources in agricultural irrigation. Using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) in a case study in Italy, findings indicate that innovative water reuse technologies can reduce demand on water resources; however, further technological improvements are necessary to optimise energy consumption in large wastewater treatment plants. Although monetised environmental benefits highlight positive outcomes, climate-related costs still outweigh direct water use costs. Scenarios that include by-products like biogas illustrate lower environmental impacts, supporting a circular resource management approach. A foresight exercise with experts from seven Mediterranean countries suggests that effective water reuse adoption requires financial incentives and targeted communication to increase public awareness and address perceived risks. Based on these findings, the study highlights essential research and policy implications for advancing sustainable water reuse practices in the region.

Keywords

Sustainability assessment; water reuse policy; LCA, LCC; foresight

3.1 Introduction

Agricultural water management plays a pivotal role in the transformation of food systems and the advancement of sustainable development goals (Ringler et al., 2022). Water imbalances, exacerbated by extreme events under climate change scenarios, are expected to have profound effects on global populations, with significant economic repercussions (Schewe et al., 2019; Trancoso et al., 2024). Water reuse has emerged as a potentially valuable strategy for enhancing water quality, mitigating water scarcity, and offering a promising alternative water supply (Christou et al., 2024). In water-scarce regions such as the Mediterranean, water reuse strategies have been particularly implemented in countries like Israel (Tal, 2016) and Cyprus (Christou et al., 2014), though their adoption is less widespread in EU countries, with some examples in Spain and Italy (Fito and Van Hulle, 2021; Maffettone and Gawlik, 2022).

Applying from June 2023, the implementation of the new EU regulation on minimum requirements for water reuse has aimed to promote efficient water resource utilisation and offer guidance to market operators and practitioners, thereby complementing existing EU Water Policy directives, including the Water Framework Directive (2000/60/EC) and the Urban Wastewater Treatment Directive (91/271/EEC). Nonetheless, despite the considerable and acknowledged potential benefits of water reuse, its adoption remains significantly below optimal levels (Gawlik, 2017). Indeed, technical, infrastructural, and financial barriers (Cipolletta et al., 2021; Voulvoulis, 2018) hinder the widespread implementation of innovative water reuse technologies, owing to the high costs of implementation and the challenges in meeting stringent requirements for safe reuse, particularly in certain countries (e.g., Italy, (Licciardello et al., 2018)). Thus, while novel innovative technologies continue emerging to ensure environmental and human safety (Cantarella, 2019; Molinos-Senante et al., 2011), a systemic analysis of the socio-economic impacts of water reuse projects are still required to identify critical hotspots and trade-offs within water reuse chains as well strategic entry points for policy interventions.

Life Cycle Assessment has proven to be an effective decision support tool for water reuse projects (Corominas et al., 2013; Kalboussi et al., 2022) by providing a quantitative evaluation of environmental impacts over the entire life cycle of the considered processes. Life cycle approaches also proved to support circular economy strategies and are effective in supporting the analysis of circular systems (Mondello et al., 2024; Opher et al., 2019). Several studies used LCA to quantify the impacts of using non-conventional water resources for irrigation purposes showing improvements in eutrophication (Moretti et al., 2019) and reduction of GHG emissions (Miller-Robbie et al., 2017; Rodriguez-Garcia et al., 2011) but also showing trade-offs and context-dependent impacts suggesting the need of carefully considering location characteristics and experimental fields (Kalboussi et al., 2022).

Despite efforts to investigate the environmental impacts of water reuse projects, stakeholders still exhibit limited awareness of the benefits of water reuse, emphasising the necessity of conducting comprehensive assessments to identify economic and societal costs associated with the deployment of current and novel water reuse technologies and to identify policy enablers that can boost their diffusion. In light of these considerations, this paper presents several elements of novelty compared to the current literature. Firstly, while several studies have attempted to investigate the environmental impacts and economic feasibility of innovative technologies (Boldrin et al., 2022; Foglia et al., 2021), there is still a lack of attempts to upscale experimental pilot data to real-scale scenarios that encompass the entire water reuse chain. Secondly, while a few studies have attempted to monetise environmental benefits (Canaj et al., 2021) and evaluate stakeholders' perceptions of water reuse (Ricart and Rico, 2019a), comprehensive and systemic assessments of the environmental and economic impacts of these projects are still lacking. Finally, building on the policy and legislative contexts outlined in existing studies (Berti Suman et al., 2023), this work aims to take advantage of trade-offs and hotspot identification to identify policy enablers that can create a favourable environment for the diffusion of water reuse projects in the future.

This paper aims to investigate possible environmental and social impacts of water reuse scenarios for agricultural irrigation by developing a methodological framework based on Life Cycle Assessment (LCA) and environmental Life Cycle Costing (eLCC). Building on this foundation, a policy foresight exercise was conducted to define a set of actions and interventions to enhance adoption. By developing and applying this method, the paper offers a concrete framework for assessing and comparing the environmental and economic impacts of water supply chains, showcasing its application through a real case study in northern Italy. Finally, the analysis results are translated into a set of actions and interventions aimed at increasing acceptance and promoting the diffusion of non-conventional water resources in the Mediterranean region.

This article is organised as follows. **Section 3.2** provides the methodological framework developed in the study. **Section 3.3** reports the results obtained at the pilot scale and upscaled scenarios and the policy enablers that emerged from the foresight exercise. **Section 3.4** discusses results and limitations and lists potential research pathways and policy implications.

3.2 Method

To test the introduction of novel innovative water reuse technologies into Mediterranean water reuse chains, we developed a methodological framework that combines *quantitative* holistic assessment based on Life Cycle Thinking with *qualitative* analysis based on a foresight approach to explore how existing trends and drivers of change may affect future diffusion of water reuse technologies.

3.2.1 Environmental and Financial Analysis

To assess the environmental impacts of water reuse technologies, we performed a Life Cycle Assessment (LCA) (ISO, 2006a, 2006b) following an attributional approach to investigate possible environmental impacts on the whole life cycle of the novel technologies. A conventional Life Cycle Costing (ISO, 2017) was applied grounding on LCA phases. Further, by applying a set of monetisation factors (Galgani et al., 2021), we attempted to unveil the environmental costs of alternative water supply for agricultural irrigation compared to conventional water sources. To this purpose, we employed an environmental Life Cycle Costing (eLCC), following Hunkeler et al. (2008) and Swarr et al. (2011), as this approach gained increasing relevance in recent years to measure and value environmental costs and benefits to support decision-making (UN Food Systems Summit, 2021).

Goal and Scope Definition

The study was conducted in the context of the PRIMA project Fit4reuse[1]. At the pilot scale the goal of the analysis is to identify the economic and environmental hotspots of the construction, operational, and disposal phases of the novel technologies to inform technology developers and private actors. When upscaling to water reuse scenarios, the goal is to unveil possible environmental and economic impacts of a whole water reuse chain from water supply to discharge by comparing it with a "*Business-as-Usual*" (BAU) scenario (no reuse) to inform public authorities on the sustainability of water reuse projects. The analysis was based on a Functional Unit (FU) of treating 1 m^3 of municipal wastewater to meet standards *Class A of EU Regulation 2020/741* over 20 years. The lifetime of the three technologies was set to 20 years, in accordance with similar studies (Molinos-Senante et al., 2010). The system boundaries were set from cradle to grave to investigate possible impacts from the construction to the disposal phase of the three technologies.

Experimental Pilots

The analysis was conducted on two intensive technologies (*Upflow Anaerobic Sludge Blanket Reactor, Molecularly Imprinted Polymers*) and on a nature-based solution (*Aerated Constructed Wetland*) at pilot level. The evaluated technologies in this study were partly situated in the pilot site of *Falconara Marittima* in the Marche Region, Italy, implemented by Università Politecnica Delle Marche, and partly in *Granarolo dell'Emilia* in the Emilia Romagna Region, Italy, implemented by the University of Bologna.

The UASB reactor functions as an anaerobic digester, treating wastewater through vertical up-flow pumping of liquid substrates into anaerobic sludge, serving as both primary and secondary treatment (Foglia et al., 2021). It is favoured for biogas recovery, enabling energy production (Rosa et al., 2018). MIPs are polymers designed to remove emerging pollutants like *diclofenac* from water (Cantarella et al., 2019). Constructed wetlands (CWs) mimic natural wetland processes using vegetation, soil, and substrates to remove contaminants and improve water quality. They are cost-effective for treating wastewater, including agricultural run-offs (García-Herrero et al., 2022b; Nan et al., 2020), with efficiency enhanced by improved aeration (Andreo-Martínez et al., 2017). At pilot scale, UASB treated pretreated municipal wastewater at 0.07 m^3/day, ACW processed municipal wastewater at 0.6 m^3/day, and MIPs handled tertiary effluent at 0.01 m^3/day. Pollutant removal efficiency is detailed in *Supplementary Materials III, Table 3.A,* and evidenced in Mancuso et al., (2024); Parlapiano et al., (2024).

Water Resue Scenarios

Pilot-scale technologies were upscaled to simulate plausible water reuse scenarios for agriculture in Northern Italy. The analysis compared two alternative scenarios: 1) a *"Business-as-Usual"* (BAU) scenario, where

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[1]The project Fit4reuse, funded by the European Union's Horizon 2020 Prima programme under Grant Agreement No. 1823, aimed to provide safe, sustainable and accepted ways of water supply for the Mediterranean basin by exploiting non-conventional water resource.

irrigation depends on groundwater resources and wastewater is treated for discharge using conventional technologies, and 2) a water reuse scenario, in which wastewater is treated for reuse to irrigation purposes through novel technologies.

The *Water Reuse scenario* simulates the upgrading of a wastewater treatment plant (WWTP) in a rural area with a capacity of 5,000 population equivalent (PE), aiming to meet Class A water quality standards (EU 2020/741). This scale has been identified as the most efficient in terms of land use for the application of constructed wetlands, requiring 1.5 hectares, reflecting the limitations of these technologies for large-scale applications. The system incorporates three innovative technologies for water reuse—UASB, ACW, and MIPs—and operates with an inflow of 800 m^3 of raw municipal wastewater. A UV disinfection treatment is considered in the WR chain to meet Class A standards. This water is treated during six months in the summer for agricultural irrigation, while in the winter it is discharged into a nearby river. Key assumptions include no hydraulic network losses, and sludge disposal via landfill.

The *BAU scenario* simulates a WWTP with a capacity of 5,000 PE, treating 800 m^3 of raw municipal wastewater using conventional technologies for treatment (using Ecoinvent v3.9.5 for wastewater treatment) and discharging the treated effluent into a nearby river. In this scenario, an additional 800 m^3 of water is abstracted from groundwater supplies to support the irrigation of ~70 hectares of typical Northern Italy crops (grape, maize, soybean, processing tomatoes), estimated considering their water requirements.

The main characteristics of the scenarios are summarised in **Table 3.1** and in *Figure 3.A, Supplementary Material III.*

Table 3.1 Assumptions and parameters of the two scenarios analysed.

Water Supply Steps		Water Reuse Scenario	BAU Scenario
Water Source	*Source*	Municipal WWT effluent (12 months)	Municipal WWT effluent (12 months) + Groundwater (6 months)
Water Extraction, transportation and storage	*Extraction*	No extraction	Energy for GW extraction
	Transportation & Storage	Same for both scenario	
Water Treatment	*Water flow*	800 m^3/d	800 m^3/d
	WWT Capacity	5,000 p.e.	
	Infrastructure	WWTP with upscaled innovative technologies for water reuse (UASB, ACW, MIPs, UV)	Ecoinvent v3.9.5 Conventional WWTP for wastewater treatment (no reuse)
	Type of treatment	Primary, secondary, tertiary	Primary, secondary
	By-products	Biomethane	None
	Sludge disposal	Dewatering + landfill	
Distribution to agricultural plot	*Hydraulic network losses*	None	
	Water Storage & supply network	800 m^3 + energy consumption for supply	None
	Irrigation type	Mix surface, sprinkler and drip irrigation	
	Irrigation surface	~70 ha	
	Water needs	144,000 m^3 (6 months)	
Water Discharge	*Discharge*	River	

Data Collection

Primary data were collected over two years (from 2020 to 2022) by developing a data collection protocol distributed to the three researchers in charge of conducting the experimental trials. Primary data were validated by the three experts and integrated with secondary data from Ecoinvent v9.3.5. Inventories of the three water reuse technologies are reported in *Table 3.B, 3.C, 3D, Supplementary Materials III*.

Life Cycle Impact Assessment

To classify and characterise the environmental impacts of the technologies, we employed the Product Environmental Footprint (PEF) methodology. Drawing upon established methodologies and global standards (Zampori and Pant, 2019), this LCA methodological framework, endorsed by the European Commission for the evaluation and communication of life cycle environmental attributes of products (EC/2021/9332), uses 16 midpoint Characterisation Factors (CFs) for environmental impact assessment. Characterised impacts were normalised into single scores for pilot scale assessment, while characterised environmental impacts for the full-scale scenarios were investigated for selected impact categories considered more relevant in the water reuse field (Corominas, 2020). The complete list of 16 Impact Categories and indicators is reported in *Table 3.E, Supplementary Materials III*.

We conducted a financial analysis of the life cycle costs of the technologies at pilot and full scale considering a loan and depreciation rate with a 1.5% interest rate over an operation period of 20 years. The cost impact is measured in €/m^3 and monetisation factors for true pricing were retrieved from European Commission (2020) as compatible with the PEF method, following the approach of Galgani et al. (2021). Monetisation factor values were adapted to 2023 prices by using the Italian inflation rate and Consumer Price Indexes (*Table 3.F, Supplementary Materials III*), as indicated in Amadei et al. (2021).

We solved the multifunctional processes that generated by-products (e.g., UASB) via economic allocation. Hence, we considered the producer price at the farm gate of biomethane provided by the Italian Energy Services Manager (GSE S.p.a) equal to €230/Gj and using the energy conversion rate provided by Cappelli et al. (2021). Finally, the wastewater price was considered equal to €0.03/m^3 (Ozgun et al., 2021).

Sensitivity Analysis

A sensitivity analysis of low and high monetisation values for monetary coefficients for the eLCC analysis was performed to show variability under different evaluation approaches. Further information on low, central and high monetisation values for the coefficients for the selected impact categories can be found in *Annex B* of European Commission (2020).

3.2.2 Policy Foresight

Foresight is a systematic, participatory process designed to inform present decision-making by anticipating future challenges and opportunities, thereby facilitating joint actions that support policymaking (Cook et al., 2014; Störmer et al., 2020; Wiebe et al., 2018). In this work, a combination of trends and megatrends analysis and scenarios co-development and exploration was employed to explore potential future scenarios for the diffusion of water reuse in the Mediterranean region. Following the typical six steps of foresight processes

(Cook et al., 2014; Hines, 2016), we structured the exercise as follows: (1) gathering evidence of *signals* and *drivers of change* that could influence the future uptake of water reuse by achieving consensus on the most influential drivers according water reuse experts through two rounds of Delphi consultations; (2) developing four potential future scenarios for water reuse diffusion; and (3) conducting an experts focus group to explore the scenarios and identify potential policy interventions to enhance water reuse adoption. The survey and focus groups were conducted by first and second authors (VG and SA), respectively female and male PhD students with precedent experiences in qualitative research.

Step 1) Delphi e-Surveys

The Delphi method is a structured expert survey methodology in which individuals' opinions are gathered through a series of iterative questions to achieve consensus (Mahajan et al., 1976). This method is particularly well-suited to questions requiring expert judgement, especially where multiple potential answers exist, and can be utilised to develop complex solutions (Hakami, A., Ghiran, A., and Bontoux, 2020).

An extensive list of experts was compiled by leveraging the networks of partners involved in the Fit4reuse project. Snowball sampling was employed to identify representatives from academia and research centres, non-governmental organisations (NGOs), private companies, farmers and/or farmers' associations, and public authorities within the water reuse sector. Experts were defined as individuals possessing specialised knowledge of water reuse practices and technologies. The expert selection panel, comprising members of the research team (VG, SA, and MV), aimed to ensure diversity in the types of stakeholders involved and to achieve geographical representation across the Mediterranean region.

An anonymous survey was distributed via email using the Fit4reuse mailing list, which comprises 52 recipients, and via a talk in the Fit4reuse Multistakeholder Platform including 108 participants, with a request for partners to further disseminate the invitation to additional experts. The Delphi surveys were conducted in two rounds using the Qualtrics platform (*Figure 3.B, Supplementary Materials III)* and were pilot tested by the two researchers with major expertise in the water reuse field (LGH and RD). Participants were informed about researchers' purpose of the study and methods of data processes. Round 1, which took place from September to October 2022, garnered 64 responses, while Round 2, conducted two weeks after the conclusion of the first round, received 22 responses. Incomplete responses where participants had completed less than 25% of the survey and those lacking explicit consent to data treatment were excluded, accounting for 46% of the total responses. Consequently, the final sample size consisted of 47 responses. Demographics of participants are reported in **Table 3.2**.

The exercise sought to establish consensus on the top five drivers influencing water reuse diffusion in the Mediterranean, by asking experts to select from a list (*Table 3.G, Supplementary Materials III*) based on the LCA analysis and the literature review of Berti Suman et al. (2023). The list included 8 internal drivers of water reuse diffusion (related to WR technologies) and 18 external drivers (related to the socio-eco-institutional context of technology adoption). Experts engaged in an exercise to select and classify the most influential environmental, social, political, technological, and financial drivers. In the first round, respondents ranked drivers from 1 (most influential) to 5. Rankings were scored on a scale from 5 (highest score for 1st rank) to 1 (lowest score for 5th rank) to produce preliminary results. The second round validated rankings, seeking agreement or alternatives to refine consensus on the top influential drivers. Data were analysed and coded by first and second author using Microsoft Excel and graphics produced using Tableau software.

Step 2) Scenarios Building

Scenario analysis adopted a systemic approach, incorporating key drivers of change identified in previous methodological steps. Scenarios offer multidimensional visions of the future, enabling participants to evaluate opportunities and threats associated with these drivers (Störmer et al., 2020). Using insights from Delphi consultations, the authors contextualised these drivers within potential megatrends—long-term forces observable today, likely to influence future developments. Megatrends were selected from the EU Megatrends Hub[2], which identifies 14 global forces shaping the EU's strategic sectors. This informed the creation of a scenario matrix and the development of four future scenarios, accompanied by actionable strategies to achieve the most desirable outcome.

Step 3) Focus Group

Focus groups are essential qualitative research methodologies, facilitating exploration of social interactions and consensus-building through group discussions on predetermined topics. For this study, two hours focus group of 15 water experts was convened to review the Delphi exercise results and developed scenarios (**Table 3.2**). Convenience sampling was employed by conducting a focus group during the final meeting of Fit4reuse project to advantage of water reuse experts and of the knowledge advanced in the four years project. The session was conducted fully in person and moderated by first and second authors (VG and SA). A Miro board (*Figure 3.C, Supplementary Material III*) was used to illustrate the scenario-building process and detailed instructions. Participants were divided into five subgroups of three to discuss ideas, which were then shared in a plenary discussion. This structure facilitated coherent idea organisation and encouraged diverse perspectives.

Table 3.2 Delphi e-surveys and focus groups participants demographics.

	Delphi Round 1 (n=36)	**Delphi Round 2 (n=11)**	**Focus Group (n=15)**
Public Authorities	16 (44%)	3 (27%)	1 (7%)
Academia and Research Centres	12 (33%)	3 (27%)	12 (80%)
Private Sectors (*e.g.*, consultancy)	6 (17%)	1 (9%)	2 (13%)
Farmers and Farmer Association	1 (3%)	2 (18%)	0
NGOs	1 (3%)	2 (18%)	0
France	4 (11%)	1 (9%)	1 (7%)
Greece	7 (19%)	0 (0%)	3 (20%)
Israel	7 (19%)	1 (9%)	0 (0%)
Italy	9 (25%)	5 (45%)	5 (33%)
Spain	5 (14%)	1 (9%)	1 (7%)
Tunisia	0 (0%)	0 (0%)	3 (20%)
Turkey	4 (11%)	2 (18%)	2 (13%)
Prefer/Did not respond	0 (0%)	1 (9%)	0 (0%)

[2] https://knowledge4policy.ec.europa.eu/foresight/tool/megatrends-hub_en

A tailored tool guided the exercise: each subgroup received a double-sided dashboard (*Figure 3.D, Supplementary Materials III*). The first page detailed the future scenarios, while the second provided a list of stakeholders and policy interventions aligned with the identified drivers of change. Initially, subgroups discussed the four scenarios, determining the likelihood of each, identifying the most preferable, and ranking them from most (1) to least (4) likely. The subgroups then presented their insights to the larger group. In the second phase, participants developed policy strategies to achieve their preferred scenario, drawing on policy recommendations from literature (EU, 2016; Hopson & Fowler, 2022) and Regulation (EU) 2020/741 on water reuse. Subgroups were also invited to propose additional policies. These strategies were shared in the plenary session. Finally, participants identified stakeholder groups from the dashboard essential to the success of their policy strategies. Data were collected through notes reported in Microsoft Excel for further analysis.

3.3 Results

3.3.1 Hotspots and Recommendation from Pilot Scale Analysis

The analysis at the pilot scale allowed us to identify environmental and financial hotspots of innovative technologies for wastewater treatment.

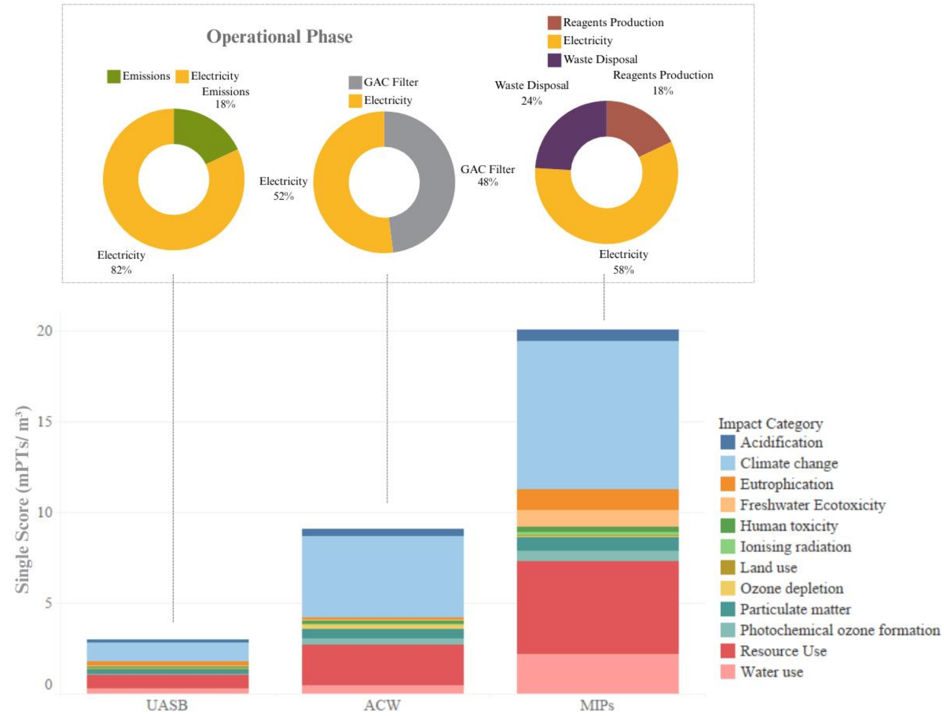
Environmental and Financial Hotspots of Pilot Technologies

The analysis of the pilot technologies indicates that energy consumption constitutes the primary environmental impact across all the evaluated technologies, with potential trade-offs identified in the upscaling of molecularly imprinted polymers (MIPs). As shown in the bar charts in **Figure 3.1**, which presents the impacts of the 16 categories normalised and weighted into single scores, MIPs emerge as the most environmentally impactful technology. Much of this impact arises from the polymers' synthesis process, which is energy-intensive, accounting for 58% of the total operational impacts, as illustrated in the pie charts in **Figure 3.1**. Additionally, the production and disposal of reagents contribute 18% and 24% of the total operational impacts, respectively. These processes result in significant global warming potential, contributing to half of the total environmental impact, and affect water resources due to the use of chemical reagents, alongside broader resource use implications.

Energy consumption is also a critical factor for the Aerated Constructed Wetland (ACW) and Upflow Anaerobic Sludge Blanket (UASB) technologies, which, while less input-intensive, still exhibit notable environmental impacts. For ACW, the use of the four air compressors constitutes a major environmental hotspot in terms of energy consumption (82%), while nitrous oxide and methane emissions from the wetland present a hotspot (18%) in relation to global warming potential, indicating the need for careful consideration during the wetland upscaling. Similarly, for UASB, the biogas valorisation unit, specifically the Granular Activated Carbon (GAC) filter, accounts for 48% of the total environmental impact.

When considering the life cycle costs of the three technologies, from construction to disposal, the analysis highlights potential financial barriers associated with the upscaling of MIPs technology. Due to the low flow rate and the significant chemical and energy inputs required for polymer synthesis, **Table 3.3** demonstrates that the cost of treating 1 m^3 of wastewater could reach €474.27/m^3 when accounting for the full life cycle

Figure 3.1 Environmental impacts of treating 1 m^3 of municipal wastewater with the three pilot scale technologies. Single scores were obtained by using normalisation and characterisation factors of the Environmental Footprint method (EF 3.1) (colour should be used for this figure in print).



Source: Authors own elaborations

costs over 20 years. A financial hotspot is identified in the synthesis process of MIPs, which alone may incur costs of €366.90/m^3 of wastewater treatment. Additionally, disposal costs for MIPs are notably higher compared to other technologies (€7.99/m^3), largely due to the expenses associated with hazardous waste management.

Table 3.3 Life cycle costs of the three pilot scale technologies over 20 years. Values are expressed in €$_{2023}$.

Items	UASB (0.07 m^3/d)		ACW (0.6 m^3/d)		MIPs (0.01 m^3/d)	
	Value (€)	LCC Value (€/m^3)	Value (€)	LCC Value (€/m^3)	Value (€)	LCC Value (€/m^3)
Acquistion Costs (€)	**5,410.00**	**10.59**	**10,646.49**	**2.43**	**4,903.79**	**58.31**
Hydraulic systems	1,250.00	2.44	8,055.00	1.83	1,488.79	17.70
Reactors and Sensors	3,525.00	6.89	-	-	940.00	11.18
GAC Filter	635.00	1.24	-	-	-	-
Ponds	-	-	1,207.49	0.28	-	-
Air Compressors	-	-	1,384.00	0.32	-	-
MIPs Synthesis	-	-	-	-	2,475.00	29.43
Operative Costs (€/yr)	**153.16**	**5.99**	**8,298.41**	**37.89**	**1,703.21**	**405.06**
Activated Carbon	11.75	0.46	-	-	-	-
Sludge Disposal	2.48	0.10	104.89	0.48	-	-
Electricity	138.93	5.44	8,193.52	37.41	160.43	38.16
MIPs Synthesis	-	-	-	-	1,542.77	366.90
Maintenance Costs (€)	**270.50**	**0.53**	**519.33**	**0.12**	**245.19**	**2.92**
Pumping & Treatment*	270.50	0.53	519.33	0.12	245.19	2.92
Disposal Costs (€)	**6.13**	**0.01**	**129.84**	**0.03**	**671.03**	**7.98**
Municipal Waste	6.13	0.01	129.84	0.03	11.00	0.13
Hazardous Waste	-	-	-	-	660.03	7.85
Total Costs (20 yrs)	**8,749.86**	**17.12**	**177,276.77**	**40.47**	**39,884.19**	**474.27**

*Maintenance costs were estimated as 5% of acquisition costs according to experts' interviews.

In contrast, treating 1 m^3 of wastewater using constructed wetlands incurs a life cycle cost of €40.47 over 20 years (**Table 3.3**). Electricity emerges as a key financial hotspot, corroborating the environmental analysis and highlighting the necessity for efficient wetland designs, optimised in terms of size and capacity to ensure effective treatment. Despite this, the technology benefits from low investment (€2.43/m^3) and disposal costs (€0.03/m^3). The UASB technology, on the other hand, demonstrates the lowest life cycle costs at €17.13/m^3, with the majority of expenses concentrated in the acquisition phase (€10.59/m^3). Electricity costs are the primary financial hotspot during the operational phase, amounting to €5.44/m^3.

Although the results from the pilot-scale tests may not fully capture the dynamics of full-scale operations and did not consider wider benefits on the society and environment, **Table 3.4** provides a summary of recommendations regarding potential environmental and financial hotspots, which informed the upscaled analysis and scenarios development.

Table 3.4 Recommendations for the upscaled analysis grounded in the environmental and financial hotspots identified.

UASB	ACW	MIPs
-Mitigate energy consumption and costs -Design efficient biogas valorisation process	-Mitigate energy consumption for air compressor -Consider size and capacity efficiency in terms of energy costs and potential nitrous oxides and methane emissions	-Mitigate energy consumption for polymer synthesis -Design strategies for hazardous waste disposal -Cost-effectiveness of the treatment and upscaling hypothesis

3.3.2 Scenarios Analysis at Full Scale

Environmental Impacts of Water Reuse Scenarios

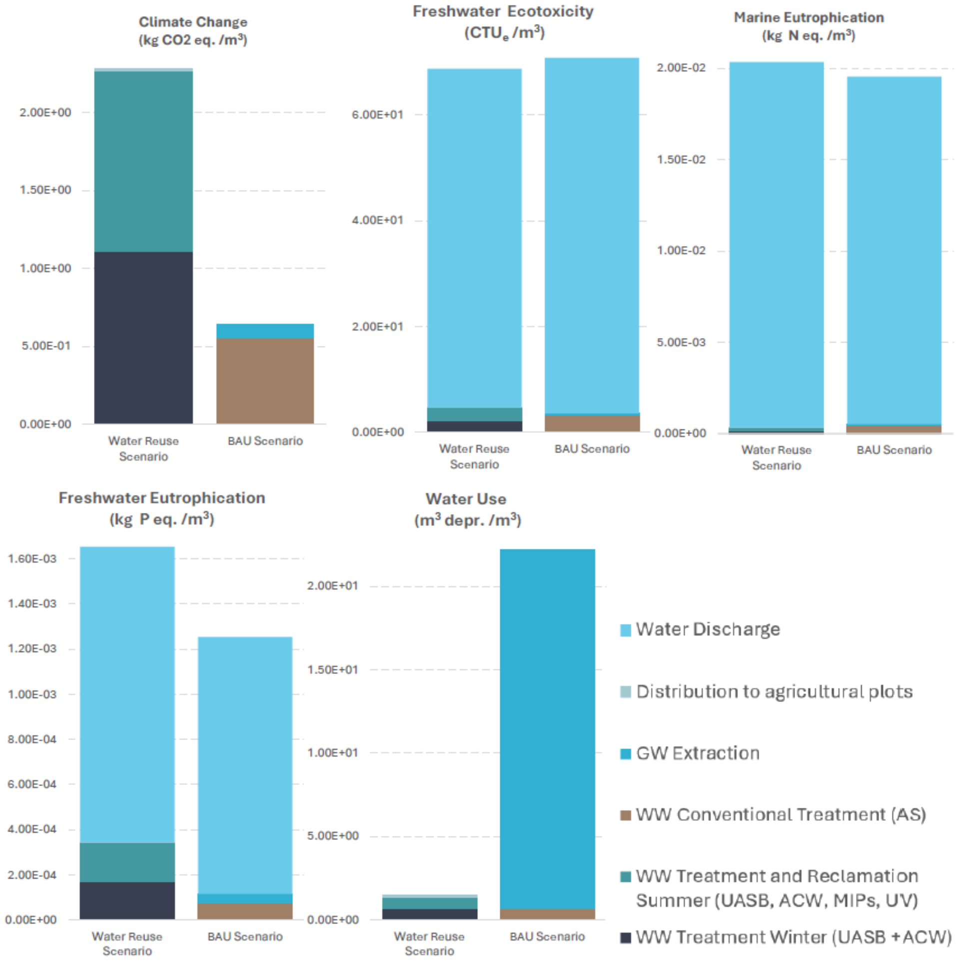
When scaling up the analysis, the results indicate that water reuse offers substantial benefits by reducing the water footprint of the scenario. **Figure 3.2** presents the environmental impacts of the WR (Water Reuse) scenario compared to a BAU (Business-as-Usual) scenario, in which fields are irrigated with groundwater and wastewater is discharged into the environment. The results demonstrate that the WR scenario can reduce impacts on water resources by 94%. Specifically, while the BAU scenario depletes water resources by ~22 m^3 for every cubic meter used for irrigation, treated wastewater results in a depletion of ~1.3 m^3 for every cubic meter of reclaimed water, primarily due to the construction processes involved in wastewater treatment plants (WWTPs).

However, WR has a higher impact on climate change compared to the BAU scenario, with no significant changes observed in terms of discharge. As shown in **Figure 3.2**, the WR scenario results in four times greater impact compared to the baseline, generating more than 2 kg of CO_2 equivalent per cubic meter treated. These impacts are primarily due to energy consumption, particularly from air compressors used for aeration, associated with aerated constructed wetlands (ACW), which are employed in both the treatment and reclamation processes. Additionally, the impacts of water discharge on freshwater and marine ecosystems show no significant differences across the scenarios, with the main impacts attributed to nitrogen and phosphorus loads in the wastewater. Tertiary treatment in this context primarily addresses microbiological parameters, while nitrogen and phosphorus loads are subject to stringent limits only in specific sensitive areas.

Environmental and Financial Costs of Water Reuse Scenarios

The upscaling of lab-scale technologies showed some limits in terms of financial costs; indeed, MIPs implementation has proven to be costly representing a financial hotspot in a full-scale scenario. **Table 3.5** shows the results of the financial analysis of upscaled water scenarios expressed in euro per cubic meter of wastewater treated. Results show that reclaimed water costs €2.40/m^3, which is significantly higher than the baseline scenario, where irrigated water costs €0.51/m^3. When the analysis is conducted without MIPs, the costs of treated wastewater decrease substantially, amounting to €0.79/m^3 treated.

Figure 3.2 Characterised impacts of WR and BAU scenarios over the water supply steps for five selected impact categories. Reclamation process is intended as the process of treating water to meet Class A quality standards (EU 2020/741) for reuse for irrigation purposes (colour should be used for this figure in print).



Source: Authors own elaborations

WW: Wastewater; **GW:** Groundwater; **UASB:** Up-flow Anaerobic Sludge Blanket reactor; **ACW:** Aerated Constructed Wetlands; **MIPs**: Molecularly Imprinted Polymers; **UV:** Ultra-violet disinfection; **AS:** Activated Sludge.

When environmental impacts are monetised, the WR scenario reduces costs related to water resources but results in higher overall costs compared to the baseline. Specifically, the total cost of the WR scenario is €1.19/m^3 with environmental costs accounting for €0.39/m^3, the majority of which are attributed to CO_2 emissions (€0.29/m^3). In contrast, the BAU scenario costs €0.81/m^3 with environmental costs accounting for €0.30/m^3 half of which are related to water impacts (€0.14/m^3 compared to €0.01/m^3 in the WR scenario). Nonetheless, when performing a sensitivity analysis with high monetisation values (€0.29/m^3 water (world) eq.) WR scenarios (€3.44/m^3 and €1.86/m^3 compared to €7.25/m^3) show lower total costs compared to the BAU illustrating results variability to the valuation approach.

Table 3.5 Life cycle financial and environmental costs of the three full-scale scenarios. Values are expressed in €$_{2023}$ and include ranges from the sensitivity analysis of monetary coefficients.

Scenario	**Financial Costs** (€/m^3)	**Climate Change** (€/kg of CO_2 eq./m^3)	**Marine Eutrophication** (€/kg of N eq./m^3)	**Freshwater Eutrophication** (€/kg of P eq./m^3)	**Freshwater Ecotoxicity** (€/CTU$_e$ /m^3)	**Water Use** (€/m^{3}water eq./m^3)	**Total** (€/m^3)
Business as Usual	0.51	0.08 (0.05-0.15)	0.08 (*)	0.00 (0.00-0.00)	0.00 (0.00-0.02)	0.14 (0.12-6.31)	**0.81** (0.75-7.25)
Water Reuse	2.40	0.29 (0.17-0.55)	0.09 (*)	0.01 (0.00-0.01)	0.00 (0.00-0.02)	0.01 (0.01-0.40)	**2.80** (2.66-3.44)
Water Reuse (without MIPs)	0.79	0.29 (0.17-0.54)	0.09 (*)	0.01 (0.00-0.01)	0.00 (0.00-0.02)	0.01 (0.01-0.39)	**1.19** (1.05-1.86)

*Marine eutrophication coefficients do not report low and high monetisation values.

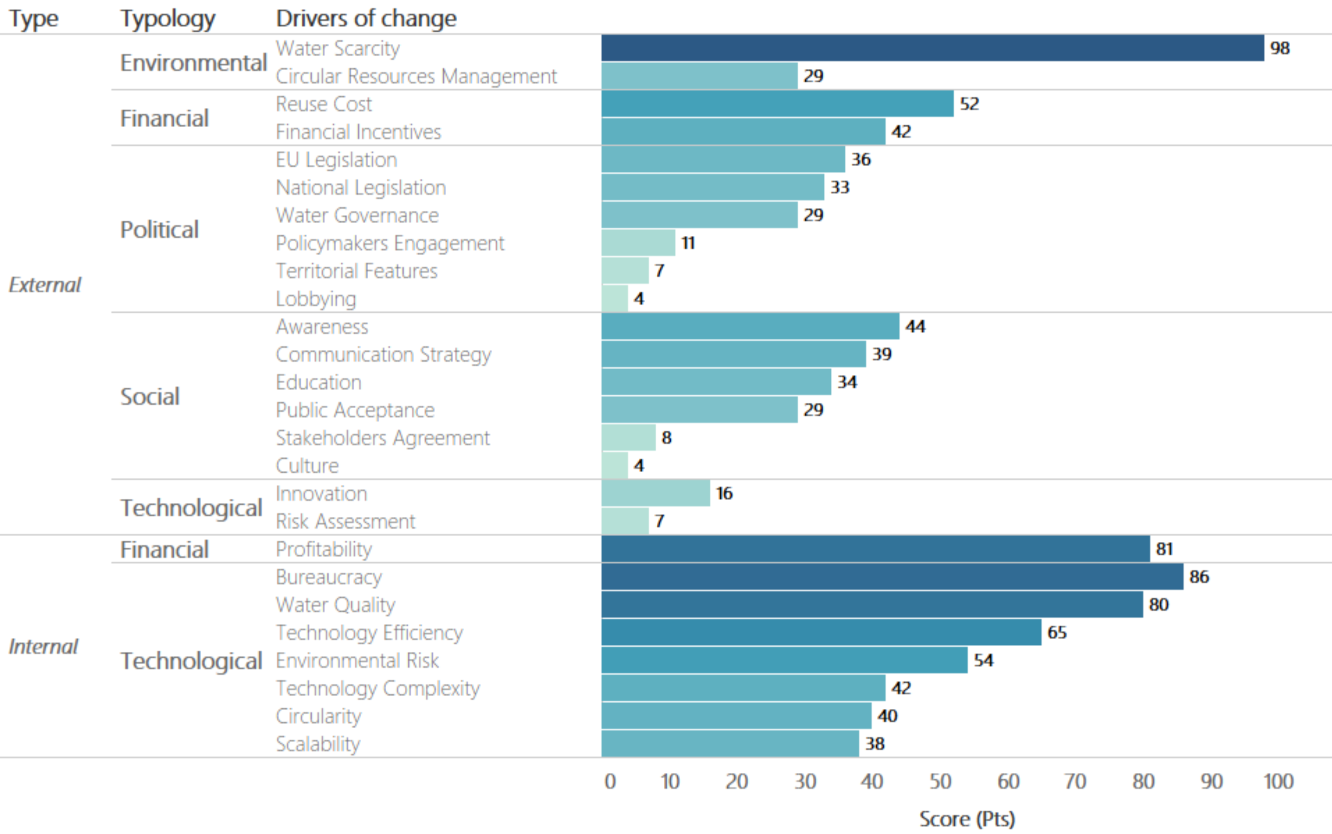
3.3.3 Future Scenarios for Water Reuse Diffusion in 2050

Key Drivers of Change

Water experts identified five key external drivers of change as the most influential in the diffusion of non-conventional water resources in the Mediterranean region: *water scarcity*, *reuse costs*, *public awareness*, availability of *financial incentives* and *communication strategy* as shown in **Figure 3.3** which report the scores obtained from the two rounds of Delphi e-surveys. Experts highlighted the perception of the risks associated with water scarcity as a critical driver. Water scarcity is expected to spark social conflicts and competition among different uses of water (*e.g.*, agriculture vs. tourism) in a context already increasingly under stress by the climate crisis and the rural-to-urban migration (Megatrend: aggravating resource scarcity). These concerns are anticipated to impact both consumer attitudes and policymaking. High water reuse costs for farmers could also hamper the diffusion of unconventional water resources, especially if coupled with low freshwater pricing. According to experts, water reuse uptake will be affected by the gap in awareness between water experts, farmers, and investors, as well by low levels of public awareness and mistrust on the quality of reclaimed water. Further, experts recognised the lack of an effective communication strategy as a barrier to combating misinformation about the risks associated with water reuse, which would otherwise promote the reliability and efficacy of treatment solutions. At the institutional level, experts indicated that the lack of adequate financial incentives for reusing wastewater might also constitute a lock-in situation, although incentives embedded in water tariffs, as established by EU Regulation on Water Reuse (EU, 2020/741), may encourage increased water reuse in the future.

When examining the most influential technological (internal) drivers for the diffusion of water reuse, experts identified *bureaucracy*, *profitability*, *water quality*, *technological efficiency*, and *environmental risk* as the five primary internal drivers of change (**Figure 3.3**). According to experts, the current difficulties in authorising water reuse plans by enabling nature-based solutions are hampering the diffusion of the technologies. Moreover, the construction of full-scale WWTPs is still perceived as a low attractive investment, mostly due to poor returns. Indeed, the current technologies engage with complexities in meeting water quality regulation requirements while maintaining a low cost of treatment. For instance, experts noted that treatment costs are also likely to be impacted by the increasing presence of emerging pollutants (microplastics, PFAs, pharmaceuticals) and antibiotic-resistant bacteria. The possibility of combining different treatments in a blended technology with sustainable costs is expected to trigger water reuse diffusion. Further, reducing the environmental impacts of water reuse technologies—through improvements in pathogen removal, reductions in nitrate and phosphorus concentrations, and better treatment of brine and brackish groundwater—was recognised as a crucial factor in promoting water reuse in the future. This aligns with the anticipated exponential rise of technological efficiency expected in the future due to the general acceleration and transformation in technological advancements (Megatrend: accelerating technological change and hyperconnectivity).

Figure 3.3 Scores of the ranked drivers of change identified in the two Delphi e-surveys. (colour should be used for this figure in print).



Source: Authors own elaboration

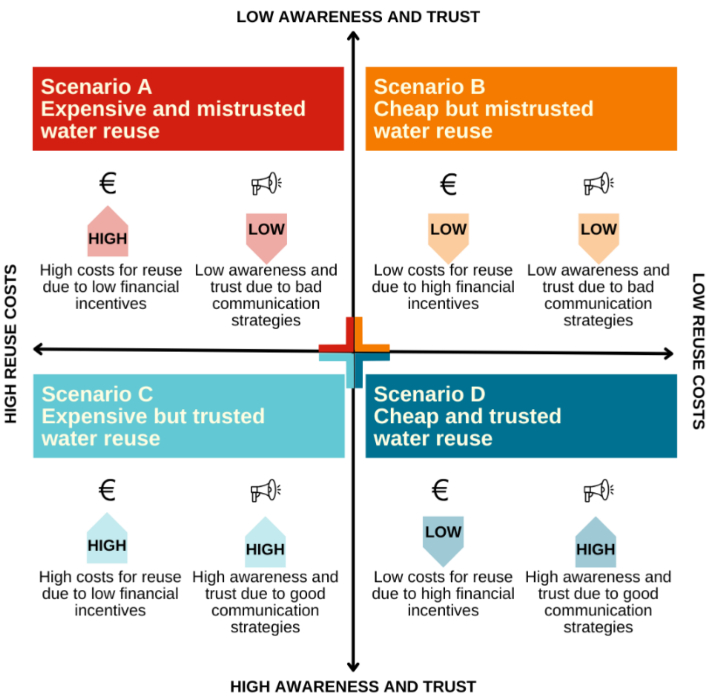
Scenario Co-design

The drivers of changes identified by water experts and their interlinkages resulted in the definition of four future scenarios of non-conventional water resource use. While water scarcity is expected to affect all the scenarios and to increase in the next years consistently, the other most relevant drivers of change were clustered in two axes defining the four scenarios as depicted in **Figure 3.4**.

The vertical axis maps the level of awareness of the reliability of reclaimed water. The low end of the axis represents a situation where the level of awareness of water reuse is low, and the communication strategy on the benefit of water reclaiming technologies is inefficient. In this situation, there is a general mistrust towards reclaimed water, as well as information asymmetries between farmers, experts, and other involved stakeholders. Conversely, the high end of the axis describes a situation where the communication strategy is efficient, helps in generating high awareness of water reuse benefits and contributes significantly to the diffusion of non-conventional water resources.

The horizontal axis describes the levels of financial incentives to adopt water reuse solutions as well as the level of reuse costs of water treatment. On the left end, the axis captures a situation where the level of financial incentives for water reuse is low, and the market fails to attract investments. As a result, the costs for water reuse are high, and farmers are less prone to pay for reclaimed water. On the opposite end, the incentives are higher, and investors are driven to the sector. This situation lowers the costs for water reuse, and the willingness to pay of farmers for reclaimed water increases. The four scenarios resulting from the crossing of the two axes are summarised in *Table 3.H, Supplementary Materials III***.**

Figure 3.4 Future scenarios for the diffusion of non-conventional water resources in the Mediterranean. Based on the most influential drivers of change identified by water experts (colour should be used for this figure in print).



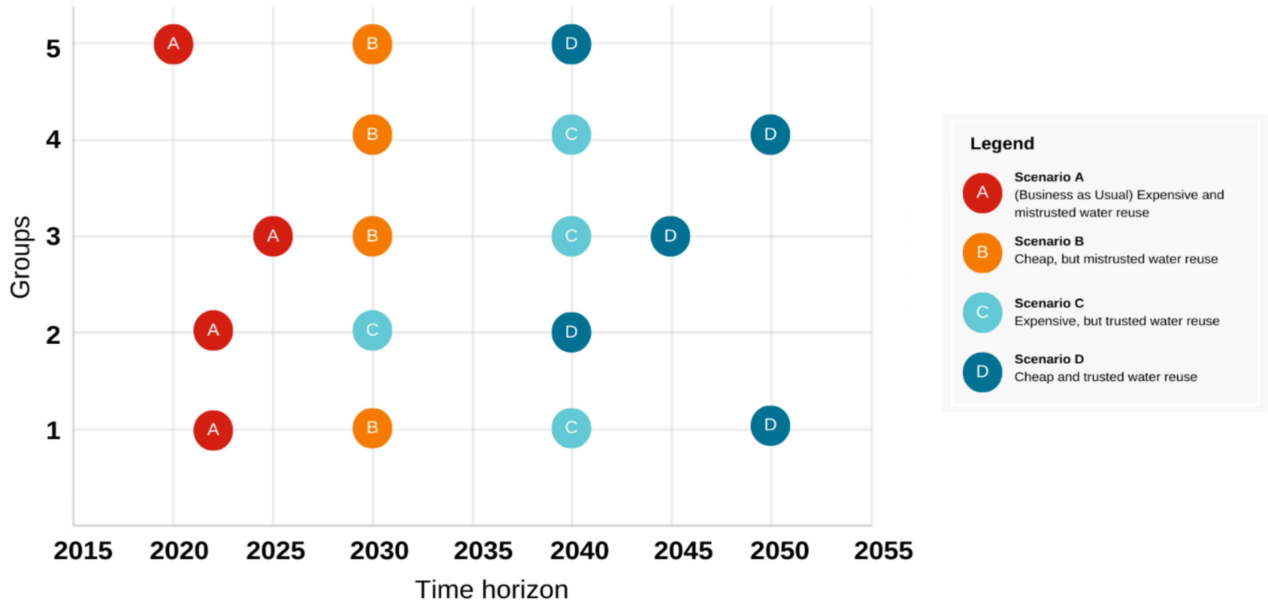
Source: Authors own elaboration.

3.1.4 Scenario Exploration

A focus group including water experts from academia, national water agencies and water consultancies drawn from the drivers' exploration exercise allowed to explore the scenarios identified to investigate the probability of their realisation and the time horizon in which the scenarios are expected to realise (**Figure 3.5**). According to three of the five groups participating in the focus group, Scenario A (high cost, low awareness) is the one that depicts the current situation. Group 4 indicates that Scenario A realised already in the past, while Group 5 recognised this scenario as unlikely to happen since they foresee that technological advancement in water reuse will contribute to tackling water scarcity. Scenario C (high costs, high awareness) is expected to concretise in the short term by 2030, while Scenario B (low costs, low awareness) is expected to be realised in the next 20 years according to three groups. However, Group 3 set Scenario B in 2030, while Group 5 deemed the scenario unlikely to happen because of the impacts of the energy crisis.

All the groups agreed that Scenario D (low cost, high awareness) could materialise between 2040 and 2050. According to three groups (Group 1, 3, 5) out of five the most desirable scenario and the one most likely to happen is Scenario D. Group 3 discussed that reaching low costs is one of the most challenging issues. Instead, Group 2 expects that Scenario A is the most likely to happen although it states Scenario D is the most desirable one. Group 4 indicates Scenario C as the most likely and desirable one, as it deems Scenario D too optimistic and unrealistic.

Figure 3.5 Time horizon in which the scenarios are expected to happen according to focus group participants.



Source: Authors own elaboration.

3.1.5 Actions and Interventions

After having discussed the time horizon and the desirability of the 4 proposed scenarios, the 5 groups identified 17 policy interventions to move from the current situation to their most desirable outcome. **Table 3.7** summarises the results following three policy approaches suggested by Ejelöv et al. (2022). The most preferred policy intervention revolved around enforcing rules on freshwater and wastewater pricing (4 groups), integrating WR in guidelines for best practices on agriculture (3 groups), and implementing education and awareness campaigns (3 groups). After that, the groups mapped the stakeholders that were deemed more relevant in ensuring that the selected policies would reach their aim. Among them, the most relevant were recognised to be Public Authorities (n=18) and Farmers and Farmers Cooperatives (n=12), while the involvement of partners coming from the Private Sector (n=8) and Academia and Research Centres (n=7) was less frequent. Consumers and Citizens were selected as key partners only four times, and NGOs only twice.

Despite these common trends, the policy strategies discussed in the five subgroups differed. All the groups decided to target public authorities, but only three of them deemed that teaming up with farmers (Group 1, 2, 4) would be key to reaching their policy aims. Group 3 opted for a narrower policy strategy focused on a strict legislative framework to enforce water reuse for farmers. Group 5 instead designed a more diversified strategy and pivoted on the private sector and academia to create a partnership for the promotion of water reuse.

3.4 Discussion

3.4.1 Summary of Evidence

We aimed to evaluate the sustainability of water reuse initiatives, aiming to identify potential drivers of change and prospective scenarios for the diffusion of non-conventional water resources in agricultural irrigation. Through the development of a methodological framework that integrates Life Cycle Thinking with policy decision-making tools, we identified key hotspots and trade-offs associated with the implementation of innovative water reuse technologies at both pilot and full-scale levels. This was achieved by estimating the financial and environmental costs of water reuse and proposing a set of policy interventions to promote the diffusion of water reuse practices by 2050.

The UASB process has demonstrated considerable effectiveness regarding environmental impacts, particularly due to its capacity to produce biogas. Nonetheless, when biogas production is considered, the environmental impacts associated with water reuse processes decrease, as biogas contributes a significant portion of the overall allocated impacts due to its high economic value. This highlights that the valorisation of by-products could serve as a valuable strategy for enhancing the profitability of water reuse projects and promoting circular approaches in water reuse chains (Christou et al., 2024; Giakoumis et al., 2020). Indeed, as energy consumption represents the most critical environmental hotspot in WWTP (see **Figure 3.2**), creating energy loops within the wastewater treatment plant (WWTP) can mitigate the impact associated with wastewater treatment (Foglia et al., 2021b; Marangon et al., 2020) Furthermore, the UASB process exhibits lower costs compared to other technologies, even at the pilot scale, indicating its suitability also for smaller WWTPs.

ACW has been identified as a considerable contributor to energy consumption due to the artificial aeration process. While emissions of methane and nitrous oxide have been shown to have a substantial impact at pilot-scale flow rates, as demonstrated in other studies (Fuchs et al., 2011; Resende et al., 2019), the hypothesis of scaling up to a 5,000 p.e. system suggests the potential for optimising the contribution of emissions relative to other impacts per cubic metre of wastewater treated. However, notable impacts arise from the aeration process itself and the need to upscale compressors for aeration (See *Supplementary Materials, Figure 3.D*). Similar studies have shown that aeration improves treatment performance and energy efficiency (Resende et al., 2019) particularly under intermittent aeration regimes (Mancuso et al., 2024). Nevertheless, these studies were conducted in smaller or decentralised plants with lower capacity, implying that the effectiveness of aeration at a larger scale (*e.g.,* 5,000 p.e. as in this study) might need further investigation. Optimisation is needed to address both emissions (from the constructed wetland and energy consumption) and treatment performance.

Table 3.6 Groups of experts' selection of policy interventions to achieve the most desirable scenario.

Policy Approach[5]	Policy Intervention (push/ pull)	Nr. of groups selecting the intervention	Key targeted stakeholders					
			Public Authorities	Farmers and Farmers Cooperatives	Private Sector	Academia and Research Centres	Consumers and Citizens	NGOs
Push	Develop guidelines on good practices and success stories on WR	1	1	1		1		
	Enforce rules on freshwater and wastewater pricing	4	4	2			1	
	Enforce freshwater abstraction tariffs	1	1	1			1	
	Improve compliance rates on wastewater treatment for public long-term investment planning	1	1					
	Increase monitoring for freshwater used for irrigation	1	1	1				
	Investment in R&D to boost technology efficiency	2			2	1		
	Payment for Ecosystem Services schemes for farmers	1	1	1				
	Integrate WR in fertilisation guidelines and legislation	1	1					
	Integrate WR in guidelines for best practices on agriculture	3	2	2				
Pull	Initiatives to support market uptake of water reuse technologies	2	1		1	1		
	Develop voluntary ecolabels and GPP criteria for WR	2	1		1	1		
	Promote cooperation between water supply and sanitation stakeholders	2	1	1	1			
	Promote industrial symbiosis	1			1			
	Promote integration of water footprint in voluntary environmental product declaration (EDP)	1	1		1			
	Support innovation in reclamation technologies and the up skilling of professionals in the water sector	1		1		1		
Inform	Implement education and awareness campaign	3	1	1	1	1	1	2
	Promote water citizen science for wastewater monitoring	1	1			1	1	
	Total		**18**	**12**	**8**	**7**	**4**	**2**

[5] Based on the taxonomy by Ejelöv et al. (2022)

MIPs have been found to be resource-intensive at the pilot scale, nonetheless, upscaling scenarios indicate no notable differences in resource consumption at full-scale implementation, largely due to the regeneration capacity of their substrate (Parlapiano et al., 2024). However, from a financial perspective, MIPs have proven to be costly (**Table 3.3** and **Table 3.5**), offering minimal benefits to eutrophication and ecotoxicity impacts (**Figure 3.2).** Despite this, the life cycle assessment (LCA) did not fully capture the environmental and human health risks associated with MIPs, which must be considered. Emerging pollutants are not adequately addressed by existing WWTP technologies, particularly those associated with the overuse of anti-inflammatory drugs, which have been shown to exhibit high toxicity to both human health and ecosystems (Samal et al., 2022). Nonetheless, as MIPs serve as an additional treatment method—supplementing, rather than replacing conventional tertiary treatment (*e.g.,* UV) in water reuse systems—they contribute to increased operational costs. Hence, while other studies have proven their adaptability to treat sensitive sites (*e.g.,* hospitals) (Yang et al., 2022), their upscaling hypothesis suggests further evaluation of health costs and the technology downscaling to smaller capacities.

The analysis shows that the whole water reuse scenario can reduce pressure on water resources by up to 94%, but it might generate GHG emissions for energy consumption (**Figure 3.2**), highlighting the need for further technological improvements to mitigate trade-offs in WR project implementation. The WR scenario was €0.20/m^3 more expensive than the conventional system when considering full life cycle costs. Even accounting for environmental benefits, WR costs remained higher than the BAU scenario (€0.40/m^3 versus €0.30/m^3), mainly due to the high monetisation values associated with climate change impacts. However, using a high monetisation factor for water impacts, the cost of water in the BAU scenario rose to €7.30/m^3 compared to €1.44/m^3 in WR, indicating results variability to monetisation values and suggesting context-specific considerations when selecting coefficients (e.g., water scarce areas or sites).

3.4.2 Limits of this Research

This study presents several limitations that must be carefully considered in interpreting the results. Data constraints pose a significant challenge for the LCA approach, as much of the available inventory data (e.g., Ecoinvent) relies on average datasets, which may overlook context-specific characteristics of the site under analysis (Hellweg and Milà i Canals, 2014). Moreover, data collection for LCA analysis is time-consuming for involved stakeholders, and data quality is not always consistent or accurate. At the pilot level, we conducted several rounds of interviews to gather high-quality primary data, but the data collected did not always realistically reflect the actual conditions. Conversely, in the upscaling phase, assumptions were made to approximate real-world conditions, relying predominantly on secondary data.

Secondly, LCA has limitations regarding characterisation factors for biological parameters, such as *Escherichia coli* and COD parameters in the water, resulting in minimal differentiation in water quality and discharge impacts and revealing the lack of integration of human health and environmental risks as a limitation of this study. Furthermore, certain social impacts associated with water reuse, as discussed in (Opher et al., 2019), were not addressed in this study due to a lack of data considering experiments were conducted at the pilot level.

Lastly, the monetisation approaches employed in this study also exhibit limitations and remain subject to methodological inconsistencies inherent in these novel approaches (Galgani et al., 2021), making the results highly sensitive to variations in monetisation techniques.

3.4.3 Research Implications and Policy Recommendations

The findings of environmental and financial analysis were also reflected and explored in the consultation of water reuse experts. The results of the two-round of experts' consultation confirmed that as water scarcity intensifies, the cost of reclaimed water will play a critical role in enhancing the market appeal of these solutions (Christou et al., 2024; Fagundes and Marques, 2023). Reuse costs are influenced by various techno-economic factors, including technological efficiency and expenses associated with attaining adequate water quality and safety, as well as overcoming bureaucratic barriers. While scientific advancements have the potential to enhance technological performance and a growing number of legislative frameworks are setting standards to ensure the safe reuse of water resources (*e.g.,* ISO 16075:2020, EU Regulation 2020/741), policy intervention is essential to foster a supportive environment for the development of a water reuse market. This requires a foundation in cost-benefit evaluations that assess the broader economic and social benefits of water reuse projects (Expósito et al., 2024). Such evaluations necessitate integrated analysis at the territorial level, with a clear delineation of where costs are incurred and by whom they are borne (Hadjimichael et al., 2016).

Furthermore, experts have highlighted that the level of public awareness is expected to significantly impact the adoption of these technologies. Social acceptance remains relatively low, hindered by factors such as the perception of disgust, mistrust in public authorities, and concerns over the quality and safety of recycled water (Nkhoma et al., 2021; Ricart and Rico, 2019). This underscores the need for further research into the behavioural factors affecting water reuse adoption among stakeholders, especially farmers, and for exploring potential interventions to address these factors effectively (Smith et al., 2018).

The scenario analysis highlights that these drivers of change must work synergistically to achieve the most desirable outcomes and accelerate the adoption of non-conventional water resources. Indeed, experts identified the most desirable scenario as one that includes financial incentives, investment in technological reliability, and an increase in public awareness through effective communication strategies. Enforcing regulations on freshwater and wastewater pricing, along with promoting education and awareness campaigns, were deemed the most critical interventions for achieving this scenario (**Table 3.6**). Indeed, although wastewater pricing policies encounter several challenges associated with local institutional, economic and technical specificities (Fagundes and Marques, 2023), they can guarantee the profitability of WWTPs and stimulate market uptake of water reuse solutions.

Further, nudging strategies, education and awareness campaigns can increase levels of acceptance to promote bottom-up approaches that involve a wider range of stakeholders (**Table 3.6**) in the process of accelerating the adoption of water reuse solutions (Poch et al., 2023). These highlight the importance of participatory and innovative forms of governing non-conventional water resources that can increase trust and acceptability, for instance establishing living labs and co-designing activities, such as water-oriented living labs (Water Europe, 2023) or citizens' science initiatives for water quality monitoring (Loghmani-Khouzani et al., 2024).

Finally, in this study, the hotspots identified through environmental and financial analyses informed a foresight exercise, serving as potential drivers of change for developing future scenarios regarding the diffusion of water reuse practices in the Mediterranean region. This integration suggests a pathway for more effectively incorporating Life Cycle Thinking into policy decision-making frameworks. Although LCA has been demonstrated as a valuable tool for supporting decision-making processes (Sala et al., 2021), further case studies are required to validate its integration with policy development (García-Herrero et al., 2022a). Specifically, alternative types of Life Cycle Assessment, such as consequential or prospective LCA, may be particularly suitable for this purpose due to their forward-looking orientation (Cucurachi et al., 2022), which might enable the combination of data-driven sustainability assessments with qualitative, collective society-based explorations such as foresight (Wiebe et al., 2018). Future research should investigate this approach as it could be especially beneficial for assessing emerging technologies impacts and supporting circular economy strategies and policies (De Laurentiis et al., 2024).

3.5 Concluding Remarks

This study assessed the sustainability of water reuse initiatives, aiming to identify potential drivers of change and explore future scenarios for the adoption of non-conventional water resources in agricultural irrigation. By applying LCA and LCC to a case study in Italy, the findings suggest that innovative technologies in water reuse can reduce the demand for water resources. However, technological advancements are still needed, particularly to optimise energy consumption in large wastewater treatment plants (WWTPs), which would enhance the overall sustainability of these systems.

The study also indicates that profitability remains a significant challenge for water reuse projects, as operational costs for these technologies are generally higher than those for conventional irrigation. Even when environmental costs are monetised, climate change costs continue to outweigh the direct costs of water use. Nonetheless, in cases where the technology produces a by-product (*e.g.,* biogas in the UASB) the environmental impacts can be allocated across multiple outputs, thereby reducing the total environmental footprint. This finding highlights the potential benefits of a circular approach to resource management, where the reuse process can serve multiple functions and reduce overall environmental impact.

Cost considerations continue to play a critical role in the sustainability of water reuse initiatives, as evidenced by expert consultations that identified financial incentives and investments in technology reliability and efficiency as key components of the most desirable scenario. Additionally, a low level of public awareness poses a barrier to the widespread adoption of water reuse. This underscores the need for an effective communication strategy to highlight the benefits of water reuse while addressing perceived risks, which is essential to facilitate greater acceptance and adoption of these sustainable practices.

CRediT Authorship Contribution Statement:

VG: *Conceptualisation, Methodology, Data Curation, Formal analysis, Visualisation, Writing - Original Draft;* SA: *Formal analysis, Data Curation, Writing - Original Draft;* LGH: *Conceptualisation, Methodology, Validation, Writing - Original Draft*; RD: *Data Curation, Validation, Formal Analysis, Writing - Review & Editing*; MV: *Conceptualisation, Validation, Supervision, Resources, Writing - Review & Editing*;

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements:

The authors thank all the partners of the Fit4reuse project. A special thanks to Stevo Lavrnic from the University of Bologna and Alessia Foglia and Marco Parlapiano from Università Politecnica delle Marche, who supported data collection activities.

Ethical Approval:

The research has been conducted within *Fit4reuse - Safe and Sustainable Solutions for The Integrated Use of Non-Conventional Water Resources in The Mediterranean Agricultural Sector*, funded by the European Union's Horizon 2020 Prima programme under Grant Agreement No. 1823. The research was approved by the project coordination and the project was subject to rigorous ethical review, as per institutional requirements and in accordance with the European Union data protection law (GDPR).

Data included in this study were collected complying with European regulation on protection (GDPR). Written informed consent was obtained at the moment of the interview for the Delphi e-surveys, while oral consent was obtained for the focus groups. Respondent provided consent to participate in the study, to use of data and to publication. All participants have been fully informed that their anonymity is assured, why the research is being conducted, how their data will be utilised, and if there are any risks to their participation.

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Conclusions

Summary of Evidence

The thesis aimed to explore potential transition pathways toward sustainable food systems by analysing economic, environmental and social impacts of introducing sustainable resource management practices in farming systems and by investigating their synergies and trade-offs. The three chapters explored and tested how systemic approaches and sustainability assessment tools can support evidence-based decision-making by grounding in supply chain analysis, sustainability science and future thinking. The thesis answered to the outlined research questions investigated in the three chapters and summarised in the following paragraphs.

1. *How does academic literature conceptualise potential systemic pathways for transitioning to sustainable food systems in Europe after UN Agenda 2030?*

A thorough systematic review of academic studies reveals that current scientific agendas predominantly focus on environmental, health, and nutrition goals, often overlooking socio-economic and governance dimensions, which underscores the need for more systemic approaches to address governance and power dynamics within food systems. The analysis identified critical sources of trade-offs that impact the achievement of sustainable food systems, offering valuable entry points to promote greater policy coherence. Further, results suggest that while institutional and political barriers are commonly cited obstacles to food system sustainability, comparatively few studies explore the techno-economic and behavioural drivers that could catalyse meaningful transformation. Key barriers include the lack of a shared vision and collective coordination, exacerbated by ineffective institutional frameworks. Finally, academic studies increasingly point to system design (e.g., social structures, information flows) and feedback mechanisms (e.g., negative feedback loops) as leverage points, advocating for the exploration of solution interactions across systemic levels to advance sustainable food systems. Finally, it provides a general overview of the status of academic research on food systems narratives, dynamics, and pathways for systemic transformation in Europe after the launch of Agenda 2030.

2. *How can systemic sustainability assessment framework unveil the environmental, economic, and social performance of introducing carbon farming practices in the Mediterranean?*

A holistic sustainability assessment based on LCA, eLCC and sLCA unveiled synergies and trade-offs in introducing conservation agricultural practices (reduced tillage, cover crops and crop rotations) in Mediterranean dryland farming systems. These practices, and particularly the integration of camelina as a cash-cover crop, benefit soil conservation and biodiversity in the Mediterranean. Nonetheless, outcomes vary with local conditions, with the occurrence of possible trade-offs in terms of an increase in nitrous emissions and pesticides and fertiliser use due to additional inputs for cover crop cultivation. Socially, these practices are positively perceived as they can increase knowledge in the community but also support job creation in some countries though adoption challenges persist, including slow crop integration and variable impacts on community development. Economically, camelina market perspectives can increase profitability, even though higher costs for farmers can represent a barrier to adoption illustrating the need for possible policy interventions.

3. *How can systemic sustainability assessment identify policy actions to enhance the diffusion water reuse for agricultural irrigation in the Mediterranean?*

Combining an LCA and eLCC with a policy foresight, the analysis illustrates that water reuse initiatives for agricultural irrigation can reduce from superficial to groundwater demand in the Mediterranean area. However, technological improvements, particularly in energy efficiency for large-scale wastewater treatment plants (WWTPs), are necessary to enhance the overall sustainability of these systems. The study further highlights profitability as a central challenge, as operational costs for water reuse technologies often exceed those of conventional irrigation. Even with the monetisation of environmental costs, the costs associated with climate change continue to surpass the monetised costs of water use. Cost considerations remain critical, with expert consultations underscoring the importance of financial incentives and investment in technology reliability and efficiency as essential drivers of change for the diffusion of non-conventional water resources. Additionally, the study identifies low public awareness as a barrier to the adoption of water reuse, emphasising the need for strategic communication to enhance public acceptance by effectively conveying the benefits and managing perceived risks associated with these sustainable practices.

Navigating Sustainability Complexity: Challenges and Future Implications

The findings of this thesis should be interpreted considering several limitations arising from the inherently complex nature of sustainability assessment, which necessitates integrating economic, social, and environmental data and indicators across diverse geographical supply chains.

This study explored transition pathways towards sustainable food systems, identifying objectives, trade-offs, lock-ins, and leverage points for transformation outlined in the academic literature. However, further work is required to operationalise and contextualise this framework in local, national and global policy settings, with the aim of identifying gaps, barriers, and solutions for achieving systemic transformation across multiple governance levels.

While Life Cycle Assessment (LCA) is a standardised methodology, its application across a diverse array of products and processes remains relatively novel and entails limitations, particularly regarding comparability and methodological harmonisation (Hélias et al., 2022; Konradsen et al., 2023; Minkov et al., 2020). This is especially relevant given that several environmental labelling and certification frameworks (e.g., EPD or PEF) are grounded in LCA principles. This research employed an attributional approach to impact assessment in a static context, which may not capture specific spatial and temporal variations within production systems (Li et al., 2023). Future studies should contribute to ongoing efforts to harmonise LCA and investigate consequential or prospective forms of this methodology (Dominguez Aldama et al., 2023). Methodological challenges in terms of harmonisation and integration with Life Cycle Costing and Social Life Cycle Assessment remain substantial, as choices regarding system boundaries, scope, and selected indicators impede comparability with other studies (Costa et al., 2019). For instance, Social Life Cycle Assessment studies are highly heterogeneous; further research into social impact pathways and quantitative metrics is necessary to address methodological inconsistencies, facilitate standardisation, and enhance the representation of the social dimension within food systems (Blackstone et al., 2024).

Data quality and the data collection process remain persistent challenges in LCT. Data collection imposes a significant burden on food system stakeholders and is further complicated by challenges associated with the heterogeneity and integration of primary data, experts' estimates, and secondary sources. Additionally, limited transparency in existing databases, the absence of country-specific inventories, and uncertainties regarding data accuracy warrant consideration when interpreting this thesis's findings (Olanrewaju et al., 2024). Further, the analysis was conducted on selected case studies, indicating that context-dependent dynamics may not be universally applicable or generalisable.

Lastly, the complexity and broad scope of these tools introduce challenges for operationalisation in decision-making. Results can be complex and challenging for policymakers to interpret, potentially leading to misinterpretations and difficulties in distilling key information for stakeholders. Further research is required to determine optimal institutional arrangements for measuring and communicating sustainability impacts, as well as to identify strategies for acquiring accurate data while managing transaction costs by balancing the need for detailed information with low monitoring costs (Deconinck et al., 2023).

Detailed limitations specific to each of the three research studies undertaken are provided in the discussion sections of the respective chapters.

The Growing Need for Science-Policy Integration

Policymaking now faces complex and "wicked" sustainability challenges, underscoring a growing demand for scientific evidence to support a research-based policy agenda and to facilitate the integration of knowledge into policies at local, national, and global levels (European Commission, 2022; Lacey et al., 2018). In recent years, science-policy interfaces, such as expert panels and advisory groups (e.g., IPCC, HLPE), have proliferated to enhance this integration (Singh et al., 2021), illustrating that these two aspects can no longer be regarded in isolation within the sustainability field.

The analysis of how sustainability narratives are entailed in academic literature and connected to the Agenda 2030 illustrates the growing influence of science-policy interfaces (SPIs) on food system agendas post-2015, emphasising their crucial role in steering food systems towards global sustainability goals (Singh et al., 2021). Although scientific narratives focus mainly on environmental and health externalities, food systems governance faces complex challenges due to conflicting interests, diverse goals, and varying decision-making power, complicating efforts to establish a cohesive vision for sustainability. Creating this shared vision could enable both the repurposing of existing policy instruments, such as subsidies, and the development of new policies addressing innovation gaps and social or cognitive drivers of food consumption (Gautam et al., 2019; Mazzucato, 2018; Reisch, 2021). Furthermore, the emphasis on higher leverage points indicates an academic shift towards acknowledging the powerful role of underlying social structures in food systems and the recognition of novel and innovative forms of governance in the food system domain. While power asymmetries may limit the effectiveness of these changes, bottom-up reconfigurations, such as alternative food networks (AFNs), could drive systemic change and foster more inclusive governance in European food policy (Petruzzelli et al., 2023) as evidenced in the analysis conducted in **Chapter 1**, which shows rearrangement of power reconfigurations as frequently mentioned drivers of transformation in the current scientific literature around sustainable food systems.

This research demonstrates how sustainability assessment can comprehensively inform policymakers and industry stakeholders, supporting the development of resilient, sustainable, and equitable agricultural systems across the Mediterranean (Notarnicola et al., 2017). In **Chapter 2** the sustainability assessment framework unveiled the economic and environmental advantages of conservative agricultural practices and the use of camelina as a cash cover crop compared to alternative systems. To unlock its full potential, policies should a) support research to optimise its cultivation across the Mediterranean's diverse climates; b) facilitate its transition from field to market (Sydor et al., 2022) and c) integrate social analysis into agricultural planning, ensuring that benefits are equitably distributed within communities (Bastos Lima, 2021). Further, it outlines the possibility of extending these systemic assessments to other sustainable farming practices (e.g., organic) to enhance understanding of sustainability benefits and trade-offs, enabling policies that address challenges and enhance positive outcomes. This approach could help close policy gaps, and identify burden-shifts across the supply chain, offering multi-faceted insights for sustainable agricultural development (Deconinck et al., 2022).

Nonetheless, further integration of sustainability assessment with policy decision tools is necessary to facilitate communication of multiple environmental, economic and social impacts. In **Chapter 3**, the findings from the environmental and financial analyses of water reuse initiatives in the Mediterranean reveal potential drivers for their future diffusion in the Mediterranean and illustrate how policy decision tools, such as foresight, can be integrated with Life Cycle Thinking. By providing a comprehensive overview of sustainability impacts, this integration can inform policymakers with entry points for policy action. The study illustrates the benefits of water reuse in decreasing pressure on water resources, although challenges in reuse costs and technology efficiency in terms of emissions persist. The analysis of possible future scenarios for water reuse diffusion highlights the need for synergistic drivers—financial incentives, technological reliability, and public awareness—to optimise outcomes and accelerate the adoption of non-conventional water resources. Key interventions include enforcing freshwater and wastewater pricing policies, which, despite local challenges, could support WWTP profitability and boost market uptake of water reuse (Fagundes and Marques, 2023). Education and awareness campaigns, including participatory approaches like living labs and citizen science initiatives, are also critical for fostering trust and acceptance among stakeholders (Loghmani-Khouzani et al., 2024).

Final Remarks

This thesis highlights the necessity for a coordinated, science-informed approach to the sustainable transformation of food systems in Europe and the Mediterranean. Through a systematic scoping review, the research identifies critical sustainability objectives, trade-offs, barriers, and enablers reported by academics in pursuit of a shared vision and coherent policy following Agenda 2030. By employing a sustainability assessment framework grounded in LCT, this thesis evaluates the social, economic, and environmental impacts of implementing sustainable soil and water management practices across diverse Mediterranean contexts.

The findings indicate that research agendas continue to prioritise environmental issues, while a comprehensive investigation of sustainability necessitates a systemic approach that encompasses multiple sustainability dimensions, alongside governance and policy considerations. The thesis demonstrates that sustainable resource management can mitigate environmental impacts, enhance social sustainability, and generate economic benefits, although trade-offs may arise within and between these dimensions. For instance, the adoption of conservation agricultural practices can lead to improvements in biodiversity, soil quality, profitability, and social perception, although it may also result in increased nitrous emissions, the use of synthetic inputs, and barriers related to cost adoption. Similarly, while water reuse practices can help alleviate water scarcity, they remain energy-intensive and costly compared to conventional alternatives. In summary, this thesis provides a series of policy recommendations that are both science- and society-informed, illustrating the importance of holistic sustainability assessment methodologies in supporting evidence-based policymaking. The findings present actionable strategies to address barriers, manage trade-offs, and reinforce solutions that are essential for the systemic transformation of food systems in Europe and the Mediterranean region.

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Supplementary Materials

Supplementary Materials I - Chapter 1

Time to Transform? Exploring Sustainability Narratives for European Food Systems

Supplementary Table 1.A Description of databases and search queries.

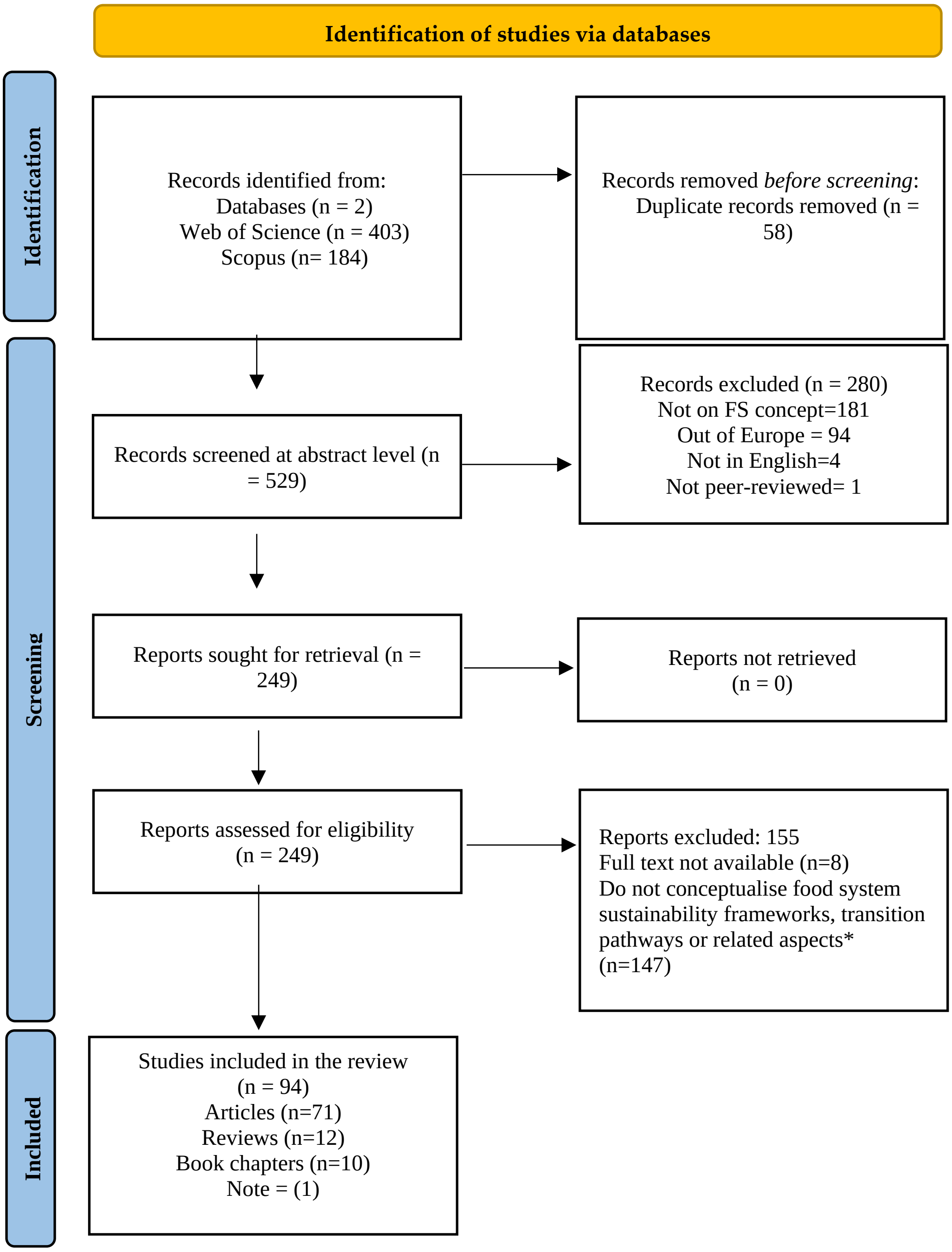
Database	Search Query	Observations
Web of Science	((((TI=((((food system AND sustainabl*) OR ("sustainable food system") OR (sustainabl* NEAR "agri-food system")) AND (concept OR framework OR conceptual* OR element OR dimension OR defini*)))) OR AK=((((food system AND sustainabl*) OR ("sustainable food system") OR (sustainabl* NEAR "agri-food system")) AND (concept OR framework OR conceptual* OR element OR dimension OR defini*)))) OR AB=((((europ* OR EU) AND (food system AND sustainabl*) OR ("sustainable food system") OR (sustainabl* NEAR "agri-food system")) AND (concept OR framework OR conceptual* OR element OR dimension OR defini*)))) OR KP=((((food system AND sustainabl*) OR ("sustainable food system") OR (sustainabl* NEAR "agri-food system")) AND (concept OR framework OR conceptual* OR element OR dimension OR defini*)))[a]	403
Scopus	TITLE-ABS-KEY ((("food system" W/5 sustainabl* OR "sustainable food system" OR "agri-food system" W/5 sustainabl*) W/10 concept OR framework OR conceptual* OR element OR dimension OR defini*)) AND (LIMIT-TO (PUBYEAR , 2023) OR (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "bk"))	184

[a]Refined by Year (2015-2023) and type of doc (article, book chapters, review), query link.

Supplementary Table 1.B Including and excluding criteria.

Information	Including	Excluding	Justification
Type of Language	English	All other languages	Academic language
Type of publications	Papers, book chapters, reviews	Full book, grey literature	Knowledge synthesis of only academic documents
Type of Databases	Web of Science, Scopus	Other	Two of the most widely used scientific databases
Year of publication	After 2015	Before 2015	Review the literature after the UN 2030 Agenda

Supplementary Figure 1.A PRISMA flow chart. Process of selection of eligible documents.



Source: *Authors own elaboration*

**Further explaination on eligibility criteria are available in Table 1.1 of Chapter 1*

Supplementary Table 1.C Bibliography of the 94 studies resulted from PRISMA methodology.

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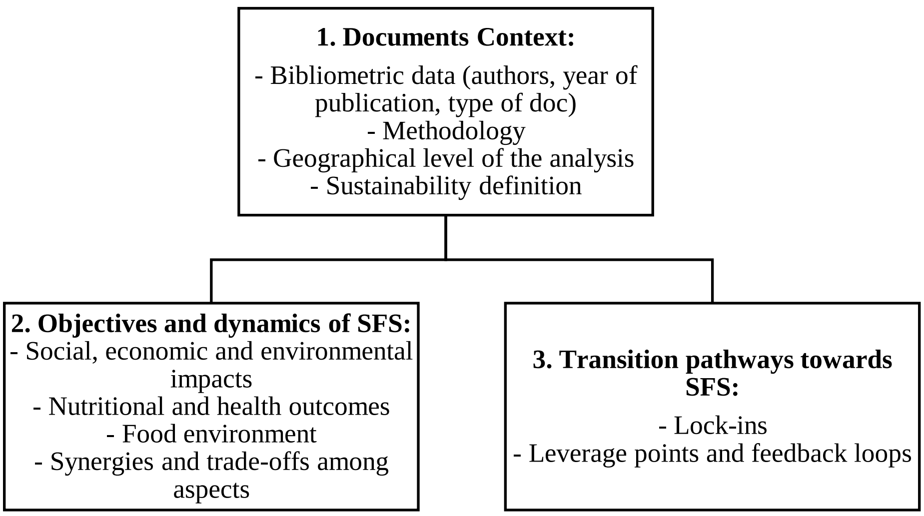
Supplementary Figure 1.B Framework for concept coding.



Source: *Authors own elaboration*

Supplementary Table 1.D. Glossary of the terms used for content analysis.

Term	Definition	Reference
Impact	A dynamic concept that presupposes a relationship of cause and effect and can be measured through the evaluation of the outcomes of actions.	(Fedorciow and Bayley, 2014)
Outcome	Outputs of the activities that relate to the production, processing, distribution, preparation, and consumption of food.	(HLPE, 2017)
Food Environment	The physical, economic, political, and socio-cultural context in which consumers engage with the food system to acquire, prepare, and consume food.	(HLPE, 2017)
Trade-off	A trade-off is a situation where an improvement in the status of one aspect of the environment or of human well-being is necessarily associated with a decline in or loss of a different aspect.	(IPBES, 2018)
Synergy	The interaction or cooperation of two aspects or agents produce a combined effect greater than the sum of their separate effects.	(IPBES, 2018)
Feedback Loops	A feedback loop is a closed chain of causal connections from a stock, through a set of decisions, rules, physical laws, or actions that are dependent on the level of the stock, and back again through a flow to change the stock.	(Meadows, 1999)
Leverage Point	Places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything.	(Meadows, 1999)
Lock-in	Self-reinforcing mechanisms that reproduce the status quo and impede change.	(Geels, 2019)

Supplementary Table 1.E Examples of data analysis for sustainability categories.

Collection of individual text lines	Extraction of keywords	Classification in clusters	Association to SDG target
'Incorporating the local context by extending GHGE as a global indicator with locally relevant parameters such as land and water use, eutrophication of waterways, presence of heavy metals or pesticides, and biodiversity losses would add valuable information to better assess co-benefits and trade- offs at local and national levels and develop national food- based dietary guidelines (FBDGs) for sustainable diets (Biesbroek et al., 2023)'	*GHGs emissions; biodiversity; land use; water use; eutrophication; heavy metals and pesticides;*	Climate Change; Natural Resources Use; Natural Resources Quality; Fertilisers, Pesticides and Antimicrobials Use; Biodiversity State	Climate Change: **2.4, 13.1, 13.2, 13.3, 13.a, 13.b, 7.2, 7.3**; Natural Resources Use; **14.1, 15.2, 6.4, 6.5, 12.2, 8.4, 2.4, 14.4;** Natural Resources Quality: **15.3, 6.3, 2.4;** Fertilisers, Pesticides and Antimicrobials Use: **12.4, 3.9;** Biodiversity State: **15.5, 15.4, 15.9, 15.a**
'The concept of community food security focuses principally on the problem of ensuring adequate and appropriate food access for urban communities (rather than individuals)—either as an endpoint in and of itself, or as a means of community empowerment, which is perceived as an essential step in community development (Eakin et al., 2016)'	*Food security; community empowerment; community development*	Food security; Territorial/community engagement	Food security; **2.1, 2.2, 2.3**; Territorial/community engagement: **11.a**
'AFNs have also been considered instrumental to provide fairer returns for producers, develop high quality products, minimise environmental impact of food production through organics and low chemical input agricultural practices, and embed territorially food production and consumption by reconnecting actors with specific territories (Cerrada-Serra et al., 2018)'	*Fair returns; high quality products; organics; low chemical inputs; territorial reconnection*	Income for food workers; Fertilisers, Pesticides and Anti-Microbial Use; Territorial/community engagement	Income for food workers; **2.3;** Fertilisers, Pesticides and Anti-Microbial Use: **12.4, 3.9;** Territorial/community engagement: **11.a**

Supplementary Table 1.F Examples of data analysis for lock-ins and leverage points.

Collection of individual text lines	Classification in clusters	Source
Primary producers and manufacturers are put under commercial pressure to reduce prices by a highly concentrated retail sector, which is expanding aggressively. This results in lower, sometimes even unfair, supplier prices, enhancing the development and consolidation of large, powerful farm corporations with mono-culture economies of scale. (Paloviita et al., 2017)	Lock-in: techno-economic System failures: structural, interaction/network failure	Geels (2019); Woolthuis et al. (2005)
EU and national policies send conflicting objectives to promote health and to support sustainable development objectives (De Schutter et al., 2020)	Lock-in: institutional-political System failures: transformational, policy coordination failure	Geels (2019); Weber and Rohracher (2012)
Monitoring and accountability mechanisms for food actions to undermine corporations 'social licenses and pledging good environmental behaviour (Friel, (2020))	Leverage Point: Negative feedback loops (*Strengthening negative feedback controls to improve system's self-correcting abilities (e.g., monitoring systems, taxes*)	Meadows (1999)
Shift from monocentric, hierarchical, and well-in-framework to govern the EU food system, which they attributed to the institutionalised forms of government towards less formalised governance frameworks in which state authority considers mutual interdependencies with other stakeholders (Moragues-Faus et al., 2017)	Leverage Point: Self-organisation (*The power to add, change, evolve, or self-organise system structure changing physical structures*	Meadows (1999)

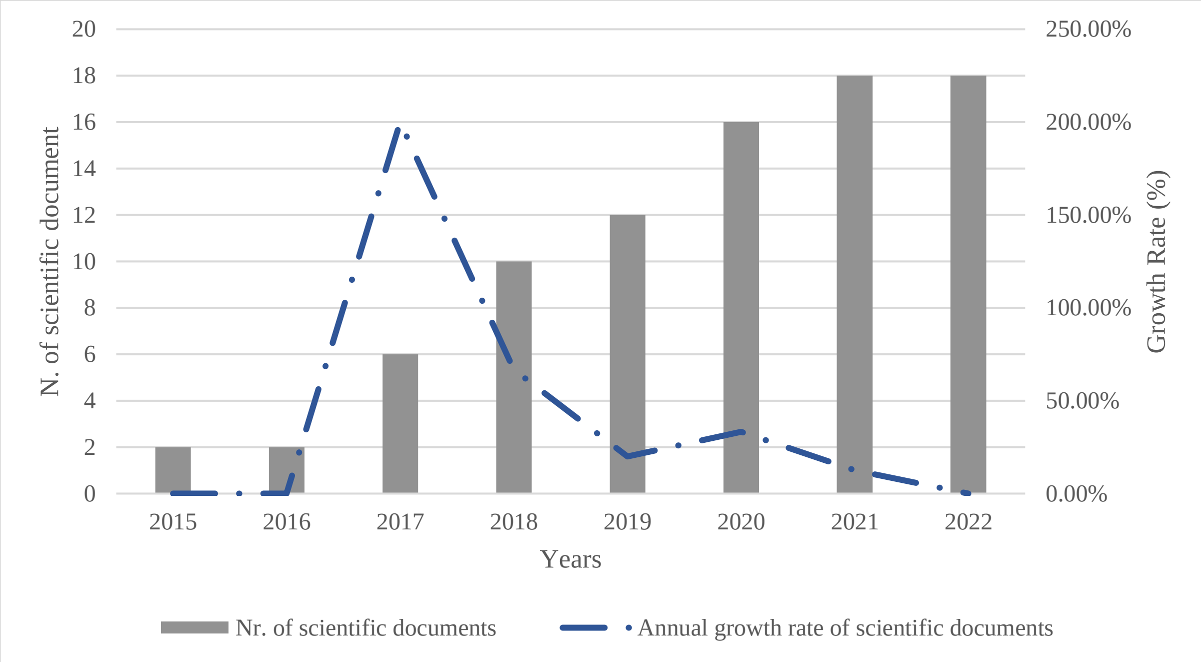
Supplementary Table 1.G Description of failures based on (Klein Woolthuis et al., 2005; Weber and Rohracher, 2012).

	Type of failure	Mechanism
Market Failures	Externalisation Costs	The possibility to externalise costs leads to innovations that can damage the environment or other social agents.
Structural System Failures (Klein Woolthuis et al., 2005)	Infrastructural Failure	Lack or deficits in the existing physical and knowledge infrastructures
	Institutional Failure	Absence, excess, or shortcomings of formal (regulations, and standards) or informal institutions (social norms).
	Capabilities Failure	Absence of the necessary capabilities to adapt to new and changing circumstances and opportunities.
	Network Failures	Closely tied networks, lack of weak ties to third actors and dependence on dominant partner
Transformational System Failures (Weber and Rohracher, 2012)	Directionality Failure	Lack of shared vision and of collective coordination of agents in shaping systemic change
	Policy coordination Failure	Lack of multi-level policy coordination across different systemic levels
	Demand articulation Failure	Deficit in anticipating and learning about food actors needs
	Reflexivity failure	Insufficient ability of the system to monitor, anticipate and involve actors in processes of self-governance

Supplementary Table 1.H Description of Leverage Points for systemic interventions from the least to the most effective based on (Meadows, 1999).

Order of effectiveness	Leverage Points	Description
12	Constants, parameters, numbers (such as subsidies, taxes, standards)	Establishing limits on parameters to regulate the system. This does not alter the behaviour of stagnant systems.
11	The sizes of buffers and other stabilising stocks, relative to their flows.	Adjusting the buffer size to stabilise stocks within the system, (*e.g.*, minimum breeding population for an endangered species).
10	The structure of material stocks and flows (such as transport networks, population age structures)	The configuration of the system, including its structure, stocks, and flows. It has a low leverage impact because it is challenging to modify.
9	The lengths of delays, relative to the rate of system change	The time delay between intervention and its effectiveness.
8	The strength of negative feedback loops, relative to the impacts they are trying to correct against	Enhancing negative feedback controls, like monitoring systems and internalising externalities through taxes, improves the system's self-correcting capabilities.
7	The gain around driving positive feedback loops	Implementing interventions to diminish self-reinforcing mechanisms (*e.g.,* progressive income tax) reduces their self-multiplying impact.
6	The structure of information flows (who does and does not have access to what kinds of information)	Introducing or restoring information can create new feedback loops in areas where information is lacking, serving as a potent intervention because missing information is a common cause of system malfunction.
5	The rules of the system (such as incentives, punishments, constraints)	Modifying the rules of the system, including laws, punishments, incentives, social norms, and informal agreements.
4	The power to add, change, evolve, or self-organise system structure	Self-organisation involves altering any aspect of the system lower on this list, such as physical structures or adding new loops.
3	The goals of the system	Changing the goal of the system necessitates adjustments in everything on the list—self-organising behaviour, feedback loops, physical stocks, and information flows—to align with the new objective.
2	The mindset or paradigm out of which the system—its goals, structure, rules, delays, parameters—arises	Altering the shared societal ideas, the paradigm, and the deepest beliefs about how the world works.
1	The power to transcend paradigms	Recognising that no paradigm is inherently true.

Supplementary Figure 1.C Scientific production trend after 2015.



*Year 2023 was excluded due to possible delays in the update of scientific documents in databases as the searches run in January 2024
Source: *Authors own elaboration*

Supplementary Table 1.I Overview of the sustainability definitions provided in the scientific documents.

Concept	Definition	Source	Provided by
Food Security ***(n=7)***	"Food security exists when all people, at all times, have **physical** and **economic** access to **sufficient**, **safe** and **nutritious** food that meets their **dietary needs** and **food preferences** for an active and healthy life."	World Food Summit, 1996	Cerrada-Serra et al. (2018); Eakin et al. (2016); Moragues-Faus et al. (2017); Verger et al. (2018); Adamczak-Retecka and Śniadach (2021) ; Olssonn (2018) ; Byaruhanga et al. (2023)
	"Food security is defined here in terms of a sustainable food system, where the core goal is to feed **everyone sustainably, equitably and healthily**, which addresses needs for **availability**, **affordability** and **accessibility**, is **diverse**, **ecologically sound** and **resilient**, and which builds the capabilities and skills necessary for **future generations**."	Sustainable Development Commission (2009)	Paloviita et al. (2017)
Sustainable Food Security ***(n=1)***	"The long-term capacity of the food system to provide an adequate quantity of nutritious food [and] its ability to respond to the environmental and socio-economic challenges that threaten its resilience and to minimise its impacts on human and environmental health"	Sonnino et al. (2014)	Byaruhanga et al. (2023)
Sustainable Diets ***(n=7)***	"Sustainable diets are those diets with l**ow environmental impacts** which contribute to f**ood and nutrition security** and to **healthy life** for present and **future generation**s. Sustainable diets are **protective and respectful** of **biodiversity** and **ecosystems**, **culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy**, while optimising natural and human resources."	FAO (2012)	Gjerris et al. (2015); Boylan et al. (2020); Nicholls and Drewnowski (2021); Mazac, et al. (2021); Lang and Mason (2017); Bach-Faig et al. (2022); Poppe (2023)
Nutritional Sustainability ***(n=1)***	"Nutritional sustainability is the ability of a food system to provide **sufficient energy** and the amounts of **essential nutrients** required to maintain **good health** of the population without compromising the ability of **future generations** to meet their nutritional needs."	Swanson et al. (2013)	Smetana et al. (2019)
Food Systems ***(n=8)***	"Food systems as including all **elements** and **activities** related to the **production, processing, distribution, preparation and consumption of food**, the **market** and **institutional networks** for their **governance**, and the **socio-economic and environmental outcomes** of these activities."	HLPE (2017)	Brower et al. (2020); Kennedy et al. (2020); Nicholls and Drewnowski (2021); Fanzo et al. (2020)
	"Food systems consists of all the **inputs** (environment, people, processes, infrastructures, institutions, etc.), **activities** and **actors** that relate to the **production, processing, distribution, preparation and**	FAO (2014)	Fanzo (2019)

Concept	Definition	Source	Provided by
	consumption of food, and the **outcomes** of these activities, namely **nutrition**, and **health, economic, social and environmental** outcomes"		
	"Food system as a coupled **social-ecological system**, in which efforts to achieve **food security** both influence and are influenced by **environmental outcomes** and broader aspects of **social welfare** and **livelihood security**."	Ericksen (2008)	Eakin et al. (2016); Verger et al. (2018)
	"Food systems embrace the entire **range of actors** and their interlinked value adding activities involved in the **production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products**, that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal, and physical environments, in which they are embedded"	FAO (2018)	von Braun et al. (2023)
Sustainable Food Systems ***(n=9)***	"A sustainable food system (SFS) is a food system that delivers **food security and nutrition for all** in such a way that the economic, social and environmental bases to generate food security and nutrition for **future generations** are not compromised. This means that: – It is **profitable** throughout (economic sustainability); – It has **broad-based benefits for society** (social sustainability); and – It has a **positive or neutral impact on the natural environment** (environmental sustainability)"	FAO (2018)	De Bernardi and Azucar (2020); von Braun et al. (2023)
	"Sustainable food system as one that **achieves and maintains food security** under uncertain and dynamic **social-ecological conditions**, through **respecting and supporting the context-specific cultural values** and decision-processes that give food social meaning, and the integrity of the social-ecological processes necessary for food provisioning today and **for future generation**s."		Eakin et al. (2016)
	"Sustainable food regimes are cross-cutting concept referring to food system that ensure **food security health and environmental protection."**	EEA (2017)	Gonzalez and Lorenzini (2021)
	"Food systems that ensure **food security** and **nutrition** for all, without compromising the **socioeconomic**, **environmental**, and **social bases** for current and **future generations**."	HLPE, (2017)	Nicholls and Drewnowski (2021); Kennedy et al. (2020); Fanzo et al. (2020)
	"A sustainable food system enables a **sustainable** and **healthy diet** for all, while taking into account **environmental, social and economic dimensions**."	Caron et al. (2018); Rockström et al. (2020)	Kugelberg et al. (2021)
	"A sustainable food system is a system that continuously balances between frozen states and chaos, hence does not lose track and thus does NOT **compromise future generations** regarding the outcomes of food systems. These outcomes are **access**, **availability**, and **affordability** of **safe and nutritious** food for **health** and **well-being**, **net-zero environmental and climatic impact**, and respected **socio-economic values** such as **employment** or **cultural diversity**. Each development goal for an SFS is characterised by both a lower and an upper limit."		de Vries et al. (2022)
Sustainable Bioeconomy Systems ***(n=1)***	"**Complex Adaptive Systems** dealing with **food** and other b**io-based products**, showing helix-like moves in the sustainability zone. "		de Vries et al. (2021)
Food Governance ***(n=2)***	"The formal and informal interactions across scales between public and/or private entities ultimately aiming at the realisation of food **availability, food access, and food utilisation, and their stability over time**."	Candel (2014)	Dìaz-Mendez and Lonzano-Cabedo (2019)
Local Food Systems ***(n=1)***	"Local food system is a system in which foods **are produced, processed and retailed within a defined geographical area** (within a 20 to 100 km radius approximately)."	Kneafsey et al. (2013)	Enthoven and Van den Broeck (2021)
Alternative Food Networks ***(n=1)***	"The literature defines Alternative Food Networks as the emerging **networks of producers, consumers and other actors** who share common objectives regarding greater **environmental sustainability**, as well as **social** and **economic equity** in the food chain."	Renting et al. (2012); Whatmore et al. (2003)	Gonzalez De Molina and Lopez-Garcia (2021)
Food Justice ***(n=1)***	"A food justice approach applies a **social justice** lens to the food system, emphasising how intersecting axes of **oppression** and **privilege** shape the experiences of differently positioned actors and groups."	Holt Giménez and Wang (2011); Sbicca (2018)	Maughan et al. (2020)
Food Democracy ***(n=1)***	"Food democracy to highlight the great struggle over the centuries, in all cultures, to achieve the **right** of all citizens to have access to a **decent, affordable, health-enhancing diet,** grown in conditions in which they can have confidence."	Lang (2005)	Baldy and Kruse, 2019
Food Sovereignty ***(n=2)***	"The right of the peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems."	La Via Campesina (2007)	Rahman et al., 2021; Byaruhanga et al., 2023

Supplementary Table 1.J. Description of sustainability objectives and associated concepts based on keywords clusters.

Sustainability Objectives		Description/definition	Associated keywords
Mitigate and Adapt	Climate Change	SFS should contribute to make the impacts of climate change less severe by preventing or reducing the emission of greenhouse gases (GHG) into the atmosphere (mitigation) and to take appropriate action to prevent or minimise the damage they can cause (adaptation).	*Reduce transport; energy use; climate action; food miles; plant-based diets; planetary boundaries; extreme events; natural disasters; livestock production decrease; fossil fuel; climate neutral; energy-water-carbon efficiency; plant-based diets; carbon footprint; carbon sequestration; GHGs emissions; carbon positive or neutral; low fossil-based inputs; short distances between consumption and production; climate-smart; offset carbon emissions; forest mass conservation*
Protect and restore	Natural Resources Quality (air, water, soil)	SFS should protect and restore natural resources by reducing air and water pollution and soil degradation.	*Environmental degradation; air pollution; land degradation; soil regeneration; planetary boundaries; soil health; soil fertility; eutrophication; heavy metals; water conservation; clean water; soil conservation; environmental integrity; soil functionality*
	Natural Resources Use (water, land)	SFS should protect and restore natural resources by reducing land and water use.	*Ecological footprint; avoid deforestation; freshwater use; planetary boundaries; freshwater withdrawals; land conversion; water resources; planetary boundaries; livestock production decrease; land use change; water conservation; soil conservation; water management; overuse of water; environmental integrity; land footprint*
	Biodiversity State	SFS should protect and restore biodiversity state by increasing genetic variability, species diversity, and ecosystem diversity.	*Agroecology; planetary boundaries; overexploitation of fish stocks; extinction rate risk; fish stocks; species extinction; erosion of genetic diversity; fish stock depletion; genetic diversity; threatened landraces; agrobiodiversity; environmental integrity*
	Ecosystems Extent and Condition	SFS should protect and restore ecosystem extent (coverage), condition (structure, composition, functioning) and ecosystem services.	*Agroecology; planetary boundaries; environmental degradation; extinction rate risk; fish stocks; fish stock depletion; ecosystems; forest mass conservation; ecosystem services; ecological degradation; environmental integrity.*
	Agricultural Landscape	SFS should protect and restore landscape appearance (including environmental features, land use types and man-made objects), functions (environmental services) and values (recreational and cultural).	*Landscape diversity; farming landscape, landscape preservation; ecological and scenic value*
Reduce	Pesticide, Fertilisers and Antimicrobial Use	SFS should reduce the use of pesticides, fertilisers and antimicrobials use in the food supply chain	*Organic production; agrochemicals use; chemical pollution and antibiotics; avoid nutrient imbalances; input reduction; nutrient loss; limit nutrient input; nutrient recycling; pests regulation; agrochemicals use; chemical pollution and antibiotics; avoid nutrient imbalances*
	Food Losses and Waste	SFS should reduce food losses and waste occurring in the food supply chain	*Food losses; food waste*
Improve	Nutrients Circularity	SFS should improve nutrient circularity in the food supply chain	*Circular economy; nutrient recycling reuse; reuse by-products; recycling; optimising nutrient cycle; closure of biogeochemical cycles at a landscape scale; close the nutrient cycle; circular and resource-efficient*
	Waste Management	SFS should improve waste management in the food supply chain	*Reduce waste; circular waste management, reduce packaging*
Ensure fair and just	Income/Salary for food workers	SFS should ensure a fair and just salary to food workers	*Income for smallholders and producers; fair return; market price stability; viable (not relying on subsidies); fair prices to producers; decent income for farmers and farm workers; fair and affordable; fair return; economically fair; support livelihood; fair distribution along the FS chain; farmer livelihoods; smallholders' livelihood; fair and profitable market; profitable, secure, and just livelihood; decent agricultural living; price stability; profit; profitable; commercially viable; decent*

Sustainability Objectives		Description/definition	Associated keywords
			livelihood; balance profitability and livelihoods; ensure long-term farmers' income; reduce economic uncertainties; resilient farm-based livelihoods; farms and rural income
	Distribution of added value	SFS should ensure a fair and just distribution of added value by building balanced power relationships	*Equal market power in SC, addressing power relationships; balanced power relationship; fiscal viability; rebalance the transnational economic relationship and power embedded in global FS; fair prices; concentrated power in retailers, distributing risks; bargaining power on price*
	Trade	SFS should ensure a fair and just distribution of added value by building balanced power relationships	*Fair trade products; fair trade rules and powers*
Boost	Local Economy	SFS should thrive local economy, hamper marginalisation of local actors and contribute to local development	*Create local opportunities; thriving local economy; local development; support small producers; reduce vulnerabilities of farmers and SMEs; prioritise local and national economies; value chain employment; territorial development; fair remuneration; regional and diversified economy; foster local food production; Hamper marginalisation of small producers and rural populations; strong link between production and consumption; valorisation of small farms; strong and diverse local economy; local green economies; local food production; local circulations of economic value*
Generate	Employment	SFS should generate employment, create jobs and contribute to economic growth	*new jobs; employment generation; economic diversification; enhance trade; economic growth; competitive; create jobs*
Guarantee	Equality	SFS should guarantee that men, women, youth and vulnerable and marginalised persons should be treated in the same way	*Equal market power; market access; land access; equal access to resources; urban equality; economic distribution; gender pay gap; inequalities; equal access to healthy food; equal distribution among countries; access to resources; fair access to nutritious food; gender equality; equal trade relationship; creates socially inclusive distributive network; equal and fair practices; access to land; gender balance; gender equality*
	Equity	SFS should guarantee equitable outcome considering differences which are marginalising certain parts of the population and adopting different approaches considering aspects of marginalisation (e.g., gender, income and poverty, life stage, youth, geography, ethnicity and disability)	*Vulnerable groups; social justice; shared governance between marginal actors; inclusive and socially equal; food justice; equity of distributions; inclusive; inclusion of marginalised; future generations; participation of women; economically equitable in access to means of production and market; environmental justice; gender equity; ecological soundness*
	Cultural and social acceptability	SFS should guarantee cultural and socially accepted diets recognising the non-nutrient-based values of eating and feeding, as well human relations which are sensitive to distinct and diverse social and ecological values (Hammelman and Hayes-Conroy, 2015)	*Preserve cultural identity; indigenous rights and knowledge; culturally relevant; cultural inclusion; cultural recognition; cultural appropriate; cultural factors; cultural values and traditions; nature and cultural heritage preservation; traditional; food heritage; cultural heritage; respect socio-cultural concept; cultural diversity; cultural identity; promote cultural survival; respect food culture.*
Boost	Rural Development	SFS should promote the improvement of the quality of life and economic well-being of people living in the rural area.	*Rural poverty; rural communities; decent living for marginalised agricultural producers; empower peasant and family farming; economic viability for rural areas; rural development; rural communities; rural poors; rural development; hamper marginalisation of small producers and rural populations; promote well-being and rural vitality*
Protect	Worker rights and conditions	SFS should protect food worker rights and conditions	*health and safety, child labour; health workers, fair conditions for FS actors; respect working conditions, fair contracts and business networks, respect workers and peasant rights, fairness for all workers*

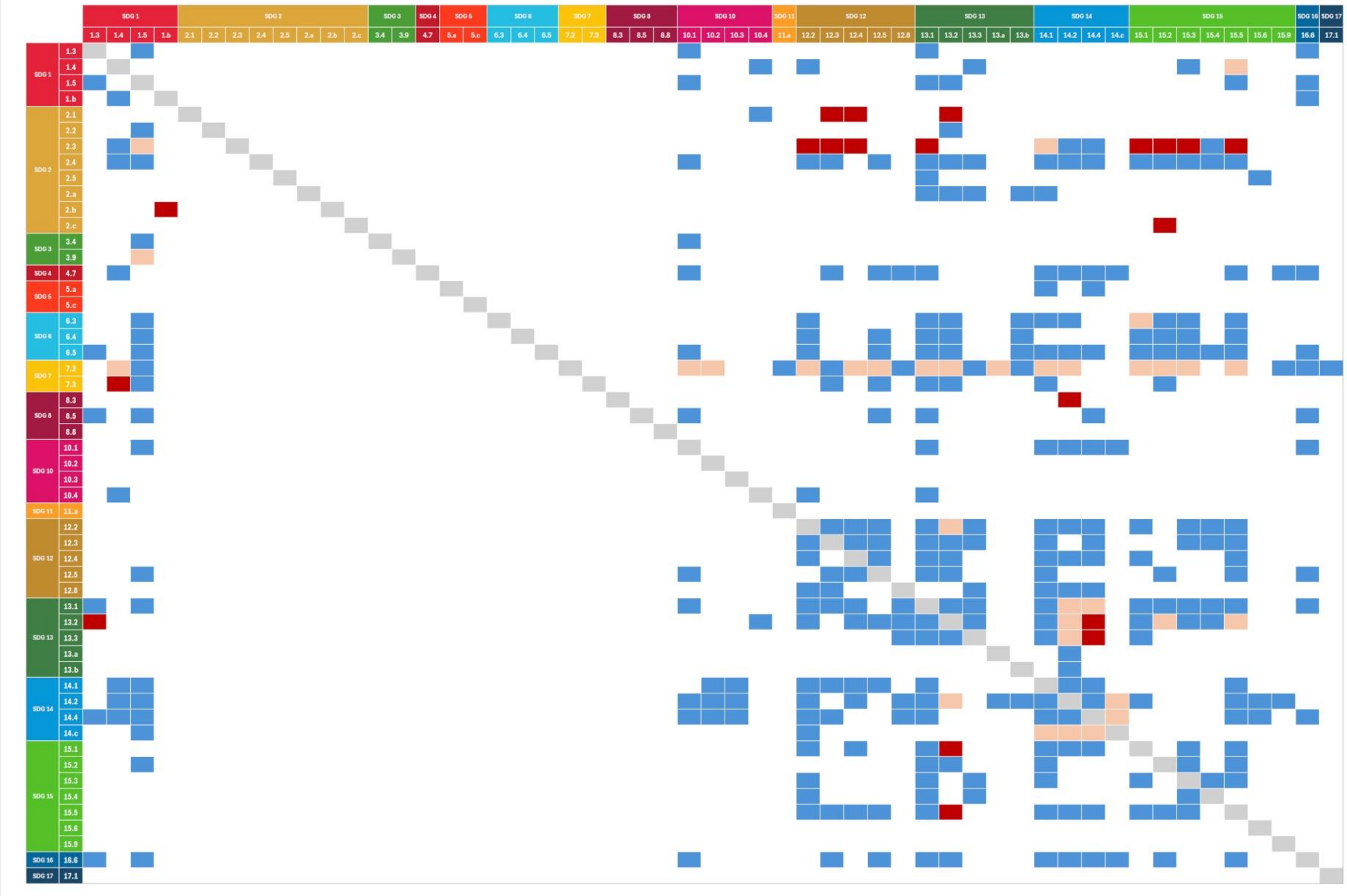
Sustainability Objectives		Description/definition	Associated keywords
Ensure	Social well-being	SFS should ensure people's capacity to be and do well in life, and achieve a state of health, happiness, or prosperity	*Well-being; welfare; social capital, social well-being*
	Animal welfare	SFS should ensure animal physical and mental well-being	*Ethical treatment of animals; animals health*
Strengthen	Community engagement	SFS should strengthen the engagement of local food communities with their territory	*Stronger communities and societies; support community; preserve local knowledge; resilient food communities; spatial inclusion; territorial heritage; community building; empower peasant and family farming; collective identity; indigenous rights; territorial development; preserve culture and knowledge; unite people with nature and the products of their labour; community pride and animation; sense of community; connection with traditional cultures and local identity; social innovation and empowerment of community*
	Connectedness of consumers and producers	SFS should strengthen the connection between consumers and producers	*Proximity of production and consumption; shorten FSC; reconnect producers and consumers; strong link between production and consumption; reduce consumer-producer distances; connection with farmers*
Provide and Promote	Food Security	SFS should provide and promote physical and economic access to sufficient, safe and nutritious food that meets dietary needs and food preferences (World Food Summit, 1996)	*Affordable; accessible; economic access to food; equal access to food*
	Food safety	SFS should provide and promote conditions and practices that preserve the quality of food to prevent contamination and food-borne illnesses	*Traceability*
	Food quality	SFS should provide and promote food product absent of defects, fraud and adulteration that satisfy consumers expected organoleptic and nutritional characteristics or food that have added value justified by the form of production (*e.g.*, organic) or territory origin (FAO, 2014)	*Fresh food; nutritious food; local; seasonal; healthy food; nutritional quality; food quality; locally grown*
	Healthy diets	Should provide health-promoting and disease-preventing diets by providing adequacy without excess, of nutrients and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (UN Food Systems Summit, 2021)	*Sufficient quality and quantity; eating habits; reduce overweight and obesity; balanced nutrient intake*
Guarantee	Food Democracy	SFS should guarantee that all the members of an agro-food system have equal and effective opportunities for participation in shaping that system, as well as knowledge about the relevant alternative ways of designing and operating the system (24th FAO Regional Conference for Europe, 2004)	*Shared governance; food policy accessible to all citizens; food citizenship; enable agency among actors to make decisions about food; political representation; reflexive governance; right to food; food citizenship; civic engagement; participation in decision-making; the democratic ability to decide what is produced; consumer empowerment; engaged governance.,*
	Food Literacy and Transparency	SFS should guarantee access to information on the impact of food choices on health, the environment, and economy	*Food literacy; supportive food environment; food fraud; trust among actors, communicating knowledge*
	Food Sovereignty	SFS should guarantee the right of the peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems	*Food sovereignty*
Increase	Resilience	SFS should increase its capacity over time to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances (Tendall et al., 2015)	*Not vulnerable to natural disasters; food scares and food prices hikes; resilience on external inputs; resilient to shocks (economic, climate disasters); Resilience to long-term (decrease of productivity due to climate change) and short-term (droughts and floods, food supply disruption, price peaks, resilient to exogenous shocks, stabilise productivity); resilient food systems*

Supplementary Table 1.K Qualitative association of sustainability objectives with SDG goals and targets

Dimension	Sub-dimension	Sustainability Objective		SDG Goals	SDG Targets
Environmental	Management of Natural Resources	Mitigate and Adapt to	Climate Change	2, 7, 13	2.4, 7.2, 7.3, 13.1, 13.2, 13.3, 13.a, 13.b,
		Protect and restore	Natural Resources Quality (air, water, soil)	6, 14, 15	2.4, 6.3, 15.3
			Natural Resources Use (water, land)	2, 6, 8, 12, 14, 15	2.4, 6.4, 6.5, 8.4, 12.2, 14.1, 14.4, 15.2
			Biodiversity State	14, 15	15.4, 15.5, 15.9, 15.a
			Ecosystems Extent and Condition	2, 6, 14, 15	2.4, 6.6, 14.2, 15.1, 15.4, 15.9
			Agricultural Landscape Diversity	2	2.5
	Food Supply Chain Optimisation	Reduce	Pesticide, Fertilisers and Antimicrobial Use	2, 3, 12	2.4, 3.9, 12.4
			Food Losses and Waste	12	12.3
		Improve	Nutrients Circularity	12	12.2, 12.5
			Waste Management	12	12.3, 12.5
Economic	Distribution	Ensure fair and just	Income/Salary for food workers	2, 10	2.3, 10.1
			Power relationship	2, 9, 15	2.5, 9.3, 15.6
	Development		Trade	2, 17	2.b, 2.c, 17.10
		Boost	Local Economy	8	8.3
		Generate	Employment	8	8.3, 8.5
Social	Welfare and well-being	Guarantee	Equality	1, 2, 5, 10, 15	1.4, 2.3, 2.5, 5.a, 10.3, 15.6
			Equity	1, 2, 8, 10	1.b, 2.3, 8.5, 10.2
			Cultural and social acceptability	-	-
		Boost	Rural Development	2, 11	2.a, 11.a
		Protect	Worker rights and conditions	8	8.8
		Ensure	Social well-being	1, 10	1.3, 1.4, 10.4
			Animal welfare	-	-
	Connectedness	Increase	Territorial/Community engagement	11	11.a
			Connectedness of consumers and producers	11, 12	11.a, 12.8
Health and Nutrition	Food environment	Provide and Promote	Food Security	2	2.1, 2.2, 2.3
			Food safety	2	2.1, 2.2
			Food quality	2, 3	2.1, 2.2, 3.4
			Healthy diets	2, 3	2.2, 3.4
Cross-cutting	Governance	Guarantee	Food Democracy	4, 5, 12, 16	4.7, 5.c, 12.8, 16.6
			Transparency	16	16.6
			Food Sovereignty	2, 12	2.1, 2.3, 2.4, 2.5, 12.3
	Resilience	Increase	Resilience	1, 2, 9	1.5, 2.4, 9.1

Source: *Authors own elaboration*

Supplementary Figure 1.D Interlinkages among SDG targets associated to sustainability objectives. Red: trade-offs; Blu: synergies; Light red: mixed (linkages reported as trade-offs or synergies in different publications*)*. Based on JRC SDG Interlinkages Tool.



Source: *Authors own elaboration*

Supplementary Materials II - Chapter 2

Unveiling Trade-Offs in Introducing Carbon Farming Practices in the Mediterranean

Supplementary Table 2.A Data collection protocol distributed to case studies for LCA and LCC.

SUMMARY OF CROP SYSTEM			
Cereal (crop) name:		*Area (in ha):*	
Harvest year:		Soil:	
Crop rotation		*Timeframe (dates from sowing to harvest)*	
Previous crop:		Specific subsidies (€/ha) :	
Field name:		Specific subsidies (€/ha) :	
Target yield (t/ha):		Obtained yield (t/ha):	
Life cycle stages	ONE SECTION PER CROP	Unit (this might change according with your data availability, such as litre instead of kg)	
Brief description of the crop, such as size, type of irrigation, seasonality, etc.	*E.g., ITALY: Rainfed winter cereal (wheat/barley) - summer cereal (corn/sorghum) based systems in both areas*		
Land preparation and sowing (inputs)	Purchasing or land rental	€/year/ha	
	Material description 1: For example: pipe for irrigation 1, type, material, origin, cost, brand or model, commercial name	€/unit and num/ha	
	Material description 2	€/unit and num/ha	
	Material description 3…	€/unit and num/ha	
	Machinery involved: excavator, tractor, etc. Relevant information here shall include years of the machinery, model, horsepower, km and type of fuel utilised, as well as the specification of the use of that machinery: land preparation, sowing, any other in this early cropping stage	description of traits	
		L/km and number of km/ha	
	Number and cost of seeds	€/kg of seeds/ha/yr	
	Personnel: Workforce	€/ha or €/production cycle or €/year	
		hours/person per day, week, or production cycle	
		gender	
		type of tasks description	
		origin-local or migrant	
	Other	units you might already use (add method and ref.)	
Production and harvesting (inputs)	Energy consumption and precise type of energy source (fossil fuel, biofuel, renewable source, etc)	kwh/yr/ha/ and € /yr/ha/	
	Reason or area where that energy is used for	description	
	Water consumption (amount and source)	m3/ha and €/yr or €/ha	
	If data for water consumption is not available indicate if irrigation is used or not. If it is used, describe technical characteristics of the system (source, type of dripper or splasher, pumping equipment and capacity)	description and data	
	Personnel: Workforce	€/ha or €/production cycle or €/year	
		hours/person per day, week, or production cycle	
		gender	
		type of tasks description	
		origin-local or migrant	
	Machinery involved- technical info: tractor, etc. INCLUDE IF RENTAL OF MACHINERIES IS NEEDED. Relevant information here shall include years of the machinery, model, horsepower, km and type of fuel utilised, as well as the	L/km or L/ ha and €/km or €/ha	

	specification of the use of that machinery: maintenance of crop, irrigation, pest control products application, or any other in this stage		
	Fuel consumption -in the case of additional engines or pumps (specify type, source and place of origin)	L/ ha and €/km or €/ha	
	OPEX	€/yr	
	Pesticides (Precise trade name, quantity of each product and unit price, as well as origin and packaging type)	€/unit and num of units/ha (units as in kg, L)	
	Fertilisers (N, P, K input + liming materials, specify if providing quantity from the trade product or final active ingredient, if possible, provide formula and origin)	€/unit and num of units/ha (units as in kg, L)	
	Herbicides (Precise trade name, quantity of each product and unit price, as well as origin and packaging type)	€/unit and num of units/ha (units as in kg, L)	
	Rate of nutritional removal or recovery	kg/ha or kg/m3	
	Rate of pesticide removal	kg/ha or kg/m3	
	Erosion rate/soil coverage (such as: https://sciencing.com/calculate-erosion-rate-6118473.html)	kg/yr/ha	
	Transport of crop to farm gate if apply (type of vehicle) - and cost correspond to the distance between plot and farm + transport of crop to collecting agency/storage organisation (country elevator) if the culture is not developed in the region, transportation to collecting agency/storage organisation or processor can be (very) long.	km/ha and L of fuel/yr or ha and €	
	Other	units you might already use (add method and ref.)	
Harvest (inputs)	Personnel: Workforce	€/ha or €/production cycle or €/year	
		hours/person per day, week, or production cycle	
		gender	
		type of tasks description	
		origin-local or migrant	
Outputs	Crop yield and market price	€/kg/yr and kg/ha/yr and € (cost or revenue)	
	Seeds sold	€/kg/yr and kg/ha/yr and € (cost or revenue)	
	Biomass production and how it is managed - biofuel? Waste?	€/kg/yr and kg/ha/yr and € (cost or revenue)	
		description and data	
	Bioproducts: type, amount	€/kg/yr and kg/ha/yr and € (cost or revenue)	
		description and data	
	Waste	€/kg/yr and kg/ha/yr and € (cost or revenue)	
	Disposal system for waste (distance, responsible party, etc)	description and data	
	Losses: water filtration, seeds or pesticides (due to atmospheric or other natural phenomena) for example, indicator of water quality (nitrate, phosphorus, residue of pesticide)	€/kg/yr and kg/ha/yr and € (cost or revenue)	
		description and data	
	opportunity/valorisation of the product and quantity for each market	description and data	
	Other	units you might already use (describe method and add reference)	
Preliminary benefits identified - descriptive	Positive visual impact	qualitative description	
	Improve biodiversity	units you might already use (describe method and add reference)	
	Financial aid (subsides) OR avoid fines	€/yr	
	Increased yield	t or kg/ha/year	
	Avoid drought/water shortage	m3/ha and €/yr	
	Reduced emission of nutrients into water bodies/reduced eutrophication	units you might already use (add method and ref.)	
	Lower fixed and maintenance costs compared to status que (current situation)	units you might already use (add method and ref.)	
	Re-cycling of nutrients	units you might already use (add method and ref.)	
	Other	units you might already use (add method and ref.)	

Supplementary Table 2.B Data collection protocol and questionnaire for social data.

		Current system				CA System			
		1	2	3	4	1	2	3	4
		Never	Slightly	Partially	Totally	Never	Slightly	Partially	Totally
Stakeholders	Does the scenario improve **community development**? (% of new job offers, % of people employed)								
	How?								
	Does the scenario improve **workers/farmers wage or labour conditions**? (higher salary or earnings)								
	How?								
	Does the scenario improve **consumers' access to food**? (% of people that with a healthy diet)								
	How?								
	Does the scenario improve **food quality**? (% of fresh products in local markets)								
	How?								
	Does the scenario improve **community health**? (number of disease related to agriculture/population)								
	How?								
	Does the scenario improve **community welbeing**?(% of new jobs, amount of salary, % of sales from local shops)								
	How?								
	Does the scenario reduce **vulnerable groups' gap**? (% of minorities hired)								
	How?								
	Does the scenario improve **community/farmers' engagement**? (number of local markets, numbe of farmers representatives within public institutions)								
	How?								
	Does the scenario improve **economic development**?								
	How?								
	Does the scenario improve **knowledge sharing**?								
	To whom?								
	Does the scenario **reduce gender gaps**? (difference in salaries)								
	How?								
	Does the scenario **promote local work**?								
	How much?								
	Does the scenario **improve profits for the farmer**?								
	How?								
Impacts on the surrounding environment	Does the scenario improve **water quality**?								
	How?								
	Does the scenario improve the **quality of the soil**?								
	How?								
	Does the scenario improve the quality of the **landscape**?								
	How?								
	Does the scenario avoid **drought/water shortage** (at territorail level)?								

Supplementary Table 2.C- Supplementary information on experimental trials conducted including yields, fertilisers and plant protection products (PPP) types and quantities.

Model	Country/Region	Area (ha)	Soil Type	Crop	Fertiliser Type	Fertiliser Quantity (kg/ha)		PPP Type	PPP Quantity (l/ha)		Yield (t/ha)	
						B	CA		B	CA	B	CA
A	Tunisia, Kef	47	Silty-Clay	Barley	Ammonitrate	300	300	Herbicide (Zoom)	1	1	1.8	1.8
					P (super 45)	100	100	Herbicide (Axial)	0.15	0.15		
				Durum Wheat	Ammonitrate	300	300	Herbicide (Puma Evolution)	1	1	1.2	1.8
					P (super 45)	100	100					
				Fallow	-	0	0	-	-	-	0	-
				Camelina	Ammonitrate	-	50	Herbicide (Select Super)	-	1	-	1.8
					P (super 45)	-	100					
	Morocco, Casablanca-Settat	1	Sandy Loam	Soft Wheat	NPK	100	100	Herbicide (Mustang)	0.6	0.6	1.9	1.9
					Urea	100	100					
				Fallow	-	0	0	-	0	0	0	-
				Camelina	-	0	0	-	0	0	-	0.5
	Algeria, Sétif	66	Clay - Loam	Durum Wheat	MAP	150	-	Herbicide (Roundup)	2	2	2.5	3.5
					Sulfat K	50	-	Fungicide (Ceriax)	1	-		
					Urea	200	200	Insecticide (Cypermethrin)	0.25	-		
								Fungicide (Amistar Extra)	-	1		
								Insecticide (Engio)	-	0.2		
				Barley	MAP	150	150	Herbicide (Roundup)	2	2	2.0	2.0
					Sulfat K	50	50	Fungicide (Ceriax)	1	-		
					Urea	200	200	Insecticide (Cypermethrin)	0.25	-		
								Fungicide (Amistar Extra)	-	1		
								Insecticide (Engio)	-	0.2		
				Fallow	-	0	0	-	0	0	0	-
				Camelina	N-34	-	100	Herbicide (Roundup)	-	2	-	1.2
	Spain, Castile-La Mancha	40	Clay - Loam	Barley	8-24-8	300	300	Herbicide (Liberator)	0.6	0.6	4.5	4.5
					Nitramon 27%	300	300	Herbicide (Trezac)	0.2	0.2		
								Herbicide (Roundup)	10	10		
				Durum Wheat	8-24-8	300	300	Herbicide (Roundup)	10	10	4.2	4.2
					Nitramon 27%	300	300	Herbicide (Broadway)	0.2	0.2		
								Herbicide (Axial Pro)	0.5	0.5		
				Fallow	-	0	0	-	0	0	0	-
				Camelina	NSA 26%	-	150	Herbicide (Roundup)	-	5	-	1.2
								Herbicide (Centurion)	-	1		
B	Italy, Emilia Romagna	2	Silty Clay Loam	Soft Wheat	Ammonitrate	200	200	Herbicide (Timeline)	1	1	6.7	6.7
					Urea	350	350	Herbicide (Trimmer)	0.02	0.02		
					N Slow Release (40%)	250	250	Fungicide (Bumper P)	1	1		
								Fungicide (Seguris Era)	1	1		
								Insecticide (Mavrik Smart)	0.25	0.25		
				Soybean	-	0	0	Herbicide (Corum)	1.9	1.9	2	2
								Herbicide (Wetting Plus)	0.9	0.9		
				Camelina	Urea	-	100	Herbicide (Roundup)	-	3.5	-	2
		177		Durum Wheat	Ammonitrate	580	590	Herbicide (Defi)	3	-	4.9	4.9

	France, Haute Garonne		Medium Chalky Clay		Ammonia Sulphate	100	-	Herbicide (Axial Practic)	0.9	0.9		
								Herbicide (Chardex)	2	2		
								Herbicide (Constel)	-	4		
								Insecticide (Karate)	0.08	0.08		
								Fungicide (Sesto)	-	1.5		
								Fungicide (Faeton SC)	-	3		
								Fungicide (Elatus Plus)	-	0.5		
								Fungicide (Arioste 90)	-	0.5		
								Fungicide (Prosaro)	-	0.8		
				Sunflower	0-25-25	300	300	Herbicide (Mercanto)	1.2	1.2	2.2	2.2
					Bore	4	4	Herbicide (Challenge)	3	3		
					Urea	100	100	Herbicide (Targa Max)	0.5	-		
				Camelina	Ammonitrate	-	180	Fungicide (Amistar)	-	0.8	-	1
								-	0	0		
	Greece, Chalkidiki	7	Sandy-loam	Soft Wheat	16-20-0	200	200	Fungicide (Amistar)	0.8	0.8	5.4	5.4
					40-0-0	250	250					
				Sunflower	18-6-12	250	250	Herbicide (Pulsar)	1	1	4	3.5
					40-0-0	250	250	Herbicide (Fusillade)	2	2		
								Herbicide (Gardoprim Gold)	4	4		
								Fungicide (Madison)	1	1		
				Camelina	13-11-10	-	360	Herbicide (Pendigan)	-	5	-	2
					40-0-0	-	120					
C	France, Haute Garonne	177	Medium Chalky Clay	Durum Wheat	Ammonitrate	580	580	Herbicide (Defi)	3	-	4.9	4.9
					Ammonia Sulphate	100	100	Herbicide (Axial Practic)	0.9	0.9		
								Herbicide (Picotop)	-	1.2		
								Herbicide (Chardex)	2	2		
								Herbicide (Constel)	-	4		
								Insecticide (Karate)	0.08	0.08		
								Fungicide (Sesto)	-	1.5		
								Fungicide (Faeton SC)	-	3		
								Fungicide (Elatus Plus)	-	0.5		
								Fungicide (Arioste 90)	-	0.5		
								Fungicide (Prosaro)	-	0.8		
				Winter Barley	Ammonitrate	480	480	Herbicide (Defi)	3		4.8	4.8
								Herbicide (Compil)	0.15			
								Herbicide (Axial Practic)	1			
								Herbicide (Chardex)	2			
								Fungicide (Elatus Era)	0.65			
				Camelina	Ammonitrate	-	180				-	0.1

Supplementary Table 2.D Fuel consumption data from academic literature and adaptation to Ecoinvent processes.

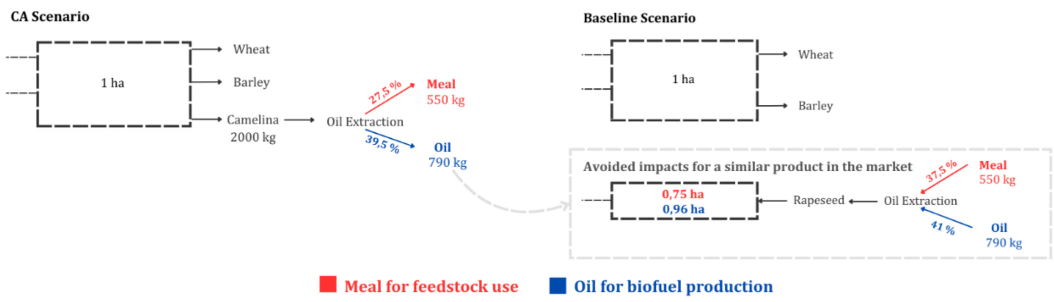
		Fuel Consumption (L)			Ratio Ecoinvent		
Country	**Operation**	**Baseline**	**CA**	**Unit**	**CT (Fuel/Fuel)**	**NT (Fuel/ Fuel)**	**Source**
Tunisia	Soil Preparation	30.7	7.2	l/ha	0.98	0.43	Rouabhi et al., 2019
	Sowing	6	28.2	l/ha	1.30	6.10	
	Phytosanitary treatment	15	7.2	l/ha	7.12	3.42	
	Fertilising	15.6	15.6	l/ha	2.46	2.46	
	Harvesting	13.5	18	l/ha	0.34	0.45	
Marocco	Soil Preparation	19.50	0	l/ha	0.62	0.00	Mrabet et al., 2014
	Sowing	10	12.00	l/ha	2.16	2.60	
	Phytosanitary treatment	30	7.2	l/ha	14.23	3.42	
	Fertilising	31.2	15.6	l/ha	4.92	2.46	
	Harvesting	36	36	l/ha	0.90	0.90	
Algeria	Soil preparation	12.6	0	l/ha	0.40	0.00	Talbi and Sgahier, 2024
	Sowing	5.1	25.662	l/ha	1.10	5.55	
	Phytosanitary treatment	38.25	26.352	l/ha	18.15	12.50	
	Fertilising	19.89	7.098	l/ha	3.14	1.12	
	Harvesting	18	18	l/ha	0.45	0.45	
Spain	Soil preparation	13.6	8	l/ha	0.52	0.31	Hernanz et al., 2014
	Sowing	7.6	9.6	l/ha	1.97	2.49	
	Phytosanitary treatment	2.2	2.2	l/ha	1.25	1.25	
	Fertilising	2	2	l/ha	0.35	0.35	
	Harvesting	18	18	l/ha	0.54	0.54	
Italy	Soil preparation	59.74	16.17	l/ha	2.29	0.62	Calcante and Oberti, 2019
	Sowing	6.90	6.90	l/ha	1.79	1.79	
	Phytosanitary treatment	4.67	4.67	l/ha	2.65	2.65	
	Fertilising	3.23	3.23	l/ha	0.57	0.57	
	Harvesting	20.72	20.72	l/ha	0.62	0.62	
France	Soil preparation	18	8	l/ha	0.69	0.31	Kahledian et al., 2013
	Sowing	6	6	l/ha	1.55	1.55	
	Phytosanitary treatment	1.76	1.76	l/ha	1.00	1.00	
	Fertilising	5.7	5.7	l/ha	1.00	1.00	
	Harvesting	33.3	33.3	l/ha	1.00	1.00	
Greece	Soil preparation	52.93	7.19	l/ha	2.03	0.28	Vatsanidou et al., 2020
	Sowing/fertilising	13.35	13.35	l/ha	3.46	3.46	
	Phytosanitary treatment	1.20	1.20	l/ha	0.68	0.68	
	Fertilising	13.35	13.35	l/ha	2.34	2.34	
	Harvesting	17.25	17.25	l/ha	0.52	0.52	

CA: Conservation Agriculture CT: Conventional tillage; NT: No Tillage

Supplementary Table 2.E Emissions from fertilisers application. Include emissions to air (N_2O, NO_x, NH_3), from bare soil (CO_2 and CH_4) from Schaufler et al. (2010) and to water (NO^{3-}, P, PO_4^{3-}).

Country	Scenario	Crop	N_2O (direct)	N_2O (indirect)	N_2O (indirect)	NO_x	NH_3	CO_2	CH_4	NO_{3-}	P	PO_4^{3-} (gw)	PO_4^{3-} (sw)
Tunisia	B	Wheat	0.91	0.04	0.00	4.08	0.01	N/A	N/A	63.01	0.03	1.04	0.12
		Barley	0.99	0.04	0.00	4.08	0.01	N/A	N/A	55.84	0.03	1.04	0.12
		Fallow	0.97			0.25		360.52	0.008				
	CA	Camelina	1.11	0.03	0.00	2.69	0.01			0.00	0.01	0.39	0.05
		Wheat	1.15	0.03	0.00	2.74	0.01			21.30	0.03	1.04	0.12
		Barley	1.42	0.04	0.00	4.08	0.01			55.42	0.03	1.04	0.12
Morocco	B	Wheat	0.88	0.05	0.00	2.44	0.05			0.00	0.19	0.69	0.12
		Fallow	0.97			0.25		360.52	0.01				
	CA	Wheat	1.44	0.06	0.00	2.44	0.05			0.00	0.19	0.69	0.12
		Camelina											
Algeria	B	Wheat	1.56	0.12	0.00	4.34	0.10			5.80	0.13	2.40	0.06
		Barley	1.56	0.12	0.00	4.34	0.10			21.56	0.13	2.40	0.06
		Fallow	0.97	0.00	0.00	0.25	0.00	360.52	0.01	0.00	0.00	0.00	
	CA	Wheat	1.42	0.10	0.00	3.40	0.08			0.30	0.00	0.00	0.00
		Barley	1.61	0.12	0.00	4.28	0.11			0.00	0.13	2.40	0.06
		Camelina	0.99	0.05	0.00	2.28	0.02			10.42	0.05	0.91	0.02
		Pea Vetch	1.99	0.15	0.00	5.18	0.18			0.00			
		Lentils	0.84	0.03	0.00	0.92	0.02			0.00	0.00	0.00	0.00
Spain	B	Durum Wheat	1.57	0.05	0.00	4.20	0.02			2.79	0.65	3.33	0.14
		Barley	1.78	0.04	0.00	4.20	0.01			9.70	0.65	3.33	0.14
		Fallow	0.97	0.00	0.00	0.25	0.00	360.52	0.01	0.00	0.00		
	CA	Durum Wheat	2.23	0.05	0.00	4.20	0.02			2.21	0.65	3.33	0.14
		Barley	2.37	0.05	0.00	3.90	0.02			2.78*	0.65	3.33	0.14
		Camelina	0.82	0.04	0	1.84	0.03			0	0.25	1.26	0.05
Italy	B	Soft Wheat	13.92	0.84	2.3	13.16	0.63			132.42			
		Soybean											
	CA	Soft Wheat	17.82	0.79	2.94	11.27	0.56			87.67			
		Camelina	6.1	0.33	1.01	4.01	0.28			0			
		Soybean											
France (2B)	B	Durum Wheat	2.48	0.09	0.00	8.20	0.03			66.41			
		Sunflower	0.72	0.08	0.00	2.75	0.07			0	0.31	1.94	0.08
	CA	Durum Wheat	2.51	0.07	0.00	7.33	0.02			48.19			
		Camelina	0.58	0.02	0.00	2.44	0.01			12.03			
		Sunflower	1.33	0.08	0.00	2.77	0.07			0.00	0.31	1.94	0.08
France (1C)	B	Durum Wheat	2.80	0.13	0.00	9.86	0.07			100.68			
		Barley	1.79	0.06	0.00	6.52	0.02			48.54			
	CA	Wheat	3.88	0.1	0.00	8.86	0.03			79.69			
		Camelina	1.22	0.02	0.00	2.44	0.01			11.39			
		Barley	2.43	0.06	0.00	6.52	0.02			47.90			
Greece	B	Soft Wheat	1.55	0.12	0.00	5.45	0.04			0.00	0.38	1.85	0.13
		Sunflower	1.42	0.12	0.00	5.59	0.04			12.38	0.21	0.31	0.07
	CA	Soft Wheat	2.19	0.12	0.00	5.49	0.04			0.00	0.38	1.85	0.13
		Camelina	1.54	0.08	0.00	3.79	0.03			13.45	0.14	0.39	0.05
		Sunflower	2.01	0.12	0.00	5.56	0.04			23.82	0.21	0.31	0.07

Supplementary Figure 2.A System expansion performed in the analysis for solving multifunctional systems comparison.



Source: *Authors own elaboration*

Supplementary Table 2.F Environmental, economic and social indicators used for the sustainability assessment.

Dimension	Impact/ Stakeholder Category	Indicator	Unit	Single Score Aggregation
Environmental	Biodiversity	Potential biodiversity risk	PBR	Normalisation and weighting set of the 16 PEF Impact Categories Sala et al. (2017)
	Climate Change	Radiative forcing as global warming potential (GWP100)	kg CO2 eq.	
	Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	
	Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	
	Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	
	Land use	Soil quality index: a) Biotic production; b) Erosion resistance; c) Mechanical filtration; d) Groundwater replenishment	Dimensionless (pt): a) kg biotic production; b) kg soil; c) m^3 water; d) m^3 groundwater	
Economic	Costs	OPEX	€	Benefit-Cost Ratio European Commission, (2014)
	Profitability	Gross Margin	%	
		Net Profit	€	
Social	Society	Vulnerable Groups Gender Knowledge Economic development	Pts	Overall Social Performance Indicator Brenes-Peralta et al. (2021).
	Community	Community Development Community Health Community Wellbeing Local work		
	Farmers and workers	Profit Engagement Wages and labour conditions		
	Consumers	Food quality Access to food		
	Environment	Water Quality Soil Quality Landscape Quality Avoid water shortage		

Supplementary Table 2.G Monetary coefficients adapted to country-based inflation rates for the 16 Impact Categories.

Country	ICs	Low ($€_{2023}$)	Central ($€_{2023}$)	High ($€_{2023}$)	CPI (2018)	CPI (2023)
Algeria	Acidification	0.13	0.25	1.16	111.82	155.85
Algeria	Climate change	0.09	0.14	0.27	111.82	155.85
Algeria	Ecotoxicity, freshwater	0.00	0.00	0.00	111.82	155.85
Algeria	Particulate matter	474956.26	562598.46	864282.14	111.82	155.85
Algeria	Eutrophication, marine	2.30	2.30	2.30	111.82	155.85
Algeria	Eutrophication, freshwater	0.19	1.38	1.56	111.82	155.85
Algeria	Human toxicity, cancer	242965.44	1258028.11	3887442.84	111.82	155.85
Algeria	Human toxicity, non-cancer	21675.93	117270.73	541894.72	111.82	155.85
Algeria	Ionising radiation	0.00	0.00	0.03	111.82	155.85

Country	ICs	Low (€$_{2023}$)	Central (€$_{2023}$)	High (€$_{2023}$)	CPI (2018)	CPI (2023)
Algeria	Land use	0.00	0.00	0.00	111.82	155.85
Algeria	Ozone depletion	31.78	43.76	177.29	111.82	155.85
Algeria	Photochemical ozone formation	0.62	0.85	1.36	111.82	155.85
Algeria	Resource use, fossils	0.00	0.00	0.00	111.82	155.85
Algeria	Resource use, minerals and metals	0.00	1.18	4.69	111.82	155.85
Algeria	Water use	0.00	0.00	0.17	111.82	155.85
Tunisa	Acidification	0.27	0.52	2.45	115.60	175.40
Tunisa	Climate change	0.09	0.16	0.29	115.60	175.40
Tunisa	Ecotoxicity, freshwater	0.00	0.00	0.00	115.60	175.40
Tunisa	Particulate matter	1004413.84	1189755.19	1827740.83	115.60	175.40
Tunisa	Eutrophication, marine	4.87	4.87	4.87	115.60	175.40
Tunisa	Eutrophication, freshwater	0.39	2.91	3.31	115.60	175.40
Tunisa	Human toxicity, non-cancer	45839.18	247998.30	1145971.96	115.60	175.40
Tunisa	Human toxicity, cancer	264501.99	1369540.19	4232027.23	115.60	175.40
Tunisa	Ionising radiation	0.00	0.00	0.07	115.60	175.40
Tunisa	Land use	0.00	0.00	0.00	115.60	175.40
Tunisa	Ozone depletion	34.59	47.64	193.00	115.60	175.40
Tunisa	Photochemical ozone formation	1.32	1.81	2.88	115.60	175.40
Tunisa	Resource use, fossils	0.00	0.00	0.01	115.60	175.40
Tunisa	Resource use, minerals and metals	0.00	2.49	9.91	115.60	175.40
Tunisa	Water use	0.01	0.01	0.36	115.60	175.40
Morocco	Acidification	0.22	0.43	2.04	103.32	130.54
Morocco	Climate change	0.08	0.13	0.24	103.32	130.54
Morocco	Ecotoxicity, freshwater	0.00	0.00	0.00	103.32	130.54
Morocco	Particulate matter	836373.27	990706.62	1521955.90	103.32	130.54
Morocco	Eutrophication, marine	4.06	4.06	4.06	103.32	130.54
Morocco	Eutrophication, freshwater	0.33	2.43	2.75	103.32	130.54
Morocco	Human toxicity, non-cancer	38170.19	206507.66	954248.41	103.32	130.54
Morocco	Human toxicity, cancer	220250.24	1140413.21	3524000.07	103.32	130.54
Morocco	Ionising radiation	0.00	0.00	0.06	103.32	130.54
Morocco	Land use	0.00	0.00	0.00	103.32	130.54
Morocco	Ozone depletion	28.81	39.67	160.71	103.32	130.54
Morocco	Photochemical ozone formation	1.10	1.50	2.40	103.32	130.54
Morocco	Resource use, fossils	0.00	0.00	0.01	103.32	130.54
Morocco	Resource use, minerals and metals	0.00	2.07	8.25	103.32	130.54
Morocco	Water use	0.01	0.01	0.30	103.32	130.54
France	Acidification	0.22	0.44	2.06	103.72	132.28
France	Climate change	0.08	0.13	0.25	103.72	132.28
France	Ecotoxicity, freshwater	0.00	0.00	0.00	103.72	132.28
France	Particulate matter	844253.00	1000040.37	1536294.72	103.72	132.28
France	Eutrophication, marine	4.09	4.09	4.09	103.72	132.28
France	Eutrophication, freshwater	0.33	2.45	2.78	103.72	132.28
France	Human toxicity, non-cancer	38529.80	208453.23	963238.68	103.72	132.28
France	Human toxicity, cancer	222325.29	1151157.39	3557200.76	103.72	132.28
France	Ionising radiation	0.00	0.00	0.06	103.72	132.28
France	Land use	0.00	0.00	0.00	103.72	132.28
France	Ozone depletion	29.08	40.05	162.23	103.72	132.28
France	Photochemical ozone formation	1.11	1.52	2.42	103.72	132.28
France	Resource use, fossils	0.00	0.00	0.01	103.72	132.28
France	Resource use, minerals and metals	0.00	2.09	8.33	103.72	132.28
France	Water use	0.01	0.01	0.30	103.72	132.28
Spain	Acidification	0.23	0.45	2.13	104.21	137.58
Spain	Climate change	0.08	0.14	0.26	104.21	137.58
Spain	Ecotoxicity, freshwater	0.00	0.00	0.00	104.21	137.58
Spain	Particulate matter	873950.51	1035217.88	1590335.55	104.21	137.58
Spain	Eutrophication, marine	4.24	4.24	4.24	104.21	137.58
Spain	Eutrophication, freshwater	0.34	2.53	2.88	104.21	137.58
Spain	Human toxicity, non-cancer	39885.13	215785.80	997121.64	104.21	137.58
Spain	Human toxicity, cancer	230145.82	1191650.60	3682329.16	104.21	137.58
Spain	Ionising radiation	0.00	0.00	0.06	104.21	137.58
Spain	Land use	0.00	0.00	0.00	104.21	137.58
Spain	Ozone depletion	30.10	41.45	167.93	104.21	137.58

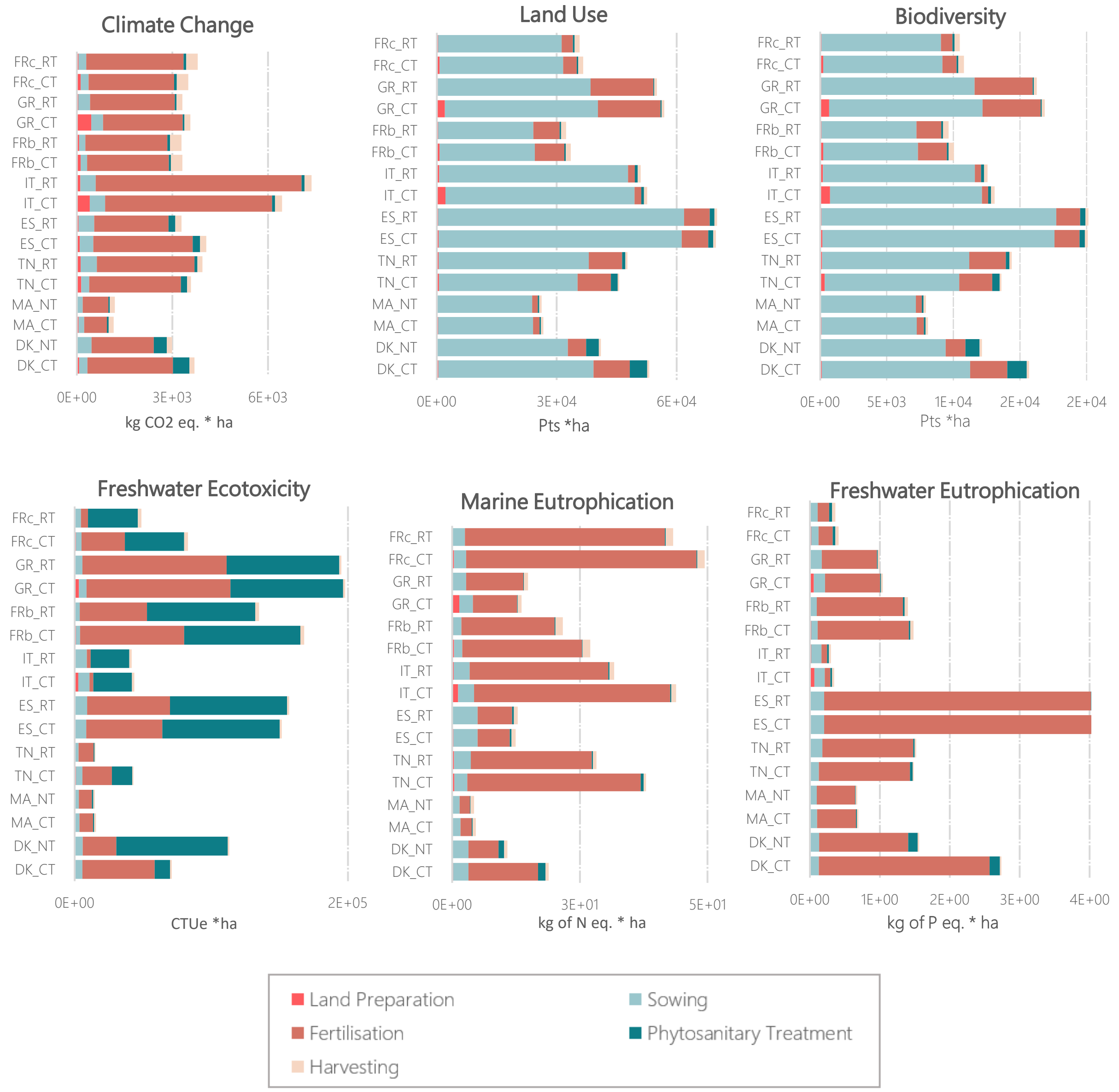
Country	ICs	Low (€$_{2023}$)	Central (€$_{2023}$)	High (€$_{2023}$)	CPI (2018)	CPI (2023)
Spain	Photochemical ozone formation	1.15	1.57	2.51	104.21	137.58
Spain	Resource use, fossils	0.00	0.00	0.01	104.21	137.58
Spain	Resource use, minerals and metals	0.00	2.17	8.62	104.21	137.58
Spain	Water use	0.01	0.01	0.31	104.21	137.58
Italy	Acidification	0.22	0.43	2.01	103.10	128.40
Italy	Climate change	0.08	0.13	0.24	103.10	128.40
Italy	Ecotoxicity, freshwater	0.00	0.00	0.00	103.10	128.40
Italy	Particulate matter	824417.67	976544.89	1500200.19	103.10	128.40
Italy	Eutrophication, marine	4.00	4.00	4.00	103.10	128.40
Italy	Eutrophication, freshwater	0.32	2.39	2.71	103.10	128.40
Italy	Human toxicity, non-cancer	37624.56	203555.72	940607.84	103.10	128.40
Italy	Human toxicity, cancer	217101.86	1124111.49	3473626.00	103.10	128.40
Italy	Ionising radiation	0.00	0.00	0.06	103.10	128.40
Italy	Land use	0.00	0.00	0.00	103.10	128.40
Italy	Ozone depletion	28.39	39.11	158.41	103.10	128.40
Italy	Photochemical ozone formation	1.08	1.48	2.37	103.10	128.40
Italy	Resource use, fossils	0.00	0.00	0.01	103.10	128.40
Italy	Resource use, minerals and metals	0.00	2.04	8.13	103.10	128.40
Italy	Water use	0.01	0.01	0.29	103.10	128.40
Greece	Acidification	0.23	0.45	2.09	100.38	129.98
Greece	Climate change	0.08	0.13	0.25	100.38	129.98
Greece	Ecotoxicity, freshwater	0.00	0.00	0.00	100.38	129.98
Greece	Particulate matter	857176.53	1015348.65	1559811.80	100.38	129.98
Greece	Eutrophication, marine	4.16	4.16	4.16	100.38	129.98
Greece	Eutrophication, freshwater	0.34	2.49	2.82	100.38	129.98
Greece	Human toxicity, non-cancer	39119.60	211644.16	977983.61	100.38	129.98
Greece	Human toxicity, cancer	225728.57	1168778.92	3611653.18	100.38	129.98
Greece	Ionising radiation	0.00	0.00	0.06	100.38	129.98
Greece	Land use	0.00	0.00	0.00	100.38	129.98
Greece	Ozone depletion	29.52	40.66	164.71	100.38	129.98
Greece	Photochemical ozone formation	1.13	1.54	2.46	100.38	129.98
Greece	Resource use, fossils	0.00	0.00	0.01	100.38	129.98
Greece	Resource use, minerals and metals	0.00	2.12	8.46	100.38	129.98
Greece	Water use	0.01	0.01	0.31	100.38	129.98

CPI: Consumer Price Index. Retrieved from FAOSTAT

Supplementary Table 2.H Characterised Impacts of Life Cycle Assessment based on the 16 ICs of Environmental Footprint Method.

Impact Category	Unit	DK_CA	DK_B	MA_CA	MA_B	ES_CA	ES_B	TN_CA	TN_B	FRb_CA	FRb_B	GR_CA	GR_B	IT_CA	IT_B	FRc_CA	FRc-B
Acidification	mol H^+ eq	33.63	45.56	12.29	30.56	31.04	47.18	39.51	43.53	37.72	58.44	54.08	73.99	31.58	68.34	40.23	60.77
Climate change	kg CO_2 eq	4096.97	4854.57	1544.82	2558.72	4072.42	5791.73	5400.71	4952.86	4177.06	4403.73	5235.82	5055.34	10100.99	8256.69	4861.30	4583.92
Ecotoxicity, freshwater	CTUe	122960.70	59658.35	13062.04	21052.10	132141.06	139399.98	45648.90	39429.90	109677.45	151240.20	202344.91	183596.79	35800.14	74772.46	45143.91	87394.28
Particulate matter	disease inc.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Eutrophication, marine	kg N eq	15.93	31.93	5.29	23.52	15.27	27.83	32.02	50.58	27.26	42.10	22.50	34.62	35.57	68.98	48.71	64.52
Eutrophication, freshwater	kg P eq	1.86	2.90	0.74	0.93	5.13	4.62	1.93	1.66	1.50	1.79	1.57	1.47	0.42	0.86	0.46	0.72
Eutrophication, terrestrial	mol N eq	144.32	189.19	54.65	134.14	135.02	193.69	165.71	187.82	162.78	242.46	163.83	266.89	163.51	315.66	197.31	277.63
Human toxicity, cancer	CTUh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Human toxicity, non-cancer	CTUh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionising radiation	kBq U-235 eq	72.69	92.00	24.41	45.25	137.39	140.18	94.12	79.01	114.40	127.79	244.22	205.81	71.60	99.42	90.52	106.69
Land use	Pt	718344.42	770747.46	421348.38	502621.18	1134761.54	1350934.68	955977.17	998601.40	1125736.43	1122109.23	1049571.26	1155211.11	1039217.27	1188983.55	1415368.18	1411483.12
Ozone depletion	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Photochemical ozone formation	kg NMVOC eq	30.65	28.98	12.02	13.45	25.59	21.24	33.51	27.64	31.09	30.62	33.54	32.84	31.56	35.69	35.35	34.99
Resource use, fossils	MJ	37221.86	39339.00	13743.99	16683.05	32948.06	34218.87	44699.14	35876.30	38489.55	40121.32	57558.64	53888.52	28656.84	37153.79	34642.79	36284.13
Resource use, minerals and metals	kg Sb eq	0.03	0.04	0.01	0.01	0.03	0.03	0.04	0.03	0.04	0.04	0.05	0.04	0.01	0.02	0.03	0.03
Water use	m^3 depriv.	4057.02	4550.66	1511.19	2051.27	4081.31	6907.66	3009.90	3083.38	2107.46	5023.48	3127.35	6531.24	2478.94	7130.74	2279.14	5142.10

Supplementary Figure 2.B Characterised impacts of minimum and conventional tillage in the two scenarios.



Source: *Authors own elaboration*

Supplementary Table 2.I Life cycle costs of cultivating 1 hectare of land under conventional and conservation agriculture scenarios in the different operational phases.

Product life cycle	OPEX (€/ha)															
	Model A										***Model B***				***Model C***	
	Tunisia		**Morocco**		**Algeria**		**Spain**		**Italy**		**France**		**Greece**		**France**	
	B	*CA*	*B*	*CA*	*B*	*CA*	B	CA	B	CA	B	CA	B	CA	B	CA
Land Preparation	109.13	93.46	65	95	14.30	0	49.47	48.48	211.45	221.60	53.08	54.92	106.00	110.34	31.08	33.92
Sowing	54.53	78.64	64	64	110.25	164.06	152.07	219.85	236.08	296.12	162.87	390.35	305.39	351.41	151.32	379.80
Fertilisation	254.41	312.87	140	140	84.95	27.17	373.38	451.80	648.57	722.75	234.11	299.21	243.52	417.94	234.11	300.21
Phytosanitary Treatment	153.90	192.20	15	15	273.86	188.23	149.88	198.04	317.42	372.39	318.27	318.27	245.99	358.78	263.01	263.01
Harvesting	33.91	56.52	95	190	18.79	17.56	51.44	77.16	87.15	87.15	29.31	29.31	292.00	438.00	29.31	29.31
Total	***611.18***	***738.98***	***379.00***	***504.00***	***502.15***	***397.02***	***789.17***	***1,008.24***	***1,657.54***	***1,856.32***	***953.28***	***1,308.75***	***1,486.42***	***1,969.99***	***918.00***	***1,224.99***

Supplementary Table 2.J Challenges and opportunities derived from 2nd rounds of respondents' interviews.

Stakeholders Categories	Opportunities	Challenges
Farmers & Workers	- Wider diffusion of CA systems has the potential to generate many jobs - Shift from monocropping to more complex systems can create new value chains (lack of oilseed crops in Morocco) - Camelina can be grown as a spring or autumn crop and in dry areas and marginal lands - It could increase farming income through CAP subsidies	- Profitability is context dependent - Lack of market and post-harvest processes in some countries (Algeria) - More time than expected was needed to introduce camelina in cropping systems (Tunisia)
Consumers	- Camelina can be valorised in oils with high nutritional quality representing more choices for consumers - Camelina can ameliorate the quality of cereals and promote access to higher-quality foods - Camelina can increase yields and consumers' access to food	- Lack of market and post-harvest processes in some countries (Algeria)
Community	- Camelina cropping has the potential to create additional jobs, especially in the oil-based industry - Increase of employment and new investments as officially registered in Greece catalogue involving more farmers and companies - .	- When implemented at full scale, impacts on economic development were less significant than expected (Tunisia)
Society	- Camelina can benefit gender inclusion, as women are mainly involved in transformation processes (Morocco, Algeria) - Knowledge increased through farmers training and dissemination activities - Camelina can foster market diversification and community engagement	- When implemented at full scale, impacts on economic development were less significant than expected (Tunisia)
Environment	- Camelina cropping showed a good soil conservation and water retention capacity, and an increase in organic matter, resulting in a strong improvement in the quality of soil. - The integration of camelina improves the quality of landscape and the integration of CA improves the adaptation to drought and water shortage. - Soil erosion and degradation will be avoided when camelina is used in the rotation crop system.	- Environmental benefits depend on the agricultural management systems applied

Supplementary Table 2.K Uncertainty ranges used for the Sensitivity Analysis. Triangular distribution was assumed.

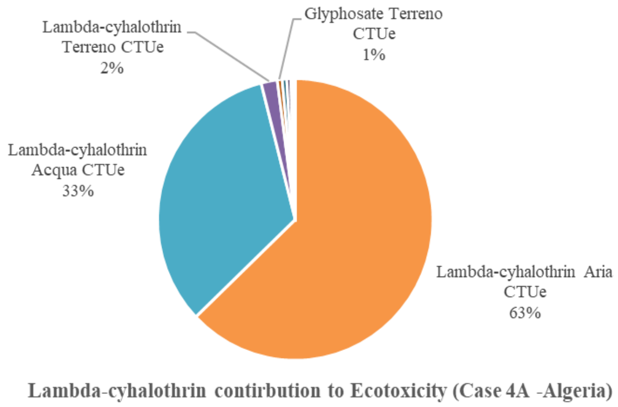
Parameter	Value	Uncertainty Range	Source
N_2O	0.005 (dry)	0.000-0.011	IPCC, 2019
(Direct and indirect volatilisation)	0.014 (wet)	0.011-0.017	IPCC, 2019
N_2O (Indirect leaching)	0.011	0.000- 0.02	IPCC, 2019
NO	0.04	0.005-0.104	EMEP/EEA, 2019
Fuel Consumption	See Table C	±25%	Experts Estimates
Camelina Oil	39.50%	30-49%	Mondor and Hernández-Álvarez, 2022
Camelina Meal	27.50%	24-31%	Mondor and Hernández-Álvarez, 2022
Rapeseed Oil	41%	38-44%	Nega, 2018
Rapeseed Meal	37.50%	30-45%	Nega, 2018

Supplementary Table 2.L Standard Error of the mean (SEM) showing the uncertainty in values from Monte Carlo simulation with 95% confidence interval.

Scenario	Model	Country	Impact Categories	Standard Error of the Mean
CA	A	Algeria	Climate change	14.04
CA	A	Algeria	Ecotoxicity, freshwater	7566.74
CA	A	Algeria	Eutrophication, marine	0.06
CA	A	Algeria	Eutrophication, freshwater	0.01
CA	A	Algeria	Land use	1997.86
CA	A	Algeria	Biodiversity	553.00
B	A	Algeria	Climate change	12.86
B	A	Algeria	Ecotoxicity, freshwater	9627.10
B	A	Algeria	Eutrophication, marine	0.13
B	A	Algeria	Eutrophication, freshwater	0.01
B	A	Algeria	Land use	6052.49
B	A	Algeria	Biodiversity	1833.52
CA	A	Morocco	Climate change	6.16
CA	A	Morocco	Ecotoxicity, freshwater	2430.77
CA	A	Morocco	Eutrophication, marine	0.03
CA	A	Morocco	Eutrophication, freshwater	0.00
CA	A	Morocco	Land use	1266.91
CA	A	Morocco	Biodiversity	410.00
B	A	Morocco	Climate change	6.14
B	A	Morocco	Ecotoxicity, freshwater	3070.19
B	A	Morocco	Eutrophication, marine	0.15
B	A	Morocco	Eutrophication, freshwater	0.00
B	A	Morocco	Land use	9029.68
B	A	Morocco	Biodiversity	2464.79
CA	A	Tunisia	Climate change	14.02
CA	A	Tunisia	Ecotoxicity, freshwater	11364.81
CA	A	Tunisia	Eutrophication, marine	0.06
CA	A	Tunisia	Eutrophication, freshwater	0.01
CA	A	Tunisia	Land use	1647.39
CA	A	Tunisia	Biodiversity	486.00
B	A	Tunisia	Climate change	9.99
B	A	Tunisia	Ecotoxicity, freshwater	9023.96
B	A	Tunisia	Eutrophication, marine	0.10
B	A	Tunisia	Eutrophication, freshwater	0.01
B	A	Tunisia	Land use	5802.67
B	A	Tunisia	Biodiversity	1646.67
CA	A	Spain	Climate change	14.82
CA	A	Spain	Ecotoxicity, freshwater	3989.31
CA	A	Spain	Eutrophication, marine	0.06
CA	A	Spain	Eutrophication, freshwater	0.01

CA	A	Spain	Land use	2910.25
CA	A	Spain	Biodiversity	843.00
B	A	Spain	Climate change	22.89
B	A	Spain	Ecotoxicity, freshwater	4736.43
B	A	Spain	Eutrophication, marine	0.14
B	A	Spain	Eutrophication, freshwater	0.01
B	A	Spain	Land use	12624.94
B	A	Spain	Biodiversity	3418.82
CA	B	Italy	Climate change	18.39
CA	B	Italy	Ecotoxicity, freshwater	8775.39
CA	B	Italy	Eutrophication, marine	0.12
CA	B	Italy	Eutrophication, freshwater	0.00
CA	B	Italy	Land use	2461.96
CA	B	Italy	Biodiversity	651.29
B	B	Italy	Climate change	17.50
B	B	Italy	Ecotoxicity, freshwater	11054.30
B	B	Italy	Eutrophication, marine	0.01
B	B	Italy	Eutrophication, freshwater	0.24
B	B	Italy	Land use	19902.00
B	B	Italy	Biodiversity	5530.68
CA	B	France	Climate change	13.54
CA	B	France	Ecotoxicity, freshwater	2436.38
CA	B	France	Eutrophication, marine	0.08
CA	B	France	Eutrophication, freshwater	0.01
CA	B	France	Land use	1171.85
CA	B	France	Biodiversity	365.22
B	B	France	Climate change	13.41
B	B	France	Ecotoxicity, freshwater	4171.28
B	B	France	Eutrophication, marine	0.15
B	B	France	Eutrophication, freshwater	0.01
B	B	France	Land use	12285.07
B	B	France	Biodiversity	3293.47
CA	B	Greece	Climate change	20.14
CA	B	Greece	Ecotoxicity, freshwater	3584.32
CA	B	Greece	Eutrophication, marine	0.07
CA	B	Greece	Eutrophication, freshwater	0.01
CA	B	Greece	Land use	1978.96
CA	B	Greece	Biodiversity	645.00
B	B	Greece	Climate change	16.99
B	B	Greece	Ecotoxicity, freshwater	5212.06
B	B	Greece	Eutrophication, marine	0.20
B	B	Greece	Eutrophication, freshwater	0.01
B	B	Greece	Land use	17348.51
B	B	Greece	Biodiversity	4766.40
CA	C	France	Climate change	20.04
CA	C	France	Ecotoxicity, freshwater	2523.90
CA	C	France	Eutrophication, marine	0.11
CA	C	France	Eutrophication, freshwater	0.01
CA	C	France	Land use	1433.51
CA	C	France	Biodiversity	413.00
B	C	France	Climate change	16.61
B	C	France	Ecotoxicity, freshwater	3765.40
B	C	France	Eutrophication, marine	0.18
B	C	France	Eutrophication, freshwater	0.01
B	C	France	Land use	12390.20
B	C	France	Biodiversity	3403.86

Supplementary Figure 2.C Contribution analysis of Lambda-cyhalothrin to Ecotoxicity with cut-off zero.



Source: *Authors own elaboration*

Supplementary Table 2.M Checklist of the consolidated criteria for reporting qualitative studies (COREQ Guidelines) for sLCA analysis.

No. Item	Guide questions/description	Reported on Page #
	Domain 1: Research team and reflexivity	
Personal Characteristics		
1. Interviewer/facilitator	Which author/s conducted the interview or focus group?	
2. Credentials	What were the researcher's credentials? E.g. PhD, MD	
3. Occupation	What was their occupation at the time of the study?	#58
4. Gender	Was the researcher male or female?	
5. Experience and training	What experience or training did the researcher have?	
Relationship with participants		
6. Relationship established	Was a relationship established prior to study commencement?	
7. Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	#58-59
8. Interviewer characteristics	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	
	Domain 2: Study design	
Theoretical framework		
9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study?	#59-61
Participant selection		
10. Sampling	How were participants selected? e.g. purposive, convenience, consecutive, snowball	
11. Method of approach	How were participants approached? e.g. face-to-face, telephone, mail, email	#59
12. Sample size	How many participants were in the study?	
13. Non-participation	How many people refused to participate or dropped out? Reasons?	
Setting		
14. Setting of data collection	Where was the data collected? e.g. home, clinic, workplace	
15. Presence of non-participants	Was anyone else present besides the participants and researchers?	#59
16. Description of sample	What are the important characteristics of the sample? e.g. demographic data, date	
Data collection		
17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	#58
18. Repeat interviews	Were repeat interviews carried out? If yes, how many?	
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?	
20. Field notes	Were field notes made during and/or after the interview or focus group?	#59
21. Duration	What was the duration of the interviews or focus group?	
22. Data saturation	Was data saturation discussed?	
23. Transcripts returned	Were transcripts returned to participants for comment and/or correction?	
	Domain 3: analysis and findings	
Data analysis		
24. Number of data coders	How many data coders coded the data?	#59
25. Description of the coding tree	Did authors provide a description of the coding tree?	#61
26. Derivation of themes	Were themes identified in advance or derived from the data?	#61
27. Software	What software, if applicable, was used to manage the data?	#59

28. Participant checking	Did participants provide feedback on the findings?	#59
Reporting		
29. Quotations presented	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	#65, #68, #71
30. Data and findings consistent	Was there consistency between the data presented and the findings?	
31. Clarity of major themes	Were major themes clearly presented in the findings?	
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?	

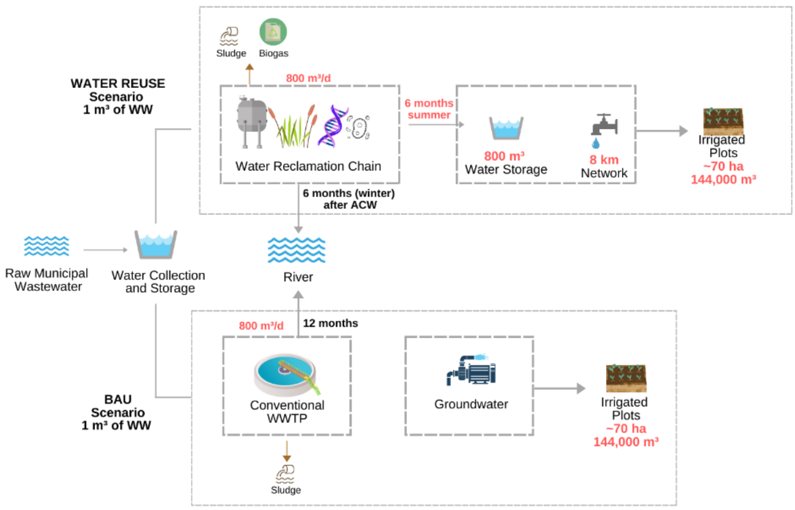
Supplementary Materials III - Chapter 3

Combining Life Cycle Thinking with Policy Foresight: Future Scenarios for the diffusion of Non-Conventional Water Resources

Supplementary Table 3.A Water quality of water inflow and outflow and abatement levels.

Parameters	Unit	Inflow	Outflow	Abatement Level (%)
UASB				
COD	mg/L	374.15	174.80	53.28
TSS	mg/L	227.67	74.17	67.42
TN	mg/L	34.00	33.80	0.61
TP	mg/L	4.8	4.39	8.52
NH4-N	mg/L	22.14	25.67	-15.98
PO4-P	mg/L	2.33	3.46	-47.61
E. coli	UFC/100mL	1000000	994771.2	0.52
HCW				
COD	mg/L	174.80	34.96	80.00
TSS	mg/L	74.17	7.41	90.00
TN	mg/L	33.80	10.14	70.00
TP	mg/L	4.39	1.75	60.00
NH4-N	mg/L	25.67	25.67	-
PO4-P	mg/L	3.46	3.45	-
E. coli	UFC/100mL	994771.2	995.77	99.90
MIPs				
Diclofenac	mg/L	5.0	3.500	30.00
COD	mg/L	61.00	N.M.*	N.M.
TN	mg/L	27.60	N.M.	N.M.
TP	mg/L	2.94	N.M.	N.M.
NH4-N	mg/L	25.41	N.M.	N.M.
PO4-P	mg/L	3.85	N.M.	N.M.

Supplementary Figure 3.A System boundaries of water reuse and business as usual scenarios used in the analysis.



Source: Authors own elaboration

Supplementary Table 3.B Inventories of input and output considered for UASB technology.

Item	Pilot Scale (m^3)	Upscaled (m^3)	Unit	Data Source
Construction Phase				
Land	9.78E-04	8.56E-06	m^2	Pilot Owner
Tank	1.66E-01	1.18E-04	kg	Pilot Owner - Material production + main process (injection moulding) + transport (PEF guidelines) - Ecoinvent
Submersible Dewatering Pump	1.82E-03	3.41E-02	p	Pilot Owner- Adaptation from Ecoinvent process for water pump production (1 piece of 22 kW)- Disposal included
Boiler/Electric resistance	1.50E-01	1.00E+00	p	Pilot Owner - 1 piece of 10 kW - Ecoinvent
Reactor	1.77E-02	3.23E-03	kg	Pilot Owner - Material production + main process (injection moulding) + transport (PEF guidelines) - Ecoinvent
Feeding Pump	2.27E-04	6.82E-02	p	Adaptation from Ecoinvent proces for water pump production (1 piece of 22 kW) - Disposal Included
Effluent Pump	1.82E-03	6.82E-02	p	Adaptation from Ecoinvent proces for water pump production (1 piece of 22 kW) - Disposal included
Tank	2.94E-04	5.48E-05	kg	Material production + main process (injection moulding) + transport (PEF guidelines) - Ecoinvent
Operational Phase				
				Input
Activated Carbon	6.85E-04	2.74E-04	kg	Hypothesis and HYDROUSA D3.1 - Ecoinvent
Electricity	2.23E+00	3.17E-03	kW	Pilot Owner- Ecoinvent
Spent Activated Carbon	2.94E+00	2.74E-03	W	Hypothesis for reactivation - Ecoinvent
				Output
Sludge	3.21E+01	2.50E-02	kg	Hypothesis drying + Sanitary Landfill - Ecoinvent
Biogas	4.57E-01	3.89E-04	m^3	Economic Allocation (1.14% pilot; 98.6% upscaled)
Disposal Phase				
Waste Tank, Reactors	1.84E-01	2.01E-04	kg	Hypothesis Municipal collection (45km) - Ecoinvent

Supplementary Table 3.C Inventories of input and output considered for ACW technology.

Item	Pilot Scale (m^3)	Upscaled (m^3)	Unit	Data source
Construction Phase				
Land	6.85E-04	2.57E-03	m^2	Pilot owner - Ecoinvent
Air Compressors	7.33E-02	3.41E+00	p	Pilot owner - Adaptation from Ecoinvent process for air compressor production (1 piece of 4 kW) - Disposal included
Pumps	1.68E-02	3.41E-01	p	Pilot owner - Adaptation from Ecoinvent process for water pump production (1 piece of 22 kW) - Disposal included
Pipes	9.77E-02	6.88E-04	kg	PVC pipe production – EF 3.1
HDPE geomembrane	5.87E-03	1.33E-03	kg	Hypothesis - Material production (HDPE) + transport (PEF guidelines) - Ecoinvent
Excavation	5.02E-04	6.88E-04	m^3	Hypothesis - Ecoinvent
Sand	7.49E-02	1.03E-04	kg	Pilot owner - Ecoinvent
Pumice	2.74E-02	3.75E-05	kg	Pilot owner - Ecoinvent
Perlite	1.83E-02	2.50E-05	kg	Pilot owner - Ecoinvent
Vermiculite	3.88E-03	5.32E-06	kg	Pilot owner - Ecoinvent
Cork	4.11E-03	5.63E-06	kg	Pilot owner - Ecoinvent
Gravel	3.07E-01	4.20E-04	kg	Pilot owner - Ecoinvent
Operational Phase				
				Input:
Electricity	2.52E+02	5.08E+00	kW	Pilot owner - Ecoinvent
				Output:
Sludge	4.35E-01	-	kg	Pilot owner - Ecoinvent
Emissions	4.18E-07	4.37E-03	kg	IPCC, 2013 – Ecoinvent
Emissions	3.88E-08	4.22E-04	kg	IPCC, 2013- Ecoinvent
Disposal Phase				
Waste Tank, Reactors	5.39E-01	2.22E-03	kg	Hypothesis Municipal collection (45km) - Ecoinvent

Supplementary Table 3.D Inventories of input and output considered for MIPs technology.

Item	Pilot Scale (m^3)	Upscaled (m^3)	Unit	Data Source

Construction Phase				
Land	9.78E-04	8.56E-06	m^2	Pilot Owner
Tanks (2)	7.00E-02	1.18E-04	p	Pilot Owner - Material production + main process (injection moulding) + transport (PEF guidelines) - Ecoinvent
Pumps (2)	2.27E-04	1.36E-01	p	Pilot Owner- Adaptation from Ecoinvent process for water pump production (1 piece of 22 kW)- Disposal included
Reactor	8.20E-02	3.23E-03	kg	Pilot Owner - Material production + main process (injection moulding) + transport (PEF guidelines) - Ecoinvent
Operational Phase				
		Input		
Electricity	4.02E-01	6.99E-02	kW	Pilot owner - Ecoinvent
deionised water	2.85E-01	7.50E-05	kg	Pilot owner - Ecoinvent
CHLORIDE ACID (HCl) 1M	6.33E-03	1.91E-06	g	Pilot owner - Ecoinvent
methaacrylic acid (MAA)	2.09E+00	5.25E-04	g	Pilot owner - Ecoinvent
ethylene glycol dimethacrylate (EGDMA)	2.40E+01	6.01E-03	g	Pilot owner - Ecoinvent
AIBN (initiator)	2.42E-01	5.24E-07	g	Pilot owner - Ecoinvent
acetonitrile	1.58E-01	2.50E-05	g	Pilot owner - Ecoinvent
methanol	7.09E+00	8.88E-04	kg	Pilot owner - Ecoinvent
acetic acid	7.27E-01	1.30E-04	kg	Pilot owner - Ecoinvent
Sand	5.61E+00	2.14E-03	kg	Pilot owner - Ecoinvent
		Output		
acidic water	2.85E+02	7.50E-05	l	Pilot owner – Ecoinvent (hazardous waste disposal)
acetic acid	7.27E-01	1.30E-04	kg	Pilot owner – Ecoinvent (hazardous waste disposal)
Methanol	7.09E+00	8.88E-04	kg	Pilot owner – Ecoinvent (hazardous waste disposal)
Sand	5.61E+00	2.14E-03	kg	Pilot owner – Ecoinvent (hazardous waste disposal)
Disposal Phase				
Waste Tank, Reactors	2.74E-01	3.35E-03	kg	Hypothesis Municipal collection (45km) - Ecoinvent

Supplementary Table 3.E Lists of the 16 Impact Categories of Product Environmental Footprint (EF 3.1).

ICs	IC Indicator	Unit	Characterisation Model
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al., 2006)
Climate Change	Radiative forcing as global warming potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC, 2013
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model 2.1 (Fankte et al, 2017)
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al., 2006)
Human toxicity, cancer	Comparative Toxic Unit for human (CTUh)	CTUh	USEtox model 2.1 (Fankte et al, 2017)
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUh)	CTUh	USEtox model 2.1 (Fankte et al, 2017)
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Land use	Soil quality index: • Biotic production • Erosion resistance • Mechanical filtration Groundwater replenishment	Dimensionless (pt): • kg biotic production • kg soil • m^3 water m^3 groundwater	Soil quality index based on LANCA (Beck et al., 2010)
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state ODPs as in (WMO 2014 + integrations)
Particulate matter	Impact on human health	disease incidence	PM method recomended by UNEP (UNEP 2016)
Photochemical ozone formation - human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002

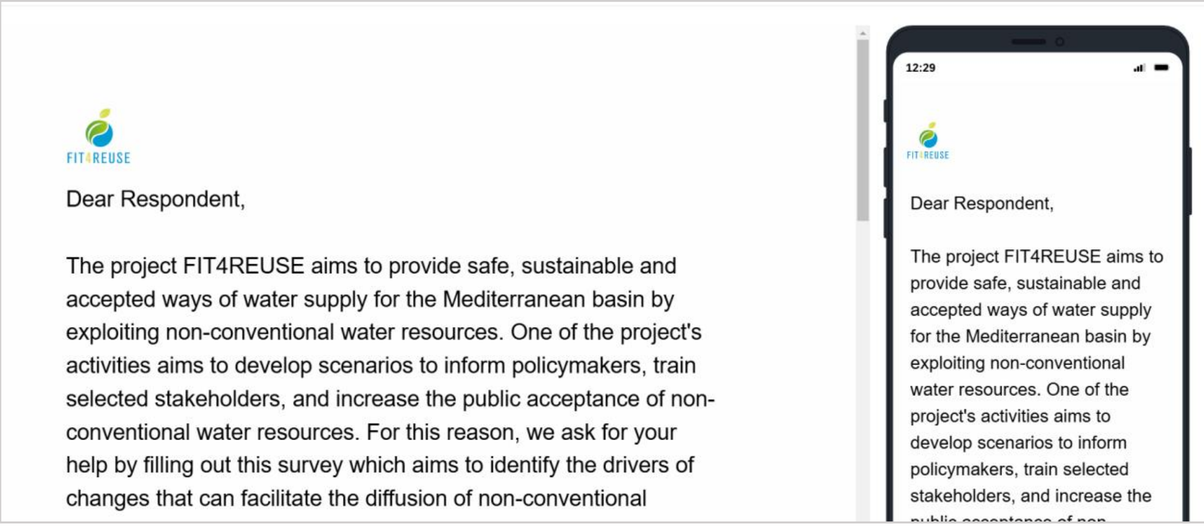
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserve)	kg Sb eq	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Water Use	User deprivation potential (deprivation weighted water consumption)	m^3 world eq	Available WAter REmaining (AWARE) as recommended by UNEP, 2016

Supplementary Table 3.F Monetisation factors and Consumer Price Index used for environmental costs accounting.

Country	ICs	Low	Central	High	CPI (2018)	CPI (2023)
Italy	Climate change	7.66E-02	1.28E-01	2.41E-01	1.03E+02	1.28E+02
Italy	Ecotoxicity, freshwater	2.98E-24	4.76E-05	2.34E-04	1.03E+02	1.28E+02
Italy	Eutrophication, marine	4.00E+00	4.00E+00	4.00E+00	1.03E+02	1.28E+02
Italy	Eutrophication, freshwater	3.24E-01	2.39E+00	2.71E+00	1.03E+02	1.28E+02
Italy	Water use	0.00E+00	2.04E+00	8.13E+00	1.03E+02	1.28E+02

Retrieved from European Commission (2020) and FAOSTAT database

Supplementary Figure 3.B Screenshot of survey outlook for the two-round of Delphi consultation.



Full preview of survey here

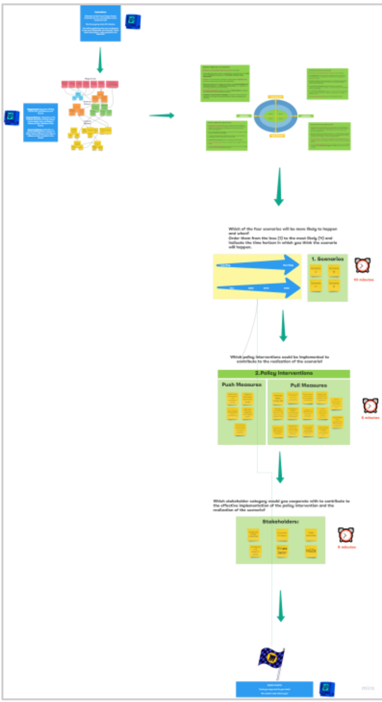
Supplementary Table 3.G Full list of internal and external drivers of change for water reuse diffusion provided to experts for the two rounds of Delphi e-surveys. Based on Berti Suman et al. (2023).

Drivers	Level	Potential Effect	Examples	Country
		External drivers		
Awareness	Social	Barrier	Gap between awareness of farmers, experts, and reviewers	Turkey
			Low public awareness and mistrust of the provided water quality of the NBS	Greece
			Lack of trust of farmers in the plant operators	Spain
Circular Resources Management	Environmental	Incentive	The opportunity to close the "nutrient cycle" supporting the transition to a sustainable agricultural system	Spain
			Energy valorisation	Greece
Communication Strategy	Social	Barrier	Lack of an effective and adequate communication strategy	Italy
			Miscommunication of the risks associated with water reuse	Spain
		Incentive	Promotion of reliability of the solutions	Greece
Public Acceptance	Social	Barrier	Negative perception associated to wastewater by "average consumer"	Italy
			Initial low public acceptance (especially remote areas)	Greece
Culture	Social	Barrier	Cultural Barriers	Turkey
Education	Social	Barrier	Education on Water Reuse (e.g. schools)	Italy

		Incentive	Partnerships with opinion makers to inform and educate about water reuse	Portugal
EU Legislation	Policy	Incentive	EU legislation that streamlines water reuse processes	Italy
		Barrier	Unclear paperwork brought by the new EU Regulation	Spain
		Incentive	Innovative legal framework for water reuse	Spain
			New European legislation	Italy
			EU benchmark that can harmonize the standards	Italy
			EU legislation that removes future bottlenecks due to different standards	Italy
		Barrier	Long and complex adaptation to new EU regulation	Greece
		Incentive	Build coherence with other food safety regulations	Italy
Financial incentives	Financial	Barrier	Not enough financial incentives for reusing wastewater	Italy
		Incentive	Incentives in the water tariff as currently in the EU regulation	Italy
Innovation	Financial	Barrier	Industries too weak for innovating	Turkey
	Social		Farmers that are leaving the field and struggle to innovate	France
Lobbying	Political	Barrier	Stronger lobbying against water reuse	Spain
		Incentive	Strong lobbying in favour	
National Legislation	Policy	Barrier	Denial of permission once already built the treatment plant	Spain
			Late adoption of reuse regulation compared to other countries	Greece
			Difficulties in obtaining permits due to national legislation	Portugal
			Stricter limit at the national level compared to EU standards	Italy
Policy-makers engagement	Social	Incentive	Involvement of city leaders to implement smart urban projects	Portugal
Reuse cost	Financial	Barrier	High reuse cost for farmers	Italy
			High reuse cost for farmers who do not want to pay for water	Spain
Risk Assessment	Technical	Barrier	Limited Capabilities in assessing real risks for water quality	Turkey
Stakeholders Agreement	Social	Barrier	Lack of agreement between involved stakeholders	Italy
			Different visions among stakeholders	Portugal
Water Governance	Policy	Incentive	The possibility to reuse water in industrial water-demanding processes	Jordan
	Political	Barrier	Cumbersome water governance structures	Italy
	Policy	Incentive	Future water planning at basin level should include water reuse	Spain
	Policy	Incentive	Effective planning on WR	Italy
	Policy	Barrier	Lack of policy tools to address water scarcity	Portugal
	Policy	Barrier	Need to respect minimum distance from urban areas for using treated water in irrigation	France
	Policy	Incentive	Promote enabling factors (treatment plants, infrastructures)	Italy
Territorial Features	Financial	Barrier	Unfavourable country structure (location of demand distant from agricultural areas)	Greece
	Social	Barrier	Urban concentration pushing to centralized water treatment	Greece
Water Scarcity	Social/ Environmental	Incentive	Water Scarcity perceived as an urgent issue	Spain
	Social	Barrier	Conflicts over water	Tunisia
			High pressure on water due to tourism	Greece
			Social conflicts on water management (agriculture vs tourism)	Greece

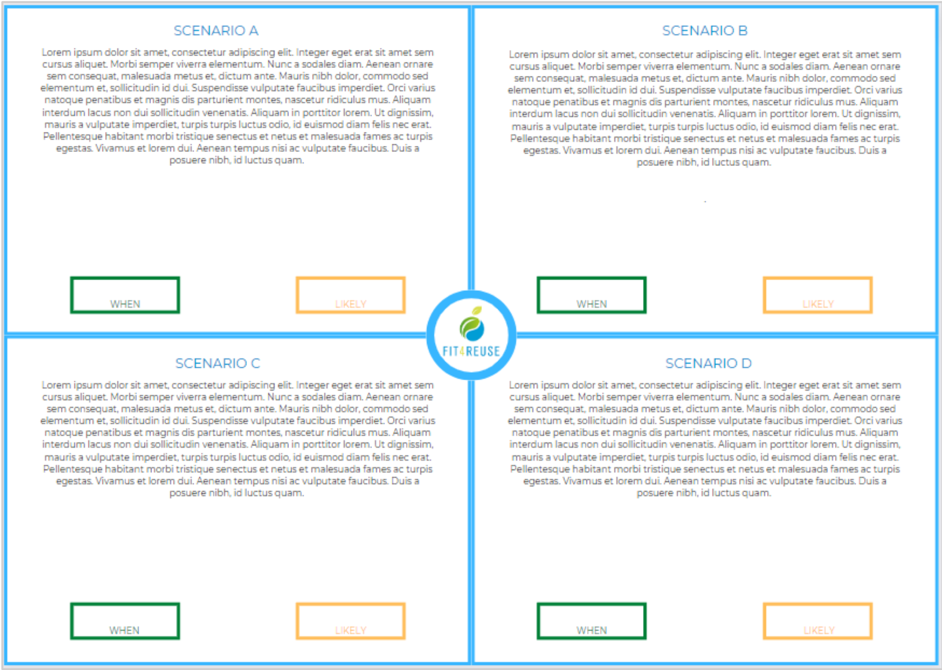
			Social conflicts over river basin during summer	Italy
Bureaucracy	Technical	Barrier	Bureaucratic matters (difficulties in authorizing water reuse plans enabling NBS	Greece
Circular Management of Resources	Technical	Incentive	By-products useful for commercial purposes	Israel
			Use of brine for irrigation of medicinal plants	Tunisia
Environmental Risk	Environmental	Barrier	Salinization risks for aquifer and soil due to over exploitation	Tunisa
Profitability	Economic	Barrier	Low motivation for private contractors involved in the construction of non-conventional wastewater treatment technologies at the stage of tender	Greece
			Combine the various treatments to have an applied technology with sustainable costs	Italy
			Lack of an accurate cost analysis	Tunisa
Scalability	Technical	Incentive	Application potential (1000m3/h)	Israel
		Barrier	Problem of scale	Italy
	Environmental	Barrier	Land Footprint of Constructed Wetlands for large areas	Italy
Technical complexity	Technical	Barrier	Difficulties in carrying out cost analysis	Tunisia, Italy
Technology Efficiency	Technical	Incentive	Improved pathogens removal	Tunisia
			Cost effectiveness	Italy
			Improvement treatment efficiency	Italy
			Treatment of domestic wastewater	Greece
			Treatment of brine and brackish groundwater	Israel
			The possibility to reuse water in industrial water-demanding processes	Jordan
			Minimal footprint of innovative solutions	Israel
		Barrier	Difficulties in implementing the pilot	Greece
	Environmental	Incentive	Reduced energy consumption	Italy
			Less required area	Israel
			Reduction of nitrate and phosphorus concentration	Israel
Water Quality	Environmental	Barrier	Poor water quality from WR technologies	Greece

Supplementary Figure 3.C Screenshot of Miro Board used in the focus group for the two-round of Delphi consultation.



Full board available here

Supplementary Figure 3.D Double sided template used for Focus Group discussion and data collection.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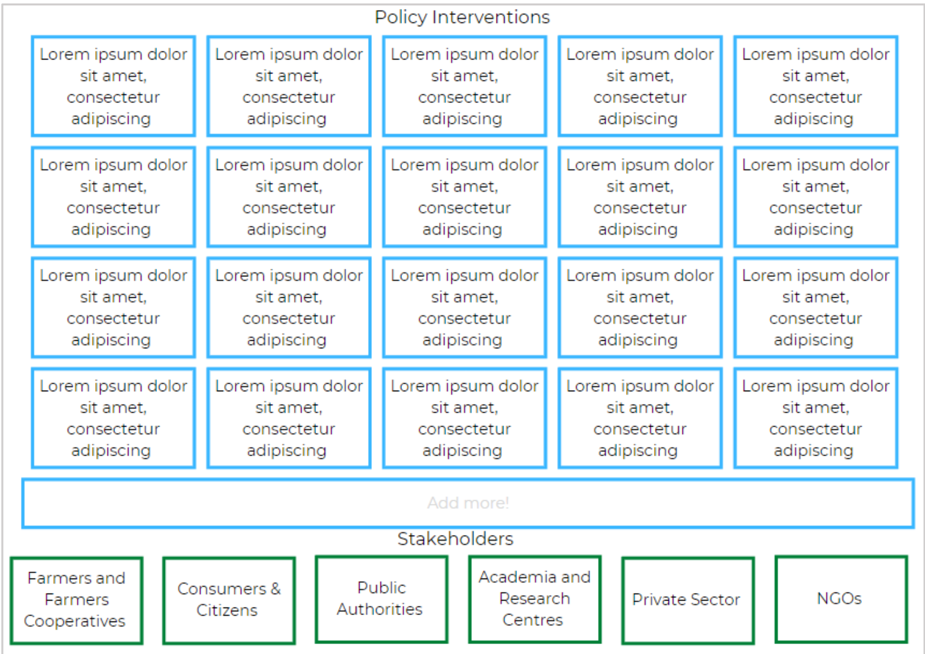
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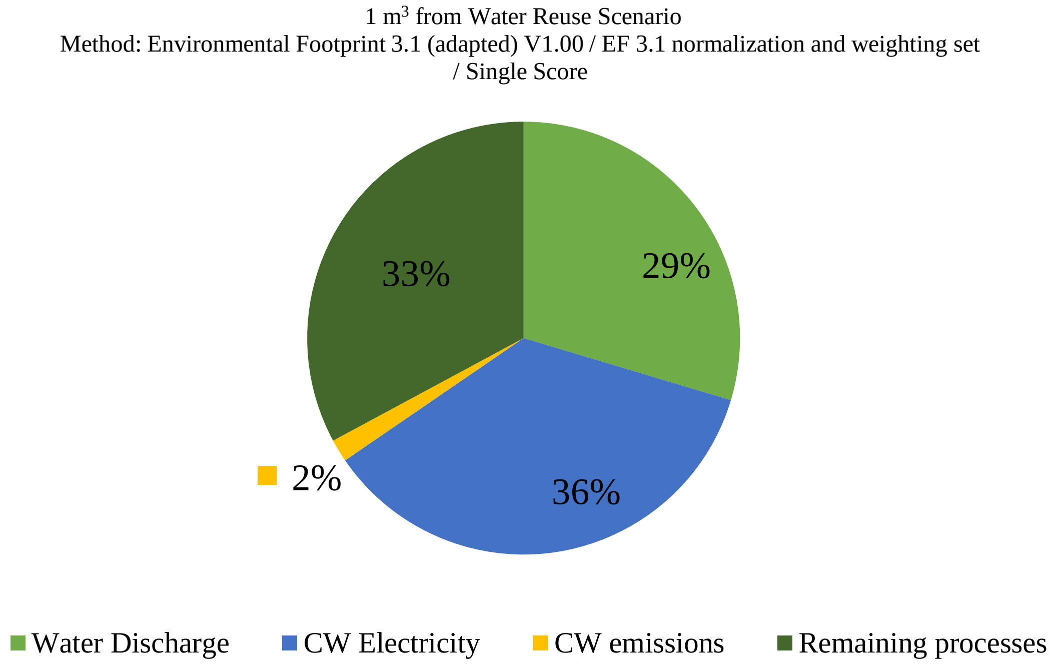
Add more!
Stakeholders
Farmers and Farmers Cooperatives
Consumers & Citizens
Public Authorities
Academia and Research Centres
Private Sector
NGOs

Supplementary Table 3.H Description of the four scenarios for non-conventional water resources diffusion by 2050.

Scenario A (Business as Usual) **Expensive and mistrusted water reuse** · Escalating demand for traditional water resources and **no water reuse** makes agriculture unviable in many areas. · **Inequitable distribution of freshwater** in marginal territories, with most users unable to meet their needs. · Insufficient investments, **low financial incentives**, and **bureaucratic inefficiencies** prevent the scaling up and adoption of water reuse technologies · **Ineffective communication** fails to convince stakeholders of the reliability of water reclamation technologies, further hampering adoption.	**Scenario B** **Cheap, but mistrusted water reuse** · Technological progress in water reclamation **reduces freshwater extraction** for agriculture. · Investments, financial incentives, and streamlined bureaucracy **boost technological efficiency and profitability in water reclamation.** · **Limited awareness** due to poor communication impedes full diffusion of water reclamation technologies. · **Uneven access to freshwater** resources, with stakeholders struggling to meet their needs, is exacerbated by rapid urbanisation which increases pressure on water resources.
Scenario C **Expensive, but trusted water reuse** · Traditional water resource strain increases, but **optimised strategies** help to **integrate alternative water sources** in agriculture. · **Rapid technological advances** support efficient water reuse solutions, that yet remain limited in accessibility due to **low investments and incentives**. · **Effective communication** improves trust in water reuse technologies, but **bureaucratic inefficiencies** hinder practical application. · **Freshwater access is inequitable**, causing significant challenges for agricultural water users. · Urbanisation increases competition for water resources.	**Scenario D** **Cheap and trusted water reuse** · Demand of traditional water resources remains high, but **adaptive strategies** optimise usage and **integrate reclaimed water into agriculture.** · **Significant investments,** incentives, and **efficient bureaucracy** led to the widespread adoption of water reclamation technologies. · Advanced technologies **improve water quality** while minimizing environmental risks, supported by market adoption. · **Effective communication** builds trust in water reclamation solutions and boosts their adoption. · Freshwater access remains inequitable, but the use of reclaimed water **reduces reliance on freshwater** despite ongoing urbanisation.

Supplementary Figure 3.D Contribution analysis of electricity to total impact in WR Scenario.



Supplementary Table 3.I Checklist of the consolidated criteria for reporting qualitative studies (COREQ Guidelines) for Delphi e-surveys and focus groups.

No. Item	**Guide questions/description**	**Reported on Page #**
Domain 1: Research team and reflexivity		
Personal Characteristics		
1. Interviewer/facilitator	Which author/s conducted the interview or focus group?	#86
2. Credentials	What were the researcher's credentials? E.g. PhD, MD	
3. Occupation	What was their occupation at the time of the study?	
4. Gender	Was the researcher male or female?	
5. Experience and training	What experience or training did the researcher have?	
Relationship with participants		
6. Relationship established	Was a relationship established prior to study commencement?	#86-89
7. Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	
8. Interviewer characteristics	What characteristics were reported about the interviewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	
Domain 2: Study design		
Theoretical framework		
9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study?	#86
Participant selection		
10. Sampling	How were participants selected? e.g. purposive, convenience, consecutive, snowball	#87-88
11. Method of approach	How were participants approached? e.g. face-to-face, telephone, mail, email	
12. Sample size	How many participants were in the study?	
13. Non-participation	How many people refused to participate or dropped out? Reasons?	
Setting		
14. Setting of data collection	Where was the data collected? e.g. home, clinic, workplace	#87-88
15. Presence of non-participants	Was anyone else present besides the participants and researchers?	
16. Description of sample	What are the important characteristics of the sample? e.g. demographic data, date	
Data collection		
17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	#87
18. Repeat interviews	Were repeat interviews carried out? If yes, how many?	#87-89
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?	
20. Field notes	Were field notes made during and/or after the interview or focus group?	
21. Duration	What was the duration of the interviews or focus group?	
22. Data saturation	Was data saturation discussed?	
23. Transcripts returned	Were transcripts returned to participants for comment and/or correction?	
Domain 3: analysis and findings		
Data analysis		
24. Number of data coders	How many data coders coded the data?	#88
25. Description of the coding tree	Did authors provide a description of the coding tree?	#87-88
26. Derivation of themes	Were themes identified in advance or derived from the data?	#87-88
27. Software	What software, if applicable, was used to manage the data?	#88
28. Participant checking	Did participants provide feedback on the findings?	#59
Reporting		
29. Quotations presented	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	#93-96
30. Data and findings consistent	Was there consistency between the data presented and the findings?	
31. Clarity of major themes	Were major themes clearly presented in the findings?	
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?	