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Eco-Efficiency and Circularity in the Olive Oil Waste and By-Products Management: An Integrated LCA-CBA Framework to Guide SMEs' Ecological Transition

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Abstract

The Circular Economy (CE) paradigm is receiving increasing attention for addressing sustainable development in various industrial sectors. The olive oil industry is particularly involved in the transition towards sustainability due to the severe environmental impacts associated with its massive waste generation (e.g., olive pomace and wastewater) and its crucial socio-economic role in the Mediterranean basin. In this context, a lack of multidimensional studies explicitly focusing on the actual eco-efficiency of circular practices in the olive oil sector is highlighted. Particularly, a strategic framework or operational guidelines integrating environmental and economic assessments to guide Small and Medium-sized Enterprises (SMEs) are less investigated. Consequently, aligning with the core objective of the doctoral research project, i.e., the identification and application of tools for improving process and product eco-efficiency in a circular economy perspective in the olive oil sector, the present thesis aims to provide tangible support for olive oil industries. It seeks to overcome decision-making paralysis by offering an accessible methodological tool to assess and implement economically viable and environmentally sound circular practices. To achieve this aim, the thesis is structured in five chapters.

Chapter 1 introduces the background and general context of the thesis, provides a description of the literature gaps the research seeks to address, and outlines the research questions and approaches. It also describes the thesis structure.

Chapter 2 explores the state of the art through a bibliometric and systematic literature review, mapping the existing treatment technologies and valorisation patterns for olive oil waste and by-products, while critically analyzing their explicit and implicit link with the concept of eco-efficiency, environmental sustainability and CE.

Chapter 3 presents an empirical analysis based on an integrated Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) of a representative Sicilian olive oil supply chain, measuring the actual environmental credits and financial performances of implemented circular practices.

Chapter 4 proposes the Life Cycle Thinking Decision Framework (LCT-DF), i.e., a semi-quantitative, operational tool complemented by a five-step managerial roadmap, intended to guide olive oil companies in assessing technological trade-offs and achieving systemic circularity.

Finally, Chapter 5 discusses the key findings of the research presented in Chapters 2, 3, and 4, which, overall, provide many insights into the implementation, assessment, and management of the CE at the supply chain level in the olive oil sector.

Firstly, the results of this PhD thesis highlight an abundance of validated treatment technologies, though frequently lacking practical economic feasibility frameworks. Secondly, despite growing attention to circularity, the empirical analysis reveals a structural logistical bottleneck demonstrating that transporting and downcycling wet biomass is financially unsustainable for individual SMEs. Thirdly, the research conceptually advances the idea of "systemic eco-efficiency", proving that circular waste and by-product management must be approached as an integrated corporate investment, strategically subsidized by the premium revenues of the core product (EVOO). Finally, the conceptual and operational framework represents a concrete attempt to guide companies of the sector in navigating financial complexities and communicating the circular value generated. Following that, the present thesis provides insights into policy and managerial implications, such as the need for agro-industrial districts, also identifying the next steps to foster future research and to ensure a sustainable and circular transition in the Mediterranean olive oil industry.

Keywords: Olive oil sector; waste and by-products; Circular Economy; Systemic eco-efficiency; Life Cycle Assessment (LCA); Cost-Benefit Analysis (CBA); Decision-support framework.

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List of abbreviations

- **2-P** – Two-Phase (extraction system)
- **3-P** – Three-Phase (extraction system)
- **AC –** Acidification
- **BCR** – Benefit-Cost Ratio
- **BMP** – Biochemical Methane Potential
- **BOD** – Biochemical Oxygen Demand
- **CAPEX** – Capital Expenditure
- **CBA** – Cost-Benefit Analysis
- **CC –** Climate Change
- **CE** – Circular Economy
- **CH_4** – Methane
- **COD** – Chemical Oxygen Demand
- **CO_2** – Carbon Dioxide
- **DEA –** Data Envelopment Analysis
- **EF** – Environmental Footprint
- **ES** – Environmental Sustainability
- **ESI** – Energy Sustainability Index
- **EU –** European Union
- **EVOO** – Extra Virgin Olive Oil
- **FE –** Eutrophication-freshwater
- **FET –** Ecotoxicity-freshwater
- **FU** – Functional Unit
- **GHG –** Greenhouse Gas
- **HT** – Human Toxicity
- **IR –** Ionizing Radiation
- **ISO** – International Organization for Standardization
- **LCA** – Life Cycle Assessment
- **LCC** – Life Cycle Costing
- **LCI** – Life Cycle Inventory
- **LCIA** – Life Cycle Impact Assessment
- **LCSA** – Life Cycle Sustainability Assessment
- **LCT-DF** – Life Cycle Thinking Decision Framework
- **LHV –** Lower Heating Value
- **LU –** Land Use
- **ME** – Eutrophication-marine
- **MOLP** – Multi-Objective Linear Programming
- **OD –** Ozone Depletion
- **OMWW** – Olive Mill Wastewater
- **OMWSR** – Olive Mill Wastewater Steam Reforming
- **OP** – Olive Pomace
- **OPEX** – Operational Expenditure
- **PM –** Particulate Matter
- **POF –** Photochemical Ozone Formation
- **Q1** – Query 1
- **Q2** – Query 2
- **RU-mm** – Resource Use-minerals and metals
- **SDGs** – Sustainable Development Goals

- **S-LCA** – Social Life Cycle Assessment
- **SMEs** – Small and Medium-sized Enterprises
- **SRMs** – Secondary Raw Materials
- **TE –** Eutrophication-terrestrial
- **VOCs –** Volatile Organic Compounds
- **WF** – Water Footprint
- **WoS –** Web of Sciences
- **WU –** Water Use

Chapter 1
Introduction and scientific background

1.1 Importance of the ecological transition in the agri-food sector

The agrifood sector stands at the crossroads of some of the most urgent global challenges, including climate change, resource depletion, biodiversity loss, and social inequality. As an integrated system connecting agriculture, industrial processing, distribution, and consumption, it acts as both a major contributor to environmental degradation and a primary enabler of sustainable development. Currently, the global agrifood system is a principal driver of anthropogenic climate change, consistently accounting for approximately one-third of total global greenhouse gas (GHG) emissions. According to the most recent consolidated data from FAOSTAT (2025), agrifood emissions reached an estimated 16.5 Gt CO_2 eq in 2023, representing roughly 31% of the global total (FAO, 2023). While historical estimates, such as those by Popova et al., (2022), have placed the sector's contribution between 20–25%, recent comprehensive accounting highlights a growing footprint that could increase by 50–90% by 2050 under business-as-usual conditions. The internal composition of these emissions reveals a critical structural shift within the global food value chain. While on-farm activities (crop and livestock production) remain the largest contributor at approximately 48.5% (8.0 Gt CO_2 eq), driven primarily by enteric fermentation and synthetic fertilizer use, the most significant growth is now observed in the pre- and post-production stages (FAO, 2023). As highlighted by Tubiello et al., (2022), the rapid growth of emissions from food processing, packaging, and retail implies that climate mitigation strategies can no longer focus solely on on-farm interventions but must systematically address the entire post-harvest value chain. This agrifood supply chain segment, which encompasses food processing, packaging, transport, and waste or by-product management, accounts for roughly 34.5% (5.7 Gt CO_2 eq) of the system's total footprint. On other hand, the rising trajectory in this sector's emissions is compounded by the necessity to meet the needs of a growing population. In the first half of this century, global demand for food, feed, and fiber is expected to grow by 70% (FAO, 2023), placing unprecedented pressure on limited agricultural resources such as arable land, freshwater, and nutrients. Within this context of resource scarcity, global food waste has reached alarming proportions, representing a significant inefficiency in the system. According to the United Nations Environment Programme (UNEP, 2024), approximately 1.05 billion tonnes of food were wasted in 2022, equivalent to nearly 19% of all food available to consumers. Most of this waste (60%) occurred at the household level, followed by food services (28%) and retail (12%). Ultimately, the FAO's 2024 State of Food and Agriculture (SOFA) report emphasizes that the hidden environmental costs of these systems, including nitrogen runoff and the 8–10% of global emissions specifically linked to food loss and waste, necessitate a holistic transformation of the entire value chain to meet the mitigation targets set by the Paris Agreement (United Nations, 2015a).

These numbers underscore the critical scale of food waste: despite the persistence of global hunger and food insecurity, a substantial portion of food is lost or discarded, representing an ethical tragedy as well as a profound environmental and economic concern. The generation of waste and by-products within the agri-food sector often stems from systemic inefficiencies, suboptimal resource management, and unsustainable consumption patterns (Islam and Zheng, 2025). These residues are produced across all levels of the supply chain, ranging from harvesting and post-harvest practices to storage, processing, logistics, retail, and ultimately, household consumption. Consequently, food losses make global scarcity worse, inflict severe environmental harm, and impose high economic costs (Islam and Zheng, 2025). To address these systemic failures, the Sustainable Development Goals (SDGs), adopted by the United Nations in 2015, provide a universal framework to protect the planet and ensure prosperity. Comprising 17 interconnected goals and 169 targets, the SDGs offer a comprehensive approach to integrating social, economic, and environmental challenges (United Nations, 2015b). Unlike the previous Millennium Development Goals (MDGs), which provided a 15-year framework (1990–2015) to improve global well-being (World Health Organization, 2018), the SDGs emphasize a triple line, balancing economic growth, social inclusion, and environmental protection, while prioritizing innovation and systemic change. Within this global agenda, agriculture and food systems occupy a pivotal role; they are directly linked to the eradication of hunger (SDG 2), responsible production and consumption (SDG 12), climate action (SDG 13), and the preservation of biodiversity (SDGs 14–15) (United Nations, 2015b). Achieving these targets requires more than incremental technological gains; it demands a profound transformation of production models, consumption habits, and governance structures (FAOSTAT, 2025). To respond to these escalating demands, the agricultural sector must adopt transformative technologies. Addressing these interrelated challenges requires an urgent ecological transition toward production models that are resource-efficient, circular, and regenerative. This shift necessitates "producing more with less" by fostering technological innovation, closing material loops, and valorizing waste and by-products, in alignment with circular economy (CE) principles and sustainable development objectives (Donner et al., 2022a; Ghisellini et al., 2016). The current global consumption of resources is inherently unsustainable, a fact well-established in contemporary literature (Figge and Thorpe, 2023). The magnitude of this environmental overshoot has been widely communicated through indicators such as the Ecological Footprint and Earth Overshoot Day (Global Footprint Network, 2022), which have brought the issue of systemic overconsumption into mainstream discourse. At its core, humanity is consuming beyond the planet's regenerative capacity. To analyze the drivers of this impact, scholars frequently utilize the IPAT identity (Barry Commoner, 1971), which provides a mathematical framework linking environmental impact (I) to population (P), affluence (A), and technology (T). In this model, Impact (I) represents an absolute measure, such as CO_2 emissions in tonnes or energy use in Gigajoules (GJ). Population (P) refers to the total number of individuals in each region, while Affluence (A), typically measured as Gross Domestic Product (GDP) per capita, serves as a proxy for material well-being. Finally, Technology (T) reflects the resource intensity of that affluence. The relationship is expressed through the following equation:

$$I = Px\ A\ x\ T$$

Using standard units where Impact is measured in tonnes (t), population in number of people (nr), and affluence in GDP (USD), the identity functions as follows:

$$I(t) = Population\ (nr)\ x\ Affluence\ \left(\frac{USD}{nr}\right) x\ Technology\ \left(\frac{T}{USD}\right)$$

As noted by Figge and Thorpe, (2023), the equation demonstrates that to reduce the absolute environmental impact (I) while population (P) and affluence (A) continue to rise, the only viable leverage point is a radical improvement in the efficiency of technology (T).

This basic formulation highlights two main levers for reducing impacts at any given population level: lowering affluence (absolute consumption) and improving technology (reducing resource use or emissions per unit of economic output) (Chertow, 2000). The ecological transition in the agri-food sector cannot be achieved merely by reducing emissions and resource use. While these are essential, sustainability in this field must also account for economic and social dimensions, alongside environmental ones. In this sense, the CE has emerged as one of the most influential and widely applied frameworks for rethinking production and consumption systems.

According to the Ellen MacArthur Foundation (2015), the CE is based on three core principles: (i) eliminate waste and pollution by design, (ii) circulate products and materials at their highest value, and (iii) regenerate natural systems. Moving from a linear to a circular model represents a crucial step toward sustainability, particularly in agri-food systems where waste valorisation and resource regeneration are highly relevant. The CE offers a valuable framework to reconcile environmental, economic, and social objectives, drawing on foundations that are at once ecological and political, as well as economic and business-oriented. By fostering a more efficient and sustainable use of resources, CE supports the transition toward a greener economy based on innovative business models and new employment opportunities (Ellen MacArthur Foundation, 2015). Beyond its economic benefits, the CE contributes to improved well-being and greater inter- and intra-generational equity regarding resource access and use (Ghisellini et al., 2016). However, the inherent complexity of the sustainable development vision necessitates new strategies and models to implement circular approaches that can trigger radical changes in practices, policies, and decision-making tools. It is crucial to acknowledge that not all circular practices are inherently sound; some may present high economic costs or sustainability trade-offs that hinder their practical implementation (Kounani et al., 2023). Consequently, scholars emphasize the necessity of developing multi-perspective and integrative methods to embed the CE within a more comprehensive sustainability framework. Building on this reasoning, Figge and Thorpe, (2023) proposed a model that examines the integration of the CE, eco-efficiency, and sufficiency, highlighting the complex interactions between these approaches. In this framework, eco-efficiency, often described as 'doing more with less', underlies the idea that creating 'more value with less impact' can steer companies and society toward a more sustainable use of resources (WBCSD, 2000). This can be understood as "operational efficiency," meaning that the value generated per unit of resource is maximized. At the same time, by reusing resources multiple times, the system reduces the need for new (virgin) inputs while still creating economic value, thus putting the principles of circularity into practice. However, further investigation is required to identify the conditions under which specific combinations become most effective: for instance, a critical limitation of the circular model is that recycling is ultimately constrained by the laws of thermodynamics. These physical laws render the prospect of infinite material recycling a utopian ideal rather than a realistic solution, as energy degradation and material dissipation are inevitable (Figge and Thorpe, 2023). Consequently, integrating circular technologies and regenerative practices into well-established production systems require more than technical adjustments; it demands profound managerial shifts and radical business model innovation. Even though organic farming and corporate social responsibility programmers have made the agrifood sector more sustainable over time, comprehensive long-term strategies aimed at decoupling growth from resource depletion are still lacking (Spina et al., 2024). A truly circular agri-food system would integrate restorative agroecological practices with waste and by-product valorisation through multi-output and integrated production chains (e.g., biorefineries) (Liu et al., 2021), where cascading processes are organized according to the biomass value pyramid, prioritizing the most valuable and efficient uses of resources. In conclusion, the transition to a circular food economy cannot be reduced to the mere adoption of greener technologies or incremental increases in efficiency. Rather, it represents a profound socio-technical transformation that requires systemic change along the entire agri-food supply chain. This involves not only promoting technological innovation and policy reforms but also rethinking production and consumption models in line with CE principles, eliminating waste and pollution, maintaining materials in use, and regenerating natural systems (Ellen MacArthur Foundation, 2019). Furthermore, the combination of eco-efficiency with circularity allows for a more holistic and systemic transition, which allows for a more holistic vision that can be applied to the agri-food production context from the perspective of ecological transition. By improving resource productivity and minimizing losses, eco-efficiency complements circular approaches, making them more feasible and scalable in real-world contexts. For the agri-food sector, responsible for a substantial share of global greenhouse gas emissions and resource depletion, this means moving beyond fragmented solutions toward integrated strategies that reconcile productivity with resilience, equity, and ecological regeneration. Achieving such a transformation is critical for the realization of the SDGs, especially those related to zero hunger (SDG 2), responsible consumption and production (SDG 12), and climate action (SDG 13) (United Nations, 2015; FAO, 2022; UNEP, 2024).

1.2 The olive oil supply chain

Focusing attention from the global agri-food system to specific regional contexts, the olive oil supply chain emerges as a paradigm of immense economic importance and, at the same time, complex environmental challenges. Derived from the fruit of the olive tree (Olea europaea L.), olive oil is not only one of the most globally demanded agri-food products but also a foundational cultural, social, and economic symbol in the Mediterranean basin (Kapellakis and Tsagarakis, 2024; Kirmizakis et al., 2020). Today, its unique flavor, well-documented health benefits, and strict quality standards continue to drive substantial global demand. According to the latest statistical reports from the International Olive Council (IOOC, 2025), the global olive oil market is characterized by massive volumes and high geographical concentration. Global production fluctuates between 2.5 and 3.4 million tonnes annually, driven heavily by climatic conditions and the natural alternating bearing of the olive tree. The Mediterranean basin remains the undisputed center of this industry, accounting for over 90% of global output, with the European Union (EU), led by Spain, Italy, and Greece, producing roughly 60% to 70% of the world's supply. Non-EU Mediterranean countries, such as Tunisia, Turkey, and Morocco, are also consolidating their roles as major global players. In terms of consumption, the market absorbs approximately 2.8 to 3.2 million tonnes globally per year. While traditional producing countries in the EU maintain the highest per capita consumption, there is a distinct paradigm shift toward non-producing regions. Driven by the recognized nutritional and health benefits of the Mediterranean diet, countries such as the United States have emerged as dominant global importers and consumers, absorbing roughly 400,000 tonnes annually (IOOC, 2025). The global demand for extra virgin olive oil (EVOO) is fundamentally driven by its unique chemical composition, which confers a favorable nutritional profile and exceptional oxidative stability. EVOO is characterized by a dominant lipid matrix, with triacylglycerols constituting approximately 98% of its total lipids. This fraction exhibits a strong predominance of oleic acid, a monounsaturated fatty acid, coupled with a limited presence of polyunsaturated fats. This specific lipidic balance is a central pillar of the Mediterranean diet. Beyond its lipidic base, EVOO is highly valued for its minor, yet critical, unsaponifiable fraction. Phenols and other bioactive micronutrients, including hydroxytyrosol, tyrosol, oleuropein, and lignans, are closely associated with potent antioxidant and anti-inflammatory activities, as well as protective contributions to cardiovascular and metabolic health. These compounds govern the oil's distinctive sensory attributes, specifically its characteristic bitterness and pungency (Gorzynik-Debicka et al., 2018). Similarly, the typical aroma of EVOO (often described as fruity or green) is defined by a complex mixture of volatile compounds generated through the lipoxygenase pathway during the mechanical crushing and malaxation of the olives. In the broader Mediterranean context, olive oil serves as a vital dietary and cultural milestone that drives regional economies and shapes sustainability practices across the entire supply chain (OECD and Food and Agriculture Organization of the United Nations, 2025) . This massive and globally expanding market underscores a critical environmental reality: to sustain an annual output of over 3 million tonnes of virgin olive oil, the industry concurrently generates up to 15 million tonnes of toxic agro-industrial by-products each year. From a mass balance perspective, the olive oil extraction process is highly disproportionate. Only a small fraction of the olive fruit, typically 15% to 20%, is converted into the noble product, virgin olive oil. The remaining 80% to 85% is discharged as agro-industrial by-products. (Soares et al., 2024). However, the precise volume and physicochemical characteristics of these generated by-products can vary significantly, as they are heavily dependent on both the specific olive cultivar processed and the extraction method employed. The production process of EVOO involves several fundamental mechanical and physical stages: the preparation and washing of the olives, crushing (milling), malaxation, and, finally, solid-liquid separation. This last stage, carried out using centrifugal machines (decanters), represents the technological core of the plant and crucially affects the type and volume of the generated by-products (Cecchi et al., 2020; Cuffaro et al., 2023). Extraction technologies are divided into three-phase (3-P) and two-phase (2-P) systems. In the 3-P system, a significant addition of processed water is required during centrifugation. This setup divides the olive paste into three distinct flows: olive oil, a solid or semi-solid fraction known as olive pomace (OP), and a massive aqueous fraction, namely olive mill wastewater (OMWW). The environmental impact of this system is substantial; it is estimated that for every liter of EVOO produced, approximately 2.5 liters of OMWW are generated, creating significant disposal problems (Cuffaro et al., 2024, 2023). To overcome excessive water consumption and the production of wastewater, modern plants predominantly adopt the 2-P system, which does not require the addition of external water. This process separates the oil from a single residual semi-solid by-product with a very high moisture content, called *alperujo* (a wet OP that includes the pulp, skin, the natural vegetative water of the fruit and crushed olive pits) (Ortega-García and Peragón, 2010). These technological differences result in waste streams with distinctly different chemical and physical profiles. Solid residues (olive mill solid waste, OP, or *alperujo*) and liquid ones (OMWW) require specific treatments to mitigate their ecological impact (Gomes et al., 2023). In particular, OMWW represents one of the main sources of agro-industrial pollution due to its high organic load and the high concentration of phytotoxic phenolic compounds. To fully grasp the environmental burden of the olive oil supply chain, it is essential to examine the distinct impacts generated across its primary stages. On one hand, the agricultural phase, encompassing tree cultivation, orchard management, and harvesting, contributes heavily to the overall ecological footprint. This impact is primarily driven by the intensive application of synthetic agrochemicals, including nitrogen- and phosphorus-based fertilizers, herbicides, and pesticides. Through agricultural runoff and soil leaching, these chemical inputs permeate local watersheds, triggering severe freshwater and marine eutrophication (the over-enrichment of water bodies leading to oxygen depletion). Furthermore, the persistence of these active ingredients in the environment induces significant terrestrial and aquatic ecotoxicity, a problem frequently exacerbated by the GHG emissions and soil compaction associated with the use of fossil-fuel-dependent agricultural machinery (Salomone and Ioppolo, 2012). On the other hand, the industrial milling phase represents a key environmental hotspot, closely linked to both the volume of waste generated and the extraction technology used. This stage requires significant inputs of electricity for crushing and centrifugation, as well as freshwater. However, its main environmental impact derives from the large amount of agro-industrial by-products produced. As previously illustrated, the mass balance of the extraction process is highly disproportionate: up to 85% of the total processed olive biomass is discharged as solid OP and liquid OMWW. Compounding this issue is the strict seasonality of olive oil production. This staggering volume of waste is generated within a very narrow temporal window, typically between October and December, rapidly overwhelming local waste management infrastructures and posing an acute threat of concentrated soil degradation and groundwater contamination (Falcone et al., 2022; Maffia et al., 2022; Salomone and Ioppolo, 2012). In addition, olive oil waste has been shown to negatively impact soil microfauna, natural water resources, and aquatic ecosystems when improperly managed (Azbar et al., 2004). To mitigate these impacts, the specific processing technology employed is pivotal. Comparative studies indicate that the 2-P extraction system can achieve approximately a 46% reduction in CO_2 equivalent emissions compared to the traditional 3-P regime. This significant disparity is primarily attributed to the higher electricity demands of the 3-P process, particularly during the malaxation and centrifugation stages, as well as its substantial water consumption, which inherently requires further energy for pumping and heating (Cinardi et al., 2024; Restuccia et al., 2022). Consequently, a profound understanding of these processing technologies is essential to identify key areas for environmental improvement, allowing producers to simultaneously optimize extraction yields, the chemical profile of olive oils, and the management of by-products (Cinardi et al., 2024). However, transitioning to more sustainable practices entails complex logistical challenges. The installation of modern decanters or the integration of advanced wastewater treatment systems is rarely a simple mechanical upgrade; it often necessitates substantial structural changes to the mill. Despite the high toxicity of the organic matter in these wastes and by-products, they also contain high concentrations of bioactive substances such as polyphenols, phytosterols, tocopherols, and carotenes that confer several functional properties and enable long storage times due to their high oxidative stability (Roig et al., 2006). Indeed, the very characteristics that make these by-products polluting also make them extraordinary matrices for the extraction of bioactive compounds. Both OMWW and OP have attracted considerable scientific interest from a CE perspective, as they are rich in polyphenols and other less polar molecules (Mulinacci et al., 2001; Obied et al., 2005). Various studies have quantified and tested recovery methods (e.g., organic solvents, enzymatic treatments, membrane separations) to isolate high-added-value molecules such as hydroxytyrosol, tyrosol, oleuropein, and their derivatives. These compounds offer enormous potential for applications in the food, nutraceutical, cosmetic, and bioenergy sectors (Cuffaro et al., 2024, 2023). Finally, it is crucial to emphasize that the phenolic profiles and extraction yields of these by-products are not universal; rather, they are strongly influenced by agronomic and processing variables, including the olive cultivar, fruit ripening stage, and extraction system (Cuffaro et al., 2024). When circularity is implemented, industrial residues and end-of-life products are processed and recycled into secondary raw materials. In the olive oil supply chain, this shift implies that olive oil waste and by-products are recovered to generate bio-based materials and renewable energy sources, which can be used both within and beyond the system boundaries (Cinardi et al., 2024). Under this perspective, the adoption of sustainable agricultural practices and advanced extraction technologies must be coupled with the comprehensive valorisation of all olive oil by-products. This entails a holistic approach that targets not only OP and OMWW but also olive tree pruning, waste cooking oil, and packaging materials. By aligning these recovery strategies with sustainability-oriented management hierarchies (Statuto et al., 2019), the industry can drastically reduce its associated environmental footprint, close the production cycle, and ensure the long-term ecological viability of the sector.

1.2.1 Bridging circular economy and eco-efficiency in olive oil sector

The CE is increasingly recognized as the definitive model for efficient resource management and environmental sustainability (ES), effectively superseding the traditional linear "take-make-waste" paradigm (Sauvé et al., 2016; Stempfle et al., 2021). The EU has made circularity a key part of its industrial, environmental, and economic policies. Important strategies, such as the Circular Economy Package (European Commission, 2015a) and the EU Circular Economy Action Plan (European Commission, 2020a), have placed the CE at the center of Europe’s long-term growth strategy. These policies aim to reduce waste, increase recycling, and improve resource efficiency across agri-food supply chains (Zarbà et al., 2021). This effort is further strengthened by the European Green Deal (European Commission, 2019) and its main agricultural plan, the Farm to Fork Strategy (European Commission, 2020b). These major policies push for real change, combining ES with food security and economic competitiveness. By setting strict goals for waste reduction and resource recovery, the EU encourages the agri-food sector, including the traditional olive oil industry, to move away from linear production models, by adopting more resilient, eco-efficient, and fully circular processes (Marques et al., 2025; Zarbà et al., 2021). However, transitioning to a circular model is not without challenges. The effective implementation of sustainable circular strategies faces significant structural and operational barriers. The olive oil industry continuously struggles with bureaucratic hurdles in obtaining authorizations, a highly fragmented territorial production, and the strict seasonality of raw material availability (European Commission, 2013). Furthermore, the management of these residues is frequently outsourced to third-party entities that often lack the specialized technologies and expertise required for high-value valorisation. This systemic inefficiency is particularly critical in the Italian context, where the olive oil supply chain is not merely an industrial sector but a profound cornerstone of the national economy and cultural heritage. Beyond these logistical hurdles, a critical theoretical issue persists while CE-driven models are frequently proposed to minimize waste, circularity does not automatically guarantee actual ES. The economic feasibility of CE supply chains in the olive oil industry requires rigorous, site-specific assessments that account for processing costs, logistical constraints, and the actual market potential of the resulting secondary raw materials (SRMs). Literature suggests that, in some scenarios, the high energy costs associated with biopolymer processing or active compound extraction could outweigh the environmental and economic benefits. This highlights the critical need for optimized processes, economies of scale, and targeted public incentives (Difonzo et al., 2021). Consequently, the successful adoption of CE practices is heavily contingent upon regional infrastructural conditions and a solid market demand for recycled or bio-based products (Cinardi et al., 2024; Kounani et al., 2023). Transitioning the olive oil supply chain toward a CE is not solely a technological challenge, but a profound socioeconomic one, heavily influenced by the size and organizational structure of the enterprises involved. While large corporations generally possess the financial resources, specialized expertise, and economies of scale necessary to invest in advanced infrastructure, comprehensive traceability systems, and environmental certifications, Small and Medium-sized Enterprises (SMEs) encounter severe structural and governance obstacles that can significantly delay or entirely prevent the adoption of circular practices (Lombardo et al., 2021; Spina et al., 2024). The primary bottleneck for SMEs is the limited access to the initial capital required for circularity investments. The installation of modern wastewater treatment plants or advanced by-product valorisation facilities demands substantial upfront expenditures. Large enterprises can efficiently amortize these high capital costs over massive production volumes, leveraging economies of scale to ensure the profitability of large-scale reuse and treatment systems. Conversely, SMEs inherently operate with smaller processing volumes and tighter profit margins. This scale disadvantage extends the time needed to recover investments, making substantial spending on circular infrastructure financially challenging and strategically less attractive for smaller producers (Spina et al., 2024).

Furthermore, the successful operationalization of CE practices demands a highly integrated governance model across the entire value chain. It requires proactive co-design and seamless coordination among olive growers, millers, and distributors. Large companies exert significant bargaining power, allowing them to dictate sustainability standards and efficiently coordinate complex, vertically integrated supply chains. In contrast, SMEs typically operate within highly fragmented local networks. They often lack both the structural integration and the market influence necessary to orchestrate unified, supply-chain-wide sustainability efforts (Lombardo et al., 2021; Silveira et al., 2022; Spina et al., 2024). Finally, there is a pronounced disparity regarding technological accessibility and innovation transfer. While large corporations can rely on greater financial resources and broader networks to support this transition, SMEs often lack the internal technical expertise and the advanced digital infrastructure required to effectively manage these sophisticated circularity tools. The transition to a CE is not just about investing in new technologies; it represents a big organizational and governance change. Literature clearly shows that to create sustainable and scalable circular models; companies must rethink their entire business strategies. To overcome these barriers, SMEs need to build strong cooperation networks and join integrated supply chains. Engaging in co-design practices with other actors in the sector, such as farmers, millers, and distributors, is recognized as a key factor for success. Working together allows smaller companies to share costs, knowledge, and infrastructure, making the circular transition possible (Lombardo et al., 2021; Silveira et al., 2022; Spina et al., 2024). However, establishing these collaborative business models is only the first step. Once a SME joins a circular network and adopts new waste and by-products valorisation practices, it needs a reliable way to measure the actual success of these efforts. Specifically, decision-makers must evaluate if these new organizational changes are truly balancing environmental benefits with economic profitability. To navigate this complexity and effectively measure the performance of these collaborative circular models, the concept of eco-efficiency emerges as a necessary and fundamental framework for identifying strategies that are simultaneously circular, environmentally sound, and economically viable. Despite its growing prominence as a vital bridge between economic and environmental performance, a primary conceptual obstacle is the absence of a universally standardized definition, leading to varied interpretations and methodological inconsistencies (Huppes and Ishikawa, 2005; WBCSD, 1996). Nevertheless, it is generally understood as the ratio between the reduction of environmental impacts and the increase in production value (Huppes and Ishikawa, 2005). The World Business Council for Sustainable Development defines it as a managerial strategy that combines economic and environmental performance, essentially creating "more value with less impact" (WBCSD, 1998; WBCSD, 1996). Evaluating eco-efficiency ensures that the integration of circular practices facilitates resource recovery while genuinely minimizing the ecological footprint (EF) of the systems involved. Despite this tremendous potential, the concrete application of eco-efficiency within the olive oil sector remains notably scarce and disjointed. Most of the current research tends to adopt a narrow focus, concentrating primarily on the theoretical identification of optimal valorisation strategies (Zahi et al., 2022), technical assessments of treatment efficiency (Mancuso et al., 2022), or the general promotion of sustainable management practices (Abu Shmeis et al., 2021). What is conspicuously absent is a holistic framework that synergistically integrates ES, CE principles, and eco-efficiency. Comprehensive evaluations of the sector from a life cycle perspective are still rare (e.g., Ncube et al., 2022), leaving a significant research gap regarding the systematic mapping of available treatment technologies evaluated through combined environmental and economic lenses. To overcome these theoretical and operational obstacles, Life Cycle Assessment (LCA) is widely adopted as the premier analytical tool (Restuccia et al., 2022; Spada et al., 2024). Standardized by ISO 14040 and 14044 (ISO 2006a; ISO 2006b), LCA allows for in-depth analyses of input/output inventories and environmental hotspots throughout the production cycle (Salomone and Ioppolo, 2012). LCA is increasingly recognized as highly effective in supporting corporate management to prioritize sustainability-oriented improvements, thereby facilitating the concrete implementation of the SDGs within their specific operational fields (Cinardi et al., 2024; Zingale et al., 2022). Finally, while environmental optimization is essential, it must be combined with economic feasibility. Since LCA primarily focuses on the environmental criticalities of the production chain, it should be integrated with methodologies that also assess economic performance in order to evaluate true eco-efficiency. To effectively measure the eco-efficiency of circular business models, companies must rely on robust economic evaluation tools. Life Cycle Costing (LCC) is traditionally used to provide a comprehensive estimate of total costs throughout the lifespan of an investment or technology. While it is highly useful for understanding the economic maturity of a solution and for internal budgeting, LCC has notable limitations. When used in isolation, it does not automatically incorporate monetizable social or environmental benefits. Consequently, it may undervalue indirect public incentives and the broader advantages derived from the ecological transition (Dong et al., 2018). In addition, although LCC provides a comprehensive economic counterpart to LCA, its data-intensive requirements can hinder its practical and timely application in the agricultural sector (Martinez-Sanchez et al., 2016). In contrast, Cost-Benefit Analysis (CBA) represents a more accessible decision-support tool for SMEs (European Commission, 2015), enabling the evaluation, comparison, and prioritization of investment options based on their economic performance, and offering clearer and more transparent guidance for both firms and policymakers (Vagdatli and Petroutsatou, 2022). By emphasizing the feasibility and efficiency of investments, CBA emerges as a pragmatic alternative in line with the EU's simplification agenda, allowing stakeholders to assess the economic viability of modernization strategies without the complexity associated with full life-cycle costing approaches. Therefore, CBA offers a more inclusive framework that captures both economic and social costs and benefits over the long term, actively including indirect effects, environmental externalities, and impacts, and eventually, on community well-being. These elements are particularly relevant for ecological transitions, where the positive effects often extend far beyond the profit margins of a single company. By monetizing social and environmental impacts, CBA serves as a consolidated tool for both public and private decision-making. Rather than viewing these tools as mutually exclusive, current research strongly advocates for their integration to achieve a truly holistic assessment of economic and ES. Literature often proposes hybrid approaches, such as combining LCC within a CBA framework, or moving toward a Life Cycle Sustainability Assessment (LCSA), which unites LCA, LCC, and Social Life Cycle Assessment (S-LCA). For SMEs, a combined LCA-CBA approach provides a complete perspective: CBA offers the overarching decision-making framework, and LCA quantifies the physical environmental impacts. These integrated models are well-documented as effective tools for sustainability-oriented decision-making (Esteves et al., 2022; Gigli et al., 2019). Practical evidence highlights that for SMEs engaging in CE practices, the adoption of simplified and accessible tools is crucial. In the European context, public procurement practices and CE policies increasingly emphasize the need for widespread, understandable economic evaluation tools. Integrating CBA with LCA directly supports these policy goals, guiding SMEs through feasible, low-risk, and well-justified investment decisions (Martinez-Sanchez et al., 2016; European commission 2015). To ensure these methodologies are adopted by industry, it is essential to translate advanced analytical tools into accessible, everyday practices. Developing simplified CBA and LCC modules, providing basic LCA guidelines, and sharing practical case studies can significantly facilitate their daily application. These simplified frameworks enhance SMEs' ability to communicate sustainability performance to key stakeholders, including financial institutions, public bodies, and environmentally conscious markets. By incorporating environmental benefits into economic evaluations, CBA facilitates access to green finance and supports investment decisions in circular technologies, improving the assessment of long-term profitability (Sgroi et al., 2015). Overall, the integration of LCA and CBA provides a practical tool to evaluate economic sustainability and the costs of green transitions, supporting both business strategies and policy development (Hsu, 2021).

1.3 Research objectives and methodological approaches

To address the identified literature gaps regarding the treatment and valorisation of olive oil by-products, this Ph.D thesis pursues a threefold objective. First, it offers an in-depth analysis of available technologies for olive oil waste and by-products treatment, assessing their operational strengths and limitations through the combined lenses of the CE, ES, and eco-efficiency. Second, it bridges the gap between theory and practice by applying an integrated LCA and CBA to a real-world case study in Sicily. Ultimately, this research aims to develop a replicable decision-making framework to support enterprises and stakeholders in advancing the ecological transition of the olive oil supply chain in alignment with the SDGs.

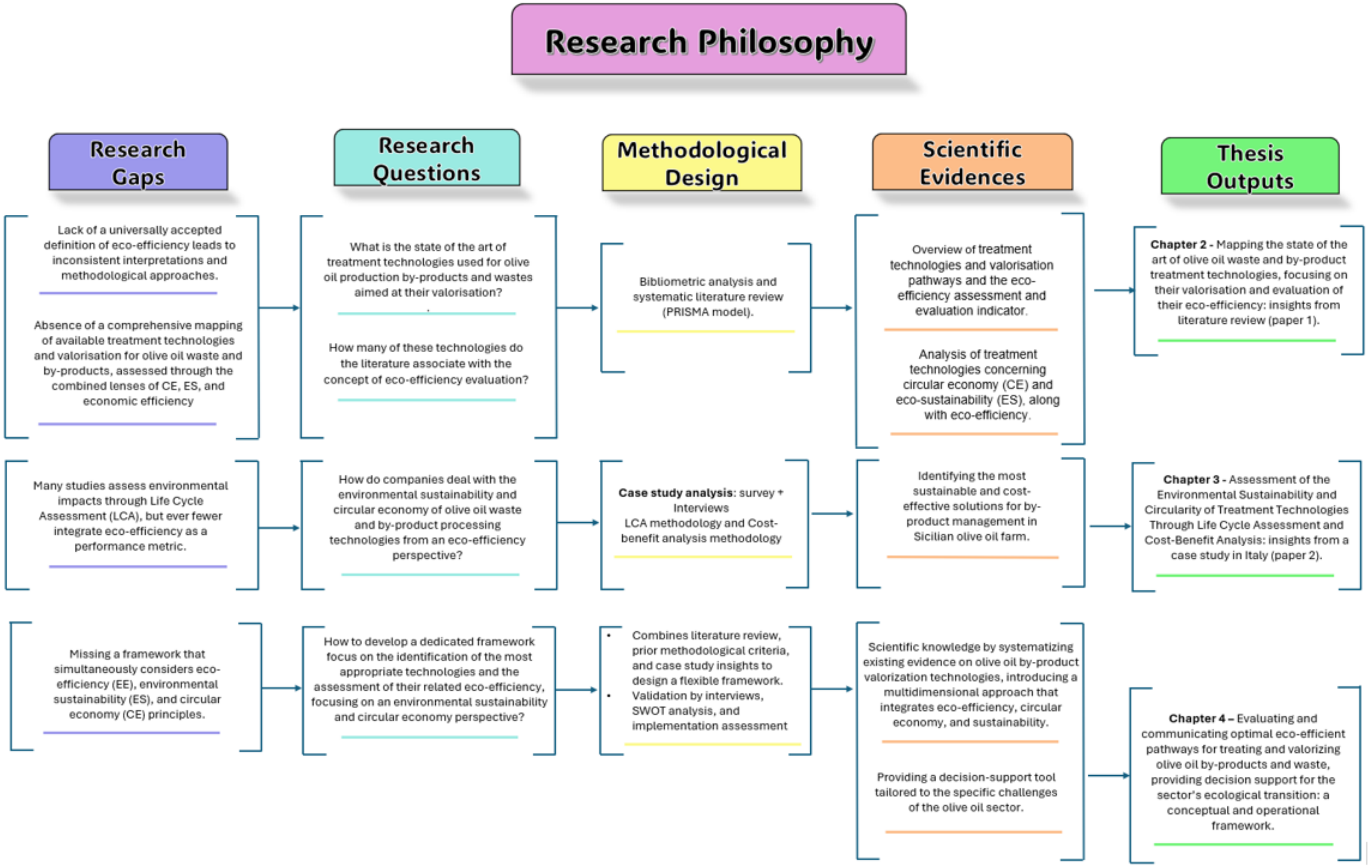
To achieve these objectives, the study is organized into sequential research phases, as illustrated in Fig. 1. All phases are closely linked and guided by a qualitative-interpretive research philosophy, which enables an in-depth exploration of complex technological, environmental, and economic contexts in the olive oil sector, with the focus on waste and by-products treatment and valorisation. This approach aligns with (Creswell, J. W. and

Creswell, J. D., 2018) framework, which emphasizes that constructivist research aims to generate rich understandings and nuanced interpretations of complex phenomena through the integration of qualitative and multi-method strategies. Because the olive oil supply chain involves deep technological, environmental, economic, and organizational complexities, a single-method approach would be fundamentally insufficient to capture the entire picture. Therefore, this Ph.D thesis adopts a multi-stage, mixed-methods design. This allows for the combination of conceptual rigor with empirical applicability, producing outputs that are scientifically sound and practically relevant. Specifically, three main research gaps were identified and translated into corresponding research questions. For each question, an appropriate methodological design was defined to achieve the stated objectives. In detail, the core of the thesis is articulated across three main chapters (Fig. 1):

- Chapter 2 provides a comprehensive mapping of the state of the art regarding olive oil waste and by-product treatment technologies. Through a systematic literature review and bibliometric analysis (based on Page et al. (2021) PRISMA guidelines) the chapter identifies currently available technologies, examines their valorisation potential, and explores the extent to which they are linked to eco-efficiency assessments in the literature. This work not only systematizes existing knowledge but also highlights conceptual and methodological gaps, particularly concerning the integration of eco-efficiency, CE, and ES principles.
- Chapter 3 moves from the conceptual level to empirical validation by focusing on a Sicilian olive oil farm as a primary case study. Building on the evidence gathered from the literature review, an LCA is conducted to evaluate the sector’s environmental performance, with particular attention to the actual treatment and valorisation of waste streams. To complement this, a CBA is applied to assess the economic viability of alternative management strategies. This chapter highlights how a combined approach enables the identification of the most sustainable and cost-effective solutions, while simultaneously exposing the practical economic and organizational barriers that affect the adoption of eco-efficient practices in real production contexts.
- Chapter 4 develops and applies a dedicated decision-support framework. Drawing on the insights from the literature review and the empirical case study, this framework is designed to be flexible, multidimensional, and highly adaptable. It integrates eco-efficiency with CE and ES principles, offering companies a practical tool for selecting the most appropriate valorisation strategies.

Overall, this methodological framework ensures coherent progression from theory to empirical application, and ultimately to actionable decision-support tools. By systematically combining literature-based evidence, quantitative environmental and economic assessments, and qualitative validation methods, the research design allows for a comprehensive and balanced evaluation of eco-efficient and circular solutions within the olive oil supply chain. This integrated approach enhances the internal consistency and robustness of the findings while strengthening their external relevance, aligning scientific rigor with the practical decision-making needs of agrifood SMEs. Consequently, the methodology adopted in this Ph.D thesis provides a solid foundation for advancing academic knowledge while simultaneously supporting the ecological transition of the sector through evidence-based, context-sensitive, and implementable solutions.

The next sections report a summary of the contents of Chapters 2, 3 and 4, focusing on the research gaps and objectives, the methods, and the scientific contribution.



Lack of a universally accepted definition of eco-efficiency leads to inconsistent interpretations and methodological approaches.

Absence of a comprehensive mapping of available treatment technologies and valorisation for olive oil waste and by-products, assessed through the combined lenses of CE, ES, and economic efficiency

Many studies assess environmental impacts through Life Cycle Assessment (LCA), but ever fewer integrate eco-efficiency as a performance metric.

Missing a framework that simultaneously considers eco-efficiency (EE), environmental sustainability (ES), and circular economy (CE) principles.

What is the state of the art of treatment technologies used for olive oil production by-products and wastes aimed at their valorisation?

How many of these technologies do the literature associate with the concept of eco-efficiency evaluation?

How do companies deal with the environmental sustainability and circular economy of olive oil waste and by-product processing technologies from an eco-efficiency perspective?

How to develop a dedicated framework focus on the identification of the most appropriate technologies and the assessment of their related eco-efficiency, focusing on an environmental sustainability and circular economy perspective?

Bibliometric analysis and systematic literature review (PRISMA model).

Case study analysis: survey + Interviews
LCA methodology and Cost-benefit analysis methodology

- Combines literature review, prior methodological criteria, and case study insights to design a flexible framework.
- Validation by interviews, SWOT analysis, and implementation assessment

Overview of treatment technologies and valorisation pathways and the eco-efficiency assessment and evaluation indicator.

Analysis of treatment technologies concerning circular economy (CE) and eco-sustainability (ES), along with eco-efficiency.

Identifying the most sustainable and cost-effective solutions for by-product management in Sicilian olive oil farm.

Scientific knowledge by systematizing existing evidence on olive oil by-product valorization technologies, introducing a multidimensional approach that integrates eco-efficiency, circular economy, and sustainability.

Providing a decision-support tool tailored to the specific challenges of the olive oil sector.

Chapter 2 - Mapping the state of the art of olive oil waste and by-product treatment technologies, focusing on their valorisation and evaluation of their eco-efficiency: insights from literature review (paper 1).

Chapter 3 - Assessment of the Environmental Sustainability and Circularity of Treatment Technologies Through Life Cycle Assessment and Cost-Benefit Analysis: insights from a case study in Italy (paper 2).

Chapter 4 – Evaluating and communicating optimal eco-efficient pathways for treating and valorizing olive oil by-products and waste, providing decision support for the sector's ecological transition: a conceptual and operational framework.

Fig. 1. Overview of the research philosophy, illustrating the logical progression from the identified research gaps and questions to the methodological design, scientific evidence, and final thesis outputs.

1.4 Eco-efficiency and sustainable pathways in olive oil waste management: a comprehensive literature review

1.4.1 Research gaps and objectives

Due to the steady global growth of olive oil production, a major challenge is the significant increase in agricultural and industrial waste and by-products. This generates millions of tonnes of residual biomass, including OP, OMWW, leaves, and branches. Disposing of this growing volume of waste causes severe environmental problems (Batuecas et al., 2019). These residues contain high levels of organic matter and toxic compounds, such as complex phenols. If they are not properly managed, they can cause serious ecological damage. Traditional disposal methods harm local ecosystems by degrading soil health (changing its pH, salinity, and microbial balance) and polluting water resources (Jimenez-Lopez et al., 2020). To reduce these environmental impacts, the application of advanced treatment technologies and valorisation systems is essential to turn hazardous waste and by-products into valuable secondary resources. Instead of treating OP and OMWW merely as environmental burdens, modern circular systems recover valuable bioactive compounds used in other industries (Faraloni et al., 2023). They can also convert waste into bioenergy, biopolymers, and eco-friendly fertilizers. Using these methods is vital for ES because they reduce pollution, cut disposal costs, and improve overall resource efficiency (Donner et al., 2022a; Stempfle et al., 2021).

To ensure that CE strategies are truly effective and do not cause hidden environmental or economic costs, "eco-efficiency" is a fundamental metric. However, since eco-efficiency is strictly determined by the specific operational costs and environmental impacts of the chosen processes, accurately assessing these circular strategies requires a systematic overview of the available technological options. Despite this fundamental connection, scientific literature remains with significant gaps: there is currently no comprehensive mapping that categorizes the available treatment and valorisation technologies for olive oil waste and by-products in terms of their actual eco-efficiency potential, and current research is highly fragmented. Studies usually focus only on the technical efficiency of a single treatment, propose theoretical CE strategies for one type of waste and by-product, or evaluate general environmental impacts (e.g., Ghisellini et al., 2016; Ncube et al., 2022). Because a complete overview is missing, there is no holistic framework in the olive oil sector that maps these technologies and evaluates them using CE, ES, and eco-efficiency together.

To address these gaps, this study conducts comprehensive bibliometric and systematic analysis. It has a twofold objective, based on the following research questions:

1. RQ1: What is the current state of treatment technologies for olive oil production by-products and waste aimed at their valorisation?
2. RQ2: How many of these technologies are associated with the concept of eco-efficiency evaluation in literature?

By answering these questions, this research first aims to clearly characterize the available waste and by-product processing technologies and valorisation pathways. It provides the missing comprehensive mapping to identify the best solutions for each specific waste stream, highlighting their practical advantages and limitations. Second, the study evaluates these mapped technologies within the integrated framework of CE and ES. The ultimate goal is to assess how much scientific literature currently investigates the eco-efficiency of these treatments. This will determine their real potential to drive truly sustainable and economically viable practices in the olive oil industry.

1.4.2 Methods

Following the PRISMA guidelines for the identification, screening, and inclusion of the sample studies retrieved from the Scopus and Web of Science (WoS) databases, a bibliometric and systematic literature review was conducted to analyze the final sample of relevant contributions. To systematically address the research questions, two distinct search queries are defined. Query 1 (Q1) is structured as: (‘olive oil’) AND (‘by-product’ OR ‘olive mill’ OR ‘mill waste’) AND (‘treatment technolog*’ OR ‘waste* treatment*’). Query 2 (Q2) is defined as: (‘olive oil’) AND (‘by-product’ OR ‘olive mill’ OR ‘mill waste’) AND (‘ecoefficienc*’ OR ‘environmental impact*’ OR ‘resource management’ OR ‘environmental sustainability’)*. The search for the selected keywords is performed using the "Title, abstract, keywords" search field on Scopus and the "Topic" field on WoS. A specific starting time frame is not defined, and the search is updated on December 31st, 2024. The initial sample size is characterized by 707 and 245 articles for Q1 and Q2, respectively.

Firstly, database exclusion criteria are employed to remove types of publications different from articles and reviews, scientific articles not in English, and duplicates. Then, the screening of the abstract and full text of scientific articles is performed according to specific eligibility criteria. For Q1, studies must strictly address olive oil waste and by-product treatment technologies, as well as strategies for their valorisation. For Q2, the criteria further mandate the selection of articles that explore eco-efficiency, CE, and ES, either as individual concepts or discussed in an integrated manner.

After the application of such criteria, the final sample of scientific articles is identified, consisting of 239 articles for Q1 and 65 articles for Q2, which are subsequently subjected to bibliometric and systematic analyses.

1.4.2.1 Bibliometric analysis

A bibliometric analysis of the sample is employed as the first analytical step to provide information through exploring texts and outlining the broad scientific landscape. Crucially, performing this bibliometric mapping first provides a data-driven overview of the research field, directly guiding and structuring the subsequent in-depth systematic analysis. The categories included in the analysis are the year of publication, the journal source, the related subject areas, and the authors’ keywords.

The analysis of the year of publication allows the identification of potential trends in the time frame in which the sample of articles is published. The analysis of journal sources permits the identification of those that contribute the most to the research on the topic under analysis. The analysis of subject areas enables the understanding of the different themes and disciplines related to olive oil waste valorisation; to ensure consistency, the WoS subject areas are manually reclassified according to the Scopus classification system. Finally, the analysis of authors’ keywords allows for strengthening the connections that emerged from the subject areas by identifying the most recurring themes in the sample, which is investigated through a network analysis using the VOS-viewer software.

1.4.2.2 Systematic literature review

Guided by the thematic trends identified in the bibliometric phase, a systematic analysis is carried out using clear and explicit research criteria with the aim of providing a state of the art with minimal bias and more reliable results. According to the aim of the study, the final sample is investigated and classified according to the following macro-categories: i) characterization of the waste and by-products streams and treatment technologies (for Q1); ii) link with eco-efficiency, CE, and ES (for Q2).

The i) characterization of waste and by-products streams and treatment technologies includes the analysis of the treated biomass classified into macro-categories to strictly align specific technologies with their corresponding valorisation pathways. The waste and by-product are categorized into solid, semi-solid, liquid, and general waste. To simplify the analysis, olive leaves, pits, and branches (typically solid residues from initial processing), as well as OMWW sludge and dried OP, are grouped into the solid category due to their physical state.

The ii) link with eco-efficiency, CE, and ES includes the analysis of how the concept of eco-efficiency is contextualized within the sample. For this study, the considered concept excludes the purely financial component of the eco-efficiency definition to highly emphasize the environmental dimension and the value created through valorisation. In detail, three levels of eco-efficiency approaches are defined as follows: *theoretical eco-efficiency*, when the definition conceptually bridges treatment effectiveness and environmental challenges without the application of formal assessment tools; *integrated eco-efficiency*, when the approach involves specific environmental indicators or concrete methods for eco-efficiency assessment; and *absent eco-efficiency*, when neither theoretical nor integrative approaches to eco-efficiency are identified in the analyzed article.

All the information collected from these categories is extracted and processed concurrently using Microsoft Excel, allowing for a comprehensive description of the state of the art of olive oil by-product treatments and their actual capacity to foster sustainable and eco-efficient circular models.

1.4.3 Scientific contribution

The main scientific contribution of this article lies in providing the first systematic mapping of olive oil waste and by-products treatment technologies, evaluated simultaneously through the lenses of eco-efficiency, CE, ES. The study fills a significant methodological gap by demonstrating that, although valorisation strategies are widely debated, the actual measurement of their eco-efficiency is often fragmented, absent, or limited to purely theoretical assumptions. By identifying LCA as the primary tool to quantify these impacts and warning against the risks of the rebound effect linked to increased efficiency, the research lays the essential base-work for creating a holistic decision-making framework. Ultimately, the article transforms a fragmented body of literature into a strategic guide. It provides the necessary theoretical foundation to help companies, particularly Small and Medium-sized Enterprises (SMEs), select ecological transition pathways that are truly sustainable from both an environmental and economic perspective.

1.5 Sustainability and circular economy strategies in Italian olive oil company: an application of life cycle assessment and cost benefits analysis

1.5.1 Research gaps and objectives

The global agri-food sector is increasingly challenged to reconcile high-quality production with the urgent need to reduce environmental impacts, a tension that is particularly evident in the Mediterranean olive oil industry (Donner et al., 2022a). This industry, while economically and culturally significant, especially in countries such as Italy and regions like Sicily, is currently facing mounting pressures from climate change, resource scarcity, rising production costs, and the complex management of large volumes of by-products generated during the extraction process (De Luca et al., 2023). In this context, the transition toward sustainable and circular production models requires the adoption of robust and accessible decision-support tools. However, despite the growing body of literature on sustainability in the olive oil supply chain, several critical gaps remain. First, although LCA is widely recognized as the standard methodology for quantifying environmental impacts, its complexity and data-intensive nature often limit its practical applicability, particularly for SMEs (Martinez-Sanchez et al., 2016). Furthermore, for the rapid implementation of ecological transition in the agricultural sector, according to the European Commission (2015), CBA serves as a streamlined, decision-support tool. This highlights a key methodological gap in the development of operational, multidimensional evaluation tools. Second, while numerous studies propose CE strategies for the valorisation of olive oil by-products, their real adoption is still limited by a persistent trade-off: the unquestionable environmental benefits of circular systems rarely translate into immediate economic feasibility for producers. This issue is especially pronounced in regions such as Sicily, where fragmented farm structures, logistical constraints, and the seasonal concentration of biomass create significant barriers, leading to a territorial and implementation gap. Furthermore, although eco-efficiency is widely acknowledged as a crucial concept linking environmental performance and economic value, its practical application in the agrifood sector remains underdeveloped, with a lack of standardized guidelines. Considering these challenges, this study aims to address these gaps by developing and applying an integrated LCA and CBA framework to the Italian olive oil supply chain. The research focuses on the combined evaluation of environmental impacts and economic performance across key production phases, including cultivation, processing, as well as the management and internal valorisation of olive oil waste and by-products. By assessing alternative technologies and strategies within a CE perspective, the study seeks to identify solutions that are both economically viable and environmentally sustainable, ultimately enhancing eco-efficiency and supporting more informed decision-making in the transition toward resilient and sustainable olive oil production systems.

1.5.2 Methods

The case study focuses on a Sicilian olive oil mill located in the Valle dello Jato area, representative of small-scale, high-quality production systems, and extends the analysis to downstream valorisation processes, including OP treatment and anaerobic digestion for energy recovery. The analysis is structured around a unified system definition, including a common functional unit (FU) (1 tonne of harvested olives) and cradle-to-gate system boundaries, encompassing cultivation, olive processing in EVOO, and the subsequent treatment and valorisation of waste and by-products. The methodological model is articulated into two parallel and complementary components: the environmental assessment, conducted through LCA in accordance with ISO 14040/14044 standards, which quantifies resource use, emissions, and environmental impacts across the entire supply chain (ISO 2006a; ISO 2006b); and the economic assessment, based on CBA (European Commission, 2015b), which evaluates costs, revenues, and profitability indicators associated with production and alternative by-product management strategies.

The Life Cycle Inventory (LCI) phase integrates primary and secondary data to comprehensively map material and energy flows. Primary data, referring to the 2023–2024 production season, were collected through structured questionnaires administered to the farm owner and processing facility managers, including detailed information on inputs such as fertilizers, water, diesel, lubricants, and electricity consumption, as well as operational data for milling and transport logistics. Transport activities were explicitly modelled by considering distances and vehicle types across all stages of the supply chain. Where direct measurements were not available, secondary data and established models were employed to estimate emissions from fertilizer application, fuel combustion, and energy conversion processes, including biogas production. Background data were sourced from the Ecoinvent v3.9 database, and the entire inventory and impact assessment were implemented using SimaPro software. Version 10.2 (PRé Sustainability, 2025). A substitution approach was applied to account for avoided impacts associated with energy and material recovery, ensuring a consistent representation of circular processes.

The environmental analysis was conducted using the European Commission's Environmental Footprint (EF) 3.1 method, evaluating 16 midpoint indicators to identify the main environmental hotspots along the life cycle and to quantify the net benefits generated by circular valorisation strategies. In parallel, the economic analysis translated physical flows into monetary terms. Using primary data collected through questionnaires, revenues (derived from the sale of EVOO and by-products) and total costs were calculated. These costs were strictly categorized as variable, fixed, and opportunity costs (such as the foregone income from renting the land or selling raw olives). While the economic parameters for the cultivation and milling phases are based on real company data, the capital and operational costs for by-product treatment were modeled from literature, also integrating transportation costs based on updated ministerial parameters. The economic performance was measured over a 20-year timeframe, applying a 3% interest rate in accordance with European guidelines, and evaluated through three key indicators: Gross Margin, Net Margin, and the Cost-Benefit Ratio (BCR). Finally, to allow for a holistic evaluation, the economic results were normalized to the FU. This enabled a direct comparison with the environmental impacts, providing a structured basis for determining the true eco-efficiency of the system.

1.5.3 Scientific contribution

The main scientific contribution of this study lies in the development and empirical application of an integrated LCA-CBA analysis method designed to evaluate the true eco-efficiency of the olive oil supply chain. This approach fills a significant methodological gap in the existing literature, where environmental impact analyses and economic feasibility assessments are typically investigated separately and are not well-suited for SMEs. By adopting a rigorous cradle-to-gate perspective whit the inclusion of the olive oil waste and by-products treatment and valorisation phase, the work introduces a multidimensional method capable of simultaneously quantifying environmental burdens, financial performance, and, more importantly, the inherent trade-offs between these two dimensions throughout the entire production life cycle.

Empirically, the value of the research is strengthened by the use of primary data from a real case study located in Sicily. This methodological choice allows for an accurate mapping of the complex production, logistical, and management dynamics that characterize olive oil SMEs. This is a crucial contribution to current literature because traditional and small-scale farms, despite representing the core operational base of the Mediterranean agri-food sector, are often underrepresented or overly simplified in previous academic models.

A further innovative element is the quantitative demonstration of a structural trade-off between ES and economic profitability. The research clearly highlights a logistical limitation: although the valorisation of waste and by-products generates significant environmental benefits by substantially reducing the system's ecological footprint, this practice is economically unsustainable when analyzed as an isolated process. The prohibitive costs associated with the transport and logistics of wet OP eliminate any potential revenue, demonstrating that the adoption of CE practices does not automatically translate into a direct economic advantage for the operator. In response to this issue, the study proposes conceptual advancement through the introduction of the principle of "systemic" eco-efficiency. The work demonstrates that the true economic sustainability of circular models should not be evaluated at the level of the single recovery process, but rather through holistic integration at the company level. This balance is made possible by a cross-subsidy mechanism: the high profit margins guaranteed by the core product (EVOO) finance and offset the operational losses resulting from circular activities. In this context, the management of waste and by-products is no longer considered an independent profit center, but rather a necessary strategic investment to complete the production cycle. To make the transition toward the CE not only ecologically effective but also economically scalable, it is imperative to develop local agro-industrial districts capable of minimizing logistics and maximizing the actual eco-efficiency of the territory.

1.6 A systemic decision-support framework for olive by-products valorisation: integrating life cycle assessment and cost-benefit analysis

1.6.1 Research gaps and objectives

Building upon the empirical and methodological insights derived from the first two chapters, this study advances the research toward the development of an operational decision-support framework. While the second chapter provided a comprehensive mapping of existing treatment technologies and exposed significant gaps in integrated assessments, the third chapter findings highlighted both the potential and the limitations of circular valorisation strategies, particularly in terms of their economic feasibility and ES. Combined, these insights underscore the need to translate analytical results into actionable tools that can help decision-makers implement the ecological transition in SMEs. The limitations are largely driven by decision-making complexity, high investment uncertainty, regulatory constraints, and the lack of accessible tools capable of integrating environmental and economic dimensions into practical business strategies.

Although the literature has made significant progress in developing advanced assessment methodologies, including multi-cycle LCA models, economic evaluation tools, and optimization approaches such as mixed-integer linear programming, these solutions often suffer from high computational complexity, limited flexibility, and low usability in real-world contexts (Argoubi and Mili, 2026; European Commission, 2024). As a result, a critical gap persists between the availability of scientifically robust models and their effective implementation in day-to-day managerial decision-making. Furthermore, while the concept of CE promotes the valorisation of olive oil by-products as high-value resources, existing approaches rarely provide clear, user-friendly guidance on how to select the most suitable technological pathways under real operational constraints (Donner et al., 2022a; Soares et al., 2024). This highlights a dual gap: on the one hand, a methodological gap related to the lack of simplified, integrative, and decision-oriented tools; and on the other, a managerial gap concerning the translation of sustainability assessments into concrete and feasible investment choices.

To address these limitations, this study proposes the development of a Life Cycle Thinking Decision Framework (LCT-DF), designed as a semi-quantitative, multi-criteria tool that combines the analytical robustness of life cycle thinking with the practical needs of business decision-making. The framework aims to: (i) systematically map the available treatment and valorisation pathways for olive oil waste and by-products within a CE perspective; (ii) apply environmental and economic feasibility criteria, derived from LCA and CBA logic, to filter out non-viable options; and (iii) support the visual identification of optimal strategies that simultaneously ensure ES and economic profitability. By moving beyond purely algebraic optimization models toward a more accessible and strategic approach, this research seeks to bridge the gap between theory and practice, providing olive oil SMEs with a pragmatic tool to navigate complexity, reduce decision uncertainty, and facilitate the adoption of circular and sustainable business models.

1.6.2 Methods

The LCT-DF is developed as a semi-quantitative multi-criteria methodological approach designed to support decision-making in the valorisation of olive oil waste and by-products. The framework translates environmental and economic evaluation outputs, through LCA and CBA, into an operational and accessible decision-support tool. The methodological structure of the LCT-DF is articulated into four sequential and interconnected stages. The first phase synthesizes the outcomes of the previous steps of this research to establish a robust baseline. For instance, the results of the systematic literature review were utilized to comprehensively map the state of the art of treatment technologies and circular valorisation pathways for olive oil waste and by-products. On the other hand, the empirical data derived from the application of the integrated LCA and CBA model to the Sicilian case study provided real environmental and economic metrics. Together, these theoretical and empirical pillars allowed for the precise identification of the fundamental aspects, structural trade-offs, and critical bottlenecks of the olive oil system.

Based on the fundamental system dynamics identified in the first phase, the second stage focused on defining the core requirements of the decision-support tool. To effectively guide managers in overcoming the application paradox, it was determined that the framework must be inherently modellable, multidimensional (capable of jointly evaluating environmental integrity and economic feasibility), and highly adaptable to the diverse logistical contexts, business sizes, and technological maturities typical of the agri-food sector.

To translate these conceptual requirements into an operational tool, an exploratory literature review was conducted to identify and analyze existing sustainability assessment frameworks. Among the scrutinized studies, the Multi-Objective Linear Programming (MOLP) model proposed by Argoubi and Mili, (2026) emerged as a comprehensive baseline. However, to meet the adaptability required and overcome its high mathematical complexity the model was adapted into the agile, semi-quantitative LCT-DF tool. This adaptation bridges theoretical optimization with practical LCA and CBA indicators, making it immediately applicable in daily business operations. Finally, the results are synthesized into a visual decision-support output, designed to clearly identify optimal operational solutions that balance ES with economic profitability.

1.6.3 Scientific contributions

The main scientific contribution of this third chapter is the development and definition of LCT-DF. By moving away from the structural rigidity and mathematical complexity of traditional optimization models, which often cause decision-making paralysis among SME managers, this work introduces an agile, semi-quantitative approach. It translates advanced LCA and CBA metrics into accessible and actionable business strategies.

A key element of originality is the systematic categorization of physical waste and by-product streams into specific operational patterns. This classification clearly exposes the structural trade-offs inherent in different valorisation routes. For instance, it highlights the severe financial and logistical deficits associated with downcycling wet biomass, contrasting them with the high-value market potential of upcycling wastewater into bioactive compounds.

Furthermore, the study significantly advances the theoretical concept of ‘systemic eco-efficiency’ by fully operationalizing the ‘cross-subsidy’ model. It provides a structured methodology demonstrating that circular waste and by-product management should not be evaluated as an isolated profit center, which often leads to financial losses. Instead, it must be managed as an integral corporate investment, strategically subsidized by the robust profit margins generated by EVOO production.

Finally, the study offers a highly practical managerial contribution by delivering a concrete, five-step operational roadmap. This guide equips olive oil-growing SMEs with the essential business intelligence needed to navigate complex regulatory constraints and justify green investments. Ultimately, it helps companies transform environmental compliance from a structural financial burden into a certifiable, competitive advantage on the international market.

Chapter 2
Eco-efficiency and sustainable pathways in olive oil waste management: a comprehensive literature review

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The contributions to the article are defined according to the CRediT, as follow:

- Eleonora Recupero: Conceptualization, Formal analysis, Methodology, Writing – original draft, Visualization.
- Giuseppe Saija: Conceptualization, Methodology, Writing – review & editing.
- Giovanni Mondello: Conceptualization, Methodology, Writing – review & editing.

ABSTRACT: Among the various agri-food supply chains, olive oil production draws particular attention due to its economic and cultural significance and the ever-growing global production. This growth has led to a corresponding rise in the olive oil waste and by-products production, which pose significant environmental challenges due to their high phytotoxic organic content. At the same time, these by-products also contain valuable compounds with potential applications across multiple industrial sectors. Much of the existing literature focuses on identifying efficient technologies to reduce the toxicity of these wastes and by-products and to allow their valorisation. However, few studies comprehensively examine these treatment and valorisation strategies through the eco-efficiency lens, considering the circular economy (CE) and environmental sustainability (ES) combined perspective. This study aims to explore the current landscape of olive oil waste and by-product treatment technologies, with a focus on their valorisation potential and alignment with eco-efficiency concepts, along with CE and ES principles. The results point out a range of treatment methods, including anaerobic digestion, composting, membrane filtration, and thermal processes, each linked to specific valorisation pathways and types of waste/by-products. Particularly, liquid waste received the most attention due to its environmental toxicity. Furthermore, eco-efficiency was mainly evaluated through theoretical and integrated frameworks, with Life Cycle Assessment (LCA) as the dominant tool. The study highlights that the integration of eco-efficiency with CE and ES remains a challenge due to the lack of standardised methods.

Keywords: Olive oil; Waste/by-product management; Eco-efficiency evaluation; Circular Economy; Environmental sustainability.

2.1 Introduction

The agri-food sector is one of the most complex industries, as its production rate is intrinsically linked to natural factors that cannot be controlled, such as climate, soil, and water availability. Although technological advances have significantly improved the efficiency of food production, the rapid growth of the world's population and its daily food needs have led to increased demand for agri-food products. According to the OECD-FAO 2025–2034 projections, global consumption of agricultural and fish commodities is expected to increase by 13% by 2034, primarily in low- and middle-income countries (OECD & Food and Agriculture Organization of the United Nations, 2025), driven by population growth and rising incomes. This rising demand is driven by a steadily increasing population, which is projected to grow to between 9.6 and 12.3 billion by 2100, with a strong probability (80%) of reaching 10 billion as early as 2056 (Webb & Buratini, 2016). This places significant pressure on the agri-food sector, leading to environmental issues and related challenges for agricultural systems (Islam & Zheng, 2025). For instance, according to the latest FAOSTAT release, the global agrifood sector generated approximately 16.2 Gt CO_2 eq in 2022, virtually unchanged from 2021 and representing a 10% increase since 2000. Namely, 7.8 Gt CO_2 eq (48%) came from farm-gate crop and livestock operations, 3.1 Gt CO_2 eq (19%) from land-use change, and 5.3 Gt CO_2 eq (33%) from pre-and post-production stages across the supply chain (Food and Agriculture Organization of the United Nations, 2023). According to Popova et al. (2022) (Popova et al., 2022), the agri-food sector accounts for as much as one-fifth to one-quarter of global anthropogenic emissions, with projections indicating a potential increase of 50–90% by 2050.

Among the various agri-food supply chains, olive oil production draws particular attention due to its economic and cultural significance, as well as the steadily increasing global production (Cappelli et al., 2023). According to the latest estimates from the International Olive Oil Council (IOOC), global olive oil production in the 2024/25 crop year is expected to reach approximately 3.38 million tonnes, compared with 2.76 million tonnes in the 2022/2023 crop year, while worldwide consumption of olive oil amounts to about 2.83 million tonnes for the same period (International Olive Oil Council, 2025). Spain is the leading global producer, accounting for 28.6% of total production, followed by Greece (12.8%) and Italy (8.6%). The olive oil supply chain, from cultivation to processing, involves several resource-intensive steps. In particular, the agricultural phase, especially fertilization and irrigation, has been identified as the largest contributor to the environmental footprint of olive oil production. This is due to intensive use of water, fertilisers, and pesticides, which degrade soil health, deplete water resources, and increase greenhouse gas emissions. Several studies have highlighted these impacts, emphasizing the need for sustainable practices to reduce the environmental burden of olive oil cultivation (Banias et al., 2017; Pattara et al., 2017; Salomone & Ioppolo, 2012). Nonetheless, the manufacture of olive oil packaging, the choice between glass or plastic bottling, and the use of refrigerants for olive oil storage have further significant impacts on the carbon footprint of olive oil production (Rinaldi et al., 2014). Meanwhile, the extraction phase of olive oil, unlike other stages of the olive oil life cycle, causes lower environmental impacts due to less resource input requirements (Ncube et al., 2022). Despite its relatively low energy and chemical input need, the extraction phase of olive oil production generates considerable amounts of waste and by-products. Indeed, about 20% of the olive is converted into oil, while the remaining 80% consists of by-products and waste materials, including olive tree leaves and branches, OP, stone fragments, and OMWW (Soares et al., 2024). These residues are characterised by high organic load and phytotoxic compounds, which can pose significant environmental risks if not properly managed (Batuecas et al., 2019), severely affecting soil properties, including hydrophobicity, water retention, pH, salinity, and microbial balance (Doula et al., 2017). Therefore, the management of the resulting waste represents a critical environmental concern within olive oil industries.

Many studies have focused on identifying even more efficient technologies to reduce olive oil waste and by-products and to treat them properly (e.g. Khdair and Abu-Rumman, 2020). As a result, one of the main challenges currently facing the olive oil sector is identifying solutions that are not only effective but also environmentally sustainable and economically feasible (Ncube et al., 2022; Roig et al., 2006). In response to these environmental and economic challenges, the olive oil sector is increasingly turning to CE strategies to enhance sustainability and resource efficiency. CE approaches promote the reuse, recycling, and valorisation of waste and by-products, allowing their transformation into valuable resources such as fertilisers, bioenergy, or other bioproducts. Indeed, these by-products contain bioactive compounds with high added value, including oleuropein, hydroxytyrosol, and related phenolic substances. These compounds have attracted significant interest across diverse industries, including pharmaceuticals, cosmetics, and agri-food, due to their antioxidant, anti-inflammatory, anticancer, and biopesticide properties (Jimenez-Lopez et al., 2020). In this context, improving the management of olive oil residues and implementing effective valorisation pathways can support the sector's sustainable development and circularity, reducing environmental impacts and production costs and enhancing resource efficiency (Donner et al., 2022a; Valta et al., 2015). The CE is increasingly recognized as an effective model for addressing olive oil waste management, beyond the business-as-usual linear 'take-make-waste' scheme (Stempfle et al., 2021). The Ellen MacArthur Foundation describes the CE as 'an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts toward renewable energy, eliminates the use of toxic chemicals that impair reuse, and aims to eliminate waste through the superior design of materials, products, systems, and, within this, business models (MacArthur, E, 2013). This CE model, centred on resource efficiency, is crucial for fostering environmental sustainability (ES) (Sauvé et al., 2016). Nonetheless, not all CE strategies guarantee ES (Kounani et al., 2023). In this context, the eco-efficiency concept helps define strategies that are both circular and sustainable from environmental and economic perspectives. Eco-efficiency is generally defined as a valuable metric for evaluating the effectiveness of economic activities in terms of resource utilization and environmental impact. However, there is no universally recognised standardized definition of eco-efficiency in the literature; it is commonly understood as the ratio of environmental impact reduction to production value (Huppes & Ishikawa, 2005). Indeed, according to the World Business Council for Sustainable Development (WBCSD), eco-efficiency is an index of economic and environmental efficiency, namely as a management strategy that links financial and environmental performance to create more value with less ecological impact (World Business Council for Sustainable Development, United Nations Environment Programme, 1998; World Business Council for Sustainable Development, 1996). Furthermore, according to Koskela and Vehmas (2012) (Koskela & Vehmas, 2012), eco-efficiency permits to achieve 'more from less', focusing either on productivity (achieving higher value-added with fewer environmental impacts) or on intensity (reducing the environmental footprint per unit of economic output). This concept underscores the potential of eco-efficiency assessments in linking CE strategies with ES goals. Furthermore, by measuring eco-efficiency, policymakers gain crucial insights to design policies that promote sustainable management and the efficient use of natural resources, particularly within the agricultural sector (Coluccia et al., 2020).

In the scientific literature, while many studies on olive oil waste and by-product management focus on identifying optimal valorisation strategies within the framework of the CE (Zahi et al., 2022), or assessing treatment efficiency from a technical perspective (Mancuso et al., 2022), or emphasizing the environmentally sustainable management of waste and by-products (Abu Shmeis et al., 2021), none of these studies combine all these aspects into a single unified approach. Indeed, while many significant reviews have explored the use of CE principles in managing olive oil waste and by-products, few have focused on an in-depth analysis of the potential environmental consequences of these methods and technologies (Donner et al., 2022a; Stempfle et al., 2021). An important review, which represents a valuable initial contribution to linking CE principles with ES in the olive oil sector, was proposed by Ncube et al. (2022) (Ncube et al., 2022). This review provides a comprehensive environmental assessment of olive oil production, comparing the environmental performance of various scenarios from a life cycle perspective, including the company's linear production model, and some innovative CE scenarios. However, a specific focus on the eco-efficiency, which is crucial for a more holistic analysis from an environmental and economic point of view, is still missing, particularly in the olive oil industry. In this context, this study aims to carry out a bibliometric and systematic analysis in order to answer two main research questions:

i) RQ1 – *What is the current state of treatment technologies for olive oil production by-products and wastes aimed at their valorisation?*
ii) RQ2 – *How many of these technologies are associated with the concept of eco-efficiency evaluation in the literature?*

Thus, on the one hand, an in-depth analysis and characterisation of olive oil waste and by-product processing technologies, examining the related advantages and disadvantages, is carried out. The scope is to identify the most suitable technologies for each type of olive oil waste and by-product, highlighting their key characteristics and effectiveness. On the other hand, the identified technologies are evaluated within the CE principles and ES perspectives, both individually and in concert with eco-efficiency concept. The scope is to evaluate how extensively the eco-efficiency of these treatment and valorisation technologies is investigated in the scientific literature, and to what extent it contributes to promoting more sustainable and economically viable practices within the olive oil sector.

2.2 Materials and methods

To achieve the research goals of this study, the bibliometric (Mengist et al., 2020) and systematic (Snyder, 2019) literature review was conducted. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) are adopted as the standardised framework for identifying, selecting, and reporting the articles included in the review.

2.2.1 Search strategy

The flowchart in Fig. 1 details the research method adopted, developed in accordance with the PRISMA guidelines. To systematically address the research questions, two research queries were defined. In particular, Query 1 (Q1), referring to RQ1, was structured as: (‘olive oil’) AND (‘by-product’ OR ‘olive mill’ OR ‘mill waste*’) AND (‘treatment technolog*’ OR ‘waste* treatment*’). Meanwhile, Query 2 (Q2), related to RQ2, was defined as: (‘olive oil’) AND (‘by-product’ OR ‘olive mill’ OR ‘mill waste*’) AND (‘eco*efficienc*’ OR ‘environmental impact*’ OR ‘resource management’ OR ‘environmental sustainability’). To ensure a broad and comprehensive literature sample, both Scopus and Web of Science (WoS) databases were used, restricting the search to the title, abstract, and keywords, without applying any specific time restrictions. The literature review was completed in December 2024. The initial sample size was characterised by 707 and 245 articles for Q1 and Q2, respectively. A first screening process was carried out focusing on articles and reviews published in English and removing duplicates. The resulted sample was analysed through title and abstract, and full-text screening. For both queries, the eligibility criteria focused on studies addressing olive oil waste and by-product treatment technologies, as well as strategies for their valorisation. The key difference between the two queries is that, while these criteria were applied solely to Q1, Q2 further included the selection of articles that explore eco-efficiency, CE, and ES, either as individual concepts or discussed in an integrated manner. The screening process allowed the identification of the final sample, consisting of 239 articles for Q1 and 65 articles for Q2.

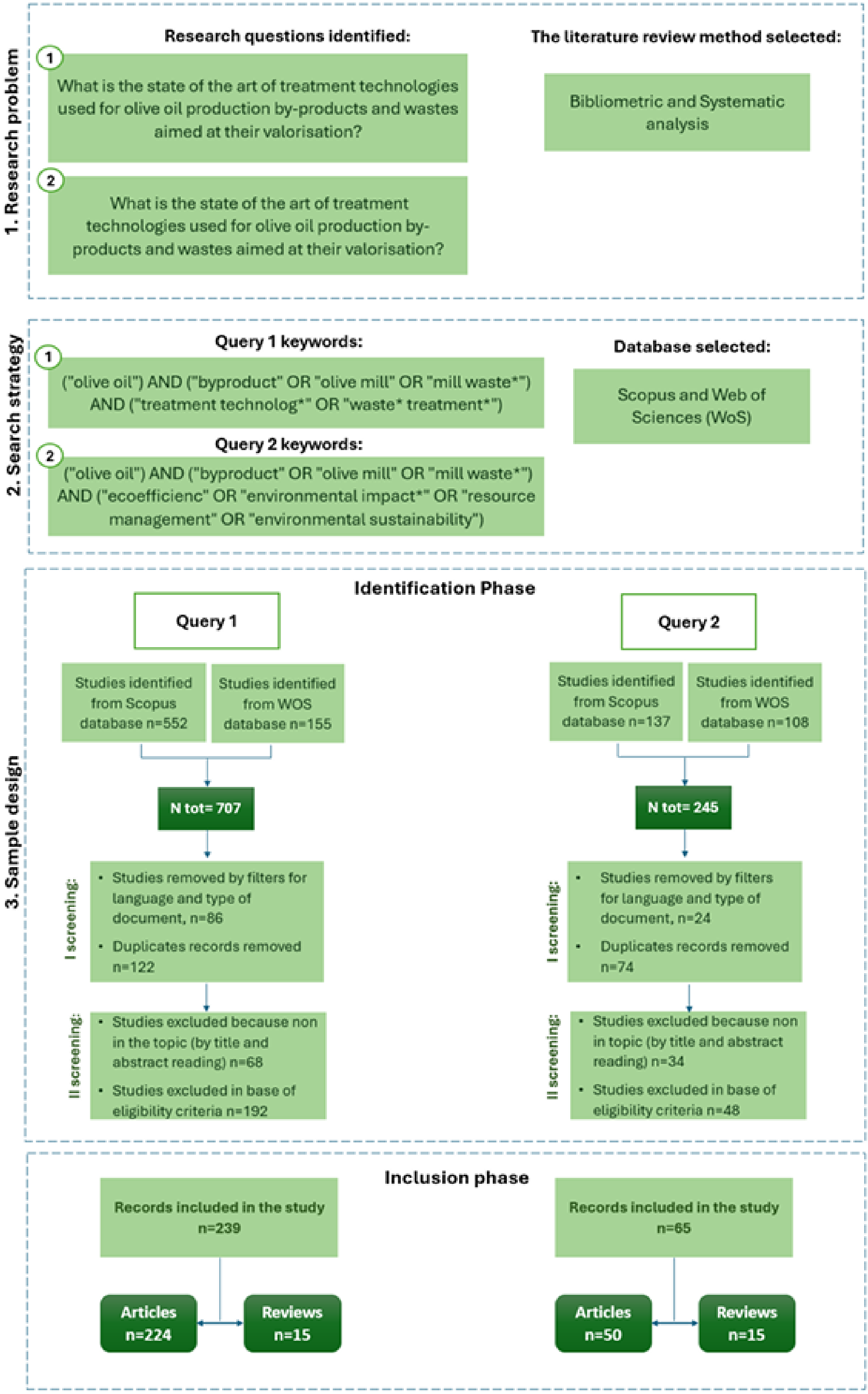

Figure 2 flow chart synthesis of the research method based on the PRISMA protocol

2.2.2 Sample design

In Q1, each treatment technology is identified based on the types of waste and by-products produced, and the valorisation pathways were defined for each type of treatment. Table 1 shows the olive oil waste and by-products classification used in this analysis. In particular, three main categories of olive oil waste and by-products can be distinguished, i.e., solid, semi-solid, and liquid, for which the type and characteristics depend on the olive oil production process (e.g., 3-P decanter, 2-P decanter, etc.). Olive leaves, pits, and branches are not commonly considered solid waste and by-products, but rather as solid residues (Abbattista et al., 2021). However, to simplify the analysis, olive leaves, pits, and branches, typically generated during the initial processing and cleaning stages, are categorised as solid waste and by-products. Similarly, OMWW sludge, which results from the sedimentation and partial treatment of liquid effluents, and dried OP, a dehydrated residue rich in lignocellulosic material remaining after oil extraction, are also grouped in the solid category, due to their dry physical state and solid content (Abbattista et al., 2021; Aranda et al., 2007). Considering that various reviews in the sample of Q1 lack of specifying the type of by-product or waste treated, a 'general olive oil waste and by-products' category is also included in this analysis to ensure completeness.

Table 4 Classification of olive oil waste and by-products used to analyse treatment technologies and valorisation pathways in Q1 sample.

Category	Waste and by-product type	Description	Production process	References
Solid	**Dried OP**	Residual dry fibrous material left after olive oil extraction, with low oil content.	Drying of wet OP after olive oil extraction or 3-P system olive oil extraction.	(Aranda et al., 2007)
	OMWW sludge	Residual dark sludge rich in phenols and lipids remaining in evaporation ponds.	Derived from the decantation of olive oil wastewater after the evaporation process.	(Bouhia et al., 2021)
	Olive husk	The coarse outer part of the olive remains after processing.	Olive crushing and milling.	(Greco et al., 1999)
	Olive pits (or olive stones)	Hard inner seed of the olive, separated during processing.	Extracted from OP or olive pulp.	(García Martín et al., 2020)
	Olive tree branches and leaves	Pruned small branches and leaves from olive trees, often collected during harvesting.	Olive harvesting and tree pruning.	(Manios et al., 2006; Maragkaki et al., 2016)
Semi-solid	**Wet OP**	Moist residue containing olive pulp, skin, and some oil and water.	2-P olive oil extraction.	(Podgornik et al., 2022)
Liquid	**OMWW and vegetation water**	Dark liquid rich in polyphenols, sugars, and organic acids, generated during oil extraction.	Olive oil extraction (mainly in 3-P systems).	(Bottino et al., 2020)
General olive oil waste and by-products	-	Non-specific category used by authors that refers generally to 'olive	-	(Arvanitoyannis et al., 2007;

		oil waste' or 'by-products'.		Vargas-Garcı´a et al., 2007)

To investigate the samples related to Q2, the eco-efficiency concept considered in this study excludes the financial component and highlights the environmental dimension, as well as the value created in outputs, through the valorisation of waste and by-products. In this regard, three different approaches are considered, i.e., *theoretical*, *integrated*, and *absence of eco-efficiency*. This choice aligns with the critical analysis of how the concept is discussed within the Q2 sample. Accordingly, the *theoretical* definition incorporates a perspective between treatment and valorisation effectiveness, with its relative environmental challenges associated, without necessarily involving the application of formal assessment tools (Huppes & Ishikawa, 2005). In contrast, *integrated* definition involves eco-efficiency approaches along with specific environmental indicators or methods for eco-efficiency assessment (Rybaczewska-Błażejowska & Gierulski, 2018). The *absence of eco-efficiency* approach implies that neither *theoretical* nor *integrative* approaches were identified in the sample.

2.2.3 Sample analysis

The samples for Q1 and Q2 are analysed using bibliometric and systematic methods. The bibliometric information is collected with a focus on journals, publication years, journal subject areas, and authors' keywords. The subject areas analysis is carried out through a multiple response analysis, which allows examination of variables with multiple categorical responses (Edwards & Allenby, 2003). To ensure better representation and consistency in the analysis, the WoS subject areas are reclassified according to the Scopus classification system. This mapping is done manually by identifying the closest thematic correspondences between the WoS categories and the typical Scopus subject areas. Authors' keywords are investigated through a network analysis using the VOSviewer software (Van Eck & Waltman, 2010). Meanwhile, the systematic analysis for Q1 is carried out by analysing the identified olive oil waste and by-products (see section 2.2) together with the treatment technologies and valorisation pathways that emerged from the sample. For Q2, the analysis focuses on investigating whether the articles address the application of CE principles and ES aspects, either together or separately. Additionally, it focuses on identifying *theoretical* or *integrated* approaches to eco-efficiency and how these approaches were connected to CE and/or ES within each article. Both bibliometric and systematic data are gathered and analysed using Microsoft Excel workbooks. The analysis is carried out concurrently and followed the same methodology for both queries under investigation.

2.3 Results and discussion

In this section, the results of the bibliometric and systematic analysis of the samples obtained from Q1 and Q2 are reported. The results of the systematic review for Q1 and Q2 are reported separately to present the data more coherently and precisely and to address the research questions.

2.3.1 Bibliometric and network analysis

The analysis of the journals and their respective years of publication for Q1 and Q2 is presented in Fig. 2. For both queries, the analysis of journal publication frequency was simplified by including only those journals that appeared more than once in each sample. The results show a clear understanding of the impact of olive oil waste and by-product processing technologies within the scientific community. Regarding Q1 (Fig. 2a), the results show that 6% of the literature is published in Bioresource Technology, 5% in the Journal of Environmental Management, and 5% in Waste Management. This highlights the significant technological, economic, and environmental relevance of the subject matter they cover. Indeed, these journals are renowned for their comprehensive coverage of topics related to bioenergy production, biomass conversion, waste valorisation, and environmental impacts. The results also reveal a fluctuating interest in olive oil waste and by-products management technologies, with two main peaks in publication activity: the first from 2004 to 2007 and the second from 2015 to 2023. These peaks correspond to shifts in environmental policies and funding priorities. The first peak aligns with the implementation of European regulations, such as the Water Framework Directive (2000/60/EC) (50), which encouraged sustainable waste and by-product management in the olive oil sector (Doula et al., 2017). The second peak reflects the global push for sustainability, driven by the Paris Agreement (2015) and the European Green Deal (2019), which promoted CE principles and resource efficiency (European Commission, 2019; United Nations, 2015a). Focusing on Q2 (Fig. 2b), 8% of the sample is published in the *Journal of Cleaner Production* and *Sustainability*, followed by *Science of the Total Environment*, contributing 5%. These journals are affiliated with publications focused on environmental protection, resource recovery from waste, and promoting clean production goals. Although slowly, this literature sample has been registering an increasing interest in the scientific community concerning eco-efficiency, environmental, and circularity approaches in this analysis context, beginning around 2016, when sustainability concepts, such as eco-efficiency, were increasingly integrated into agri-food research (Huppes & Ishikawa, 2005; United Nations, 2015b). The renewed interest between 2021 and 2024 is attributed to the shift towards life-cycle thinking and sustainability assessment tools, especially within the context of European sustainability policies and funding initiatives (Sala et al., 2021). This trend reflects the increasing importance of aligning production systems with CE models and green transition goals.

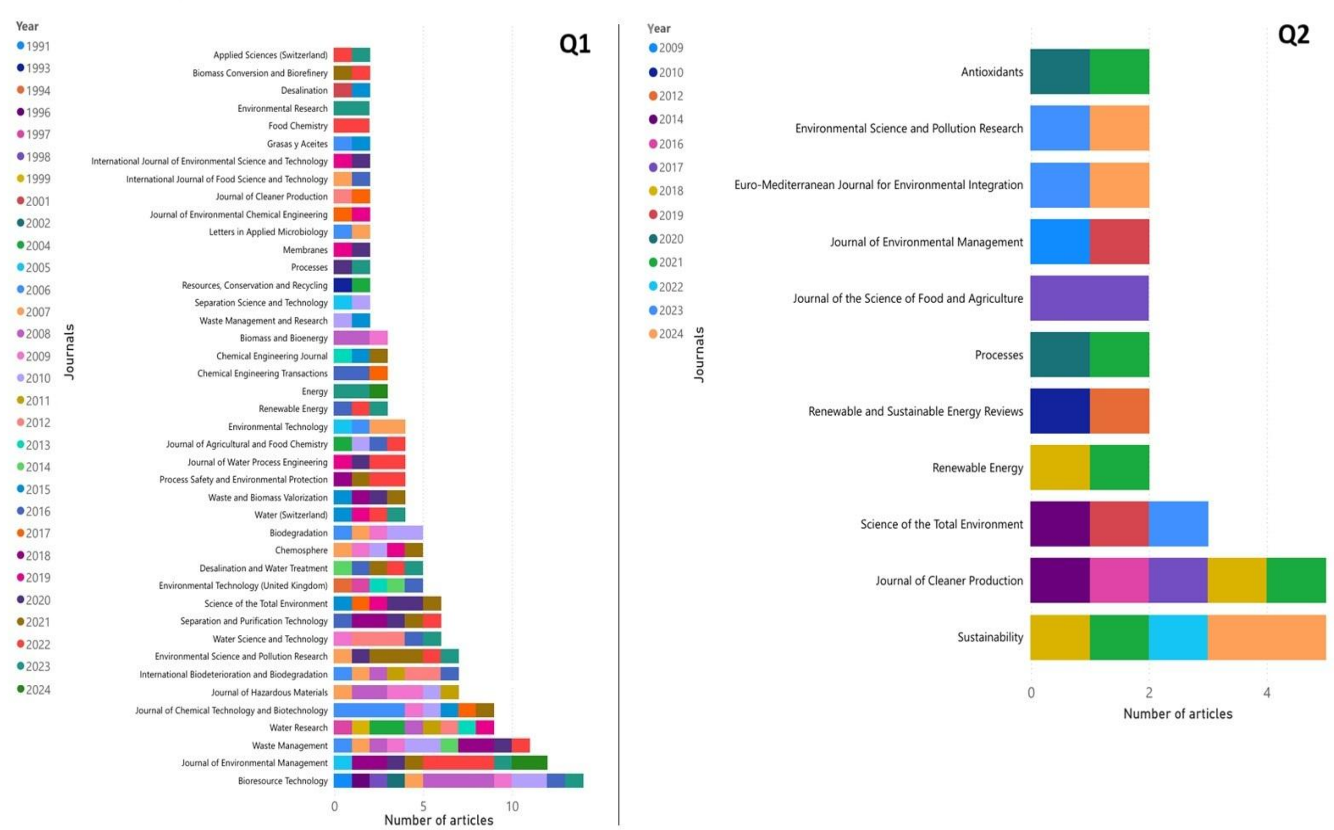

Figure 2 Journals and years of publication related to the sample of Q1 and Q2 – journals with one occurrence are excluded

The multiple-response analysis indicates that the most predominant subject areas for Q1 (Fig. 3) reflect the field's technological and sustainability focus, with a focus on optimising resource recovery processes. In particular, 'Environmental Science' emerges as the dominant subject area, consistently promoting clean production strategies. This is supported by 'Chemical Engineering', which plays a key role in the development of innovative technologies for the treatment and valorisation of olive oil waste and by-products. The analysis also permits the assessment of which combinations of subject areas most frequently occur in the sample, providing a more detailed understanding of their correlations with the respective publishing journals. For instance, in Q1, the *Journal of Environmental Management* focuses on 'Environmental Science' and 'Medicine' as its core subject areas, while *Bioresource Technology* encompasses 'Environmental Science' and 'Medicine', along with 'Chemical Engineering' and 'Energy'. Furthermore, the combination of 'Environmental Science', 'Chemical Engineering', 'Chemistry', and 'Energy' is among the most frequent, suggesting an interdisciplinary approach focused on sustainability, energy efficiency, and technological innovation related to olive oil waste treatment. The presence of subject areas such as 'Energy' and 'Agricultural and Biological Sciences' highlights interest in CE applications, such as bioenergy and agricultural reuse. Overall, the subject areas correspond to the research fields addressed in Q1, with particular emphasis on the environment, the technological dimension, and the key areas relevant to valorisation pathways. Similarly, results related to the subject areas analysis for Q2 are reported in Fig. 3. The most represented subject areas are 'Environmental Science', 'Energy', 'Engineering', 'Agricultural and Biological Sciences' and 'Chemical Engineering', similar to Q1, and 'Social Sciences'. These topics highlight the strong connection between processing technologies, valorisation strategies, and broader goals of environmental and social sustainability. Furthermore, the results highlight the importance of understanding the social dimension of waste and by-product management and valorisation. This includes the potential to create new job opportunities and foster collaboration between different industries, which in turn requires skilled professionals to oversee and manage sustainable and eco-efficient solutions. Overall, the alignment of these main topics is coherent with the journals most frequently represented in the Q2 literature sample. Results also underscore the frequent combinations between multiple subject areas, such as 'Environmental Science' and 'Chemical Engineering', 'Environmental Science' and 'Agricultural and Biological Sciences', and 'Energy' and 'Engineering'. These combinations demonstrate the interdisciplinarity of eco-efficiency research, which requires technological expertise and environmental assessment to develop innovative processes.

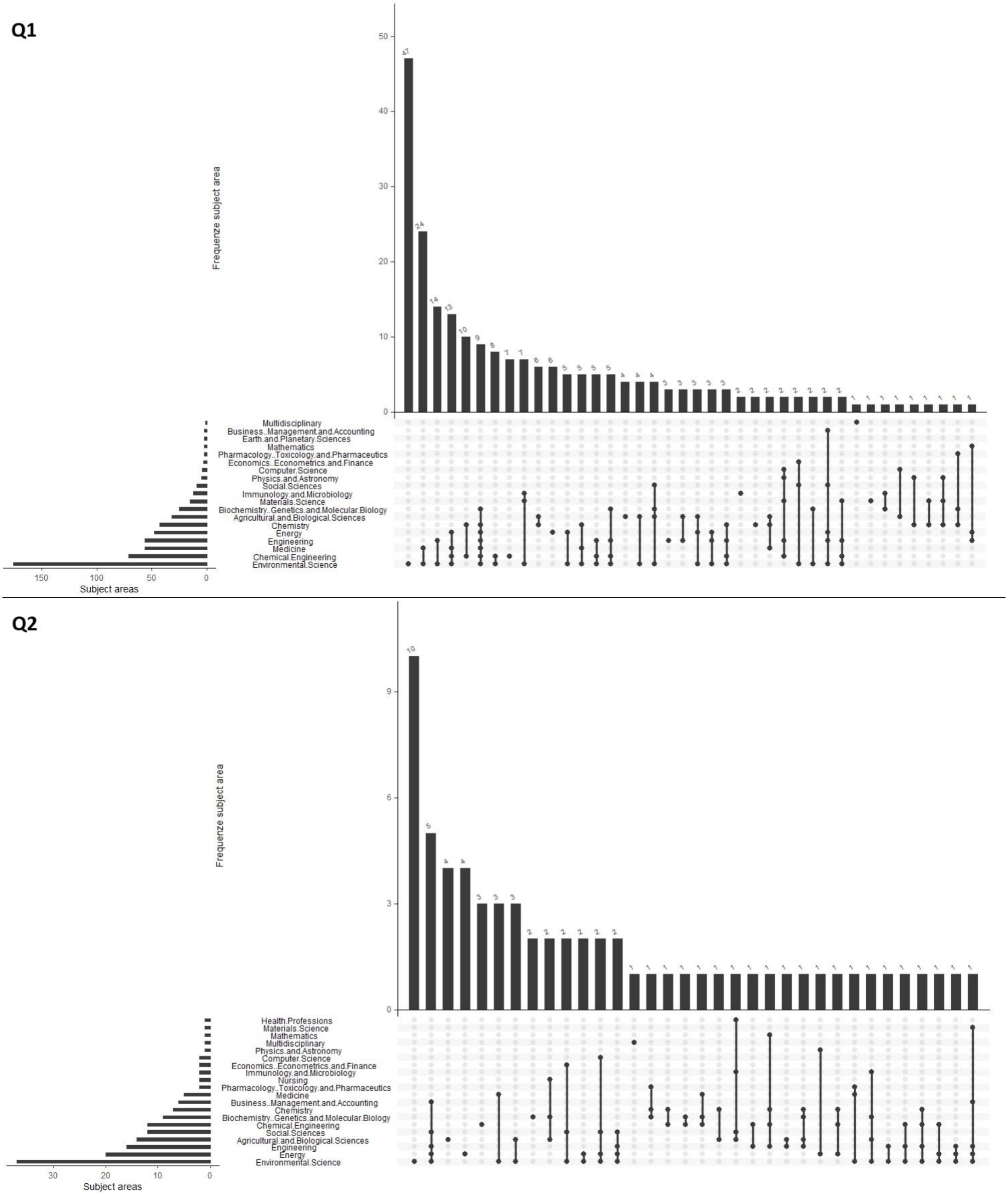

Figure 3 Main subject areas frequencies and their combination for Q1 and Q2

The results related to the network analysis of keyword co-occurrence are presented in Fig. 4. Concerning Q1

(Fig. 4), the most frequently used keywords are ‘olive oil mill waste’, ‘olive mill wastewaters’, ‘value-added compound’, ‘anaerobic digestion’, ‘physical-chemical treatment’, and ‘composting’, aligning with the topics covered in the query. Notably, the high presence of the keyword ‘olive mill wastewaters’ highlights a particular focus in the literature on the topic of OMWW treatment and its management. Indeed, OMWW is the most abundant waste of the olive oil sector (Banias et al., 2017).

The network analysis also allows the identification of three main clusters: i) related to biological treatments (green cluster), including the reuse in agriculture as fertiliser or soil conditioner, ii) related to the treatment and pre-treatment of wastewater through physico-chemical processes (blue cluster), and iii) related to olive oil waste and by-product treatment for biogas production and polyphenols recovery (red cluster). It is important to note that the keyword ‘circular economy’ appears in the latter, suggesting that waste treatment for energy production and the recovery of high-value substances, such as polyphenols, are strongly integrated into CE strategies. The spontaneous emergence of the keyword ‘circular economy’, despite not being a primary research term reported in the analysed literature, indicates a growing interest in integrating these practices into circular resource management models. The network analysis of authors’ keywords for Q2, which explores the eco-efficiency of treatment technologies for olive oil waste and by-products, is illustrated in Fig. 4b. The most prominent keywords include ‘olive mill wastewaters’, ‘olive oil by-product valorisation’, ‘environmental sustainability’, ‘circular economy’, and ‘phenolic compounds’. This confirms the OMWW as the most commonly studied waste stream, while concepts such as CE and ES are more central here than in the Q1 sample. The strong association between ‘circular economy’, ‘olive oil by-product valorisation’, and ‘phenolic compounds’ reflects growing interest in recovering high-value compounds to support sustainable and circular models within the sector. The co-occurrence of ‘life-cycle assessment’ and ‘eco-efficiency’ with ‘thermochemical processes’ and ‘environmental sustainability’ highlights an increasing tendency to evaluate treatment technologies through systemic and quantitative approaches. This suggests a shift towards integrating LCA and eco-efficiency metrics, particularly in the assessment of thermal processes. Furthermore, the appearance of terms such as ‘green chemistry’ and ‘bioremediation’ reveals a multidisciplinary orientation in current research, reflecting a broader trend toward integrative approaches that aim not only to reduce the environmental impacts, but also to generate added value across multiple sectors.

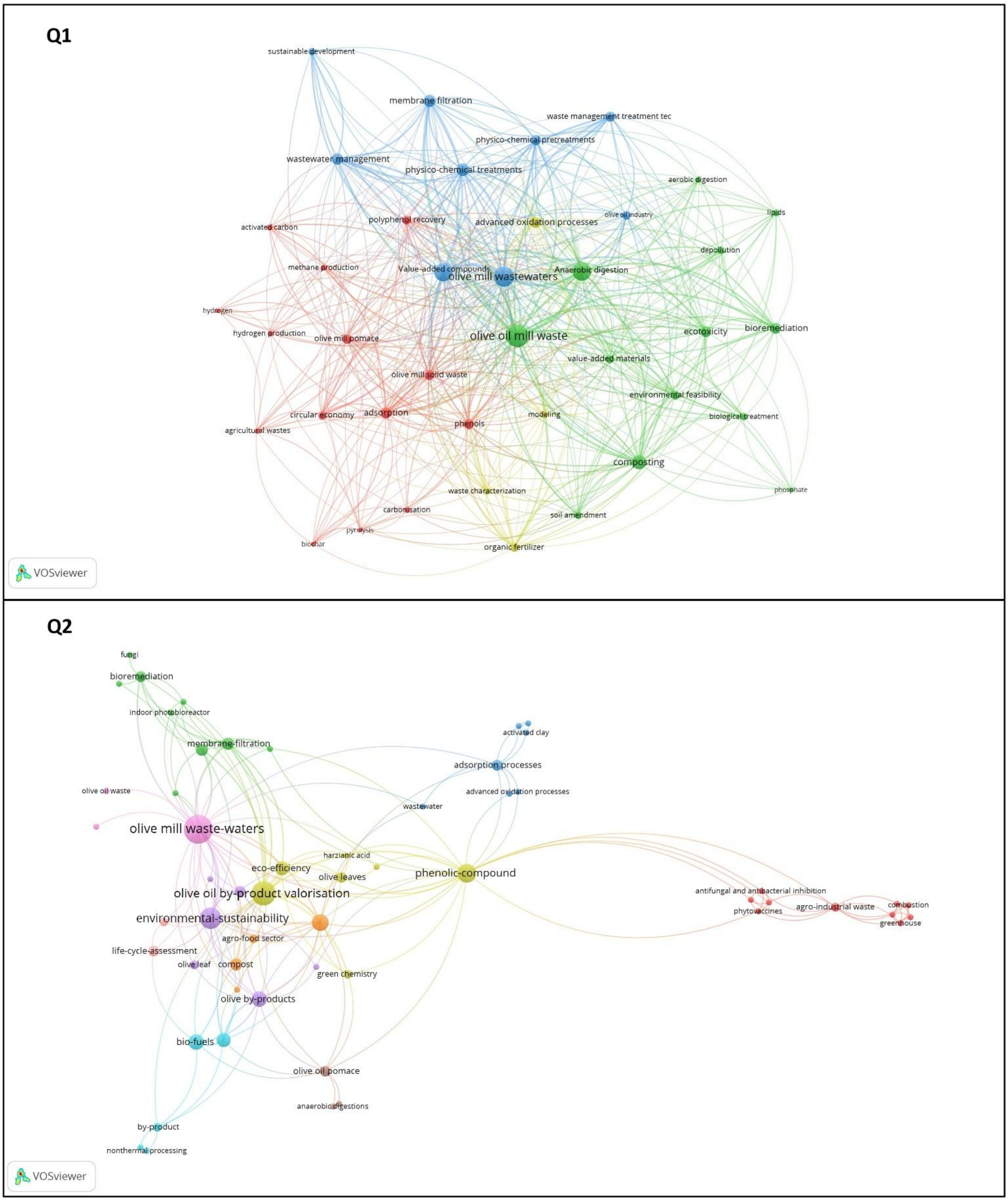

Figure 4 Visual network mapping related to the authors' keywords for Q1 and Q2

2.3.2 Characterisation of treatment technologies and valorisation routes

The results of the systematic literature review for Q1 primarily concern the characterisation of treatment technologies and valorisation pathways for olive oil waste and by-products. The main technologies identified in the sample are summarised in Table 2, which highlights the key advantages and disadvantages of each treatment. Results are reported by characterizing each treatment technology according to its principles and process type. The identified treatment technologies differ significantly, employing a wide range of principles, from biological processes to thermal and physico-chemical methods. Biological treatments, for instance, are praised for their environmental friendliness and cost-effectiveness, particularly for handling biodegradable pollutants. Anaerobic processes are particularly valuable for their capacity to generate biogas and digestate suitable for agricultural reuse, especially when OMWW is co-treated with other organic streams (Athanasoulia et al., 2012; Marques, 2001). However, the presence of polyphenols, known for their phytotoxicity and biodegradation resistance, can inhibit microbial activity (Marques et al., 1997), requiring pre-treatment such as electrocoagulation or membrane filtration (Hanafi et al., 2011). Aerobic treatments, especially composting, are widely adopted for their operational simplicity, ability to produce stable compost, and removal efficiencies of up to 80% BOD, 69% COD, and 61% polyphenols (Fleyfel et al., 2022). Although this technology is well regarded for its economic and ES, it requires a large area to establish compost piles (Bouhia et al., 2023). Membrane filtration technologies, such as nano -, ultra-, and micro-filtration and reverse osmosis, offer high efficiency in removing phenolic compounds (La Scalia et al., 2017) and enable the recovery of treated effluent suitable for irrigation or fertilization (Bottino et al., 2020). Nonetheless, membrane fouling remains a key limitation, often caused by the organic load, e.g., in OMWW (Ochando-Pulido & Martinez-Ferez, 2012). Pre-treatment tailoring is thus essential for optimizing filtration performance (Ochando Pulido, 2015), with ceramic membranes often preferred for their durability and resistance to cleaning agents. Thermal processes such as pyrolysis, gasification, and combustion are also well represented in the literature due to their ability to rapidly reduce waste volume and recover energy (Balmuk et al., 2023; Caputo et al., 2003). The energy generated can be reused in the olive oil production process or redistributed locally (Pattara et al., 2010). However, the initial capital investment and the high moisture content of the waste are major drawbacks. To overcome these issues, hydrothermal carbonization is gaining traction because it enables the treatment of wet waste without the need for drying (Ncube et al., 2022). In parallel, bio- and phyto-remediation techniques emerge as low-cost and environmentally friendly alternatives. These include the use of fungi, algae, or bacteria capable of degrading phenolic compounds and generating useful by-products such as fungal biomass or bioethanol (Aguilera et al., 2008; Amaral et al., 2012; Koutrotsios et al., 2022). Similarly, microalgae can also be used for bio-phytoremediation to transform harmful substances into useful ones (Fernández-Rodríguez et al., 2022). This treatment method is gaining attention for its simplicity, low cost, and ease of implementation (Diamantopoulou et al., 2021). Combined strategies that integrate different technologies, such as biological and chemical-physical processes, are also commonly evaluated to enhance pollutant removal efficiency and improve the overall effectiveness of subsequent valorisation steps. One such example is electrocoagulation followed by anaerobic digestion, which significantly enhances polyphenol removal and improves methane production (Khoufi et al., 2006). Similarly, membrane technologies are often implemented after biological treatments to polish the effluent and recover high-quality water (Ochando Pulido, 2015). Another promising approach is co-composting, in which OMWW is mixed with other organic waste, such as sewage sludge or household refuse, to enhance composting (Atif et al., 2020). Integrated systems that combine biological and physicochemical treatments show the greatest potential to balance cost-efficiency with environmental performance. Khoufi et al. (2006) (Khoufi et al., 2006) underscore the benefits of using an electrochemical pre-treatment, i.e., the electro-Fenton reaction, before an anaerobic bio-treatment, which allows removing 65.8% of the total polyphenolic compounds. Despite the high efficiency of these treatment technologies, they are often not feasible for Small and Medium Enterprises (SMEs). Indeed, SMEs tend to prefer more cost-effective methods like land-spreading, evaporation in storage lagoons, and sewer disposal within regulatory limits. Overall, the analysis highlights an emerging trend toward the adoption of more advanced treatment technologies and integrated disposal processes, which represent a promising pathway for advancing CE objectives within the olive oil industry.

Table 2 Overview of treatment technologies for olive oil waste and by-products identified in the sample of Q1, including process type, operating principles, advantages, disadvantages, and references (BOD: *biochemical oxygen demand*; COD: *chemical oxygen demand*; CH_4: *methane*; CO_2: *carbon dioxide*; VOCs: *volatile organic compounds*; OMWSR: *olive mill wastewater steam reforming)*

Treatment technology	**Type of process**	**Operating principles**	**Advantages**	**Disadvantages**	**Reference**
Aerobic treatment and composting	Biological	Uses oxygen to degrade organic matter through aerobic microorganisms and to produce compost.	Reduces BOD, COD, and polyphenols; produces compost; easy to control (C/N ratio, pH, temp); cost-effective.	Requires long retention time, odour emission. Requires a large space; efficiency depends on initial toxicity levels; COD tolerance <1 g/L. inhibited by polyphenols	(Ahmed et al., 2019; Bouhia et al., 2023; Chilosi et al., 2018; Fleyfel et al., 2022)
Anaerobic treatment	Biological	Breakdown of organic matter in the absence of oxygen, producing biogas which mainly contains 50–65% methane (CH_4) and 35–50% carbon dioxide (CO_2) gases like hydrogen sulphide, nitrous oxide etc.	Energy recovery through biogas; suitable for co-treatment; safe digestate reuse for agricultural purposes.	Sensitive to pH/temperature, slow process. Limited large-scale implementation. Inhibited by polyphenols	(Hanafi et al., 2011; Marques et al., 1997; Pluschke et al., 2023; Tsigkou et al., 2022)
Steam reforming (OMWSR) process	Thermal	Thermochemical conversion with steam to produce syngas.	High energy output, syngas valorisation.	Requires high temperatures, gas cleaning needed.	(Rocha et al., 2022)
Carbonization	Thermal	Heating biomass in the absence of oxygen to produce biochar (a porous carbonaceous substance) at 450 °C in a muffle furnace.	Produces stable biochar, useful in agriculture.	Limited energy recovery, possible VOC emissions.	(Mohamed Abdoul-Latif et al., 2023)
Pyrolysis	Thermal	Thermal decomposition breaks down biomass at high temperature in an oxygen-limited environment (or without oxygen) to produce bio-oil (liquid fraction), gas (gas fraction), and char (solid fraction).	Multiproduct output, flexible feedstock.	Expensive, varying product quality.	(Del Pozo et al., 2022)
Combustion	Thermal	Complete oxidation with heat generation and gas emissions.	Simple, effective for waste reduction and energy.	Air pollution, low material recovery.	(Caputo et al., 2003)
Gasification	Thermal	thermal decomposition at a temperature of around 1000 °C of biomass with partial oxygenation to generate syngas (synthetic gas).	Energy-efficient, converts diverse biomass.	Complex, high initial cost.	(Vera et al., 2014)

Bio/phytoremediation	Biological	Use of microorganisms (bacteria, microalgae, fungi, yeast) or plants to remove contaminants from soil and water.	Simple, low-cost, bioethanol and biomass valorisation, suitable for high-phenol waste.	Slow process, limited scalability, specific strains required.	(Diamantopoulou et al., 2021; Faraloni et al., 2023; Goren et al., 2021; McNamara et al., 2008; Scioli & Vollaro, 1997)
Enzymatic catalysis	Biological	Use of enzymes to break down specific organic compounds.	High selectivity, mild conditions.	Enzymes are expensive, sensitive to pH/temp.	(Crognale et al., 2006)
Evaporation	Physical	Separation of water from solutions for concentration or component recovery.	Simple, reduces volume.	High energy demand.	(Martínez-Gallardo et al., 2022)
Electrocoagulation	Physical	In the electrocoagulation process, the anodic and cathodic reactions generate a coagulant, which is essential for destabilising colloids.	Effective for pollutants, few chemicals are needed.	High electricity use, sludge production.	(Fleyfel et al., 2022)
Liquid-liquid extraction	Chemical	Separation of compounds using immiscible solvents based on solubility.	Selective recovery, especially of phenolics.	Solvent handling and disposal issues.	(Azzam & Hazaimeh, 2021)
Adsorption and biosorption	Physical	Removal of substances by adhesion to solid surfaces or biomass.	Inexpensive, efficient, reusable materials.	Saturation over time, disposal of media.	(Abu-Dalo et al., 2021; Achak et al., 2009)
Nano-ultra-micro filtration membranes and reverse osmosis	Physical-Chemical	Separation of components using selective membranes under pressure.	High phenol removal (~90%); low energy; preserves agronomic value; reusable water.	Membrane fouling, high organic load interference, and high cost requires pretreatment.	(Ochando-Pulido & Martinez-Ferez, 2018; Saf et al., 2023; La Scalia et al., 2017; Bottino et al., 2020)
Advanced oxidation processes	Physical-Chemical	Degradation of pollutants using oxidative radicals (e.g., ozone, peroxides).	High pollutant removal; safe effluent reuse (e.g., irrigation); efficient oxidation.	High chemical cost, sludge generation (e.g., ferric), needs optimization.	(Amaral-Silva et al., 2017)
Combination of biological and chemical-physical treatment	Biological-Physical	Integrated approach combining biological processes with physico-chemical techniques to improve the effectiveness of treatments.	Broader removal spectrum, synergy effects.	More complex, higher operational cost.	(Cifuentes-Cabezas et al., 2022; Savarese et al., 2016; Zorpas & Costa, 2010)
Combination of physical and chemical treatment	Physico-Chemical	Combined use of different type of physical and chemical treatments to remove contaminants.	Effective on mixed waste streams.	Costly, complex process control.	(Chouchene et al., 2010; Crialesi et al., 2022; Padilla-Rascón et al., 2020)

Regarding the frequency of treatment technologies identified in Q1 (Fig. 5), the results show that anaerobic treatments (26%) are the most widely assessed, likely due to their potential for energy recovery through biogas production and their compatibility with resource recovery strategies. Aerobic processes and composting (23%) follow closely, confirming the relevance of cost-effective and sustainable solutions. Membrane-based technologies (nano/micro/ultrafiltration and reverse osmosis) represent 16%, reflecting a growing interest in high-efficiency systems capable of producing reusable water and separating valuable compounds, despite their higher operational costs. Thermal treatments (13%) are less frequent but remain essential in handling non-biodegradable or high-strength waste, offering effective volume reduction and energy recovery, albeit with higher energy demands and infrastructure requirements. Bio-phytoremediation (12%), although slower and less scalable, is valued for its low environmental impact and simplicity, making it suitable for localised or agricultural contexts. Overall, the trends indicate a balanced approach between sustainability and technological performance, with treatment selection influenced by the nature of olive oil waste and by-products, their valorisation potential, and economic and regulatory constraints.

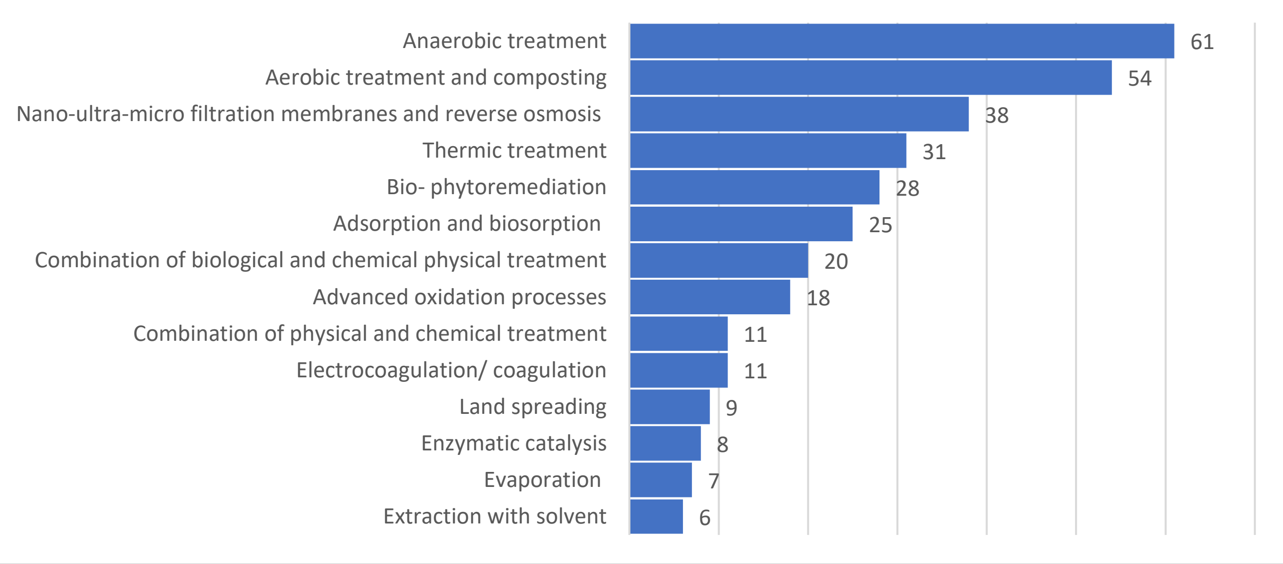

Figure 5 Frequency of treatment technologies identified in the Q1 sample, reported by the number of articles discussing each technology

The treatment technologies adopted for each of the identified categories of olive waste and by-products (see Section 2.2 for more details) are presented in Fig. 6, as derived from the Q1 sample. Results highlight that olive oil liquid waste and by-products, and specifically OMWW, are well considered in each treatment technology, especially for anaerobic (20%) treatments, aerobic treatment and composting (15%), nano-ultra-micro filtration and reverse osmosis (13%), thermal treatments (9%), and bio-phytoremediation (8%). This indicates that liquid effluents are the most problematic and widespread waste fraction, requiring a wide range of treatment solutions. In this context, the large volume, coupled with the relatively brief production period (from November to March), and the high concentration of phytotoxic compounds (15-18% of phenols, polyphenols, and tannins) (Inglezakis et al., 2012) has drawn significant interest from the scientific community toward this olive mill waste and by-products. The second most frequent type of waste and by-product is the solid one, which is mainly treated through aerobic (21%) and thermal (19%) processes (e.g., steam reforming, pyrolysis, gasification, and combustion). Several studies (e.g., (Martinez-Garcia et al., 2006; Pattara et al., 2010) highlight the high efficiency of these technologies for energy valorisation of olive oil waste and by-products. Specifically, thermal treatment produces biochar, which, owing to its high nutrient content, can be used as a fertilizer (El-Bassi et al., 2021). Semi-solid olive oil waste and by-products (mainly wet OP) treatment appears to receive less attention in the articles, with only a few technologies investigated for its management, e.g., aerobic treatment (P. Rueda et al., 2024), membrane filtration (Greco et al., 1999), and liquid-liquid extractions (Azaryouh et al., 2024). This suggests that the high moisture content that characterises wet OP poses significant challenges for its processing, which often requires pre-treatment support and transportation, e.g., logistics and costs associated with moving bulky, heavy material (Sánchez Moral & Ruiz Méndez, 2006). Regarding the category 'general olive oil waste and by-products', results underscore that there is a fair presence of studies, mainly review articles, in which olive oil waste and by-products are analysed in a broader context, without specifying the type. For example, the review proposed by Azbar et al. (2004) (Azbar et al., 2004) provides a broad overview of treatment technologies and management strategies (e.g., aerobic or anaerobic treatment, natural or forced evaporation, chemical coagulation and flocculation, chemical oxidation processes, membranes filtration and several pre-treatment chemical processes) for liquid, solid, and semi-solid waste and by-products from the olive oil sector, also highlighting the economic and environmental feasibility of these techniques.

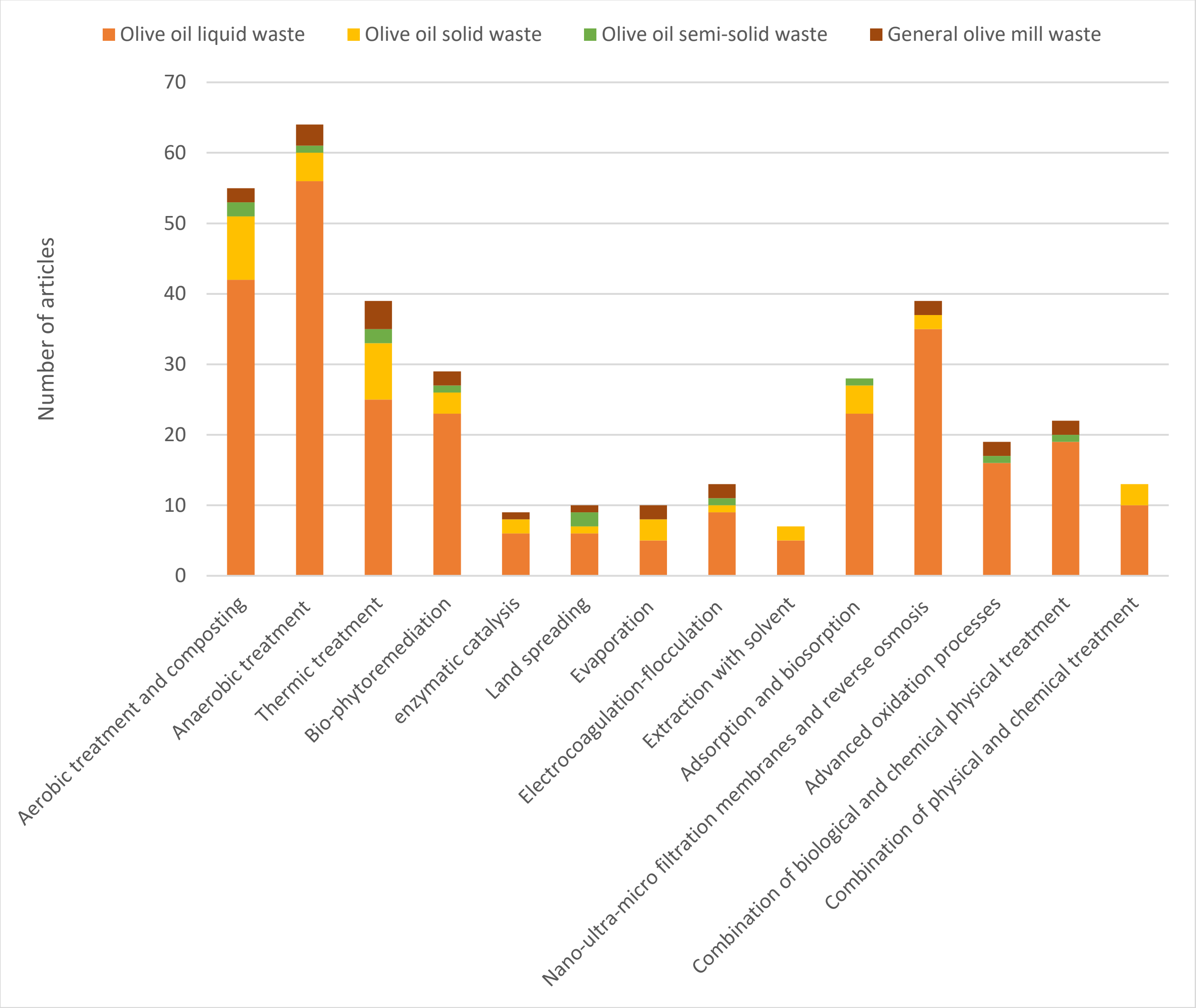

Figure 6 Treatment technologies and the related categories of processed waste and by-products (i.e., solid, semi-solid, liquid, and general olive mill waste and by-products), as identified in Q1

There is a notable effort and growing interest among the olive oil industry and researchers to embrace CE principles to improve the management and valorisation of waste and by-products, from a sustainability perspective. The valorisation strategies that emerged for each of the identified treatment technologies in the Q1 sample are presented in Fig. 7. The findings align with the initial bibliometric results, showing that the agricultural reuse of olive oil waste and by-products as fertilisers, compost, or soil amendments (Shabir et al., 2023) is common across most treatment practices, specifically biological treatments, such as aerobic digestion and composting. The exception is solvent extraction processes, which primarily aim to recover value-added substances for use as natural antioxidants in the health sector or for the preparation of functional foods as a preservation method (Gueboudji et al., 2023; Zahi et al., 2022). Irrigation reuse (referred to as land spreading of olive oil liquid effluents treated and fertigation), biogas production (methane and hydrogen), and the recovery of value-added compounds are all considered valid valorisation pathways across different treatment technologies. However, the analysis reveals that each treatment tends to prioritise one of these outputs depending on its technical characteristics and application goals. In addition, the findings reveal that the selection of a specific circular oriented valorisation approach depends on factors like the mill's operational needs, economic constraints, availability of infrastructure, and market requirements (Enaime et al., 2024). Additional constraints are related to bureaucratic and authorization challenges, bottlenecks in planning the supply of raw materials dispersed throughout the territory, and the seasonal availability of these. In this context, the study conducted by Donner et al., (2022a) investigates, through surveys, the political-legal conditions that influence, both positively and negatively, the adoption of CE strategies in the treatment and valorisation of olive oil by-products in four major Mediterranean olive oil-producing countries. The results show that farmers' perceptions about the CE are still poorly consolidated. For example, in Spain, waste and by-product valorisation strategies tend to be limited to low-value practices (downcycling), such as selling OP to pomace factories to extract the residual oil. However, small-scale entrepreneurs generally support the adoption of strategies that involve recycling by-products within their farms, as this reduces waste and provides economic and production benefits. Despite this, adoption of these practices remains limited due to the significant initial investment required for the supporting infrastructure.

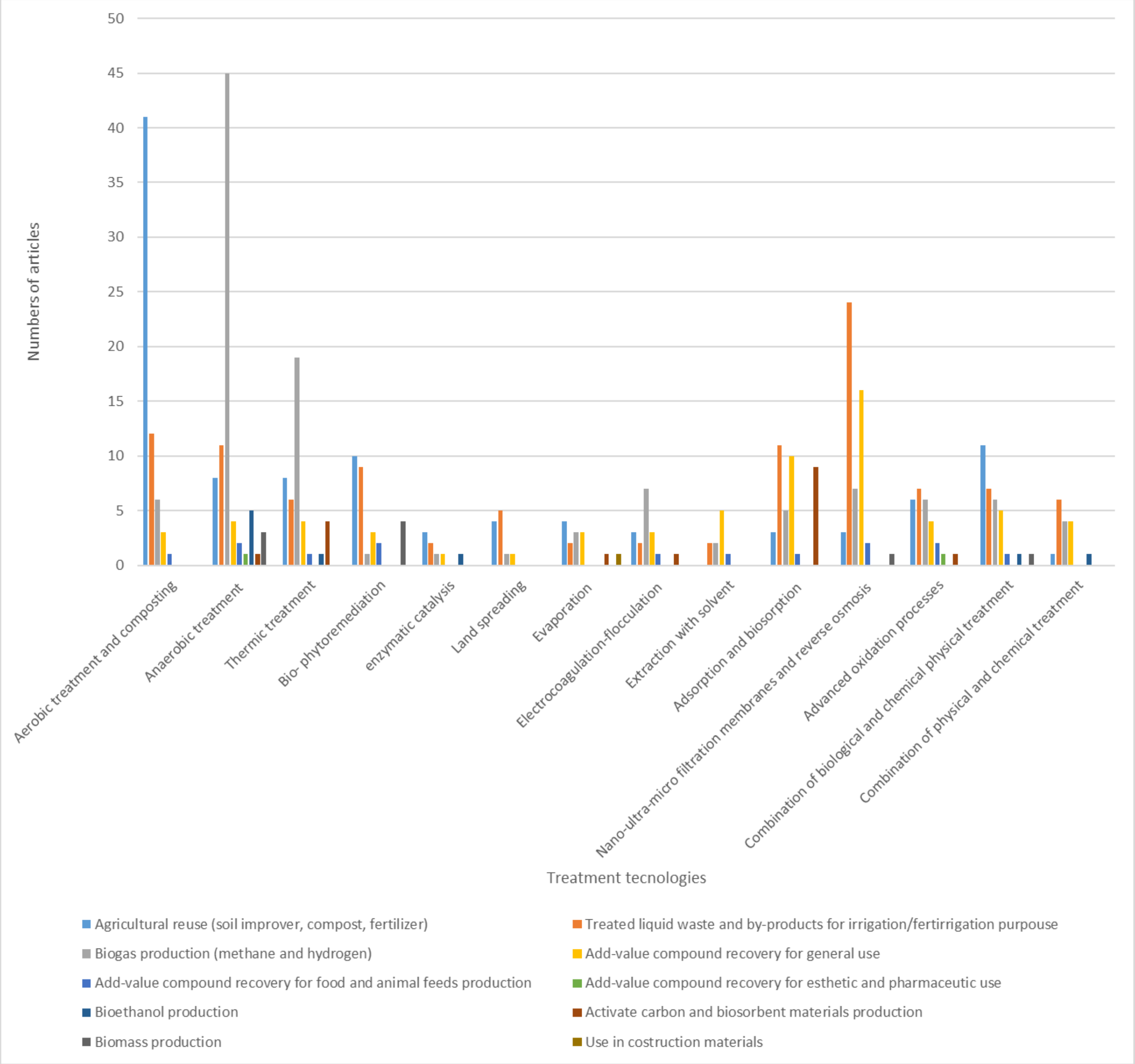

Figure 7 Valorisation strategies associated with each treatment technology

2.3.3 Eco-efficiency assessment of treatment technologies and link with circular economy and environmental sustainability

Among the 65 analysed articles in Q2, 58% (38 articles) address eco-efficiency, of which 55% focus on *theoretical* perspectives and 45% explore *integrated* approaches (Fig. 8). Although the term 'eco-efficiency' is not explicitly mentioned in the sample, its underlying principles are evident. In particular, the results indicate that a large share of the technologies is discussed within a *theoretical* eco-efficiency perspective, particularly for thermal treatments, aerobic and anaerobic digestion, nanofiltration, ultrafiltration, and microfiltration membranes, and reverse osmosis. In these cases, technologies are often described as environmentally advantageous because of their demonstrated ability to remove pollutants and recover energy efficiently. Despite this, the environmental performance of these technologies has not been assessed using dedicated eco-efficiency methods. The results also show that a subset of studies, especially those addressing thermal processes, aerobic and anaerobic digestion, and combinations of physical and chemical treatments, adopt an *integrated* eco-efficiency approach. This is primarily attributable to the intrinsic complexity of these technologies, which generate multiple outputs (e.g., energy, compost, or recovered materials) and involve trade-offs among environmental performance, resource efficiency, and process intensity. In such cases, authors tend to apply more comprehensive evaluation frameworks to assess overall sustainability and the efficiency of well-recovered and reused by-products. As illustrated in Fig. 8, although a considerable number of studies (37 articles) do not explicitly address eco-efficiency, the distribution of approaches highlights a growing awareness of ES and efficiency issues, particularly in relation to thermal recovery processes. This suggests that the same technology can be framed within a *theoretical* or *integrated* eco-efficiency perspective, depending on the depth and scope of the assessment applied, and the purpose of the studies. Overall, the absence of eco-efficiency considerations is observed across several treatment technologies within the reviewed literature. This is mainly because these studies tend to prioritise valorisation outcomes from olive oil waste and by-products, such as the extraction of polyphenolic compounds or energy recovery, over a comprehensive evaluation of their associated environmental impacts.

Focusing on the *integrated* approach to eco-efficiency, the analysis also allows the identification of the methods used to assess both environmental performance and the value of output valorisation for each treatment. In particular, LCA has emerged as the most widely used method for assessing the potential environmental impacts of treatment strategies for olive oil waste and by-products, following a life-cycle perspective. Most of the studies use the LCA method to conduct comparative analyses between different treatment technologies to identify the most efficient technology in terms of treatment and ES. For example, the study conducted by Batuecas et al. (2019) (Batuecas et al., 2019) analyses two scenarios for OP and OMWW treatment and highlights that the use of these waste and by-products as feedstock for biogas production through anaerobic digestion can represent a useful alternative to the conventional olive waste disposal on soil, such as land spreading. Another relevant but less commonly applied method is the one used by Ruggeri et al. (2015) (Ruggeri et al., 2015), which integrates two indicators, i.e., the biochemical methane potential (BMP) and the energy sustainability index (ESI). The authors explore different pre-treatment methods by assessing the effectiveness of energy production in the anaerobic treatment of OMWW and OP. The study also evaluates the energy required for direct (heat and electricity) and indirect (chemical reagents) inputs. Additionally, Hocaoglu et al., (2018) propose a mass balance equations to estimate water use, oil yield, and waste and by-product production, through a Physical Input-Output analysis. This approach helps to understand the resource-use efficiency and environmental impacts associated with olive oil production and its waste and by-product treatments.

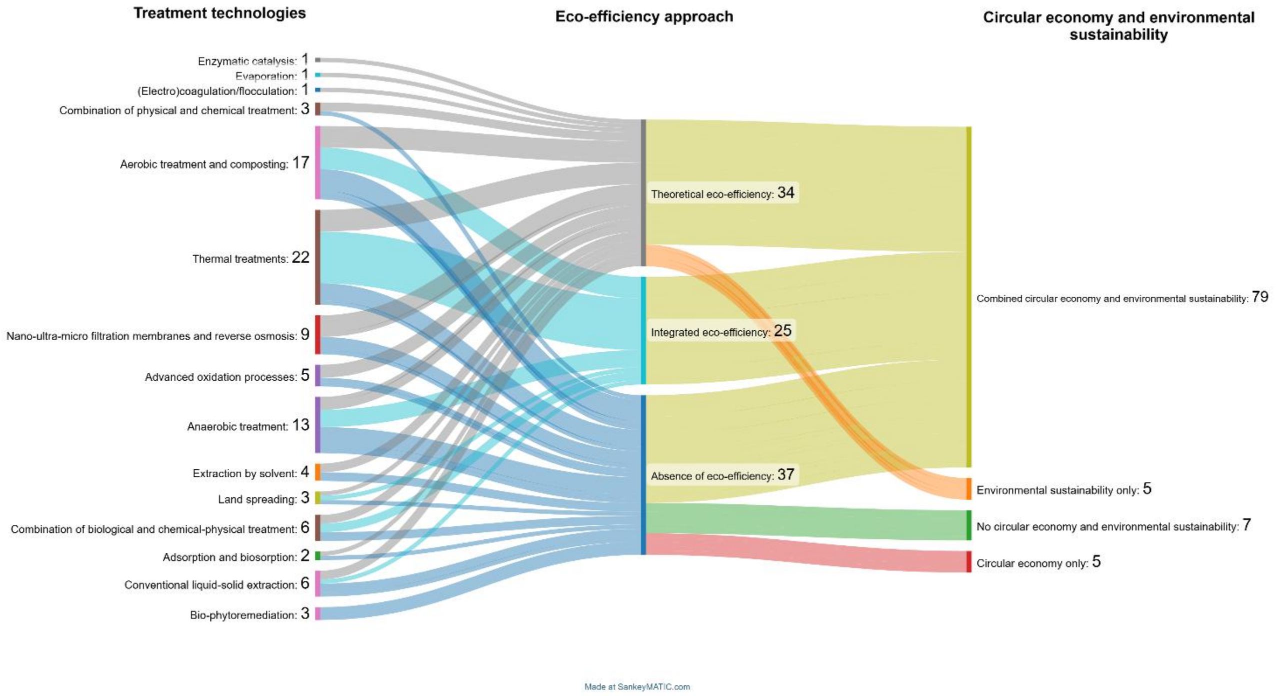

Figure 8 Distribution of olive oil waste and by-products treatment technologies with the three identified eco-efficiency approaches and related link with CE and ES concepts, in Q2 sample. The numbers indicate the frequency of each technology and the corresponding references to eco-efficiency, the CE, and ES. Image created with the Sankey Matic web program

Regarding the link between CE and ES concepts (Fig. 8), the results reveal that, while most studies engage with circularity and sustainability, only a subset explicitly connect these to eco-efficiency, either through *theoretical* or *integrated* approaches. The results show an interesting presence of studies adopting a combined CE and ES perspective, along with a theoretical eco-efficiency level, rather than through structured quantitative assessments (Cappelli et al., 2023; Dehmani et al., 2023). In particular, thermal technologies are perceived as effective not only in waste reduction and energy recovery, in line with CE principles, but also in improving environmental performance through volume reduction and pollutant control (Nunes et al., 2022). Similarly, aerobic digestion is commonly associated with environmental benefits, including organic matter stabilisation and compost production for agricultural reuse with excellent yields of fertilising power (Fleyfel et al., 2022). In these cases, eco-efficiency is addressed primarily at the theoretical level, as the environmental advantages and resource-recovery potential of these technologies are often assumed to imply efficient system performance. Furthermore, a substantial number of studies, despite investigating widely adopted technologies (e.g., nanofiltration and reverse osmosis membranes), do not include any eco-efficiency evaluation, either *theoretical* or *integrated*, even when CE and ES principles are explicitly addressed. However, this absence is observed across different treatment technologies, suggesting that the lack of eco-efficiency assessment is not limited to a single process. This highlights a methodological gap that may stem from the complexity of integrating multidimensional frameworks and from the lack of standardised tools for evaluating eco-efficiency alongside CE and ES. High pollutant removal efficiencies or significant energy recovery are frequently associated with elevated energy consumption, substantial operating costs, or indirect environmental impacts linked to infrastructure, maintenance, or auxiliary inputs. For this reason, part of the recent literature slowly begins to focus on the development and application of practical eco-efficiency measurement tools (*integrated eco-efficiency*) that are consistent with circular design strategies at the company level and aligned with ES principles (Fig. 8). This shift is driven by the need to move beyond qualitative assumptions of sustainability and to capture the trade-offs between environmental performance, resource use, and economic viability. In particular, integrated assessment tools, such as LCA, are being explored to support decision-making in complex systems involving multiple inputs and outputs (Fernández-Lobato et al., 2022; Ozturk et al., 2023). Technologies that most frequently fall within this transition include thermal treatments, anaerobic digestion, and combined biological–chemical–physical processes. These systems are characterised by high technological complexity, multiple recovery pathways (e.g., energy, heat, digestate, and secondary materials), and significant operational requirements. As a result, their performance cannot be adequately assessed using single indicators or pollutant-removal metrics alone. Instead, they require *integrated* eco-efficiency evaluations to balance ES goals with energy use, costs, and system-level impact (Klisović et al., 2021). Overall, this highlights a strong trend in the literature toward merging treatment, valorisation, economic and environmental benefits, within a CE framework. In this regard, Cappelli et al. (2023) (Cappelli et al., 2023) point out that managing olive oil waste and by-products through a circular approach could offer significant economic and environmental benefits, especially for SMEs, by reducing raw material use, minimising environmental impacts, and cutting costs. These findings indicate that, although eco-efficiency is increasingly referenced alongside CE and ES, it is often applied in a fragmented and mainly conceptual manner. Nevertheless, thermal treatments emerge as the most advanced technologies in addressing these concepts, owing to their intrinsic characteristics, such as resource recovery potential, waste volume reduction, and applicability within integrated assessment frameworks. Eco-efficiency aims to use fewer resources, reduce environmental impact, and keep the value of products and services, while also helping businesses stay competitive (Bimpizas-Pinis et al., 2021). Both eco-efficiency and CE share the goal of generating more value from the same amount of resources or of reducing the resources required to produce a given output. Although both strategies are promising, they share a common challenge, the so-called rebound effect. This effect occurs when efficiency gains reduce the price of products or services or increase their accessibility, thereby increasing consumption. For instance, more efficient and less resource-intensive production can lower costs, which in turn may boost demand. As a result, the environmental benefits of efficiency gains may be partially or entirely offset by higher overall resource use (Figge & Thorpe, 2023). This paradox is relevant to both eco-efficiency and CE, as increased efficiency can unintentionally lead to higher overall resource use (Figge & Thorpe, 2023; Szigeti & Borzán, 2025). This suggests that, without careful regulation and systemic planning, efficiency gains alone may be insufficient to achieve absolute reductions in environmental impact. Overall, the integration of eco-efficiency with CE and ES remains a critical yet underdeveloped area, underscoring the need for more consistent and comprehensive evaluation frameworks to support sustainable waste and by-product management strategies in the olive oil sector.

2.4 Conclusion

This study aimed to analyse and characterise, through a bibliometric and systematic analysis, the technologies used for olive oil waste and by-products treatment, evaluating their potential for valorisation and their alignment with CE and ES principles, as well as eco-efficiency. The scope was to provide a comprehensive picture of the current state of these technologies, focusing on their ES and eco-effectiveness in promoting a more integrated and circular system. The bibliometric analysis of Q1 and Q2 shows increasing interest in the treatment and valorisation of olive oil waste and by-products. In Q1, the most common subject areas include 'Environmental Science', 'Chemical Engineering', 'Energy', and 'Agricultural and Biological Sciences', indicating a strong link between technological innovation and sustainability goals. Keyword analysis highlights widespread interest in OMWW, biological and physico-chemical treatments, and the recovery of valuable compounds. The spontaneous appearance of 'circular economy' suggests growing integration of these strategies in research. Regarding Q2, the most represented subject areas are 'Environmental Science', 'Energy', 'Engineering', 'Chemical Engineering', and 'Agricultural and Biological Sciences', with the additional inclusion of 'Social Sciences', highlighting that eco-efficiency research increasingly addresses both technological performance and broader sustainability implications. In addition, keywords such as 'eco-efficiency', 'life cycle assessment', and 'circular economy' emerged in Q2, highlighting a systemic approach to evaluating treatment technologies. The bibliometric results were useful to guide the systematic literature review. In the Q1 sample, the main treatment technologies were identified for each type of olive oil waste and by-product. A significant portion of the treatment and valorisation technologies focused on liquid waste, specifically OMWW, which the authors addressed most. A wide range of technologies was identified, including biological (anaerobic and aerobic digestion), physico-chemical (membrane filtration), thermal (pyrolysis, combustion), and emerging bio/phytoremediation methods. Biological treatments were most common, particularly anaerobic digestion, owing to their ability to produce biogas and digestate for agricultural applications. Valorisation outcomes included agricultural reuse (compost, fertigation), energy generation (biogas, heat), and recovery of valuable compounds (e.g., polyphenols). The most effective results on treatment and valorisation were often achieved using integrated treatment systems combining biological and chemical-physical methods. Regarding eco-efficiency (Q2), most articles adopted a *theoretical* approach, linking it conceptually to CE and ES, but without formal metrics. Among *integrated* eco-efficiency assessments, the LCA model was the most frequently employed. LCA proved effective in identifying which treatment processes are more resource-efficient and have lower environmental impacts and waste. Overall, the analysis of how eco-efficiency aligns with the CE and ES in the context of the olive oil industry reveals several significant trends and insights. First, there is a growing recognition of the value of integrating these concepts, with a particular focus on waste and by-product management through circularity and enhancing ES. While many authors recognise the natural synergy between these approaches, challenges remain, particularly the absence of clear, standardised definitions of eco-efficiency and concrete guidelines for integrating these concepts. LCA can play a critical role in addressing this gap by identifying inefficiencies in production processes and providing valuable insights into the eco-efficiency of olive oil production and its by-product treatment. By highlighting current trends, technological gaps, and the integration of CE and ES principles along with the eco-efficiency approach, the study provides a basis for guiding a decision-making framework in the olive oil sector. Such a framework is essential to help businesses, especially SMEs, select the most suitable treatment technologies and valorisation strategies in accordance with environmental, operational, and regulatory contexts, thereby facilitating the sector's ecological transition. Consequently, future analyses should expand the scope by integrating the economic dimension of eco-efficiency. While the current review focused primarily on environmental aspects, aiming to simplify an otherwise overly complex assessment, evaluating the economic performance of treatment options is equally essential to fully reflect the principles of eco-efficiency. Therefore, the development of an integrated framework, incorporating environmental, economic, and technical criteria, represents a key step forward in supporting more informed and sustainable decision-making for waste and by-products management in the olive oil industry.

Chapter 3

Sustainability and Circular Economy Strategies in Italian Olive Oil Company: an Application of Life Cycle Assessment and Cost Benefits Analysis

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ABSTRACT: The olive industry is increasingly called upon to integrate the principles of the circular economy in order to mitigate its environmental impact, but it faces the complex challenge of economic sustainability. This study assesses the eco-efficiency of a vertically integrated olive supply chain and its associated circular economy strategies, using a methodological approach that combines Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA). The analysis is based on primary data from a case study of a company located in Sicily (Italy), offering a real perspective on production, and waste and by-products management dynamics in the Mediterranean. The results reveal a clear trade-off between environmental and economic performance. From an environmental point of view, the valorisation of virgin OP is confirmed as the crucial phase for reducing the carbon footprint of the entire supply chain. However, economically, this isolated circular phase operates at a significant deficit, penalized by the prohibitive logistics costs for transporting biomass. The resilience of the model lies in its systemic integration. The high profitability of premium EVOO currently acts as a cross-subsidy to offset the costs of by-product management; however, for circular strategies to be widely adopted by farmers, waste and by-products treatment must evolve from a net cost into a complementary revenue source, achieved through the production of high-value secondary raw materials. For this reason, to achieve true eco-efficiency, the sector needs local agro-industrial districts capable of minimizing logistics and transport distances.

Keywords: Olive oil; Life Cycle Assessment; Cost-Benefit Analysis (CBA); Waste/by-product management; Circular Economy.

3.1 Introduction

The global agrifood industry is currently facing the unprecedented challenge of ensuring high-quality production while drastically reducing its impact on ecosystems. In this scenario, the Mediterranean olive oil supply chain represents an emblematic case study. Olive oil is universally recognized for its extremely high nutritional and commercial value, with global demand constantly growing. World production, which averages between 2.5 and 3.4 million tonnes per year (IOOC, 2025), has historically been driven by the EU, Indeed, the EU represents the global hub for both consumption (European Commission, 2024) and production, accounting for approximately 94% of the total output among International Olive Council (IOOC) member countries[1]. Within this landscape, Italy plays a leading role with over 1.1 million hectares of olive groves concentrated mainly in the southern regions. Sicily is a key contributor, representing 15% of the total national area and 14% of Italy's organic olive cultivation; it ranks as the country's third-largest producer with an average annual

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[1] As of 2024, the IOOC membership consists of the European Union (representing all its producing member states) and 19 individual countries: Albania, Algeria, Argentina, Azerbaijan, Bosnia and Herzegovina, Egypt, Georgia, Iran, Israel, Jordan, Lebanon, Libya, Montenegro, Morocco, Palestine, Saudi Arabia, Tunisia, Turkey, and Uruguay.

output of 34,436 tonnes (IRVO, 2024). This leadership is built on the excellence and premium quality of its Extra Virgin Olive Oil (EVOO). At the same time, producers face serious environmental challenges, such as climate change and water scarcity, which create an urgent need for sustainable solutions (Fotia et al., 2021). These phenomena, combined with fluctuating market prices and rising energy and input costs, have tightened profit margins for many traditional farms. Consequently, the sector faces significant hurdles in managing waste and by-products. The extraction process generates substantial volumes of biomass, estimated at over 40 million tonnes per year, of which 20 million tonnes are dry organic matter (Di Giacomo and Romano, 2022). Improper management of these by-products can cause severe phytotoxic effects on soil and water ecosystems, leading to high recovery costs (Doula et al., 2017). Given this complex scenario, where environmental risks are high and economic margins are constrained, relying on intuitive decision-making is no longer sufficient. The olive oil industry requires structured assessment methodologies to validate new strategies. In this regard, LCA is one of the most adopted methods for quantifying environmental burdens, providing companies with a rigorous, ISO-compliant basis for ES claims (ISO 2006a; ISO 2006b). However, environmental evaluation alone is often insufficient to drive corporate decision-making. Indeed, it must be strictly integrated with a practical financial feasibility assessment. Traditionally, literature pairs LCA with LCC to achieve a multidimensional sustainability perspective. Yet, as highlighted in the European Commission's 'Transition Pathway for the Agri-food Industrial Ecosystem' (European Commission, 2024), the urgency of the ecological transition demands tools that are rigorous but also agile. The simultaneous application of two highly complex and data-intensive methods like LCA and LCC creates a severe administrative and methodological barrier for Small and Medium Enterprises (SMEs), ultimately delaying the adoption of green business models (Martinez-Sanchez et al., 2016). This operational constraint fundamentally justifies the methodological choice to integrate LCA with Cost-Benefit Analysis (CBA) in place of LCC. While LCC provides a highly detailed economic tracking across the entire life cycle, its heavy data requirements hinder rapid implementation in the agricultural sector. Conversely, CBA serves as a streamlined, highly pragmatic decision-support tool (European Commission, 2015b). It allows for rapid evaluation, ranking, and selection of investment options based on their direct economic efficiency. By doing so, CBA perfectly complements the environmental rigor of the LCA, providing SME managers and policymakers with transparent, objective, and readily actionable financial guidance (Vagdatli and Petroutsatou, 2022). By focusing on the feasibility and efficiency of investments, CBA offers a pragmatic alternative that aligns with the EU's push for simplification, enabling stakeholders to assess the economic viability of modernisation strategies without the overwhelming complexity of full-scale life-cycle costing. The choice to employ CBA and LCA is therefore grounded in the need for a multidimensional evaluation. By combining CBA with LCA, it is possible to create an integrated framework that assesses not just profitability, but also ES.

This dual approach allows decision-makers to identify 'win-win' strategies that boost competitiveness without depleting natural resources (Bruno et al., 2023a). Ultimately, this methodology supports the transition toward a CE, balancing the urgent need for modernization with long-term environmental resilience. This balance is quantitatively expressed through the concept of eco-efficiency. Although a universally recognized standardized definition is absent in the literature, eco-efficiency is generally understood as the ratio connecting environmental impact reduction to production value (Huppes and Ishikawa, 2005). As highlighted by the World Business Council for Sustainable Development (WBCSD), it functions as a management strategy linking economic and environmental performance to create 'more value with less ecological impact' (WBCSD, 1996; WBCSD, 1998). By following this approach, the present study aims to explore both the environmental impacts and the economic performance of the olive oil supply chain, focusing on potential strategies for managing waste and by-products within a CE framework. Therefore, the purpose of this study is to apply the

LCA method integrated with a CBA to an Italian olive oil farm, including the cultivation and harvesting phase, the olive oil extraction and processing phase, and the waste and by-product treatment to be reused internally to the system. Specifically, the study intends to: i) quantify the potential environmental impacts associated with the agricultural and milling phases; ii) evaluate the environmental performance of different technologies for the treatment and valorisation of solid and liquid by-products; iii) assess the costs and benefits related to production processes, resource consumption, and product revenues; and iv) draw detailed considerations on the overall eco-efficiency based on the specific context of the investigated case study.

3.2 Literature review

To address the modern challenges of olive oil production, literature has extensively relied on LCA to measure resource use, emissions, and overall environmental impacts (e.g., Banias et al., 2017; Pattara et al., 2017; Salomone and Ioppolo, 2012). To mitigate these impacts, literature increasingly offers pathways to valorise waste and by-products into high-value resources. Current research generally categorizes these circular strategies into three main clusters: (i) the recovery of valuable pharmaceutical and polyphenol compounds (Carluccio et al., 2003; Dini et al., 2020; Nunes et al., 2022); (ii) agronomic reuse through the production of compost and fertilizers (Alburquerque et al., 2006; Galliou et al., 2018); and (iii) energy recovery via thermochemical processes or anaerobic digestion (Akgul et al., 2021; Atallah et al., 2019; Caputo et al., 2003; Esteves et al., 2022; Haddad et al., 2021). Beyond the environmental burden of waste, the sector grapples with heavy sustainability challenges where the preservation of natural capital often clashes with the economic survival of small-scale traditional farms (Stempfle et al., 2021). Previous studies have highlighted that sustainability in this context is frequently hindered by a 'decoupling' between ecological benefits and social acceptability. Indeed, while circularity reduces local pollution, it may increase the carbon footprint of logistics or the financial risk for individual operators (Nunes et al., 2018; D’Amato et al., 2020). Furthermore, the seasonal nature of olive oil production creates a 'sustainability peak', a concentrated period of high resource demand and waste generation that overwhelms existing infrastructure, making permanent sustainable transitions difficult to sustain without systemic industrial symbiosis (Donner et al., 2022a). Despite these technological advancements, the practical implementation of circular strategies remains limited. While many entrepreneurs recognize the ecological potential of these approaches, they are often skeptical of their ability to generate tangible economic advantages (Walker et al., 2022). In regions like Sicily (Italy), this challenge is amplified by a highly fragmented agricultural landscape dominated by small-scale, traditional farms that often lack the capital to invest in green infrastructure (De Luca et al., 2023a; Maesano et al., 2021). Recent literature highlights a persistent 'sustainability gap' in these areas. While circularity offers a path to reduce the environmental burden of OMWW and OP, the geographic dispersion of production sites creates a logistical paradox. The carbon footprint and costs associated with transporting bulky, seasonal biomass across complex island or rural terrains can sometimes negate the very environmental benefits they aim to achieve (Maffia et al., 2022). Consequently, sustainability in these contexts involves not only ecological preservation but also economic resilience, requiring a shift from individual efforts to territorial agro-industrial districts. Circular solutions do not automatically guarantee profitability; rather, they involve highly variable processing costs that heavily depend on the chosen technology, economies of scale, and policy subsidies (Hsu, 2021). Furthermore, severe barriers persist, including bureaucratic hurdles and logistical bottlenecks related to coordinating bulky, seasonal raw material supplies across large territories (Ncube et al., 2022). Consequently, the pursuit of sustainable practices must inherently address the economic priorities of farmers, such as stabilizing income, reducing production costs, and improving market competitiveness (Falcone et al., 2022). Addressing these complex challenges requires moving beyond purely environmental assessments to incorporate real-world economic feasibility (Spada et al., 2024). In this context, integrating LCA with CBA provides a far more robust decision-making framework (Bruno et al., 2023a). CBA is invaluable in waste management for comparing the strict economic consequences of different technical options (Karmperis et al., 2013). A similar methodological synergy was successfully applied by Lovarelli et al., (2019), who combined LCA with economic indicators to jointly assess small-scale anaerobic digestion plants. Ultimately, this integration forms the foundation of eco-efficiency, the measurable ratio between economic value creation and environmental impact (Mehmeti, *et al.*, 2016). Although the ISO14045:2012 standard outlines its fundamental principles (ISO, 14045:2012), specific guidelines for its practical application in the agri-food sector remain scarce. Taking inspiration from biorefinery frameworks, eco-efficiency effectively weighs the environmental performance of alternative treatments against their gross economic value (García-Santiago et al., 2021). Establishing such integrated LCA-CBA guidelines is therefore essential to support olive-growing companies in adopting clean technologies, optimising by-product valorisation, and achieving true ecological and economic sustainability (Roig et al., 2006; Khdair and Abu-Rumman, 2020).

3.3 Material and methods

To comprehensively evaluate the environmental and economic performance of the olive oil production system and its waste and by-product valorisation pathways, this study adopts an integrated methodological approach combining LCA and CBA in an Italian case study. This dual perspective aligns with the quantification of potential environmental impacts, compliant with ISO 14040/14044 standards (ISO 2006a; ISO 2006b), with robust economic assessment methodologies designed to evaluate the financial viability of current and potential valorisation strategies. This integration enables a systematic comparison of costs and revenues at each stage of the production system (Stone et al., 2020). Overall, to better define the integrated LCA-CBA methodology used in this study, a summary scheme is represented in Figure 1.

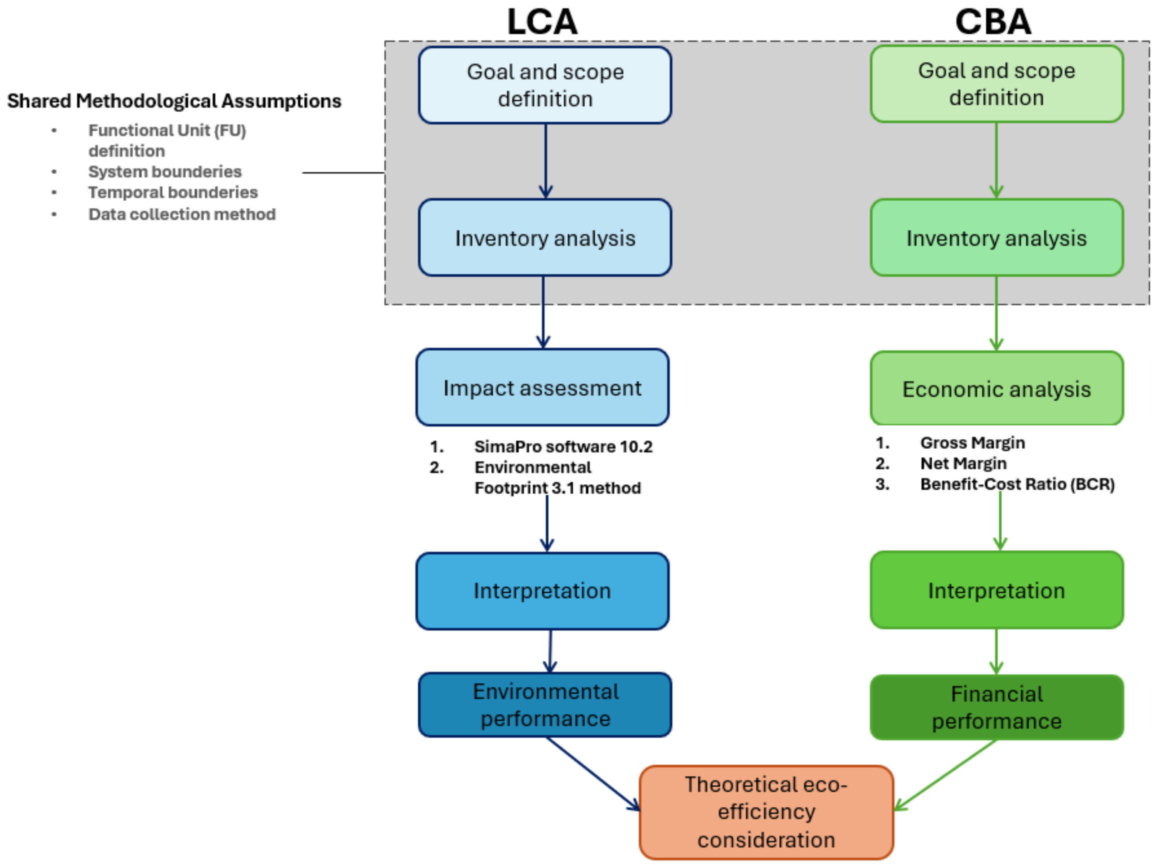

Figure 3 Flowchart of the integrated methodological framework, illustrating the parallel application of LCA and CBA to evaluate the eco-efficiency of olive oil by-product valorisation.

As illustrated in Figure 1, the methodological framework is structured into an integrated logical process. The initial phase establishes a shared methodological assumption, which outlines the goals, FU, system boundaries, temporal boundaries, and data collection methods for the entire study. Subsequently, the workflow bifurcates into two parallel analyses. The environmental pillar (LCA) processes inventory data through an impact assessment and an interpretation phase to evaluate the overall environmental performance. Concurrently, the economic pillar (CBA) processes the same inventory through an economic analysis and interpretation phase to evaluate the financial performance, calculating key profitability indicators such as Gross Margin, Net Margin, and the Benefit-Cost Ratio (BCR). Finally, the two pathways converge in the ultimate synthesis phase, where environmental and financial performances are combined to identify critical hotspots and theorical eco-efficiency approaches to guide the selection of optimal valorisation strategies.

3.3.1 Case study area: Sicilian olive oil mill company

The research focuses on the "Valle dello Jato", a highly representative rural district in Sicily, Italy. While olive cultivation is widespread across the island, this specific area significantly contributes to the regional output, with the Palermo province alone accounting for over 53,000 tons of olive oil production, representing roughly 20.3% of Sicily's total (Maesano et al., 2021). Within this context, the primary system under analysis is a family-owned oil mill established in 2019 and located in Trappeto (Palermo, Italy). The enterprise manages a

3.58-hectare intensive olive grove featuring approximately a total of 1,050 trees (corresponding to a planting density of 293 trees per hectare) of traditional Sicilian cultivars (*Cerasuola, Biancolilla, and Nocellara del Belice*). Cultivation strictly adheres to sustainable, pesticide-free practices. Annually, the mill, that operates using a 3-P decanter, processes 22 tons of cold-pressed olives, yielding roughly 5 tons of high-quality EVOO. Consequently, the primary extraction process generates 11 tons of olive mill solid waste (OP) and 6 tons of OMWW, aligning with typical regional extraction yields of 10-15% (Osservatorio Viti-vinicolo ed Olivicolo-oleario IRVO, la Regione Sicilia, 2024). To evaluate the eco-efficiency of the supply chain and its circular pathways, the system boundaries were extended to include two subsequent valorisation stages. On the one hand, the virgin OP and OMWW, obtained from the 3-P decanter, are transferred to an external processing facility. Here, 3-P OP is strategically rehydrated with OMWW to facilitate a solvent-free mechanical extraction. On the other hand, although the milling of olives for high-quality oil production is the core business, the facility also operates a secondary treatment line to process its own residues alongside OP collected from third-party mills. From this integrated valorisation phase, the facility produces crude OP oil destined for refineries, olive pits sold as solid biofuel (and partially reused internally to power thermal processes), and de-pitted, semi-defatted OP. The final valorisation stage takes place at a 1 MW biogas plant located in the Caltanissetta province (Sicily, Italy). At this facility, the residual semi-defatted OP is co-digested with other agricultural matrices, including citrus pulp, poultry manure, and corn silage, amounting to approximately 16,425 tonnes of biomass annually processed. This anaerobic digestion process generates renewable energy (producing roughly 23,976 kWh/day of electricity), while the resulting digestate is destined for use as an organic soil amendment, though its actual field application falls outside the current system boundaries. By tracking the mass and energy flows across these interconnected phases, the selected case study provides a comprehensive framework to quantitatively assess the transition from a linear waste-producing model to a closed-loop, circular supply chain.

3.3.2 Life Cycle Assessment (LCA)

The analysis was conducted in strict accordance with the international ISO 14040 and ISO 14044 standards (ISO, 2006a; ISO, 2006b). Consequently, the LCA method was implemented according to four iterative phases: 1) goal and scope definition, 2) inventory analysis (LCI), 3) impact assessment (LCIA), and 4) interpretation. The following subsections detail each of these methodological steps as applied to the selected olive oil supply chain case study.

3.3.2.1 Goal and scope definition

The LCA method was applied to evaluate the potential environmental impacts of the local olive oil supply chain, identifying the main environmental hotspots and assessing the potential benefits of CE pathways. To accurately account for both the extracted olive oil and the quantities of residues generated during the milling process, the selected FU is defined as 1 tonne of harvested olives. Acting as the system's primary input, this FU provides a coherent baseline and serves as the reference flow for all subsequent mass and energy balances (Salomone and Ioppolo, 2012). The system boundaries are defined according to a cradle-to-gate approach, covering the agricultural phase, the olive oil extraction process, and the subsequent treatment and valorisation of waste and co-products. This framework accounts for the environmental impacts of treatment technologies used to transform olive oil waste and by-products into valuable secondary resources. This approach is consistent with recent literature on LCA applications to small olive oil producers, where system boundaries are extended to include by-product management as a fundamental pillar of circularity (Cinardi et al., 2024).

As illustrated in the system boundaries flowchart (Figure 2), the model encompasses three interconnected subsystems:

1. agricultural phase – cultivation of olive trees, including fertilization, irrigation, pruning, and manual harvesting
2. olive mill phase – olive washing, crushing, cold pressing via a 3-P extraction system, and EVOO decantation.
3. waste and by-product treatment and valorisation – treatment of solid residues (virgin OP and pits) and liquid effluents (OMWW) for material and energy recovery.

As shown in Figure 2, the system includes inputs from the environment (e.g., water, fertilizers, energy) and outputs (e.g., emissions to air, soil, water, and waste flows), as well as waste and by-products such as OP, vegetation water, and pruning residues, along with their valorisation pathways (e.g., OP oil recovery, biofuel pellets, anaerobic digestion). Excluded processes are tree planting, because the trees are in their full productive stages; agricultural machinery production, given its negligible contribution at the life cycle scale; and cleaning agents, due to a lack of reliable data. Downstream phases such as bottling, distribution, and consumer use, are also excluded because these phases are not within the goal of this study. This process-specific boundary choice is further justified by the findings of the systematic literature review reported in Chapter 2, which demonstrated that technical assessments of OP and OMWW valorisation pathways predominantly rely on cradle-to-gate configurations to prevent downstream noise from distorting process eco-efficiency evaluations (e.g Ruiz-Carrasco et al., 2023; Blanco et al., 2022).

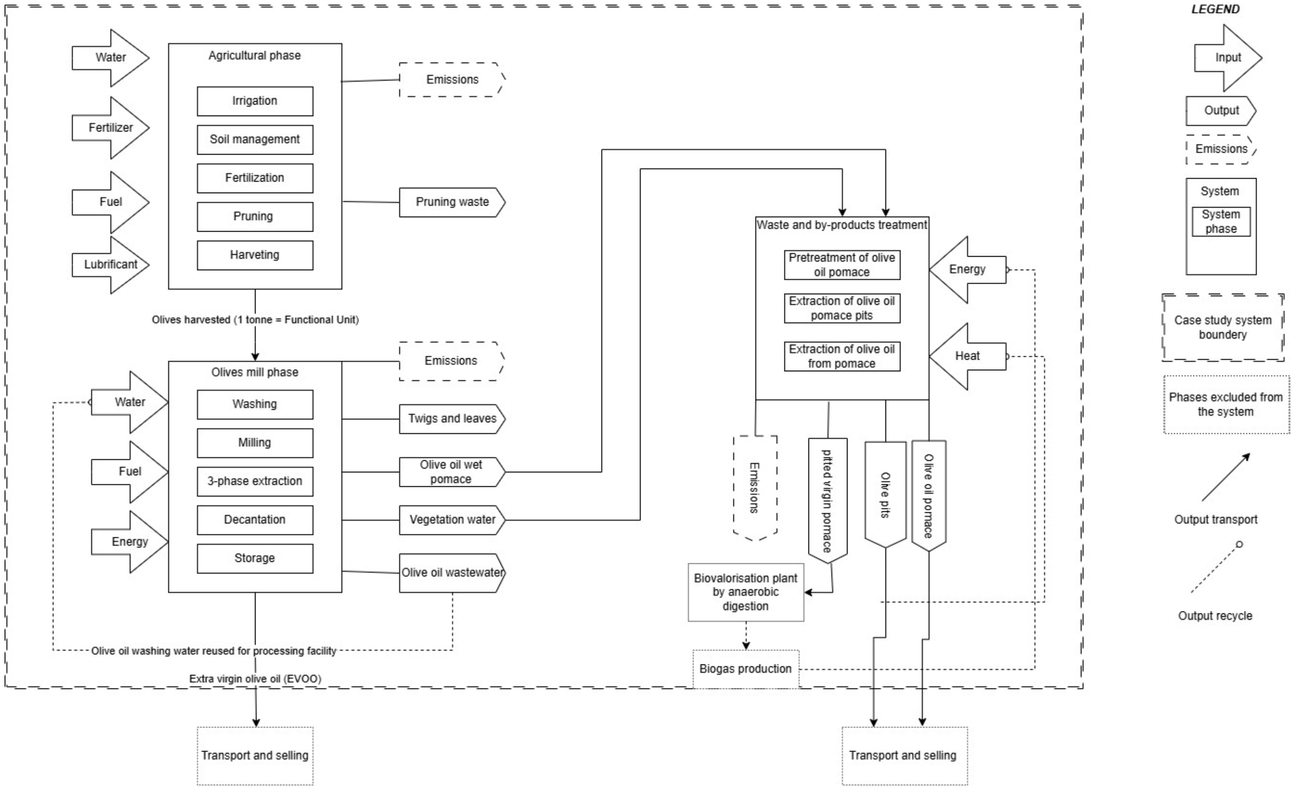

Figure 4 Flowchart Diagram of the input and output in the olive oil production system of EVOO and its waste and by-products treatment and valorisation according to cradle-to-gate system boundaries, including the treatment and valorisation phase**.**

Crucially, to handle multi-functionality without resorting to mass or economic allocation, a substitution approach was adopted following ISO guidelines (Alonso-Fariñas et al., 2020). In this regard, by-products (e.g., biogas, solid biofuels) are modelled by assigning environmental credits for the avoided production of conventional equivalents. Specifically, the recovered energy from biogas production is assumed to substitute electricity from the Italian national grid, while the combustions of olive pits substitute the thermal energy from natural gas combustion, effectively reducing the net environmental footprint. Furthermore, as highlighted in the literature, the inclusion of avoided products through this substitution mechanism is crucial for quantitatively assessing the actual environmental benefits linked to CE strategies at the micro level (Roos Lindgreen et al., 2021) The results are intended to serve multiple stakeholders. For the owner of the investigated case study and SME olive oil producers in general, they provide support for process optimization and waste reduction. For technology developers, they identify opportunities for innovation in by-product treatment. Finally, for policymakers, they inform the development of regulations and incentives to foster sustainable practices in the agricultural and industrial sectors.

3.3.2.2 Life Cycle Inventory (LCI)

The Life Cycle Inventory, reported in Table 1, integrates foreground data with background data to comprehensively map material and energy flows. Foreground data, referring to the 2023-2024 agricultural season, were gathered via structured questionnaires administered to the olive mill owner and to the quality manager of the OP processing facility. For the agricultural and olive mill phases, primary data include fertiliser application rates, water consumption, diesel and lubricant usage, and electricity demands for the three-phase (3-P) extraction process. Furthermore, transport logistics between the field, the mill, and the valorisation plants were fully modelled, detailing distances and specific vehicle classes using 16-32 metric ton (EURO 5) lorries. Table 1 presents the life cycle inventory data for the olive oil production system and valorisation via anaerobic digestion, structured across the main processes: cultivation and harvesting, olive oil production, treatment plant, and valorisation of OP and OMWW.

Where primary data measurements were unfeasible, robust secondary sources and models were employed. Particularly, the Ecoinvent v3.9 database was used to calculate the inventory data of raw materials and energy sources. Furthermore, the conversion of biogas into electricity was calculated according to Valenti et al., (2018). The lower heating value (LHV) of methane was assumed at 55 kJ/g, with a thermal efficiency of the anaerobic digester of 0.6 and an electrical efficiency of the gas engine of 0.3. Applying a conversion factor of 0.0002778 kWh/kJ, the specific electricity yield was estimated at 0.2721 kWh/kg of OP, corresponding to 205.47 kWh per 755.2 kg of OP processed. In addition, emissions from fertilizer application were calculated following Brentrup et al., (2000), while emissions from fuel combustion and boiler use were modeled according to Saija et al., (2024).

Table 5 Inventory data (inputs, outputs, and direct emissions) for the olive oil supply chain, referring to the FU of "1 tonne of harvested olives" across the three life cycle phases: agricultural, transformation, and waste and by-product treatment and valorisation.

Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit
Cultivation and harvesting	Mineral- organic fertilizer	143.18	kg	***Olive oil production***	Ground olives	1,000.00	kg	***Treatment plant***	Total OP and vegetation water to be treated in the plant	785.71	kg	***Valorisation by anaerobic digestion***	de-pitted OP	755.20	t
	Water from aqueduct for irrigation	2.27E+05	l		Water from the aqueduct for washing machinery	8.57	l		Energy for the treatment process	8.73	kWh/ year		**Output**		
	Water from the aqueduct for fertigation	2.27E+04	l		Water from the aqueduct for washing olives	42.86	l		Energy (heat) boilers fueled by raw OP kernels	5.89	kWh/ year		Biogas potential per OP	131	Nm3/ton
	Diesel for agricultural machinery	37.95	kg		Water from the aqueduct for processes	242.86	l		OP pits for boilers	1.31	kg		Biogas potential production (Bi)	98.93	Nm3
	lubricating oil	0.49	kg		Diesel fuel for electric generator	5.96	kg		Energy produced by the combustion of the stone pits in the plant	4.50	kWh/ kg		Energy produced from 755,2 kg	205.47	kWh
	Transport of fertilizer	15,578.2	kg/km		**Output**				**Output**						
	Transport of diesel	561.73	kg/km		Extra virgin olive oil (EVOO)	220.00	kg		OP oil	3.93	kg		Energy produced		
	Output				Virgin OP from 3-P	500.00	kg		pitted virgin OP	755.16	kg		compost		
	Transport of olives to milling site	1.00E+04	kg/km		Vegetation water (AV)	285.71	kg		OP pits	26.19	kg				

Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit
	Olives harvested	1,000.00	kg		Transport of virgin OP and AV to the pomace mill	6.21E+04	kg/km		transport of OP oil	4,148.57	kg/km				
	Collected leaves	45.45	kg		Transport to the olive oil mill	3.55E+04	kg/km		transport of pitted virgin OP	2.90E+05	kg/km				
	Collected branches	227.27	kg		Olive washing water/plants are recycled within the same company	8.83	kg		raw pits transport in three different destinations	99.52	kg/km destination within 70 km				
	NH_3 emissions from fertilizer	0.72	kg di NH_3-N		Leaves and twigs used for mulching the soil	42.86	kg			74.64	kg/km destination between 70 and 500 km				
	N_2O emissions from fertilizer	0.44	kg N_20-N/ha		Diesel emissions Ammonia	0.12	g			5.18E+04	kg/km destination in Campania				
	NO_3 emissions leached from fertilizer	31.04	Kg N/ha*year		Diesel emissions benzene	0.04	g		Carbon dioxide ILCIDAF emissions from nut combustion	2.46	g				
	Diesel emissions Ammonia	0.76	g		Diesel emissions (Benzo(a)pyrene)	0.00	g		Carbon monoxide ILCIDAF emissions from nut combustion	0.14	g				
	Diesel emissions benzene	0.28	g		Cadmium diesel emissions	0.00	g		ILCIDAF methane emissions from the combustion	0.00	g				

Process	**Input**	**Amount**	**Unit**	**Process**	**Input**	**Amount**	**Unit**	**Process**	**Input**	**Amount**	**Unit**	**Process**	**Input**	**Amount**	**Unit**
	Diesel emissions (Benzo(a)pyrene)	0.00	g		Carbon dioxide, fossil diesel emissions	1.86E+04	g		emissions from combustion of peanuts, nitrogen oxides, ILCIDAF	1.99	g				
	Cadmium diesel emissions	0.00	g		Carbon monoxide, fossil diesel emissions	32.39	g		calorific value of 0.02534 GJ/kg from ILCIDAF	0.03	Gj				
	Carbon dioxide, fossil diesel emissions	1.18E+05	g		Chromium diesel emissions	0.00	g								
	Carbon monoxide, fossil diesel emissions	206.09	g		Copper diesel emissions	0.01	g								
	Chromium diesel emissions	0.00	g		NMVOC diesel emissions, non-methane volatile organic compounds	15.81	g								
	Copper diesel emissions	0.06	g		Diesel emissions Methane	0.77	g								
	NMVOC diesel emissions, non-methane volatile organic compounds	100.58	g		Nickel diesel emissions	0.00	g								
	Diesel emissions Methane	4.90	g		Diesel emissions Mono-nitrogen oxides (NO_x)	249.31	g								

Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit	Process	Input	Amount	Unit
	Nickel diesel emissions	0.00	g		Diesel emissions Dinitrogen oxide (N_2O)	0.72	g								
	Diesel emissions Mono-nitrogen oxides (NO_x)	1,586.50	g		Particulate diesel emissions, < 2.5 um	25.77	g								
	Diesel emissions Dinitrogen oxide (N_2O)	4.55	g		Diesel emissions Sulfur dioxide	6.02	g								
	Particulate diesel emissions, < 2.5 um	163.96	g		Zinc diesel emissions	0.01	g								
	Diesel emissions Sulfur dioxide	38.33	g		Diesel emissions Heat, waste (MJ)	270.78	(MJ)								
	Zinc diesel emissions	0.04	g												
	Diesel emissions Heat, waste (MJ)	1,723.14	(MJ)												

3.3.2.3 Life Cycle Impact Assessment (LCIA) and interpretation

The environmental impacts were quantified using the SimaPro software, version 10.2 (PRé Sustainability, 2025), and applying the Environmental Footprint (EF) 3.1 impact assessment method, endorsed by the European Commission, which provides a multidimensional and robust evaluation aligned with CE principles (European Commission - Joint Research Centre (JRC), 2018). A comprehensive set of 16 midpoint indicators was evaluated to capture the diverse ecological pressures of the supply chain: Acidification (AC), Climate Change (CC), Ecotoxicity-freshwater (FET), Particulate Matter (PM), Eutrophication-marine (ME), Eutrophication-freshwater (FE), Eutrophication-terrestrial (TE), Human Toxicity (HT), Ionizing Radiation (IR), Land Use (LU), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Resource Use-minerals and metals (RU-mm), and Water Use (WU). The interpretation phase synthesizes these results to highlight the most impactful life cycle stages and quantify the net environmental benefits (credits) generated by the proposed circular valorisation strategies.

3.3.3 Cost-Benefit Analysis (CBA)

To complement the environmental assessment, an economic analysis was conducted to evaluate the cost-effectiveness and economic viability of the olive oil production and by-product valorisation strategies. This economic inventory aligns strictly with the system boundaries and FU defined in the LCA (Section 2.2). Consequently, it translates physical inputs and outputs into monetary terms by splitting each unitary process into its elementary economic components (Falcone et al., 2022). To estimate the overall economic performance of the current production model, total costs were systematically classified into variable and fixed categories (Table 2.) Variable costs account for agricultural and operational inputs (e.g., organic fertilizers, fuel and lubricant consumption by machinery), human labour required during agricultural and milling operations, and transportation. Fixed costs include machinery investment (e.g., depreciation) and infrastructure conservation costs, and general administrative expenses. Since the mill owner also owns the agricultural land and directly manages the olive cultivation, the economic analysis accounts for land rental, potential raw olive sales, and interest on capital as “opportunity costs”. This metric reflects the foregone income the company would have generated by renting out its land, selling the raw olives wholesale, or investing its capital elsewhere, rather than dedicating these combined assets to integrated olive oil production. Conversely, total revenues for the entire life cycle were calculated by multiplying the yields of the primary product (i.e., EVOO) and the valorised by-products by their respective market prices, referring to the harvest season considered. The investment and operational parameters for both the agricultural cultivation and the olive milling phases were defined using primary data directly provided by the facility owner through dedicated questionnaires, ensuring a realistic representation of the integrated enterprise. Conversely, the capital and operational costs associated with the by-product treatment and valorisation phase were hypothesized and modelled based on economic considerations, including three main factors: i) estimation of capital investment, ii) operating cost, and iii) profitability analysis (Moreno-González and Ottens, 2021; Stempfle et al., 2022). Finally, to rigorously quantify the logistical burdens, transportation costs of virgin pitted OP were calculated using the official indicative reference values for road freight transport published by the Italian Ministry of Infrastructure and Transport, updated to June 2024 (Ministero delle Infrastrutture e dei Trasporti, 2024). The economic performance was structurally evaluated through three distinct categories (Boardman, 2018; European Commission, 2014):

- Gross Margin, calculated by subtracting the total variable costs from the total revenues. It provides a snapshot of direct profitability.

- Net Margin, calculated by subtracting both variable and fixed costs (including depreciation and overheads) from total revenues. It indicates if the business is truly profitable and has enough cash left to invest in new technologies.
- Cost-Benefit Ratio (BCR), calculated as the ratio between total revenues (benefits) and total costs. This indicator evaluates the overall economic efficiency of the valorisation scenarios, determining whether the long-term economic returns proportionally justify the economic burdens of the supply chain.

These indicators were computed over a defined project lifespan of 20 years, representing the standard operational lifetime for agricultural and bio-energy facilities (Cusenza et al., 2021). To calculate the capital opportunity cost or the capital interest, an interest rate of 3% was applied. This rate was selected in accordance with the European Commission's guidelines for the economic appraisal of environmental and sustainability projects (European Commission, 2014). Ultimately, the selected indicators assess the primary economic hotspots over the lifespan of the olive-growing system, providing essential information for long-term sustainable management.

To ensure structural consistency for the final eco-efficiency considerations, the economic results were defined to the mass-based FU (€/kg) and subsequently normalized to the FU defined in the LCA (i.e., 1 tonne of harvested olives). This alignment allows for a direct comparison between the environmental impacts and the economic performance of the investigated system. Furthermore, to transition this framework into a dynamic predictive tool, the methodology embeds an operational stress-test simulating a concurrent 50% diesel price spike and a localised carbon tax. This establishes the necessary methodological foundation for future dynamic simulations.

Table 6 Economic inventory of Cost-Benefits Aanalysis (CBA). The table details revenues, variable, and fixed costs across the agricultural, milling, and waste treatment phases

Agricultural phase			Mill phase			Waste and by-product treatment and valorisation phase		
Cost voice	**Import (€/FU)**	**Cost type**	**Cost voice**	**Import (€/FU)**	**Cost type**	**Cost voice**	**Import (€/FU)**	**Cost type**
Annual cost of olive harvesting (workers' pay and operating cost)	136.36	*variable cost*	**Annual costs for plant maintenance**	7.14	*fixed cost*	**Purchase costs of virgin OP and vegetation water**	39.29	*variable cost*
Annual cost associated with purchasing fertilizer	159.09	*variable cost*	**Total annual cost of water consumption**	1.43	*variable cost*	**Cost of electricity consumption**	2.18	*variable cost*
Annual cost of fertilizer administration	13.64	*variable cost*	**Total annual cost of energy consumption and transport**	17.14	*variable cost*	**heat produced from pits burned**	1.65	*revenue*
Annual cost of transporting fertilizer	9.09	*variable cost*	**Total annual cost of storing vegetation water**	1.43	*variable cost*	**Total annual cost of OP oil production**	39.82	*variable cost*
Total annual cost of irrigation	127.27	*variable cost*	**Total annual cost of transportation waste at the destination**	10.00	*variable cost*	**Price of raw pits year 2023/2024**	5.24	*revenue*
Total annual cost of water for treatments (e.g. fertilizer spreading or fertigation)	159.09	*variable cost*	**Olive oil price**	2,090.00	*revenue*	**OP oil price year 2023/2024**	13.75	*revenue*
Total annual cost for the purchase and transport of diesel for agricultural machinery	90.91	*variable cost*	**Price of OP**	25.00	*revenue*	**Price of pitted OP**	12.84	*revenue*

Total annual cost for the purchase and transport of lubricants for agricultural machinery	22.73	*variable cost*	**Price of vegetation water**	14.29	*revenue*	**Cost transport of pitted virgin OP**	16.63	*variable cost*
Total annual cost for the maintenance of agricultural machinery	45.45	*fixed cost*	**Total annual cost for maintenance of the means of transport of virgin OP to the treatment plant (16t truck)**	2.86	*fixed cost*			
Total annual cost for labor	136.36	*variable cost*	**Total annual cost for fuel consuption for transport of virgin OP to the treatment plant (16t truck)**	4.29	*fixed cost*			
			Total annual cost for maintenance of the means of transport of vegetation water to the treatment plant (16t truck)	2.86	*fixed cost*			

			Total annual cost for fuel consuption for transport of vegetation water to the treatment plant (16t truck)	16.63				
			Annual total cost for maintenance of the means of transport and fuel for the transport of EVOO (10t truck)	2.57	*fixed cost*			

3.4 Results and discussion

Figure 2 shows the characterisation results related to the eco-profile of the investigated system, illustrating the relative contribution of each life cycle phase to the investigated impact categories. Subsequently, Table 3 provides a detailed contribution analysis, quantifying the specific environmental burdens (positive values) and credits (negative values) generated by each phase.

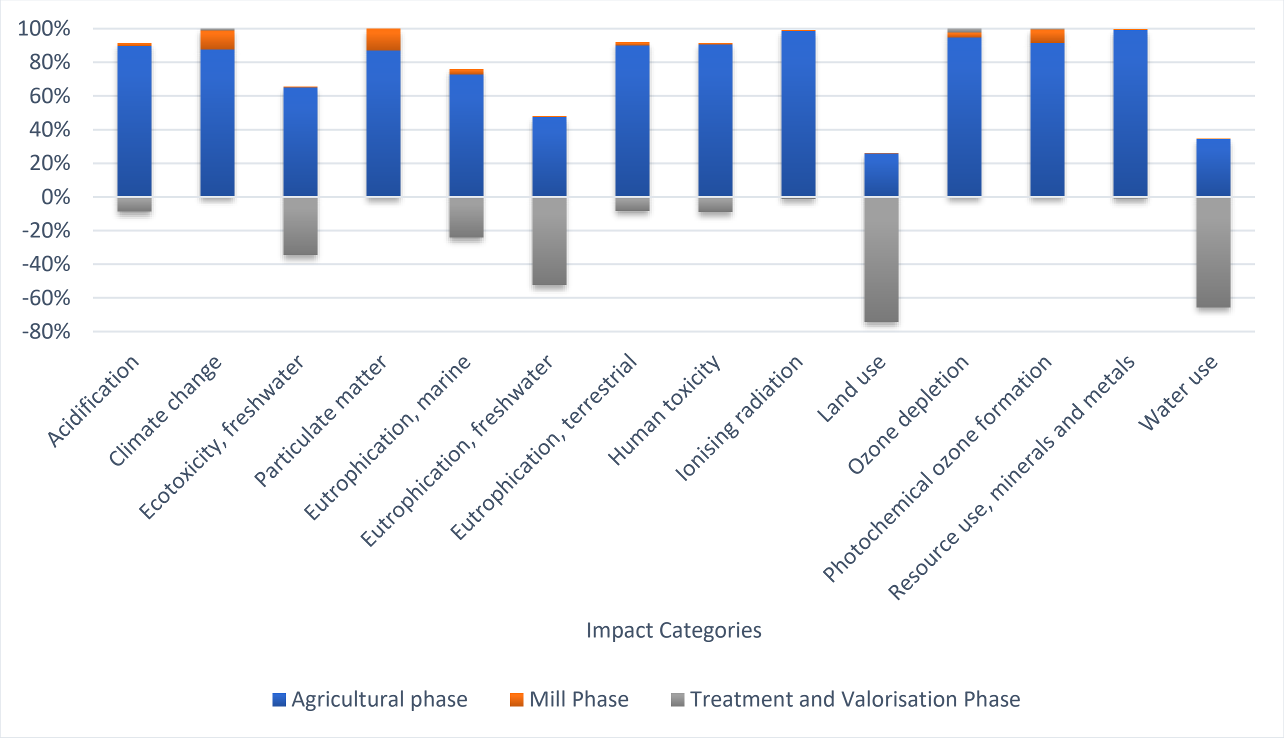

Figure 3 Impact assessment of olive oil supply chain, distinguishing the weight of each phase (agricultural phase, mill phase, and treatment and valorisation phase) per impact categories (characterisation results).

Table 3 Absolute values of the phases for each impact category (characterisation results).

Impact categories	Unit	Total	Agricultural phase	Olive Mill phase	Waste and by-products treatment and valorisation phase
Acidification	mol H+ eq	2.97	3.1	0.06	-0.31
Climate change	kg CO_2 eq	1,802.78	1,582.03	205.82	14.93
Ecotoxicity	CTUe	2,389.16	5,007.33	26.70	-2,644.87
Particulate matter	disease inc.	4.90E-04	4.27E-04	6.30E-05	-1.83E-07
Eutrophication, marine	kg N eq	2.60E-01	3.65E-01	1.55E-02	-1.20E-01
Eutrophication, freshwater	kg P eq	-1.06E-02	1.11E-01	2.03E-04	-1.21E-01
Eutrophication, terrestrial	mol N eq	8.66	9.33	0.18	-0.85
Human toxicity	CTUh	2.61E-05	2.86E-05	2.21E-07	-2.73E-06
Ionising radiation	kBq U-235 eq	35.92	36.14	0.13	-0.35
Land use	Pt	1,619.90	871.68	0.67	-2,492.24
Ozone depletion	kg CFC11 eq	3.02E-05	2.87E-05	8.43E-07	6.84E-07
Photochemical ozone formation	kg NMVOC eq	1.54	1.41	0.12	0.01
Resource use, minerals and metals	kg Sb eq	2.45E-02	2.46E-02	1.16E-06	-1.63E-04

Water use	m_3 depriv.	-12.89	14.40	0.05	-27.34

The results clearly indicate that the agricultural phase is the primary driver of environmental impacts across the entire system, even in the absence of chemical pesticide treatments. This stage dominates several critical categories, accounting for 87.8% of CC, 90% of HT, and nearly 100% of RU-mm (minerals and metals). In contrast, the olive mill phase exhibits a minor overall influence, contributing approximately 11% to CC and 12.9% to PM formation. Conversely, the waste and by-products treatment and valorisation phase generates substantial environmental benefits. The implementation of circular strategies, specifically the energy recovery via biogas production from pitted virgin OP, drastically mitigates the burdens of the treatment and valorisation phase. Notable offsets are observed in LU (reducing the agricultural impact by about 78%), WU (by roughly 65%), and FE (by over 50%). These findings strongly underscore the capacity of circular by-product management to significantly shrink the overall ecological footprint of EVOO production.

A deeper investigation into the agricultural phase (Figure 4) reveals the specific inputs responsible for the environmental hot-spots. The production and application of organic fertilizers emerge as the most critical factors across most impact categories.

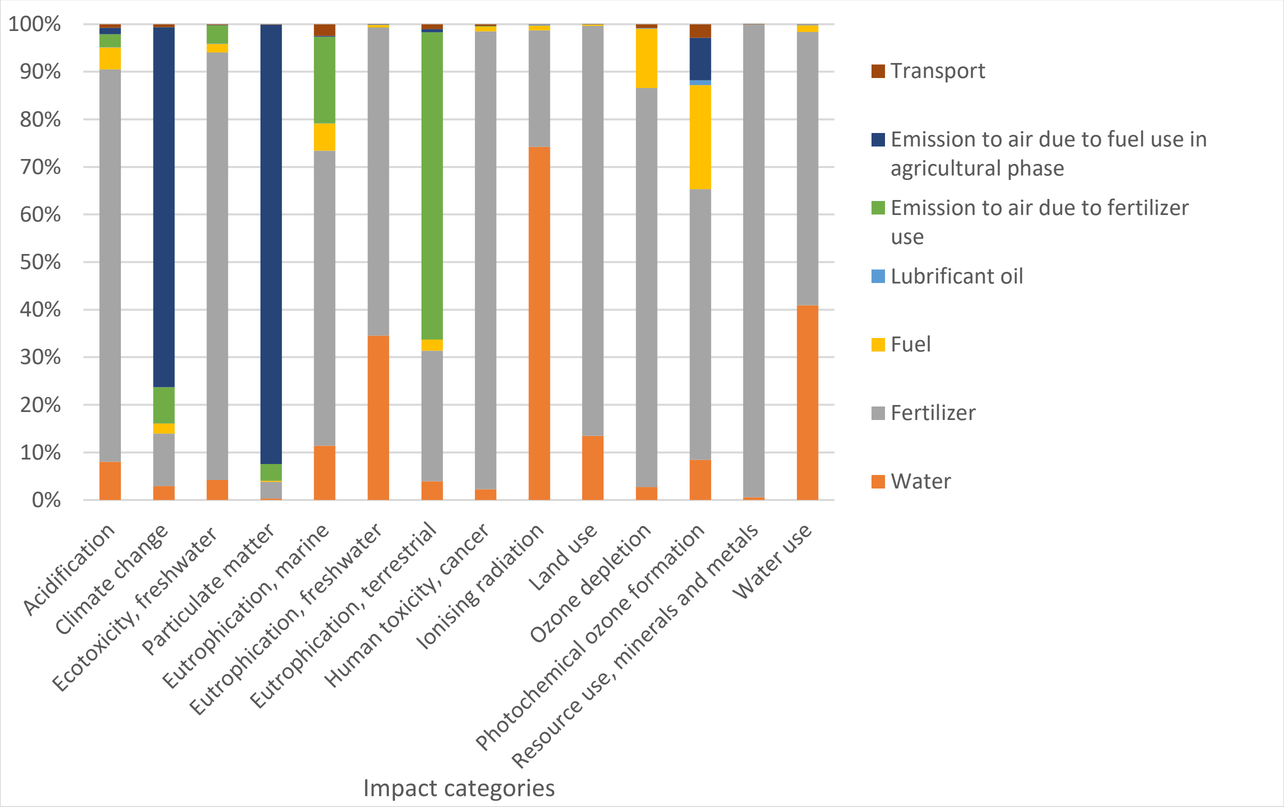

Figure 4 Impact assessment of the agricultural phase (characterisation results).

Fertilizer-related processes are the dominant contributors to Reu-mm (99%), HT (cancer and non-cancer effects, 95%), FET (about 90%), OD (83%), AC (82.5%), and LU (66%). Furthermore, airborne emissions derived from fertilizer application, particularly ammonia, exacerbate both freshwater and terrestrial eutrophication, despite the direct soil incorporation achieved through the fertigation system. In addition, in the CC impact category, the primary hotspots are fuel consumption and the associated combustion emissions (specifically CO_2 and N_2O) linked to mechanized soil and crop management, which account for 75.6% of the impact, alongside 92.3% of PM formation. Generally, the production and consumption of fuels and lubricating oils present a lower overall burden compared to fertilizers (Romero-Gámez et al., 2017; Salomone and Ioppolo, 2012). Consequently, effective mitigation strategies should simultaneously target the optimization of agricultural mechanization (to reduce carbon emissions) and the refinement of fertilization practices (to minimize toxicity and nutrient enrichment).

Focusing on the olive mill phase (Figure 5), the logistics associated with the transportation of dry OP represent a major environmental hot-spot, strongly influencing ME and TE (77% and 74%, respectively) due to fuel combustion during long-distance transit. Similar trends are observed for HT and FET. Additionally, the facility's reliance on an independent diesel-powered electricity generator, necessary to ensure continuous operation in a rural area subject to power grid interruptions, introduces significant burdens, primarily affecting RU-mm (70%), OD (66%), and FET (37%). Transport emissions, rich in sulfur and nitrogen compounds, further drive CC and PM impacts. Despite these loads, the olive mill phase also highlights the efficacy of resource-efficient practices. A notable environmental credit is achieved in the WU category, where the internal recycling of olive washing water for machinery cleaning leads to 26% reduction in total water consumption. Minor upstream benefits are also recorded in IR (-0.9%) and LU (-0.8%).

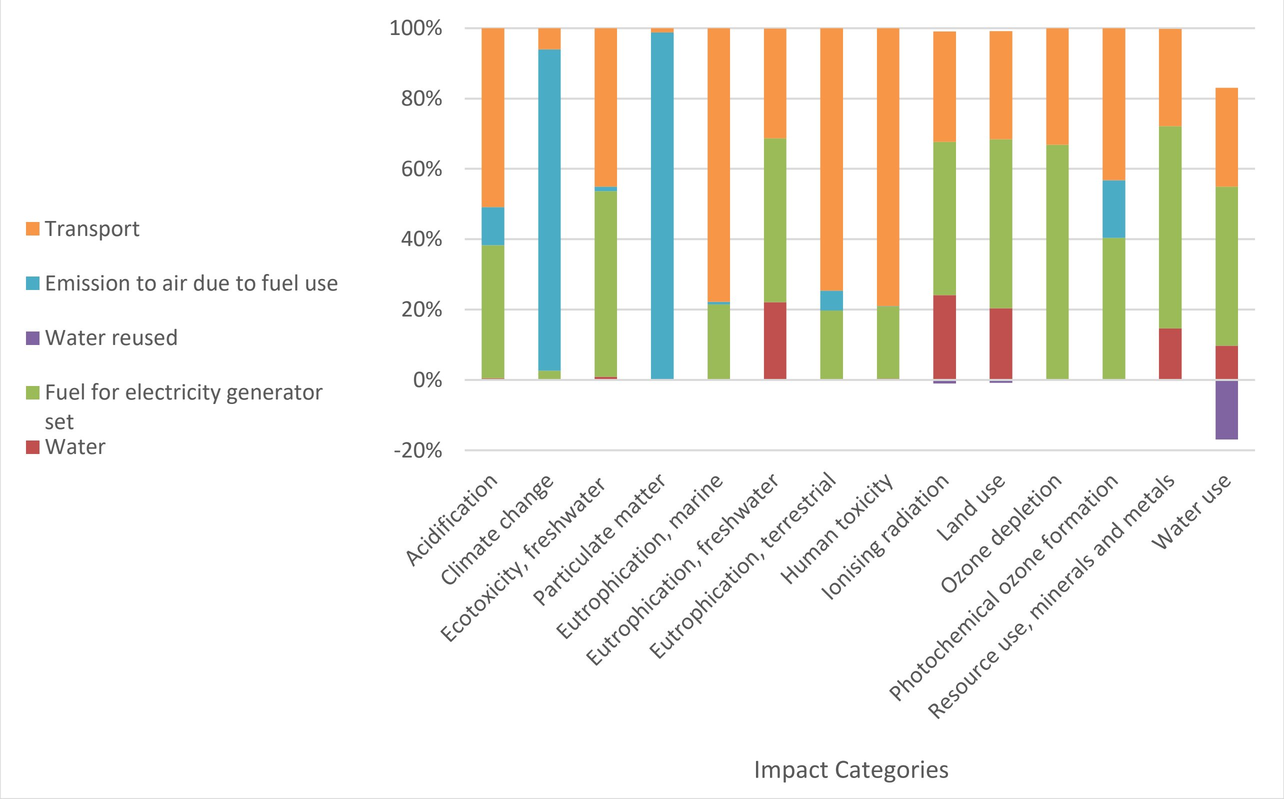

Figure 5 Impact assessment of the olive mill phase (characterisation results).

The third phase, focused on waste and by-products treatment and valorisation, proves to be the most environmentally advantageous stage of the supply chain (Figure 6). In this configuration, vegetation water is reintegrated to facilitate the mechanical separation of olive pits during OP extraction. A fraction of these recovered pits is directly utilized as biomass fuel in an on-site boiler to generate thermal energy. This avoids the use of chemical solvents (e.g., hexane) and provides immediate environmental savings. The residual virgin pitted OP is subsequently transported to an external anaerobic digestion plant, to generate biogas and electricity. As clearly illustrated by the negative values in Figure 6, the recovery of this bioenergy generates substantial environmental savings by displacing the demand for conventional grid electricity. This substitution mechanism drastically improves the environmental profile of the supply chain. As a result, this phase yields net environmental benefits (credits) across most categories, completely offsetting the impacts of FE, FET, LU, WU, and RU-mm, while significantly reducing AC (-44%), ME (-43%), and HT (-17%). These credits stem primarily from the avoided burdens of displacing conventional grid electricity and fossil-based inputs. Nevertheless, the analysis reveals a critical trade-off. Indeed, CC, OD, and POF experience a net environmental burden. This is predominantly driven by the long-distance transportation required to move the pitted OP to the biogas facility (average 200 km). The emissions generated by this logistical step surpass the carbon offsets provided by the anaerobic digestion itself. Conversely, emissions from the on-site biomass boiler remain negligible across all categories. Overall, this phase demonstrates that while integrated energy recovery is essential for advancing eco-efficiency, the logistical requirements must be carefully managed to maximize CE benefits.

The results of this study align closely with the established literature regarding the environmental dynamics of olive oil production. Consistent with previous research, the agricultural phase is confirmed as the most environmentally demanding stage, particularly concerning CC, TE, LU, and FET. These outcomes corroborate the findings of Salomone and Ioppolo (2012), who identified fertilizers and diesel fuel as the primary environmental stressors in the Sicilian olive oil supply chain. Similarly, Guarino et al., (2019) reported that the cultivation stage contributes between 70% and 90% of total impacts across various production scenarios. Comparable trends, where fertilizer manufacturing and application dominate the ecological load, have also been documented in Spanish and Greek case studies (Romero-Gámez et al., 2017; Tsarouhas et al., 2015). However, a notable divergence emerges in the present study concerning the CC category. Here, fuel combustion tied to agricultural mechanization causes a higher contribution to the impact than fertilizer use, as the principal impact driver. This specific dynamic is partially supported by Guarino et al., (2019), who observed substantial impacts from heavy mechanization in intensive production models. Furthermore, the complete absence of chemical pesticide application in the assessed farm likely explains the slightly lower toxicity values recorded compared to conventional systems. Regarding the olive mill phase, the impacts are limited but distinct, heavily influenced by the rural infrastructural context (e.g., the necessity of an independent diesel generator) and the logistics of by-product transportation. Nonetheless, the 26% reduction in WU achieved through internal recycling underscores the tangible benefits of circular water management at the facility level. Finally, the waste and by-products treatment and valorisation phase validates the core principles of the CE. As demonstrated by Salomone e Ioppolo, (2012), integrating by-product valorisation (such as biofuels) into the olive oil production supply chain generates significant environmental credits capable of offsetting upstream impacts. In this study, the substitution of fossil fuels with biogas-derived energy and the on-site combustion of olive pits proved highly effective in mitigating resource depletion and land use. However, the net burden observed in the CC category, driven by the long-distance destination of pitted OP, highlights a recognized structural challenge in circular strategies, i.e., the environmental gains of resource recovery can be easily eroded by inefficient logistics. Future system optimization must therefore prioritize the balance between valorisation benefits and transportation emissions.

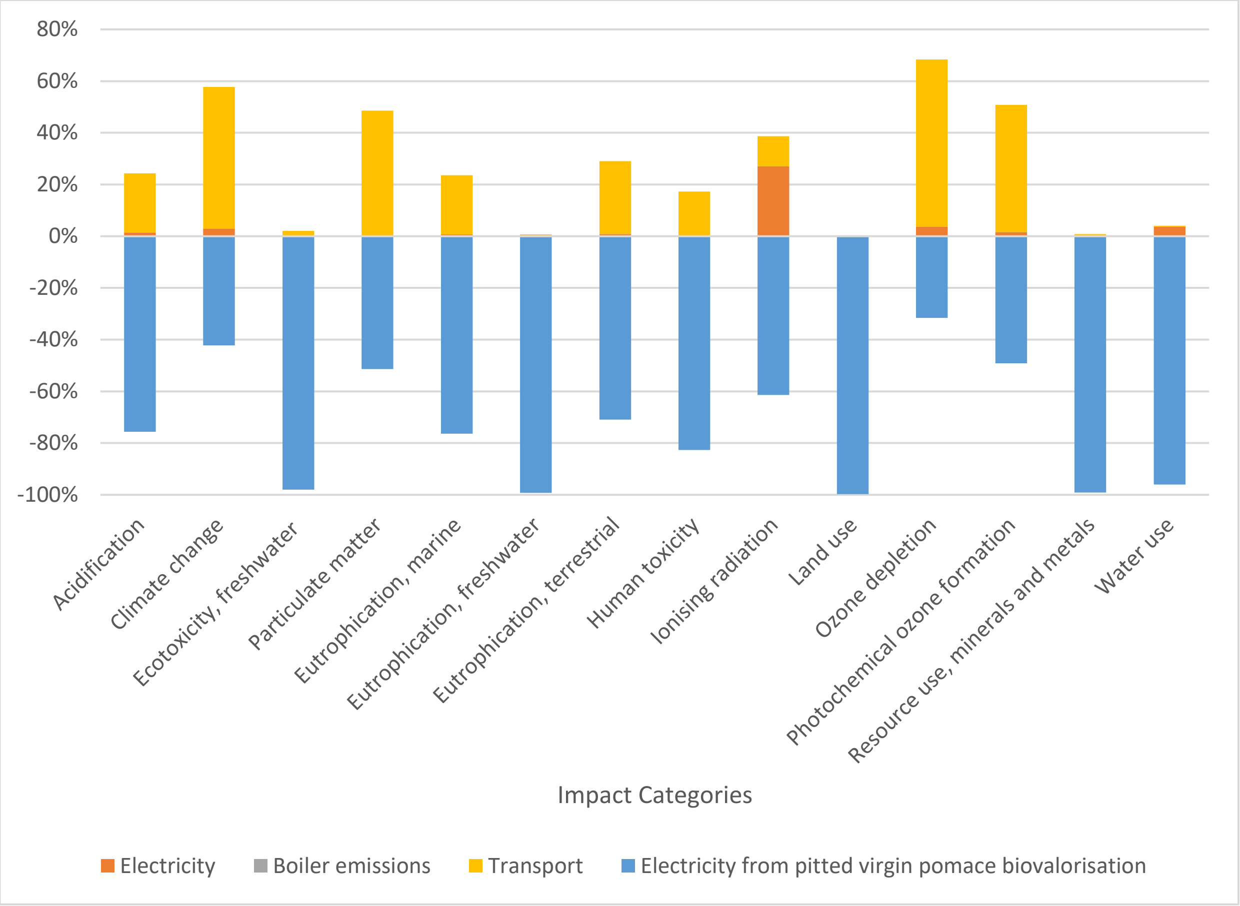

Figure 6 Impact assessment of the waste and by-products treatment and valorisation phase for (characterisation results).

To validate the eco-efficiency of these circular pathways, the LCA results provided are further integrated with the findings obtained through the application of the CBA.

Table 4 reports the results related to the economic performance of the investigated system. The economic performance of the agricultural and olive mill phases was evaluated by treating the farm and the mill as a single unified agro-industrial business. To allow for a standardized comparison, financial flows are presented as both total annual values (€) and expressed with respect to the FU. The detailed inventory of agricultural production costs, including tillage, fertilization, and harvesting, is provided in Table 4. Because the farm and the mill operate under the same ownership, the transfer of olives to the mill was accounted for at its actual agricultural production cost, effectively internalizing the supply chain and avoiding gross profit margins. This structural integration, coupled with a high market positioning, drives the system's success. Selling high-quality EVOO at a premium wholesale price of €9.50 per kg generates substantial revenues (€2,090 per FU). These high returns comfortably absorb all variable operating costs, including farm management and the energy demands of the small-scale milling plant. Consequently, the integrated primary phase achieves a remarkably high Gross Margin (1,173.72 €/FU), high Net Margin (1,152.09 €/FU) and an outstanding BCR of 2.18. This performance is strictly linked to the containment of upstream costs; as detailed in Table 4), the total agricultural production cost is €4,753.40, which represents the internal transfer price for the milling phase. Furthermore, the analysis of the Net Margin confirms the financial solidity of the agricultural-mill unified business model. After accounting for all fixed and opportunity costs, the net profit remains substantially positive, providing the enterprise with the necessary capital to internalize and finance circular practices that would otherwise be economically self-sufficient.

Table 4 Annual variable and fixed costs associated with olive cultivation, including tillage, fertilization, irrigation, and harvesting operations. Financial flows are expressed both as total annual amounts (€) and normalized values per hectare (€/ha).

Items	*Total values €*	*Unitary values €/ha)*
Variable costs:	**763.64**	**213.31**
Tillage:		
Diesel	90.91	25.39
Lubricants	22.73	6.35
Machinery maintenance	45.45	12.70
Fertilization:		
Purchase of fertilizer	159.09	44.44
Transportation of fertilizer	9.09	2.54
Administration of fertilizer	13.64	3.81
Fertigation	159.09	44.44
Irrigation:		
Water	127.27	35.55
Harvesting	136.36	38.09
Fixed costs:	**2,395.00**	**668.99**
Investment depreciation	2,395.00	668.99
Total direct costs	**3,158.64**	**882.30**
Opportunity costs:	**1,594.76**	**445.46**
Interest on capital	94.76	26.47
Land rent	1,500.00	418.99
Olive's sales	22,000.00	6,145.25
Total cost	**4,753.40**	**1,327.76**

Table 5 Detailed production costs of the olive mill phase and overall economic indicators of the agricultural and milling phases per FU.

	Quantity	*Units*	*Price €/kg*	*Value €/FU*
Revenue:				**2,129.29**
Olive oil sales	220.00	kg	9.50	2,090.00
Virgin OP sales + vegetation water	785.71	kg	0.05	39.29
Variable costs:				**927.73**
Raw materials (olives)				882.30
Mill maintenance cost				7.14
Cost with water consumption				1.43
Cost with energy consumption				17.14
Cost of storing vegetation water				1.43
Cost of waste destination				10.00
Cost of maintenance of the transportation means of virgin OP				2.86

Cost of maintenance of the transportation means of water vegetation	2.86
Cost of maintenance of the transportation means of EVO oil	2.57
Fixed costs:	**21.00**
Investment depreciation	21.00
Opportunity costs:	**28.46**
Interest rate	28.46
Total cost	**977.19**
Gross Margin	**1,173.72**
Net Margin	**1,152.09**
BCR	**2.18**

Beyond the robust profit margin guaranteed by the €9.50 per kg selling price, the circular management of by-products directly improves the mill's cost-efficiency. The economic assessment shows that the unitary production cost of EVOO decreases from €4.27 per kg (in a linear scenario without waste valorisation) to €4.13 per kg when the revenues generated from the commercialization of virgin OP and vegetation water are factored into the balance. This results in a net saving of €0.14 per kg of extracted EVOO, demonstrating that integrating waste and by-products recovery not only mitigates environmental impacts but also delivers a measurable reduction in baseline operating costs. Conversely, the economic assessment of the final stage of waste and by-products treatment and valorisation, indicates a negative financial return. As detailed in Table 6 the analysis accounts for annual fixed and variable costs, associated with transport and plant operations, alongside the economic benefits derived from energy and heat recovery. To allow for a standardized comparison, financial flows are reported as both total annual amounts and specific unit values scaled to the FU (€ per tonne of treated virgin OP). The process yields a negative Gross Margin of -€67.37 per FU, a BCR of 0.27, and a Net Margin of -€88.35 per FU. Unlike the agricultural and olive mill phases, where high oil revenues could easily absorb fixed costs, this circular stage fails to reach the break-even point even at an operational level. According to the operation costs, the revenues generated from recovered biomass and energy (pits and biogas) do not compensate for operating expenses. Specifically, two main cost drivers dominate this phase: feedstock acquisition, with virgin OP priced at €0.05 per kg, and transport logistics. The plant involves an extended transport distance of approximately 200 km to move the high-moisture OP to the anaerobic digestion facility. Consequently, transportation costs alone consume roughly half of the total revenues generated by the valorisation process.

Table 6 Economic results related to the waste and by-product treatment and valorisation phase. All values are referred to the chosen FU.

	Quantity	*Units*	*Price €/kg*	*Value €/FU*
Revenue:				**33.48**
Oil OP sales	3.93	kg	3.50	13.75
Heat produced from pits burned	5.89	kWh	0.28	1.65

Purchase of raw pits	26.19	kg	0.20	5.24
Purchase of pitted OP	755.16	kg	0.02	12.84
Variable costs:				**97.91**
Purchase of virgin OP + vegetation water	785.71	kg	0.05	39.29
Electricity	8.73	kWh	0.25	2.18
Production cost of OP oil				39.82
Cost transport of pitted virgin OP	289,631.75	kgkm	5.74E-05	16.63
Fixed costs:				**20.36**
Investment depreciation				20.36
***Opportunity costs**:*				**3.55**
Interest rate				3.55
Total cost				**121.83**
Gross Margin				**-67.37**
Net Margin				**-88.35**
BCR				**0.27**

Hence, the standalone economic assessment of waste and by-product treatment and valorisation phase paints a clearly different picture. Despite its outstanding environmental performance demonstrated in the LCA, this phase currently operates at an economic deficit. The operational data indicate that revenues generated from the recovered energy and biomass (de-stoned pits and biogas) are entirely eclipsed by two major systemic bottlenecks. The first is the feedstock acquisition model, i.e., virgin OP is accounted for at a cost of €0.05 per kg. Treating this wet by-product as a valuable commercial commodity rather than a waste liability, significantly enhances the processor's baseline margin. The second, and perhaps most critical, bottleneck is the logistical inefficiency. As previously highlighted, the extended transport distance required to move the high-moisture OP to the anaerobic digestion facility introduces prohibitive transportation costs, which alone consume roughly half of the total revenues generated by the valorisation process. However, this systemic imbalance opens the door to a more in-depth strategic discussion regarding "cross-subsidies for sustainability." Considering the absolute economic values generated across the entire supply chain, the sustainability of the model must be assessed in an objective way. While the waste and by-products treatment and valorisation phase incur a net loss in absolute terms (as shown by the negative Net Margin in Table 5), the substantial absolute profit generated by the sale of EVOO provides the necessary liquidity to internalize these costs. From this holistic perspective, the high-margin core business acts as a financial anchor, allowing the company to absorb the net operating losses of the circular practice. In this integrated framework, OP valorisation is not managed as an independent profit center, but as a strategic cost-center for environmental compliance, fully subsidized by the primary production's surplus. However, to correctly interpret these critical economic indicators, it is essential to assess the system's conditions. Indeed, the case study's treatment plant does not operate as an isolated enterprise; rather, it is an integral part of a farm whose core business and primary source of income derive from the production of superior-quality EVOO. From this holistic perspective, OP valorisation should not be viewed as an independent profit center, but rather as a key operational strategy for circular management that helps close the production loop. This is precisely where the integrated model demonstrates its resilience.

Indeed, the profits generated by the primary phase of EVOO extraction provide the company with a wide margin to compensate for and absorb the operating losses incurred during the valorisation phase. Essentially, the high profits generated by high-quality EVOO can subsidize the reduction of the ecological footprint of the entire supply chain. Looking ahead, for the valorisation phase to achieve independent economic sustainability, systemic conditions need to evolve. The current logistical model, involving a 200 km transport distance, is fundamentally incompatible with the low economic value of wet by-products. As logistics costs for agricultural waste typically become prohibitive beyond a 100 km radius, the most viable solution lies in the promotion of localized agro-industrial clusters. Such a paradigm shift would drastically reduce transport distances and transaction costs, ensuring that circular practices in the olive oil supply chain become as economically attractive as it is environmentally necessary.

The results of this economic assessment highlight a paradigmatic trade-off that often recurs in the literature on CE. Indeed, while the valorisation phase emerges as the clear winner from an environmental perspective in the LCA, it is at the same time the weak link in the supply chain from an economic perspective (Abbattista et al., 2021). The integrated farm-mill model thrives thanks to established, high-value consumer markets for EVOO, while the valorisation pathway struggles due to the notoriously low margins typical of waste-to-energy and waste-to-product systems. The negative profitability of the valorisation scenario is very much in line with recent literature, confirming that without specific supply chain effective alignment or external subsidies, investments in advanced valorisation treatment facilities often struggle to compete economically in their early stages (Restuccia et al., 2022; Spada et al., 2024).

3.4.1 Eco-efficiency considerations

In the present study, eco-efficiency was conceptualized as the capacity of the integrated system to maximize the environmental benefits derived from CE practices while maintaining overall economic sustainability. The intersection of the LCA and CBA results reveals a stark trade-off between the two dimensions. As highlighted by Hoogmartens et al. (2014), bridging the methodological gap between environmental and economic assessments often uncovers how high degrees of circularity can entail specific economic burdens. On the one hand, the LCA study demonstrated that the OP treatment and valorisation phase is crucial for drastically reducing the envrionmental impacts of the entire supply chain. On the other hand, the CBA confirmed that such environmental benefits are achieved at the expense of significant economic losses, evidenced by a negative Gross Margin, Net Margin and BCR. This misalignment between environmental performance and economic deficit reflects a structural challenge within the modern olive oil industry. As emphasized by Ncube *et al.* (2022), while CE principles are increasingly vital to mitigate the substantial environmental pressures of residue disposal in olive oil supply chain, implementing these pathways presents practical and logistical hurdles. The transport of biomass with a high moisture percentage for approximately 200 km translates into the consumption of fuel and economic resources utilized merely to move large quantities of water. Under these circumstances, the revenues generated are insufficient to cover logistical costs, rendering this ecologically virtuous practice economically unsustainable on a standalone basis. However, shifting the analysis from the isolated process unit to the entire integrated business system radically changes the paradigm. The profitability of the primary agricultural and olive mill phases, driven by the premium market value of the EVOO, acts as a powerful enabling factor. The profits generated from the EVOO serve as a cross-subsidy for CE practices. In terms of systemic eco-efficiency, the enterprise absorbs the costs necessary to ensure a drastic reduction of its environmental footprint by reinvesting a fraction of the operating margins generated by its core product. From a broader perspective, these results invite a critical reflection on the very concept of eco-efficiency applied to the agro-industrial CE. True eco-efficiency is not limited to simply diverting waste from landfill but lies in optimizing the net balance between the resources used for recovery (e.g., fuel for transport, energy for extraction) and the environmental and economic value generated. In the case under consideration, a form of 'systemic' (or strong) eco-efficiency is being witnessed at the global supply chain level, which compensates for 'weak' eco-efficiency at the level of the individual recovery process. In order to overcome this dichotomy in the future, supply chain strategies will need to focus on cascading biomass as close as possible to its place of origin. Solutions such as the use of decentralized micro-digesters or on-site drying of OP using waste heat from the olive mill would make it possible to decouple environmental benefits from logistical penalties. Only by reducing the movement of low-value-added material will it be possible to transform the management of by-products into a model of absolute eco-efficiency, in which ecological integrity fully coincides with the creation of economic value.

To evaluate the environmental and economic performance of the proposed circular loops with high operational precision, the system boundaries of both the LCA and CBA were strictly defined using a "cradle-to-gate" perspective, in structural alignment with the ISO 14040/14044 (2006) (ISO 2006a; ISO 2006b) standards for goal and scope definition. This boundary encompasses the agricultural phase, the milling process, and the subsequent waste and by-product valorisation workflows, while deliberately omitting downstream stages such as bottling, packaging, and long-distance distribution to end-markets. The primary rationale for this restriction is to isolate and optimize the eco-efficiency of internal refinery operations and local secondary raw material handling, which fall under the direct operational management of the SME under study. Furthermore, specific operational inputs, such as chemical cleaning agents used within the mill, were excluded from the quantitative inventory based on the standard cut-off criteria, due to a lack of primary accounting data. While these cut-off are methodologically consistent with the objectives of this research, their potential qualitative influence on the final systemic eco-efficiency ratios warrants critical discussion based on established agri-food LCA literature:

- Influence of bottling and packaging materials: comparisons among different packaging options (e.g., glass, PET, and other materials) show that the bottling and packaging stages can make a substantial contribution to the overall environmental impact, in some cases accounting for a significant share of the total burden (Pattara et al., 2017). These studies identify packaging and logistics as key environmental hotspots, with impacts varying according to the packaging material used and its end-of-life management. Consequently, the inclusion of packaging in the system boundaries, particularly glass bottles, would considerably increase the environmental baseline of the product system. LCA studies on Mediterranean olive oil production (e.g., Navarro et al., 2018; Pattara et al., 2017) consistently indicate that packaging materials, especially virgin glass, constitute one of the dominant contributors to the cradle-to-grave Global Warming Potential (GWP). Introducing virgin glass into the LCA model would significantly increase the absolute GWP and cumulative energy demand of the final product (Navarro et al., 2018). In terms of eco-efficiency (expressed as economic value added divided by environmental indicator), this would disproportionately expand the environmental denominator, potentially diluting or masking the relative environmental credits achieved through wet OP and wastewater valorisation at the mill scale. Conversely, integrating a closed-loop packaging strategy leveraging high-content recycled glass or lightweight alternatives, as suggested by Guarino et al. (2019), would minimize this distortion, preserve a highly favorable systemic eco-efficiency ratio, and reinforce the premium-revenue cross-subsidization framework.
- Influence of downstream distribution: omitting the transport of final products to international or distant domestic markets removes a highly volatile variable dominated by fossil fuel combustion. Heavy downstream transportation burdens can drastically lower the overall eco-efficiency of the entire supply chain. This cut-off, therefore, indirectly strengthens the study's core argument: localized, short-chain circular districts (as modelled in this chapter) are functionally mandatory to prevent downstream logistics from neutralizing the environmental benefits generated at the mill gate.
- Influence of cleaning chemicals and detergents: the exclusion of cleaning agents primarily affects toxicity-related impact categories (such as freshwater and terrestrial ecotoxicity) rather than climate

or carbon indicators (Espadas-Aldana et al., 2019). Had primary data been available, conventional chemical detergents introduced an environmental penalty within these toxicity scores, shifting the net eco-efficiency balance slightly downward. This omission highlights a strategic recommendation for the mill's ecological transition: the adoption of biodegradable, bio-based cleaning solutions is essential to safeguard the integrity of the environmental credits calculated within the integrated framework.

To summarize, maintaining a cradle-to-gate boundary allows for a targeted evaluation of the environmental and economic trade-offs directly tied to byproduct valorisation within the milling facility. Although extending the system boundaries to include downstream packaging and distribution would introduce substantial external variability at this stage, future expansions of this model should systematically incorporate the bottling phase. Specifically, evaluating bottling configurations that utilize high-content recycled glass would offer a more comprehensive representation of the entire corporate system. Integrating this downstream component would enhance the overall completeness of the eco-efficiency assessment, thereby providing a more effective tool to facilitate strategic corporate choices and accelerate the firm's broader ecological transition.

Recognising that the empirical model is based on a single integrated case study in Sicily and uses secondary literature data to financially model the valorisation phase, a critical assessment of cost variance is necessary to address the inherent limitations of statistical generalizability. In agri-food waste management models, costs modeled from the literature often mask regional macroeconomic fluctuations that can significantly alter the empirical value of economic metrics considered in this study (Net Margin, Gross Margin, and BCR). To establish the boundary conditions for the proposed circular cycles, it is necessary to assess the sensitivity of the economic results to three highly volatile external cost factors: regional energy tariffs, fuel costs for biomass transportation, and the fluctuating market value of secondary raw materials. It is important to highlight that the treatment and valorisation of high-moisture byproducts, such as wet OP and OMWW, involve energy-intensive unit operations including thermal drying, and mechanical separation. Consequently, the operational cost baseline is structurally sensitive to national and regional energy grid volatility, as highlighted in agri-food industrial ecology assessments (Stempfle et al., 2022; Donner et al., 2022b). A local spike in electricity or natural gas rates directly increases operating expenses and can compress the BCR, especially if the market valuation of by-products does not grow proportionally. When energy inflation is sustained without a corresponding increase in the value of by-products, circular pathways heavily dependent on mechanical or thermal processes risk remaining below the profitability threshold. This scenario emphasizes the strategic importance of decentralized energy generation, e.g., integrated photovoltaic systems or direct heat recovery from dried residues, to make SMEs' circular investments resilient to grid shocks (Stempfle et al., 2022; Donner et al., 2022b). The literature describes scenarios for the use of gasification, bioproducts and cogeneration as ways of local energy integration to reduce dependence on the grid energy price volatility (Teksoy and Şen 2025; García Martín et al., 2020). Simultaneously, logistics represents an important source of financial vulnerability due to the unique physical characteristics of olive milling residues. Wet OP and OMWW possess a very low economic value-to-weight ratio, meaning that transport costs increase linearly with geographic distance and fuel price volatility. A spike in regional diesel prices dramatically increases transportation costs, quickly eroding the net benefits calculated at the industry output. This high sensitivity to transport, particularly relevant in localized Mediterranean networks, validates the spatial constraints identified in the Sicilian case study (Valenti et al., 2018). This confirms that short-range operations within specialized agro-industrial clusters are an absolute prerequisite for maintaining a favourable BCR. Finally, revenues from by-products valorised as biofertilizers, soil amendments, and bioenergy feedstocks are exposed to significant market uncertainty. Unlike conventional agricultural commodities, these products are often traded in immature markets characterized by price volatility, uncertain demand, and constantly evolving regulatory frameworks (Farahbakhsh et al., 2023; Spada et al., 2025). Consequently, the profitability of circular economy pathways is highly sensitive to fluctuations in production prices and market conditions, which can directly impact the viability of investments. This uncertainty is particularly relevant for nutrient-based products, whose market acceptance depends on user trust and regulatory support, while energy products generally benefit from more mature and stable markets (Ddiba et al., 2021). Nevertheless, the overall economic performance of the system remains relatively resilient to such market fluctuations, as revenues from EVOO provide a stable and high-value income stream. This primary product effectively offsets potential losses from volatile by-product markets, acting as an economic buffer that enhances the robustness of the overall circular business model.

In conclusion, this sensitivity analysis establishes the precise operational and spatial boundaries required to safeguard the financial viability of circular olive systems against macroeconomic shocks. By framing energy self-reliance, short-range logistics, and EVOO cross-subsidization as essential pillars of economic resilience, the model transitions from a single-case study into a flexible, stress-tested evaluative framework.

3.5 Conclusions

This study evaluated the eco-efficiency of an integrated olive oil production chain, combining environmental impact analysis (LCA) with economic analysis (CBA). From an environmental perspective, the LCA results showed that the reuse of washing water for machinery cleaning in the olive mill phase combined with the environmental savings generated by energy recovery significantly improves the system's profile. Specifically, the avoided impacts achieved by displacing conventional grid electricity with energy produced by biogas, alongside the on-site combustion of olive pits as boiler fuel, are particularly effective in mitigating burdens on LU, WU, FET, and RU-mm. Ultimately, these circular strategies prove crucial for drastically reducing the overall ecological footprint of the production chain. From an environmental perspective, the LCA identified the agricultural phase as the dominant source of overall impacts, primarily driven by fertilizer application and machinery emissions, highlighting an urgent need for targeted mitigation strategies. The olive mill phase, while less impactful, balances logistical burdens with early circular opportunities, such as wastewater reuse. Ultimately, the waste and by-products treatment and valorisation phase proves to be the most advantageous phase from an environmental, delivering net ecological benefits through advanced closed-loop practices, including biogas generation and biomass recovery. However, the CBA revealed a net operational dichotomy. While the primary production of EVOO ensures excellent profitability with a high net margin and a BCR of 2.18, the circular wet OP treatment operates at a structural deficit (BCR 0.27). This economic gap is exacerbated by prohibitive logistical costs and the enterprise’s deliberate choice to renounce chemical extraction, ultimately prioritizing absolute environmental integrity over economic maximization. The results demonstrated how a systemic approach can successfully overcome the trade-off between environmental integrity and economic viability. Indeed, when evaluated holistically, the integrated supply chain reveals remarkable economic resilience. The substantial profit margins derived from the premium positioning of the EVOO act as a vital cross-subsidy, directly financing the circularity practices. Within this business model, by-product management is no longer evaluated as an independent profit center, but rather as an essential, sustainable investment required to eliminate waste and virtuously close the production loop. Despite providing robust empirical insights, the generalizability of these findings is subject to certain limitations. First, the analysis is inherently bound by its single-case study design. Second, focusing on the core production processes, the system boundaries excluded the bottling and distribution phases, which may contribute significantly to the total carbon footprint and final product cost. Third, due to a lack of primary data, cleaning agents were excluded from the LCA, although these chemicals can have notable impacts on water toxicity. In addition, while the agricultural and olive mill phases rely on primary data, the costs for the treatment phase were modelled based on literature, introducing a degree of uncertainty compared to the rest of the study. Therefore, for the broader olive oil industry to achieve absolute eco-efficiency, where ES systematically aligns with economic profitability, a profound infrastructural paradigm shift is required. Sector policies and future industrial strategies must incentivize the development of localized agro-industrial clusters and the deployment of decentralized valorisation technologies. Drastically reducing the transport distances for moisture-rich biomass may represent the main strategy to transform olive residues from a logistical liability into a shared strategic resource, ultimately rendering the CE both environmentally sound and economically self-sustaining. Finally, from a methodological perspective, the primary eco-efficiency metrics should always remain intuitive and easily interpretable by agricultural producers. However, should future studies require large-scale scenario verification or extensive benchmark evaluations across multiple facilities, advanced benchmarking tools such as Data Envelopment Analysis (DEA) or goal programming approaches could be effectively integrated as a subsequent analytical phase.

Chapter 4
A Systemic Framework for Olive Waste and By-Products Valorisation: Integrating Life Cycle Assessment and Cost-Benefit Analysis

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Abstract: The ecological transition towards circular economy and environmental sustainability in the olive oil supply chain represents a critical environmental imperative. However, small and medium enterprises (SMEs) frequently struggle to align environmental sustainability with economic viability. While advanced valorisation technologies successfully mitigate the severe phytotoxic impact of olive mill waste and by-products, their industrial application often reveals some difficulties, beacuse environmental benefits are heavily faced by prohibitive capital and operational expenditures. To bridge the gap between theoretical circularity and industrial feasibility, this study proposes a framework tailored for the olive oil supply chain, integrating Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) to guide SMEs managers through strategic decision-making. Prospects for empirical validation are also provided. The framework is based on a previous systematic literature review about the main olive oil waste and by-products treatment and valorisation pattern, ranging from high-value upcycling to energy downcycling, and based on empirical data obtained from an integrated Sicilian olive oil mill case study. The Framework starts by categorising physical waste and by-products streams into specific operational patterns and assessing them through targeted environmental impact categories (i.e., CC, ecotoxicity, WF, eutrophication and abiotic depletion) and economic metrics (i.e., Net margin, Gross Margin and Benefit Cost Ratio). The results demonstrate that while upcycling pathways can yield positive returns, the valorisation of low-value wet biomass operates at a severe financial deficit (e.g., a Net Margin of -€88.35 per FU). To guide SMEs toward viable industrial circularity, the framework establishes two pillars for systemic eco-efficiency, i.e., localized agro-industrial symbiosis and a corporate 'cross-subsidy' strategy. By integrating the supply chain, premium extra virgin olive oil profits structurally absorb waste and by-products management losses, turning environmental compliance into a sustainable systemic investment.

Keywords: Olive oil waste and by-products valorisation; Framework; Circular economy; Life Cycle Assessment (LCA); Cost-Benefit Analysis (CBA); Systemic eco-efficiency.

4.1 Introduction

The olive oil industry is a key pillar of the Mediterranean agrifood economy, generating substantial amounts of waste and by-products, including OP, olive pits, and OMWW. Managing these residues is a major challenge, as it affects production efficiency, compliance with environmental regulations, and overall sustainability. Historically treated simply as waste, these residues are characterised by a high organic load and the presence of phytotoxic compounds, which can pose significant environmental risks if not properly managed (Batuecas et al., 2019; Doula et al., 2017). In particular, they can severely affect soil properties, including hydrophobicity, water retention, pH, salinity, and microbial balance. In particular, the agricultural phase has been identified as the main contributor to the environmental footprint of olive oil production. This is largely due to the intensive use of water, fertilizers, and pesticides, which can degrade soil quality, deplete water resources, and increase greenhouse gas emissions (Banias et al., 2017; Pattara et al., 2017; Salomone and Ioppolo, 2012). Other stages of the supply chain also contribute to environmental impacts, including the production of packaging materials and the use of refrigerants during storage (Rinaldi et al., 2014). By contrast, the extraction phase generally has lower environmental impacts due to its relatively limited energy and chemical inputs, although it generates significant quantities of waste and by-products (Ncube et al., 2022). Indeed, only about 20% of the olive fruit is converted into olive oil, while the remaining 80% consists of residues such as leaves and branches, OP, stone fragments, and OMWW. Within the emerging frameworks of the CE, olive oil production residues are increasingly recognised as valuable resources with significant potential for valorisation (Cinardi et al., 2024). Rather than being treated as phytotoxic waste requiring disposal, these streams are now widely acknowledged as rich in bioactive compounds, particularly polyphenols, as well as suitable feedstocks for renewable energy, biomaterials, and nutraceutical applications (Enaime et al., 2024; Jimenez-Lopez et al., 2020). Numerous studies have highlighted the potential of these waste and by-products within integrated valorisation pathways, where multiple recovery processes are combined to maximise resource efficiency and reduce environmental impacts (Ruiz et al., 2017; Stempfle et al., 2021). In particular, cascade approaches, such as those proposed by Gómez-Cruz et al. (2024), demonstrate how the extraction of high-value bioactive compounds can be effectively integrated with bioenergy and biofuel production, enhancing both economic and environmental performance. In this context, the shift from conventional waste management referred to a predominantly linear approach focused on the collection, treatment, and final disposal of waste streams, to integrated valorisation systems represents a key strategic opportunity for improving the sustainable competitiveness of olive oil companies and achieving systemic eco-efficiency. Building on the traditional definition of eco-efficiency as the ability to maximize economic value creation while simultaneously minimizing the ecological footprint (World Business Council for Sustainable Development, 2000) systemic eco-efficiency extends this concept to the entire value chain, emphasizing the optimization of environmental and economic performance across interconnected processes and material flows (Angelis-Dimakis. et al., 2016). A range of technological solutions, including gasification, nutraceutical extraction, and advanced composting, have already proven technically viable for closing production loops and advancing circularity within the sector (Stempfle et al., 2021). Enaime et al. (2024) highlight that OMWW and derived biomasses offer high potential for bioactive compounds, yet industrialisation is still hindered by variable compositions and the need for supportive policy measures to enable large-scale production. For instance, without reclassifying and valorising this wet residue as a strategic by-product, the potential economic and social benefits that companies could achieve through CE approaches remain limited (Polonio et al., 2025). Conversely, adopting regenerative strategies for OP offers substantial prospects for financial growth while playing a pivotal role in curbing rural depopulation. Consequently, these eco-innovations transform rural olive-growing areas into hubs of sustainable development, ensuring a fairer distribution of territorial welfare. However, despite this abundance of treatment and valorisation of technological solutions, there is an application paradox. Indeed, the level of adoption of circular models by small and medium-sized (SMEs) olive oil enterprises remains marginal. As highlighted by the multi-level perspective proposed by Spina et al. (2025), the sector remains constrained by socio-technical lock-ins and a significant degree of managerial decision-making inertia. In this context, achieving eco-efficiency becomes a complex managerial challenge, as entrepreneurs must navigate a highly uncertain and multifaceted decision-making environment. In particular, technology choices require balancing capital investments (CAPEX), uncertain economic returns, and strict regulatory requirements, including those related to End-of-Waste criteria, while simultaneously addressing environmental and economic trade-offs. (Zarbà et al., 2021). To address this complexity, several studies have introduced mathematical optimization models and composite indicators aimed at identifying the optimal crossroad between economic performance and environmental impact (Argoubi and Mili, 2026; Polonio et al., 2025). However, despite their scientific robustness, these advanced tools are often characterized by high complexity and limited flexibility, which hinder their practical integration into the everyday decision-making processes of SMEs (Keskes et al., 2022). There is therefore an urgent need for holistic tools that translate the analytical power of the environment and economic evaluation setting into a strategic tool accessible to decision makers, transforming technical data into concrete business strategies (La Scalia et al., 2026). Effective dissemination and adoption among olive oil SMEs requires targeted actions on governance, policy, financing instruments, and risk management, as well as the design of biorefineries that integrate the various treatment and valorisation units on an industrial scale, as reinforced by the contributions of Spina et al. (2024) and Stempfle et al. (2021). There is a community of studies that emphasises the need for holistic assessments of the sustainability (environmental and economic) of the valorisation of olive growing by-products, including circularity indicators and life cycle thinking approaches. (Falcone et al., 2022; Kounani et al., 2023; Ncube et al., 2022). This supports the need for decision-making frameworks that integrate environmental and economic indicators to guide olive oil SMEs. To support companies in deciphering this complexity, research has developed increasingly sophisticated sustainability metrics. The evolution of analytical tools has led to the development of ‘multi-cycle’ models of LCA and economic assessment methodology (e.g., Life Cycle Costing – LCC, and Cost Benefit Analysis – CBA) capable of tracking impacts and profits across multiple material flows in the supply chain (Falcone et al., 2022; Stillitano et al., 2022). Within this context, LCA is widely recognized as the standard methodology for quantifying the potential environmental impacts, providing an ISO-compliant basis for sustainability assessments (ISO 2006a; ISO 2006b). However, assessing the economic dimension through its direct methodological counterpart, LCC, frequently imposes an unsustainable data-gathering burden on small agro-industrial operators, severely limiting the practical adoption of these sustainability assessments (Martinez-Sanchez et al., 2016). This operational bottleneck strongly resonates with the ‘European Commission’s Transition Pathway for the Agri-food Industrial Ecosystem’, which explicitly calls for more accessible and agile tools to foster the ecological transition (European Commission, 2024). To resolve this challenge, the proposed framework adopts a hybrid approach, strategically coupling the rigorous environmental accounting of LCA with CBA rather than LCC. Unlike the data-intensive LCC, CBA functions as a highly pragmatic and streamlined decision-support mechanism (European Commission, 2015b). Particularly, by replacing the highly demanding LCC methodology, the CBA effectively reduces analytical complexity, functioning as an accessible and pragmatic economic screening tool for SMEs decision-making., allowing them to rapidly evaluate, rank, and select investment options based on immediate economic efficiency and tangible financial returns (Vagdatli and Petroutsatou, 2022). By integrating LCA with CBA, the framework effectively offsets the inherent complexity of life-cycle methodologies. This multidimensional synergy provides company managers and policymakers with transparent, objective guidance, ensuring that the selected modernization strategies are both ecologically sound and competitively viable in the real market (Bruno et al., 2023).

Responding to this need, this article proposes the Life Cycle Thinking Decision Framework (LCT-DF). Moving away from a purely algebraic optimisation approach, the study adopts the strategic perspective of Life Cycle Thinking to provide a semi-quantitative, multi-criteria management tool. The framework has three objectives: (i) to map the treatment and valorisation trajectories for olive oil waste and by-products; (ii) to use the life cycle thinking method and economic feasibility indicators as a filter to discard options that are inapplicable in the business reality; and (iii) to visually identify the optimal operational solutions that guarantee the achievement systemic eco-efficiency, thereby ensuring environmental neutrality while protecting and increasing business profitability. This managerial approach allows optimal operational solutions to be viewed immediately, reducing complexity without sacrificing scientific rigour. In this way, the proposed model aims above all to be a tool that is easier to approach and immediately applicable for companies, overcoming the technical and operational barriers that often hinder the implementation of the CE.

4.2 Material and methods

The methodological approach of this study was designed to answer the following core research question: ‘How to develop a dedicated framework focused on the identification of the most appropriate technologies and the assessment of their related eco-efficiency, focusing on an ES and CE perspective?’ The purpose of the LCT-

DF framework is to support companies operating in the olive oil industry. It aims to provide a practical tool to help decision-makers choose the best strategies for managing waste and by-products, balancing CE principles, ES, and economic viability. Given the complexity and multidimensional nature of the problem, the adopted methodology departs from a purely analytical-quantitative approach, embracing an iterative research design that constantly bridges theory with industrial practice. In particular, the framework is built upon the results obtained from the previous literature review, and LCA and CBA case study carried out among the Ph.D research (see Chapter 2 and Chapter 3). Specifically, the literature review acted as the baseline to systematically map the primary waste and by-product streams generated by olive oil production, alongside their most technologically appropriate treatment and recovery pathways. Subsequently, the empirical application of LCA and CBA on the case study in Sicily (Italy), considered highly representative of the olive production sector in the Mediterranean basin, which is historically dominated by SME, provided the necessary contextual environmental and economic indicators. In this context, the preliminary application of LCA and CBA to this company's processes revealed key operational criticalities, thereby defining the backbone of the final framework.

Figure 1 illustrates the overall methodological architecture of the study, outlining the logical flow and the interconnections between quantitative modeling tools and qualitative and strategic validation processes.

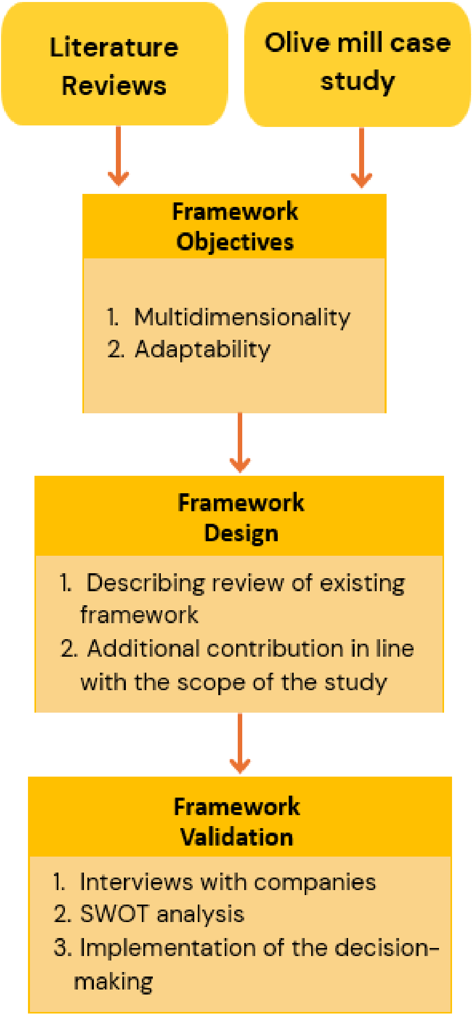

Figure 1 Overall methodological architecture of the study for the development and validation of the framework.

4.2.1 Framework design

The LCT-DF framework development starts from a preliminary phase that allows for the identification of two core objectives that the proposed framework must satisfy:

- Multidimensionality – the capacity to fully integrate both environmental and economic dimensions into a single evaluation tool.
- Adaptability – the responsiveness to different company needs, logistical constraints, and levels of technological maturity.

To design the framework, an exploratory literature review was conducted to select, analyze, and adapt previous conceptual models and assessment tools. As suggested by Almusaed et al., (2025), this type of review is highly effective in identifying key concepts and gaps within a specific research area. The literature search was performed using the Scopus database. The search string employed the following keywords: ('olive oil') AND ('circular*') AND ('sustainab*') AND ('framework'). No specific time frame was defined, and the database search was updated on March, 2026.

The initial search strategy yielded a total of 28 results. A sample design process was then applied by limiting the results to articles and reviews and restricting the search to English language publications. This filtering reduced the sample to 27 results. Subsequently, a manual screening of these 27 articles was performed based on strict eligibility criterion, thus focusing on articles that explicitly propose a framework for environmental and economic sustainability assessment and CE within the olive oil supply chain. After applying this criterion, only 6 articles satisfied the established requirements and were selected for in-depth analysis.

Among the 6 selected papers, the study by Argoubi and Mili, (2026) emerged as the closest to the objectives of this research, providing the most comprehensive approach to both environmental and economic dimensions. The authors proposed a Multi-Objective Linear Programming (MOLP) model, aimed at jointly optimizing three key dimensions: ES, product quality, and economic performance (Argoubi and Mili, 2026). The model operates simultaneously on two fronts: i) economic objective, maximizing the total profit of the supply chain, and considering the costs associated with harvesting, transportation, milling operations, and distribution; ii) environmental objective, by minimizing the overall carbon footprint and the ecological impact generated by waste and by-products disposal. Despite the scientific robustness of this method, a critical gap was identified. Indeed, the high mathematical complexity of the model makes it difficult for typical olive oil SMEs to consult and apply it in everyday business operations. Consequently, the framework here proposed adapts the comprehensive dual-focus approach (economic and environmental) provided by Argoubi and Mili, (2026), translating it into a more accessible, operational framework based on LCA and CBA methods. To bridge the gap between theoretical modeling, in accordance with Argoubi and Mili (2026), and industrial applications, the architecture of the final framework was built upon two complementary pillars: i) the targeted literature review and the empirical data derived from the LCA and CBA of the Sicilian case study, based on the results from the previous studies (see Chapter 2 and Chapter 3). This combined approach ensured that the framework not only identifies theoretical circularity but also effectively measures the actual environmental and economic sustainability, from an eco-efficiency perspective, of the main waste-to-resource strategies.

4.2.2 Framework validation

To ensure that the interaction between the framework and the company context generates results that are genuinely applicable at the managerial level, the methodology follows a three-stage validation process:

1. **Interviews with companies –** a qualitative research tool designed to capture unstructured primary data, such as the actual risk appetite of entrepreneurs, cultural barriers, and limitations related to internal technical know-how.

2. **Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis –** a strategic contextualization tool used to weigh the quantitative results of the framework against external competitive dynamics (e.g., regulatory opportunities, subsidies, market threats) and internal capabilities (Helms and Nixon, 2010).
3. **Implementation of the decision-making process** – the final synthesis of the method, where the framework is tested as a fully-fledged decision support system to guide investment choices (evaluation trade-offs) regarding waste and by-products valorisation technologies.

In the following sections, each of these methodological nodes will be expanded and detailed, defining the assumptions and system boundaries adopted for conducting the study.

4.3 Results and discussion

The LCT-DF framework systematically translates these core results from the literature review and the LCA and CBA case study into five concrete operational pathways. These patterns represent the assessment objects of the framework, encompassing both isolated technological interventions and holistic business integration models:

1. OMWW and membrane extraction – this first pathway falls within the *upcycling* paradigm. It involves the treatment of OMWW using advanced filtration technologies or adsorbent resins, with the aim of extracting bioactive compounds (such as polyphenols) for high-value-added markets in the cosmetics and pharmaceutical sectors, whilst simultaneously purifying the wastewater. Crucially, this pattern unlocks multiple circular benefits. Indeed, while the sale of premium polyphenols offsets the exceptionally high Capital Expenditure (CAPEX) of the membrane systems, the resulting purified water can be fully recirculated into the mill for washing operations or utilized for local orchard irrigation, directly mitigating the company's Water Footprint (WF). Furthermore, the residual concentrated organic retentate can be synergistically routed to anaerobic digestion plants.

2. Wet OP and anaerobic digestion/composting – classified as a *downcycling* practice aimed at recovering mass and energy, this pathway involves sending fresh OP (sometimes mixed with municipal solid waste) to biological treatment plants. The output of this process involves the production of biogas for energy cogeneration and organic soil improvements (compost) to return nutrients to agricultural soil. To maximize system eco-efficiency, the thermal energy recovered from the combined heat and power unit can be fed back into the olive oil extraction process (e.g., heating the malaxation phase), while the stabilized digestate and compost reduce the SME's reliance on synthetic fertilizers, offering a double Operational Expenditure (OPEX) saving.

3. Dry OP and thermochemical treatments – a further advanced energy *downcycling* approach that involves the recovery of exhausted OP (post-olive oil extraction) through controlled thermal degradation processes, such as gasification or pyrolysis. This pathway aims to produce cleaner energy carriers or heat/electricity, offering a technological alternative to traditional and high polluting direct combustion. A significant secondary circular advantage of pyrolysis and gasification is the co-production of biochar. When applied to olive groves, biochar acts as a powerful carbon sink and soil conditioner, enhancing water retention and allowing the company to potentially generate and trade carbon credits (El-Bassi et al., 2021; Haddad et al., 2021).

4. Olive pits and heat recovery – this pathway focuses on on-site heat recovery within the company. Through the mechanical separation of the OP from the olive pulp (either directly at the mill or in dedicated facilities), the woody fraction is used as biomass fuel to power the farm's boilers, with a view to *downcycling* aimed at achieving energy independence for the olive oil-making process. This closed-loop

system can be further optimized by recovering the residual combustion ashes, which are highly rich in potassium, and reintroducing them into the olive orchards as a natural, zero-cost mineral amendment.

5. Supply chain integration and the ‘cross-subsidy’ model – this pattern is not limited to a single technology, but frames circularity at the level of the company system (system eco-efficiency). It represents the model of an integrated business in which the entire waste and by-products management department operates in synergy (closed-loop approach) with the core business, namely the production and sale of premium-grade EVOO. In this scenario, the prohibitive implementation costs of circular technologies are absorbed by the premium pricing of an eco-certified final product. This strategic branding turns environmental compliance into a competitive market advantage, proving that ES can directly fuel economic profitability.

The conceptual architecture and logical flow of the LCT-DF framework are summarized in figure 2. The block diagram illustrates a sequential, three-stage process. Regarding the first stage of the LCT-DF framework, the physical input matrices (Operational Patterns 1-4) are systematically processed through a central analytical approach, in order to define the physical-chemical characteristics of the waste and by-products streams generated during olive oil production and their corresponding valorisation pathways. Crucially, the entire system is enveloped by pattern 5 (supply chain integration and the ‘cross-subsidy’), visually reinforcing that the internal 'cross-subsidy' model acts as the overarching structural baseline necessary to financially sustain the circular transition. When these operational patterns are established, the framework activates its core analytical engine (second stage of the LCT-DF framework) to measure their eco-efficiency. This stage integrates LCA and CBA, evaluating each technological pathway, using a set of environmental indicators, alongside economic variables including costs, CAPEX, and OPEX. These are further synthesized through CBA metrics, such as Net Margin, Gross Margin, and Benefit–Cost Ratio (BCR), enabling a comprehensive assessment of both environmental and economic performance. The outcomes of this integrated analysis led to different strategic configurations and identifying high-value market access or strict logistical constraints. The indicators are capable of identifying the vulnerabilities and trade-offs typical of the olive oil supply chain (Bruno et al., 2023). From an environmental perspective, performance measurement relies on indicators such as CC, ecotoxicity, WF, eutrophication and abiotic depletion. These indicators permit to quantify both the damage avoided, and the credits generated by circular strategies. In particular, CC category serves as the main driver for assessing the greenhouse gas (GHG) emissions avoided compared to the uncontrolled decomposition of waste and by-products in open environments, as well as for accounting for the benefits associated with replacing fossil fuels with bioenergy. Aquatic and terrestrial ecotoxicity, eutrophication (both marine and terrestrial) and WF indicators represent the former measures of the effectiveness in neutralising the severe phytotoxic load of olive mill effluent to protect soils, and to assess the benefits of water recovery. Finally, abiotic depletion (fossil) assesses the conservation of non-renewable resources, rewarding those processes that make the oil mill self-sufficient in terms of external fossil fuel supplies. The decision to focus the framework on a targeted set of environmental indicators is driven by a rigorous mapping of the actual hotspots within the olive supply chain. In particular, a review of the literature shows that, in this sector, energy use associated with the extraction and refining stages is the predominant driver of impact; therefore, limiting the analysis to CC and abiotic depletion (fossil) is the most effective strategy for effectively targeting efficiency measures and changes in the energy mix (Fotia et al., 2021; Maffia et al., 2022; Ruiz-Carrasco et al., 2023). In addition, geographical context plays a crucial role. Since the industry operates primarily in the Mediterranean basin, an area characterized by severe water stress, effluent management and irrigation practices take on vital importance. The inclusion of the WF and aquatic ecotoxicity is therefore essential for assessing the impact of OMWW and the effectiveness of circularity strategies based on water reuse and treatment (Navarro et al., 2018; Sun et al., 2022). Furthermore, the assessment of eutrophication is fundamentally justified by the need to monitor the severe risks of nutrient overloading (nitrogen and phosphorus leaching) caused both by agricultural fertilizer runoff and the inappropriate disposal of nutrient-dense olive mill residues into natural receptors (Romero-Gámez et al., 2017). In summary, this subset of indicators allows for a direct link between operational actions (such as energy recovery from OP or the treatment of OMWW) and the mitigation of the most urgent environmental damage, while offering robust and recognized metrics to facilitate sustainability communication with stakeholders and support corporate certification processes.

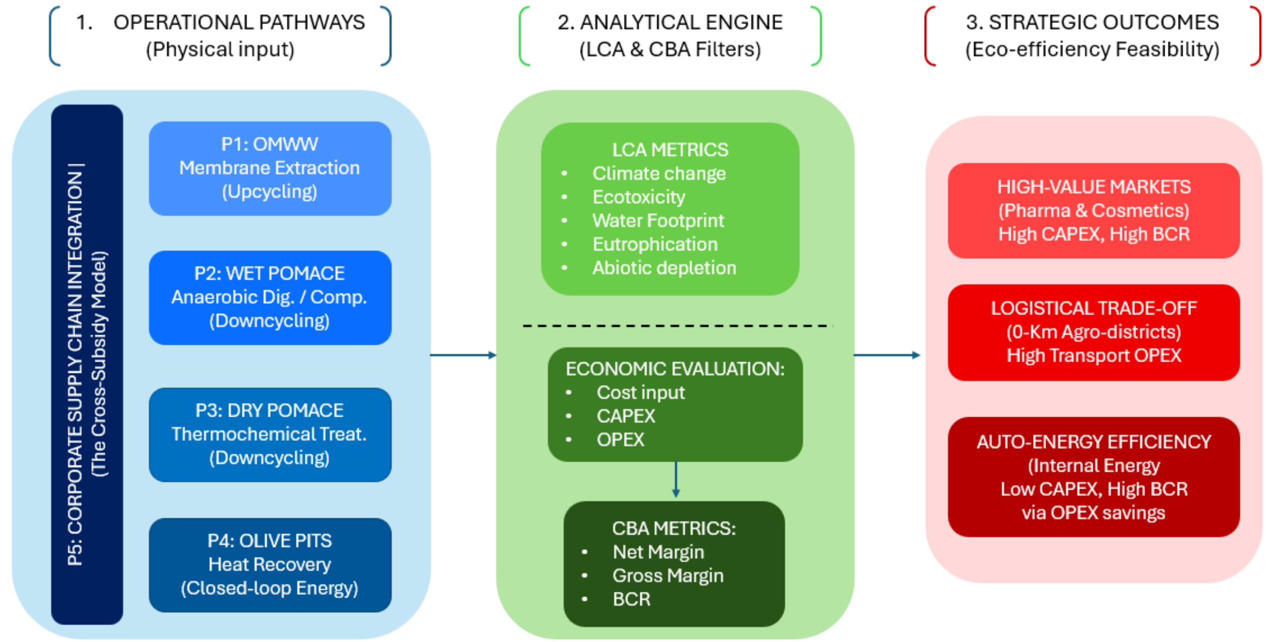

Figure 2 Block diagram illustrating the logical architecture and component integration of the LCT-DF Framework for olive oil SMEs.

To translate environmental benefits into industrial feasibility, the CBA component of the framework is based on parameters that highlight the real barriers to entry for SMEs. CAPEX is monitored to quantify the initial investment required by technologies, which is often prohibitive for small businesses. OPEX plays a central role in the framework; consequently, the inclusion of the BCR, Gross Margin and Net Margin is of decisive importance to evaluate these operational burdens. By condensing the relationship between positive and negative discounted cash flows over the entire project life cycle into a single index, the BCR allows for an unequivocal distinction between circular practices that generate value and those that, while environmentally sound, would lead the company to financial collapse if deprived of structural subsidies. Gross Margin, when used alongside the BCR, provides a picture of the ability of a single value-creation process (e.g., the sale of compost or biogas) to sustain itself independently in the market by covering its direct OPEX. In addition, the Net Margin concludes the economic assessment by considering fixed costs, capital depreciation, and opportunity costs. While the Gross Margin assesses operational sustainability, the Net Margin determines the overall profitability of the investment. This indicator is crucial for demonstrating the economic feasibility of specific CE approaches, thus providing empirical justification for the "cross-subsidy" strategy to offset the associated financial burdens.

Finally, the most innovative outcome of the LCT-DF framework pertains to the holistic, company-wide vision of system eco-efficiency (third stage). Based on the theoretical assumptions established through the literature review (see Chapter 2) and the empirical validation derived from the case study of the Sicilian oil mill (see Chapter 3) the third stage synthesizes the analytical results into three distinct strategic outcomes. First, it highlights targeting high-value markets (e.g., pharmaceuticals and cosmetics) for upcycled compounds, which, based on the analysis of circularity and ES pathways, represents the highest level of eco-efficiency; while this pathway yields a highly positive BCR, it remains constrained by significant CAPEX barriers for SMEs. Second, it promotes auto-energy efficiency through closed-loop biomass recovery (e.g., olive pits), which guarantees a high BCR via internal OPEX savings and low capital requirements. Third, it identifies a critical logistical and road transport of high-moisture matrices completely offset profit margins. This confirms that, for low-value-added pathways, circularity is exclusively sustainable within short-range, zero-kilometer agro-industrial districts. In contrast, the mechanical separation of olive stones for internal thermal consumption emerges as the most accessible and least risky strategy for SMEs. Crucially, the framework demonstrates that treating the waste and by-product management department as an isolated profit center frequently leads to negative financial assessments due to the aforementioned logistical burdens. To overcome this barrier, the strategic outcomes empirically validate the necessity of the corporate 'cross-subsidy' model (integrated within the initial operational pathways). By leveraging the robust profit margins generated by the core business (EVOO), the company can structurally absorb the operational losses incurred by circularity compliance. This systemic integration elevates the overall corporate BCR to a sustainable threshold, ensuring that environmental neutrality is achieved without compromising the true financial resilience of the SME.

The architecture of the proposed LCT-DF framework is well-supported by recent scientific literature. The focus on different circularity pathways for olive oil waste and by-products (such as wet OP, OMWW, and olive pits) is fully in line with studies highlighting their vast potential for upcycling and downcycling to produce bioenergy, agricultural fertilizers, and high-value-added compounds for green chemistry (Benalia et al., 2021; Bernardi et al., 2017; Falcone et al., 2022; Spina et al., 2024b). In fact, several authors confirm that the technological choices adopted for the management of biomass have a decisive influence not only on environmental profiles but also on the overall profitability of recovery systems (De Luca et al., 2023).

To maximize the effectiveness of the proposed framework and promote its widespread adoption by the olive oil companies, it is essential to outline certain operational guidelines. With a view to continuous improvement, the integrated LCA-CBA approach discussed so far can evolve into a broader LCSA framework. The integration of the social dimension (SLCA) alongside the environmental and economic dimensions would, in fact, allow for the evaluation of agronomic and technological interventions in their entirety, identifying solutions capable not only of minimizing impacts and maximizing profitability but also of generating social co-benefits for local communities (De Luca et al., 2023; Marques et al., 2025; Zutshi et al., 2016). However, given that olive oil production is dominated by SMEs, the development and adoption of simplified (SME-facing) tools is crucial. For these streamlined versions of LCA and CBA to be accessible yet scientifically valid, they must be continuously calibrated and compared with sector-specific reference standards, thereby ensuring the full reliability of estimates for small business owners (Ghisellini et al., 2023; Maffia et al., 2022). Finally, the implementation of this framework requires the strategic and ongoing use of the collected data. The synergistic use of the indicators in question must aim to build long-term datasets capable of monitoring performance trends throughout the entire supply chain. This traceability not only guides decision-makers toward targeted and low-risk investments but also becomes a fundamental competitive lever, providing transparent, objective, and accountable parameters for obtaining environmental certifications, proactively addressing the growing sustainability demands of premium markets (De Luca et al., 2023; Ghisellini et al., 2023; Spina et al., 2024b).

4.3.1 Operational roadmap for the corporate implementation of the LCA-DF framework

To translate the theoretical findings of the framework into a practical business intelligence tool for the olive oil supply chain, a five-step operational roadmap is proposed (figure 3). This roadmap guides company management from the initial mapping phase through to market positioning, consistently integrating environmental metrics (LCA) with budget constraints (CBA).

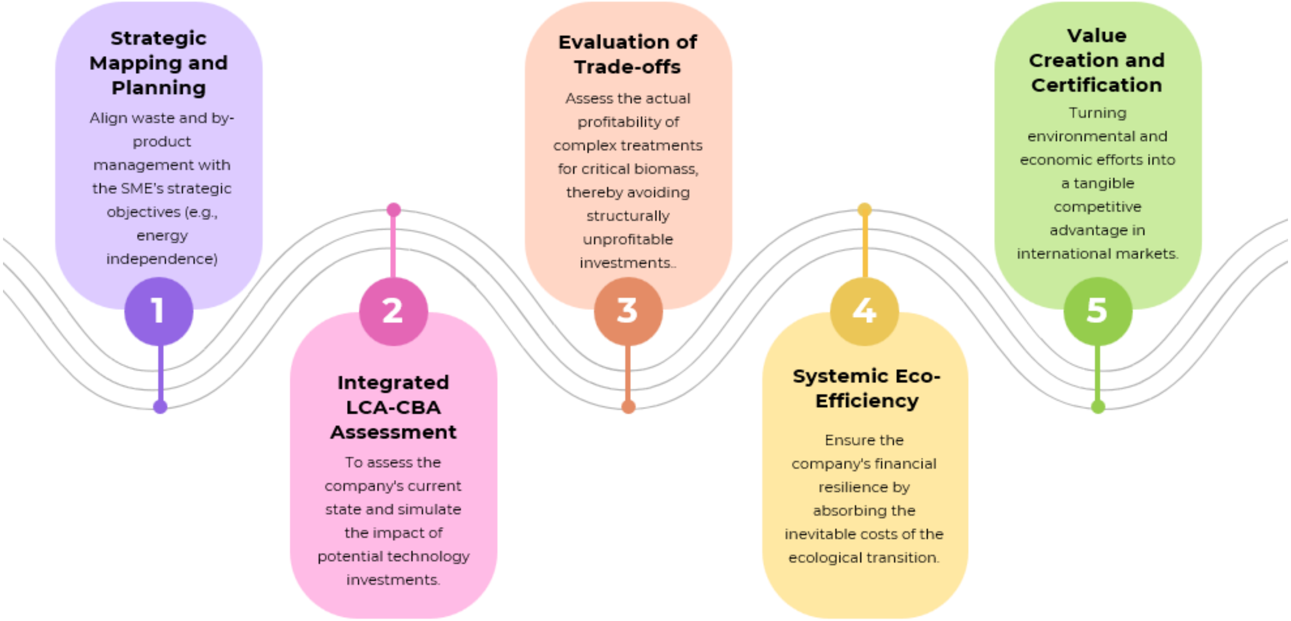

Figure 3: Five-step operational roadmap for the strategic implementation of the LCT-DF framework.

The initial phase (Step 1: Strategic Mapping and Planning) marks the transition from a purely reactive environmental approach (waste and by-products management) to a proactive and strategic one. The alignment of waste and by-products management with strategic company goals (e.g., energy independence or regulatory compliance) is based on a rigorous physical inventory of seasonal volumes and biochemical characteristics of the available materials (e.g., OP, OMWW, olive pits). Following the diagnostic phase conducted, the second step (Integrated LCA-CBA Assessment) is performed. The simultaneous application of the two methods allows for an ex-ante simulation of the impact of potential technological investments. Environmental hotspots (CC, ecotoxicity, WF, eutrofication, abiotic depletion) are systematically cross-referenced with the basic financial determinants, namely CAPEX, OPEX), and expected Gross Margin, Net Margin and BCR. The third step (Evaluation of Trade-Offs) permits to guide managers in avoiding structurally unprofitable investments, making them aware of the best systematic method to evaluate competing priorities. To identify potential trade-offs, the framework requires companies to cross-reference environmental performance (LCA metrics) with economic viability (CBA indicators). A valid trade-off typically arises when a solution that offers significant environmental benefits does not, at the same time, entail significant financial barriers, such as prohibitive initial investment costs (CAPEX) or unsustainable operating costs (OPEX). By establishing minimum acceptable thresholds for both environmental compliance and financial return (e.g., BCR > 1), managers can objectively filter out pathways that are ecologically optimal but financially detrimental. Crucially, the precise nature of these trade-offs is highly context-dependent, varying according to the specific technological, geographical, and dimensional boundaries of each SME; therefore, they cannot be generalized across the entire sector. To illustrate how this evaluation mechanism operates in practice, two representative examples from SMEs are presented based on the empirical application of the Sicilian case study (see Chapter 3). The first illustrates a logistical trade-off associated with low-value, high-moisture OP. While its recovery generates environmental credits, the framework's evaluation shows that transporting such bulky materials over long distances creates a "logistical paradox", where transport OPEX entirely negates potential profits. The second example demonstrates a technological trade-off concerning high-value upcycling processes (e.g., extracting polyphenols from OMWW). Although this pathway guarantees absolute eco-efficiency, the required CAPEX for advanced membrane systems is often prohibitive for a single SME. These specific instances demonstrate how the framework forces companies to confront real-world constraints, guiding them toward context-specific feasible alternatives, such as zero-kilometer agro-districts or consortium-based investments.

Then, the roadmap introduces a shift in managerial accounting costs and revenues in olive oil supply chain including the treatment and valorisation of olive oil waste and by-products. In the "Systemic Eco-efficiency" phase (Step 4), waste and by-products management is no longer treated as a separate and often unprofitable activity. Instead, financial results are considered at the supply chain level. The company uses a "cross-subsidy" approach, where profits from its core business (e.g., high-quality EVOO) are used to cover the losses linked to environmental management of waste. This internal offsetting may elevate the company's overall BCR to a level of full and lasting financial sustainability. Finally, the fifth step, "Value Creation and Certification" coincides with the commercial capitalization of the effort undertaken. The data provided by the LCA-CBA integration becomes a verifiable and objective communication tool. The SME can thus use these metrics to obtain eco-certifications (e.g., Environmental Product Declaration, Carbon Footprint, etc.), access subsidized green finance channels and establish sustainable positioning in the eyes of stakeholders and within highly competitive, premium international markets (European Commission, 2014).

4.3.2 Prospects for the empirical validation of the framework

The validation and calibration process of the LCT-DF framework according to the olive oil company context is structured along three strategic, sequential, and complementary pathways:

1. Direct interviews with supply chain actors – the first methodological step should rely on a participatory (bottom-up) approach, actively involving not only olive mill owners but also cooperative directors, technology providers, and local policymakers. These in-depth qualitative investigations are essential to validate theoretical assumptions and provide a qualitative ground truth for model calibration. Through interviews, it will be possible to map hidden socio-technical barriers, such as cultural resistance to innovation, the actual perception of business risk, information asymmetries, the lack of internal technical skills, and difficulties in accessing bank credit. All these socio-technical factors can determine the success or failure of a CE strategy, despite eluding traditional LCA and CBA metrics (McGonigle et al., 2020).
2. Strategic positioning analysis (SWOT analysis) – SWOT is widely recognized as a strategic planning tool for assessing internal and external environments and guiding operational decisions in agrifood contexts (Helms and Nixon, 2010; Souissi et al., 2024). Subsequently, the quantitative evidence extrapolated from the framework and the qualitative insights gathered through the interviews must converge into a structured SWOT matrix. The application of this management tool will allow researchers to 'stress-test' the circularity trajectories suggested by the model by placing them within the real competitive arena. Future validations must systematically weigh factors endogenous to the company, such as Strengths (e.g., financial solidity of the core business, availability of 'zero-

kilometer' biomass) and Weaknesses (e.g., seasonality of flows, shortage of storage space), crossing them with exogenous variables. Among the latter, Opportunities (e.g., access to European cohesion funds, subsidies for the ecological transition, growing demand for eco-certified products) and external Threats (e.g., volatility of energy prices, stricter regulations on the agricultural spreading of effluents), that must be carefully monitored.

3. Practical support for implementation choices (Implementation of the decision-making process) – the culmination of the validation process will consist of testing the framework's robustness within actual corporate decision-making processes. The goal is to empirically demonstrate how the synthesis of the economic and environmental indicators, illustrated in this work, can evolve into a decision support system to guide managerial decision-making. This tool must enable SMEs to run dynamic simulations, calculating in real time how the economic performance and environmental impacts vary in response to changing operational conditions (e.g., an increase in diesel costs or the introduction of a carbon tax). Only by demonstrating the framework's capacity to minimize the uncertainty of circular investments and to effectively guide operational choices will it be possible to certify its definitive validity.

This validation process allows providing practical support for implementation choices by testing the framework's robustness within actual corporate decision-making. To satisfy the requirement for an empirical proof-of-concept, the framework's simulation capacity can be directly demonstrated by modelling how it processes a severe operational shock, such as a concurrent 50% spike in diesel prices and a localized carbon tax and translates it into clear technical directives. For a mill manager, the framework dynamically evaluates the trade-offs of adopting a 2-P extraction system; while this setup is environmentally superior due to its minimal water footprint, it yields a much wetter, heavier OP that becomes a major logistical liability during a fuel crisis. The framework resolves this bottleneck by simulating an on-site dehydration loop powered by recovered heat from burning separated olive pits, eliminating excess water weight before the trucks depart, effectively neutralizing the financial impact of the diesel price shock on outbound logistics. Moving downstream, the tool evaluates parallel volume-reduction strategies for secondary processing facilities handling exhausted OP, testing the viability of further drying or automated pelletisation to optimize volumetric load and minimize truck trips. Crucially, the framework demonstrates that the financial viability of these engineering solutions is strictly bound to the spatial proximity of downstream processing plants, proving that short-range geographic clustering is a mandatory requirement to absorb fuel shocks. However, every operational choice, whether investing in a 2-P separator, an on-site dryer, a pelletizing line, or entering a partnership with a closer downstream processor, is dynamically weighed within the integrated eco-efficiency matrix. The framework calculates the CAPEX and net energy inputs of these choices against the achieved carbon reductions and primary product cross-subsidization margins. This holistic assessment allows the manager to understand which combination of strategies provides the highest systemic eco-efficiency, ensuring that every decision is tailored to the unique financial boundaries of the SMEs and strictly aligned with its long-term ecological transition goals.

Ultimately, this iterative research process will catalyze a paradigm shift for the olive oil industry. It moves beyond simply measuring environmental damage to providing a true predictive decision-making tool, capable of guiding agricultural SMEs toward strong, measurable, and financially unassailable sustainability.

4.4 Conclusions

This study was driven by the need to address a pivotal question for the ecological transition of the olive oil industries. Particularly, the research focused on proposing an operational framework capable of identifying the most appropriate valorisation technologies for waste and by-products while assessing their eco-efficiency through an LCT perspective. This research has provided a multidimensional tool capable of guiding decision-makers in identifying the most eco-efficient approach, overcoming the rigidity of purely mathematical models that often appear inaccessible to olive oil operators.

The LCT-DF framework is built upon two complementary pillars previously conducted: i) a rigorous exploratory literature review (see Chapter 2), and ii) an empirical analysis of a Sicilian case study (see Chapter 3). Subsequently, the framework is architected around a three-stage sequential process: it begins by defining the "Operational Pathways" for defining the main pathways for the treatment and recovery of waste and by-products, proceeds through a central "Analytical Engine" that cross-references environmental impacts (LCA) with financial constraints (CBA), and culminates in the definition of "Strategic Outcomes" to evaluate technological and logistical trade-offs. To ensure the practical implementation of this theoretical model within SMEs, the study further introduces a five-step operational roadmap. This managerial tool guides companies from the initial "Strategic Mapping and Planning" of their waste and by-products with the SME strategical objectives, through the "Integrated LCA-CBA Assessment" and subsequent "Evaluation of Trade-Offs". Ultimately, it drives the business towards "Systemic Eco-efficiency", via the internal cross-subsidy accounting shift, and culminates in "Value Creation and Certification", transforming environmental compliance into a tangible competitive advantage on the market.

The framework takes the form of a node-based decision-making infrastructure, where each technological option is filtered through parameters of biochemical, logistical, and economic feasibility. This modular structure allows companies to actively select the value-creation pattern that best suits their specific production and regional context, rather than passively accepting innovations. In this sense, the framework is not a simple mathematical formula, but a decision support system that translates the complexity of scientific data into strategic choices, drastically reducing the uncertainty associated with green investments. The research findings challenged the notion that circularity is an absolute virtue, demonstrating instead that eco-efficiency is a relative property, strictly dependent on the alignment between the waste and by-products stream and the chosen technology. By bridging life-cycle theory with industrial reality, this research provides SMEs with the clarity needed to turn environmental burdens into competitive advantages, ensuring a financially sound ecological transition, Despite the robustness of the proposed framework, certain limitations must be acknowledged, opening key directions for further future research activities. First, it currently lacks a social perspective that should be included in order to obtain a comprehensive assessment of the sustainability performance of the circular strategies potentially implementable among the supply chain. Secondly, the theoretical and empirical architecture of the framework requires rigorous, large-scale validation to ensure its full applicability and adaptability across different operational contexts. As conceptualized in this study, future research should follow the proposed three-stage validation process. This involves conducting face-to-face interviews with supply chain stakeholders to map hidden socio-technical barriers, applying a SWOT analysis to stress-test the strategic positioning of circular pathways in the competitive arena, and, finally, integrating the framework into actual business decision-making processes through dynamic simulations.

Chapter 5 Conclusions

This Ph.D thesis work developed around the central objective of the research project related to the dentification and application of tools for improving process and product eco-efficiency in a CE perspective in the olive oil supply chain. This mission was not conceived as a mere technical analysis, but rather as an evolving pathway aimed at redefining the concept of sustainability for olive oil SMEs, moving toward a research approach that combines scientific rigor with industrial applicability. The choice to adopt this specific approach stems from the awareness that, despite the wide range of waste and by-product valorisation technologies highlighted in literature, the olive oil industries still face a significant 'implementation gap', mainly due to the lack of agile and multidimensional decision-support tools. The research path was therefore structured into three logical steps (Chapters), reflecting this evolution in perspective.

The Chapter 2 focused on defining the theoretical baseline and identify the main methodological gaps in managing olive oil extraction residues, the first phase of this research investigated two main research questions: "What is the current state of treatment technologies for olive oil production by-products and wastes aimed at their valorisation?" and "How many of these technologies are associated with the concept of eco-efficiency evaluation in the literature?". The study performed a combined bibliometric and systematic literature review which revealed a final validated sample of 239 articles regarding treatment technologies and 65 articles specifically addressing their link to eco-efficiency. The analysis revealed a growing scientific interest in applying CE principles to the olive oil supply chain. By mapping the technological landscape, the study highlighted that while liquid effluents (OMWW) receive the most attention due to their acute phytotoxicity, a wide array of viable technologies currently exists. The preponderance of validated treatments, ranging from conventional biological processes (e.g., anaerobic digestion and composting) to advanced physical-chemical (membrane filtration) and thermal processes, suggests that the sector possesses a relative technological maturity to valorize its waste and by-products through both energy recovery and the extraction of high-value bioactive compounds. However, when analyzing the relationship between these circular technologies and ES, a critical conceptual gap emerged. The review demonstrated that the concept of "eco-efficiency" is frequently addressed only from a theoretical perspective. Many studies assume that adopting a circular practice automatically guarantees sustainability, without formally measuring it. Among the studies that apply an integrated quantitative approach, LCA emerged as the dominant method. Furthermore, the analysis highlighted that current literature predominantly focuses on the ecological dimension of eco-efficiency, largely neglecting the economic feasibility of these treatments. The study also warned against the risk of the "rebound effect" (Jevons paradox), emphasizing that isolated technological efficiency does not guarantee an absolute reduction in environmental impact if not managed systemically. Ultimately, while the analysis mapped a broad portfolio of theoretical circular solutions, it revealed a profound lack of standardized, multidimensional evaluation frameworks. Since the literature mostly evaluates these technologies in isolation or without robust economic grounding, it became strictly necessary to test these circular pathways empirically in a real-world, SME-driven industrial context to measure their actual economic and environmental viability.

Building upon the theoretical gaps identified in the first step, the Chapter 3 addressed the pressing need to practically measure circularity practices in the olive oil supply chain. The guiding research question was: "How can the environmental and economic performances of circular pathways be jointly measured in a real-world olive oil SME to assess actual eco-efficiency?". To answer this question, the study developed and applied an LCA and CBA model to a vertically integrated olive oil supply chain located in Sicily, Italy. The analysis evaluated the entire system, encompassing agricultural cultivation, milling operations, and the external treatment and valorisation of waste and by-products. The LCA results confirmed that the agricultural phase represents the primary ecological hotspot. Conversely, the valorisation of waste and by-products, specifically

energy recovery through anaerobic digestion and the internal combustion of olive pits, generates crucial environmental credits capable of significantly mitigating the supply chain's overall footprint.
However, the parallel economic assessment (implement through the CBA) uncovered a critical "logistical paradox". The data demonstrated that, while ecologically virtuous, the isolated valorisation of wet biomass operates at a severe financial deficit, recording a highly critical BCR (0.27). This failure is primarily driven by the prohibitive operational expenses (OPEX) associated with transporting heavy and high-moisture OP over long distances. This empirical evidence challenged the common literature assumption that circularity automatically guarantees profitability, highlighting a profound structural trade-off instead.
To resolve this dichotomy, the study advanced the concept of "systemic eco-efficiency". The research demonstrated that the true economic sustainability of these circular models cannot be achieved if the waste recovery process is evaluated as an isolated profit center. Instead, sustainability emerges through holistic corporate integration via a "cross-subsidy" mechanism. The robust profit margins generated by the core business, the sale of EVOO (BCR 2.18), provide the necessary liquidity to finance and absorb the operational losses of the circular activities. In this integrated vision, waste and by-products management is strategically repositioned as a necessary investment for environmental compliance rather than a standalone revenue stream.
Ultimately, while this empirical application provided robust multidimensional metrics, it also highlighted a clear operational barrier. Indeed, SMEs' managers need accessible tools to navigate these complex logistical and financial trade-offs before investing. This realization directly sets the stage for the development of a dedicated, user-friendly decision-support framework.

In this regard, the Chapter 4 overcomes the difficulties and the decision-making paralysis identified in the previous stages. The guiding research question was: "How can complex multidimensional metrics be translated into an accessible, strategic decision-support tool for SME managers?". The study developed the LCT-DF framework, which integrates the results from theoretical technological mapping (Chapter 2) and the results from the case study analysis (Chapter 3), categorizing physical waste and by-products streams into specific operational patterns and filtering them through targeted environmental (LCA) and economic (CBA) metrics. By addressing this central query, from a methodological point of view, the study challenges the conventional reliance on highly complex, data-intensive tools. While traditional literature often pairs LCA and LCC to measure sustainability, this research demonstrated that such approaches are not well-suited for SMEs. This multidimensional approach proved to be the optimal solution, maintaining the strict ISO-compliant rigor required for environmental quantification while providing a streamlined, pragmatic tool (through economic metrics) that perfectly aligns with the immediate financial decision-making needs of olive oil industries' managers. Specifically, the architecture of the LCT-DF framework serves as a methodological bridge between scientific rigor and the operational reality of SMEs, structured as a three-stage sequential process. The initial phase defines the "Operational Pathways", transforming the multiplicity of physical matrices into distinct value streams. This mapping feeds an "Analytical Engine" that integrates cash flows (CBA) with impact profiles (LCA), enabling the identification of the "Strategic Outcomes" necessary to balance ecological sustainability with financial feasibility. To translate this theoretical construct into business practice, the research formalized an operational roadmap structured in five preparatory steps. The pathway begins with "Strategic Mapping and Planning", marking the necessity to includes waste and by-product treatment and valorisation into the SMEs strategic objectives. Subsequently, the "Integrated LCA-CBA" Assessment enables the ex-ante simulation of the environmental and financial impacts of potential technological investments. This evidence converges in the third step, the "Evaluation of Trade-Offs", which provides management with an objective filter to discard options that are ecologically valid but structurally unsustainable from a cost perspective (CAPEX/OPEX). The overcoming of these barriers materializes in the fourth step, "Systemic Eco-efficiency", where the 'cross-subsidy' accounting paradigm is applied to absorb the inherent financial losses of waste and by-products management using the profit margins of the EVOO. Finally, the model culminates with "Value Creation and Certification". In this phase, the metrics generated by the framework are leveraged to obtain eco-certifications, definitively transforming environmental compliance into a verifiable and enduring competitive asset in international markets.

Finally, by delivering a concrete five-step operational roadmap for the LCT-DF framework implementation, this Ph.D thesis provides a highly practical managerial contribution. It equips SMEs' managers with the necessary business intelligence to navigate regulatory complexities, evaluate trade-offs, and justify green investments. This outcome successfully concludes the research project's mission, providing a tangible methodology to turn environmental compliance into a resilient, certifiable, competitive advantage on the international market.

5.1 Limitations and future research directions

While this Ph.D thesis focused on exploring how circularity and eco-efficiency are implemented and assessed at the company level within the olive oil supply chain, and on proposing a decision-support tool, it has some limitations due to the methodological choices. During the initial phase of the research, several methodological challenges emerged. The main difficulty concerned the definition of effective search queries and eligibility criteria capable of accurately capturing the intersection between eco-efficiency and the olive oil supply chain, given the highly fragmented terminology used in the existing literature. In this context, the search criteria adopted for the systematic and bibliometric literature review may have led to the exclusion of potentially relevant contributions, particularly those from grey literature. Therefore, it cannot be ruled out that the concept of eco-efficiency in this research might have been framed or interpreted differently if such sources had been included. Furthermore, the structuring of bibliometric indicators and the interpretation of network analyses required careful contextualization in order to properly identify prevailing technological patterns without oversimplifying the complexity of the sector. Secondly, the empirical analysis was exploratory and based on a single, vertically integrated case study located in Sicily. While this provided interesting and highly representative insights into how to implement and measure circularity in Mediterranean SMEs, successfully integrating both environmental and economic aspects, it inevitably limits statistical generalizability. Enlarging the sample or proposing comparative studies in other European countries, as well as with larger industrial-scale facilities, would be crucial to improve the generalization of the outcomes. Furthermore, obtaining primary economic data directly in the field proved particularly difficult, as such data is rarely systematically recorded by SMEs. This required the integration of secondary data from dedicated databases and scientific literature to properly model the by-product treatment phase. Methodologically, the system boundaries were also deliberately restricted to the agricultural, milling and valorisation processes, thus neglecting downstream phases (such as bottling and distribution) and specific inputs (e.g., cleaning agents) that could influence the overall carbon and toxicity footprints of the system. Finally, the LCT-DF framework involved the complex challenge of synthesizing interdisciplinary indicators. Translating these algorithms into an agile, semi-quantitative tool required a delicate balance. Identifying and selecting specific LCA and CBA metrics that were simultaneously scientifically rigorous and immediately comprehensible to non-expert decision-makers was a difficult process, necessitating the inevitable simplification of certain broader systemic variables. Furthermore, the current framework is strictly bi-dimensional, focusing entirely on environmental and economic performance, thus lacking the social dimension. In this regard, future studies should incorporate in the proposed framework the assessment of the social sustainability, using, for example, the Social Life Cycle Assessment (S-LCA) (ISO 14075:2024). To preliminarily bridge this conceptual gap, a qualitative analysis reveals that the proposed agro-industrial districts deeply influence the regional socio-economic landscape across three main axes: local employment, occupational health, and community dynamics. The establishment of a localized circular network acts as a catalyst for sustainable regional employment, directly addressing seasonal vulnerability in the agricultural sector. Traditional olive milling is inherently intermittent, leading to precarious, short-term labor contracts that accelerate rural depopulation (Khdair and Abu-Rumman, 2020). Thanks to the introduction of continuous byproduct recovery systems (Falcone et al., 2019), the business ecosystem generates steady year-round demand for a wide range of professionals. These positions, ranging from logistics coordinators to specialized plant operators, help to strengthen professional skills within the local community. Consequently, the economic margins secured through cross-subsidization between products translate directly into social value, thereby encouraging the younger generations to remain in marginalized rural areas. Simultaneously, the industrial operations required to process high-volume biomasses introduce specific occupational health and safety dynamics that must be managed. The handling and storage of wet OP and OMWW involve biological risks linked to malodours, potential dermal and inhalation exposure to volatile compounds, as well as risk of contact with phytotoxic components, particularly during concentrated processing or storage in ponds or impoundments (Vuksinic et al., 2024). Mitigating these risks requires the mandatory adoption of automated handling systems, localized dust extraction units, and strict safety protocols. By internalizing these protective measures, agri-food SMEs ensure that the ecological transition does not result in the externalization of physical risks onto the workforce, thereby safeguarding the human capital that drives the circular system. Finally, the shift toward short-range agro-industrial districts deeply influences broader community dynamics and local social acceptance. Historically, the traditional disposal of olive mill effluents has been a source of territorial conflict, causing severe environmental nuisances such as seasonal odors, soil degradation, and the potential contamination of local water basins, which damages the community's quality of life (Halalsheh et al., 2021). The elimination of illegal or poorly managed waste spreading reduces environmental friction and rebuilds trust between agricultural SMEs and local citizens. Furthermore, by anchoring the entire value chain within a restricted geographic radius, the district fosters a shared culture of industrial symbiosis. This collaborative framework strengthens territorial identity and social capital, transforming a traditional, fragmented manufacturing process into a collective mechanism for rural revitalization and shared ecological governance (Stempfle et al., 2021).

Additionally, although a dynamic proof-of-concept simulation has been introduced in Chapter 4 to demonstrate the framework's operational responsiveness, the holistic validation phase currently remains theoretical. A crucial limitation is that this structured validation must still be actively applied in real-world corporate settings and, where necessary, implemented and refined based on direct managerial feedback to fully prove the framework's practical validity. Thus, future research should be oriented towards the validation and application of the proposed LCT-DF framework. Particularly, it is prior to explicitly verifying its adaptability by scaling up empirical validations across different Mediterranean countries and within larger cooperative facilities, ultimately aiming to define a standardized, overall eco-efficiency score for the olive oil supply chain. The ultimate trajectory involves the digitalization of the framework into an interactive, user-friendly, software-based decision support system, to allow SMEs to run dynamic simulations, definitively closing the gap between high-level European sustainability goals and daily agrifood circular business practices.

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