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Circularity and sustainability for a new model of agro-food supply chains: application of Life Cycle methodologies to closed-loop scenarios in the olive-oil sector

PH.D. THESIS

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ABSTRACT

The Circular Economy (CE) advocates a complete rethinking of the production model, aimed at reusing materials and products as inputs for new production while minimizing waste. This model offers greater opportunities to maximize the value of available resources through advanced recovery and upcycling processes. In this regard, reuse, regeneration and recycling of materials have attracted strong interest in the scientific community in recent years.

There is growing interest in academia in the possibility of integrating life cycle analysis and CE indicators, combining the potential of the two approaches in driving the ecological transition. The simultaneous assessment of circularity and sustainability is still uncommon in the scientific literature (Stillitano et al., 2021), probably due to the lack of computational approaches that have yet to be validated by scholars. Based on these considerations, a methodological proposal is proposed in this study based on life cycle (LC) methodologies - Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) - and circularity performance indicators, which is applied to assess closed-loop pathways, providing comprehensive results on the economic and environmental impacts generated by one of the most important Mediterranean agribusinesses: olive oil production.

In the Mediterranean basin, the olive oil sector is an essential socioeconomic and cultural pillar, being part of the healthy Mediterranean diet, with great interest also linked to the landscape and territorial value. It is also a sector considered to be among those producing a large amount of waste and by-products, which in the European Union is estimated at 21.4 million tons/year, with 9.6 million tons/year coming from olive mills and 11.8 million tons from olive tree pruning (Berbel and Posadillo, 2018). Specifically, the main outputs are generated from olive pruning (wood, leaves, and branches, defined as waste) and olive oil processing (olive pomace and olive mill wastewater, defined as by-products) (Roselló-Soto et al., 2015).

Overall, olive oil production can be considered a resource-intensive sector with high environmental impacts related to water and soil pollution and carbon dioxide emissions. As with most tree crops, environmental impacts arise mainly from the agricultural phase (pesticide use, fertilizer, water and waste production) and the oil production phase (by-products, water and energy use) (Banias et al., 2017).

By validating sustainability and circularity using real case studies as proposed in this paper, can be highlighted the performance of the entire life cycle to provide the necessary solutions for the establishment of the circular model.

Given the economic, social and environmental dimensions of olive cultivation, a paradigm shift toward the adoption of circular practices could be a path toward sustainable development and ensure economic, environmental and social sustainability, as well as the conservation of biodiversity and productivity of agroecosystems and help ensure food security over the long term.

Currently in the field of sustainability, major innovative studies are attempting to solve the concerns related to CE.

Nevertheless, the innovativeness is contained in the same circularity approach that evokes towards a socio-technical transition path through the proposal of a new inspirational framework for regenerative industrial design (Borrello et al., 2020).

Considering that CE is a young concept (Blomsma and Brennan, 2017), most studies in the literature focus on methodological and conceptual approaches, while there are few application studies.

To the best of the author's knowledge in the scientific literature, this study can represent the first integrated assessment using life cycle and circularity metrics for the transition to EC in the olive oil sector.

This thesis work is divided into six chapters, some of which consist of articles published in indexed scientific journals.

RIASSUNTO

L’Economia Circolare (EC) sostiene un ripensamento completo del modello produttivo, finalizzato al riutilizzo di materiali e prodotti come input per una nuova produzione, riducendo al minimo i rifiuti. Da diversi anni, infatti, gli studiosi si stanno concentrando su un nuovo modello economico rigenerativo basato sul concetto di EC. Questo modello offre maggiori opportunità di massimizzare il valore delle risorse disponibili attraverso processi avanzati di recupero e upcycling. Nel mondo accademico sta crescendo l’interesse per la possibilità di integrare l’analisi del ciclo di vita e gli indicatori dell'economia circolare, combinando il potenziale dei due approcci nel guidare la transizione ecologica. La valutazione simultanea di circolarità e sostenibilità è ancora

poco diffusa nella letteratura scientifica (Stillitano et al., 2021), probabilmente a causa della mancanza di approcci computazionali che devono ancora essere validati dagli studiosi.

Sulla base di queste considerazioni, in questo studio viene proposta una metodologica basata sugli approcci del ciclo di vita (LC) - Life Cycle Costing (LCC) e Life Cycle Assessment (LCA) - e sugli indicatori di performance della circolarità, che viene applicata per valutare i percorsi a ciclo chiuso, fornendo risultati completi sugli impatti economici e ambientali generati da uno dei più importanti comparti agroalimentari mediterranei: la produzione di olio d'oliva.

Nel bacino del Mediterraneo infatti, il settore dell'olio d'oliva è un pilastro socioeconomico e culturale essenziale, essendo parte della sana dieta mediterranea con un grande interesse legato anche al valore paesaggistico e territoriale. È anche un settore considerato tra quelli che producono una grande quantità di rifiuti e sottoprodotti, che nell'Unione Europea è stimata in 21,4 milioni di tonnellate/anno, con 9,6 milioni di tonnellate/anno provenienti dai frantoi e 11,8 milioni di tonnellate dalla potatura degli olivi (Berbel e Posadillo, 2018). In particolare, i principali output sono generati dalla potatura degli olivi (legno, foglie e rami, definiti come rifiuti) e dalla lavorazione dell'olio d'oliva (sansa e acque reflue dei frantoi, definiti come sottoprodotti) (Roselló-Soto et al., 2015). Nel complesso, la produzione di olio d'oliva può essere considerata un settore ad alta intensità di risorse con un elevato impatto ambientale legato all'inquinamento delle acque e del suolo e alle emissioni di anidride carbonica.

Come per la maggior parte delle colture arboree, gli impatti ambientali derivano principalmente dalla fase agricola (uso di pesticidi, fertilizzanti, produzione di acqua e rifiuti) e dalla fase di produzione dell'olio (sottoprodotti, uso di acqua ed energia) (Banias et al., 2017).

Convalidando la sostenibilità e la circolarità utilizzando reali casi studio, come proposto nel presente lavoro, si possono evidenziare le performance dell'intero ciclo di vita della produzione di olio d'oliva, al fine di fornire le soluzioni necessarie per l'introduzione del modello circolare. Considerando le dimensioni economiche, sociali e ambientali dell'olivicoltura, un cambio di paradigma verso l'adozione di pratiche circolari potrebbe essere un percorso verso lo sviluppo sostenibile e garantire la sostenibilità economica, ambientale e sociale, nonché la conservazione della biodiversità e della produttività degli agroecosistemi e contribuire a garantire la sicurezza alimentare nel lungo periodo.

Attualmente, sono innumerevoli gli studi innovativi nel campo della sostenibilità che utilizzano un approccio di EC.

Tuttavia, l'innovatività è contenuta nello stesso approccio alla circolarità che evoca un percorso di transizione socio-tecnica attraverso la proposta di un nuovo quadro ispiratore per il design industriale rigenerativo (Borrello et al., 2020).

Considerando che il concetto di EC è piuttosto recente (Blomsma e Brennan, 2017), la maggior parte degli studi in letteratura si concentra sugli approcci metodologici e concettuali, mentre ci sono pochi studi applicativi. Dalle ricerche condotte emerge che questo è il primo studio in cui si presenta una valutazione integrata che utilizza metriche del ciclo di vita e della circolarità per la transizione alla EC nel settore dell'olio d'oliva.

Questo lavoro di tesi è suddiviso in sei capitoli, alcuni dei quali sono costituiti da articoli pubblicati su riviste scientifiche indicizzate.

KEYWORDS

Circular Economy, Environmental and economic impact, Sustainability, Life cycle methodologies, Agri-food sector, Olive-oil supply chain.

1. INTRODUCTION

The current global context of resource scarcity, global climate change, environmental degradation and increased demand for food affects all productive sectors, including agriculture. Considering that more than one-third of the world's land area is devoted to food production through crops and livestock, the issue is far-reaching. Unlike in the past, today the emergency condition does not only affect the farm but is immediately perceived by the consumer, shifting the problem from the farm to the community.

Moreover, recent events in the world scenario, such as pandemics and wars, have generated geopolitical and energy, techno-productive and financial instability.

These problems are so amplified that even the concept of globalization is being rethought. In this context, the agribusiness sector, which has always been resilient precisely because of its inherent characteristics, to date is particularly in crisis due to the rising prices of key agricultural inputs (fertilizers, seeds, fuels).

In the face of such alarming and tangible signs, the search for a new economic model becomes strategic not only to improve the competitiveness of enterprises, as it might have been until a few decades ago but to foster the existence of enterprises themselves and continue producing goods and services.

For several years, scholars have been focusing on a new regenerative economic model based on the concept of Circular Economy (CE). The CE supports a complete rethinking of the production model, aimed at reusing materials and products as inputs for new production while minimizing waste. Such a model offers greater opportunities to maximize the value of available resources through advanced recovery and upcycling processes. In the emerging context presented, it only accelerates the transition already underway to the CE, placing great emphasis among entrepreneurs on adopting strategies that lead back to this new model.

At the same time, the adoption of circular practices even in the agribusiness sector cannot be separated from the concept of sustainable and low-impact production, both because of the effects on climate change and because of the deep integration and dependence between the various ecosystems and production stages.

In the Mediterranean basin, the olive oil sector constitutes an essential socioeconomic and cultural pillar, being part of the healthy Mediterranean diet with a great interest also related to landscape and territorial value. It is also a sector considered to be among those producing a large amount of waste and by-products, which in the European Union is estimated at 21.4 million tons/year, with 9.6 million tons/year coming from olive mills and 11.8 million tons from olive tree pruning (Berbel and Posadillo, 2018). Specifically, the main outputs are generated from olive tree pruning (wood, leaves, and branches, defined as waste) and olive oil processing (olive pomace and olive mill wastewater, defined as by-products) (Roselló-Soto et al., 2015). Overall, olive oil production can be considered a resource-intensive sector with high environmental impacts related to water and soil pollution and carbon dioxide emissions. As with most tree crops, environmental impacts arise mainly from the agricultural phase (use of pesticides, fertilizers, water and waste production) and the oil production phase (by-products, water and energy use) (Banias et al., 2017). The amounts of water and energy used as inputs and the generation of wastewater and by-products depend on the type of plant cultivation (secular orchard, intensive and super intensive systems) and the technology used for extraction (traditional squeezing system, two-phase or three-phase continuous centrifugal system, and olive pitting system).

To validate closed-loop strategies a reliable metric is needed by measuring sustainability performances together with the degree of circularity. Evaluating CE strategies should require a systemic and synergistic approach by considering the agri-food supply chain as a whole, especially to not incur the risk of making effective only one stage or only single portions, while neglecting the others (Niero et al., 2017; Colley et al., 2020).

To satisfy these purposes, sustainability assessment methods, and among them, life cycle (LC) approaches, are particularly appreciated as a robust, scientific and useful tool not only to measure, but also to validate CE hypotheses, to help the feasibility of its implementation by obtaining feedback for improvements, and finally to communicate innovation strategies (Peña et al., 2021). All LC methodologies, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA), are gaining increasing acceptance in assessing different agri-food systems by measuring environmental, economic and social impacts. In particular, LCA is widely considered the tool “par excellence” when it comes to assessing the environmental impacts of circular-based products or systems (Elia et al., 2017). In addition to the specificity of the results, LCA is particularly valued for its flexibility, mainly because it allows it to be incorporated into many other metrics, demonstrating feasibility and usefulness for EC purposes. In these terms, the use of an LC framework, which can potentially capture all dimensions of sustainability, can be adapted to assess CE strategies in an operational and comprehensive way, moving from the typically “cradle-to-grave” to the “cradle-to-cradle” circular view.

However, the simultaneous assessment of circularity and sustainability is still uncommon in the scientific literature (Stillitano et al., 2021), probably due to the lack of computational approaches that have yet to be validated by scholars.

Based on these considerations, this study proposes and applies a methodological proposal based on LCC and LCA methodologies and circularity performance indicators to evaluate closed-loop pathways, providing comprehensive results on the economic and environmental impacts generated by oil systems.

The paper is divided into six chapters as subsequently explained.

Chapter 1 aims to provide the reader with an overview of the CE. In particular, starting from the limitations of the linear economy, the conceptual transition to the CE is discussed, explaining its origins, principles, definitions and various levels of circularity.

Chapter 2 consists of a scientific paper, which the writer co-authored, providing a systematic and critical review of the state of the art of life-cycle applications from a CE perspective. In particular, the study provides insight into how researchers adapt life cycle approaches to measuring empirical circular pathways of agri-food systems throughout their lifetime.

Chapter 3 is made up of a scientific paper that the writer co-authored, in which the LC methodologies, i.e., Life Cycle Assessment, Life Cycle Costing, and Social Life Cycle Assessment, are analyzed. After discussing the methodologies in detail, a specific methodological advancement, based on a multi-cycle approach, is reported to assess sustainability in the CE “from cradle to cradle”.

In chapter 4, after a focus on the main environmental impacts of the agribusiness sector, a report prepared by the author with a review of the main issues in the olive oil sector is presented. Specifically, after defining the “life cycle” used for life cycle approaches, all technical operations attributable to the olive oil sector are analyzed by highlighting their specific impact categories.

Chapter 5 reports on an article written by the author in which he focuses on evaluating the circularity of real case studies of the Calabrian olive oil supply chain. This chapter illustrates the different applications of circularity to the olive production chain and compares the environmental, economic and circularity performances using life cycle methodologies and the Material Circularity Indicator (MCI). The analytical results allow to outline the main implications of circular approaches and to suggest business solutions.

Chapter 6 reports the main conclusions of this thesis work and further developments of the study.

1.1 Theoretical background of Circular Economy

1.1.1 The limits of the linear economy

According to Ellen MacArthur Foundation (2012), the industrial economy during its evolution and diversification has never gone beyond a fundamental characteristic established in the early days of industrialization: a linear model of consumption of resources that follows a “take-make-dispose” model. Companies extract materials, apply energy and labor to manufacture a product, and sell it to a final consumer, who then discards it when it no longer serves its purpose. While great strides have been made in improving resource efficiency, any system based on consumption rather than restorative use of resources entails significant losses along the entire value chain.

In the early 2000s, the real prices of natural resources began to rise, essentially canceling out the decline in real prices of a century. In addition, the levels of price volatility for metals, food and non-food agricultural production in the first decade of the 21st century were higher than in any single decade of the 20th century (OECD, 2007).

Commodity prices remain high as populations grow and urbanize resource extraction moves to more difficult-to-reach places, and the environmental costs associated with depleting natural capital increase.

Against this backdrop, some companies have also begun to notice that this linear system increases their exposure to risks, particularly higher resource prices. Rising prices and market instability create more uncertainties. The linear economy model has failed to address the imbalances that are currently being created between the limited supply and demand of natural resources.

For these reasons, the search for an industrial model capable of increasing sales revenues by reducing material inputs has increased interest in concepts related to the CE.

At the heart of the CE concept is combining the minimization of inputs by innovating the way we work with output. Replace “use and discard” products for their use with "reuse" them to the fullest extent possible. This change of direction, in alignment with the patterns of living systems, is critical to ensuring that continued growth generates greater prosperity.

The main resource losses of the linear model can be summarized in the following points:

- *Waste in the production chain.* These are the materials lost in the chain between extraction and final production. For example, materials that never enter the system - such as overloading and separation materials from mining, by-catches from fishing, losses of timber and agricultural crops, as well as excavation of soil and dredged materials from construction activities.
- *End-of-life waste.* For most materials, conventional recovery rates after the end of their (first) functional life are quite low compared to primary production rates. In Europe, 2.7 billion tonnes of waste were produced in 2010, but only around 40% of this was reused, recycled or composted and digested. Looking at the individual waste streams, an even clearer picture emerges: Current recycling rates are only meaningful for a handful of waste types, mainly those that occur in large and fairly homogeneous volumes.
- *Energy consumption.* Disposing of a landfill product in the linear system leads to the loss of all its residual energy is lost. In fact, with the incineration or recycling of discarded products only a small part of this energy is recovered, while reuse saves much more energy. In the linear model, the upstream phases of the supply chain involved in extracting materials from the earth and converting them into a commercially usable form are very impactful for the environment.

After having deepened the importance of the "CE" model in the face of the problems related to the "Linear Economy" model, the writer proceeded through a systematic bibliographic search in search of the definition of "Circular Economy".

1.1.2 Transition from Linear Economy to Circular Economy

According to several authors, such as Luttenberger (2020), the main challenges of the linear economy are the wastefulness of value that can be extracted, the waste problem, landfills, increased environmental risks, lack of competitive advantage, and lack of sustainable development. One of the solutions to overcome these challenges is to shift from the linear economy to the CE (Hartley et al., 2020). Various sources, such as the

European Commission (EC), state that in a CE, waste and resource use are minimized and when a product reaches the end of its life, it is reused to create further value, so the value of products and materials is maintained for as long as possible.

According to Kirchherr et al. (2018), a CE system can bring great economic benefits, contributing to innovation, growth, and job creation by turning assets that have reached the end of their useful life into resources for others (Stahel et al., 2016, Zhang et al., 2019). Unlike other sustainability-related practices, both research and industry insights show that with the CE, waste is reduced and resource availability is maintained (Stewart & Niero, 2018). Implementing the CE in industries leads to maintaining the economic value of materials used for production (Morseletto, 2020).

Referring to the industrial and commercial sphere, several authors such as Franco et al. (2019) assert that CE is crucial for companies as it helps stimulate the growth of product differentiation strategy and ultimately helps gain competitive advantage. Government intervention and the concept of "neotechnology" in the production system act as catalysts for the success of the CE (Barquet et al., 2020). In addition to institutional intervention, a real change in mindset is needed, moving from take-make-dispose to reduce-reuse-recycle-recover. The transition from a linear economy to a green economy seems to present several obstacles, as argued by several authors. According to Barquet et al. (2020), CE requires robust technology, effective design, and technical expertise with formally trained human resources to adopt reuse and remanufacturing strategies, and these are sometimes considered key challenges. As mentioned above, recycling and waste management activities are among the key challenges. Concerning this issue, for example, it emerges that many developing countries are unable to manage waste optimally. The main causes can be the lack of monetary sources, low public awareness, ambiguous policy framework and insufficient knowledge (Ferronato et al., 2019). Other barriers to the CE include large capital requirements, higher initial costs to upgrade facilities, risks and uncertainties, and lack of institutional and legal support (De Jesus et al., 2018). As for companies, it emerges that the lack of regulatory pressure and environmental knowledge in the implementation of CE does not develop positive attitudes among managers (Zhang et al., 2019). Some authors, such as Betancourt et al. (2020), pointed out in their review work that legislation, economics, education, training, availability of funds, and management attitudes toward CE are some of the main barriers for industries during the transition from linear to CE.

To overcome the barriers of the transition to CE, some authors suggest the following initiatives:

- Raising public awareness (Smol et al., 2018);
- Eco-innovation and innovation (de Jesus et al., 2018);
- The practice of recycling and attention to the use of energy;
- The positive attitude of the management;
- Government support in infrastructure construction, political reforms and incentives for companies that implement CE in their production system (Hart et al., 2019);
- Cooperation and coordination across multiple channels such as government, government policies, business practices especially within the supply chain, social norms and consumer acceptance (Hazen et al., 2017);
- -Redesign of the institutional framework and financial systems is also significant prerequisite for the transition from Linear Economy to CE (Zucchella et al., 2019).
- -Increasing investment in emerging technologies and digitization to form a circular supply chain, improving entrepreneurs' self-efficacy, reducing entrepreneurial risk, and creating pull-enforcement demand through increased awareness of the importance of circular models among customers (Al-Awlaqi et al., 2022).

The CE approach can be considered strategic for both the environment and the companies (Mazzucchelli et al., 2022).

Indeed, where feasible, circular strategies at the company level allow to be less dependent on external factors in terms of raw materials (Linder et al., 2017), which are subject to price volatility.

The scarcity of raw materials, in particular, in the face of the 2020-2022 events, especially the COVID-19 pandemic and the outbreak of war in Ukraine, has significantly influenced the realisation of the assumptions of transition to a CE model. (Pichlak et al., 2022). In addition to the more production-related aspects, the CE approach leads companies to acquire a good reputation, which positively influences financial performance (Mazzucchelli et al., 2022).

The adoption of an CE model is increasingly institutionally embedded and supported in the European Union's policy agenda as the main cross-cutting strategy to achieve the green transition.

As early as 2018, in fact, the European Commission established a framework to promote the implementation of circular practices in member countries.

Subsequently, a full-fledged Circular Economy Action Plan was defined together with the Farm to Fork strategy (European Commission, 2020a), both main pillars of the European Green Deal (European Commission, 2019). In addition, the CE is also included in the environmental and climate goals of the Next Generation EU (European

The latter instrument is designed to stimulate the recovery of the European economy after the pandemic crisis, with the aim of creating a greener, more digital and more resilient Europe. Economically, it is the largest stimulus package ever funded in the European Union, amounting to 2.018 trillion euros in current prices Commission, 2020 b).

1.2 Circular economy: origin of the concept

The CE is a relatively new concept, although the idea behind the CE has existed for a long time (Murray et al., 2015). According to Blomsma et al. (2017) and Reike et al. (2018), the evolution of the concept of CE can be divided into three phases corresponding to three historical periods. The first phase is defined by Blomsma as "Preamble", as the period from 1960 to 1985, and by Reike as "Circularity 1.0" from 1970 to 1990. A second phase is defined by Blomsma as "Excitement" (1985-2013) and by Reike as "Circularity 2.0" (1990-2010). Finally, a third phase is defined by Blomsma as the "Validity challenge" (2013-present) and by Reike as "Circularity 3.0" (2010-present).

In the first period, the main debate focused on waste and resource management. In this period the concept of the 3Rs "reduce, reuse and recycle" receives more attention (Reike et al., 2018). Thus, the set of resource life extension strategies highlighted in this period was mainly related to the end-of-life processes of industrial and municipal waste, in addition to preventive measures focused on the production side of the industrial system. As a result, waste treatment strategies such as cleaner incineration, waste-to-energy, recycling and composting were emphasized. The main developments during this period were:

- responsible management of natural resources,

- advances in the academic fields of biology, ecology, physics, and management and business sciences.

In agreement with Blomsma et al. (2017), regarding responsible management of natural resources, an early proposal was made by thinkers such as Thomas Malthus, John Stuart Mill, and Hans Carl von Carlowitz (Lacy and Rutqvist, 2015). Works such as Silent Spring (Carson, 1962), Tragedy of the Commons (Hardin, 1968) and Handbook for Spaceship Earth (Buckminster Fuller, 1969) brought attention to these ideas by highlighting toxicity and scarcity. Commoner (1971) posed a focus on environmental pollution that goes beyond superficiality and localization.

Boulding (1966) describes the current situation as the open economy of cowboys and compares it to the desirable situation, which he calls the closed economy of spaceships.

According to Murray (2017), based on these ideas, Stahel and Reday (1981) formulated the concept of closed-loop economy.

The concept of scientific progress that led to CE is reported by various authors such as Fischer-Kowalski (2002); Boons (2009); (Capra and Luisi 2014). In fact, new fields and disciplines were created, such as environmental economics and ecological or green design, industrial economics. These fields have generated new insights, attitudes and ideas, such as the willingness to learn from nature and the use of natural systems as a model for human society, the efficiency of industrial systems.

From an operational perspective, environmental measures in recent decades have focused on the “output side”; waste is not prevented, but pollution is limited through principles such as “polluter pays” and “end-of-pipe” treatment becomes the rule (Gertsakis and Lewis, 2003; Tyler Miller and Spoolman, 2002).

During the Preamble period, waste was primarily framed as a negative force because of the environmental, social and economic costs associated with it. Restoration and prevention of (further) damage to human and environmental health and well-being emerged at the center of the waste and resource debate. However, no clear solutions have emerged. Instead, debates on waste and resource management strategies began: the growing scarcity of landfill space in some places, such as the Netherlands and Japan, and the rising financial and environmental costs of incineration.

In this context, growing global connections through media, such as television, fuel the realization that local and global problems are linked and that such problems can ultimately affect even economically strong nations (Reike et al., 2018). This thinking is not yet well embedded in systems, with large amounts of waste treated across borders and often dumped in less affluent countries (Moyers, 1991).

The second period, according to Reike et al. (2018), is characterized by greater integration between preventive and output measures. The idea of a win-win between environment and business, as established in the Brundtland Report (WCED, 1987), is promoted through the statement “pollution prevention pays off” (Ochsner et al., 1995). Absolute reduction theory, typical of the 1960s and 1970s, receives less attention during this period. More interest is placed on technologies to increase product longevity, repair, refurbishment, upgrading and remanufacturing (Blomsma et al., 2017). Environmental problems are framed as an economic opportunity: proactive companies can benefit from efficiency and reputational gains. In this context, the theories of Life Cycle Thinking (Boons and Howard-Grenville, 2009) remain very much anchored in industrial thinking (Frakel et al., 1995). Other concepts, such as Design for the Environment, emerge during this period, and increasing attention is paid to issues of prevention and efficiency through design, since a reduction in human resources ultimately requires a reduction in inputs (Ayres and Ayres, 1994). The emergencies of the early 2000s, such as global warming, water scarcity, and biodiversity loss, create a new sense of urgency. In this period, digitization and the Internet lead to increasingly rapid sharing of environmental problems. Although scholars such as Stahel and Reday wrote about a closed-loop economy as early as 1976 and the concept of CE itself was coined in the 1960s, it is only at this stage that CE slowly gains importance (Murray et al., 2015).

The third period is characterized by an increasingly concrete commitment to the implementation of the concept of CE. This acceleration is linked according to Reike to the latest threats to the survival of the human race emerging in light of seemingly insurmountable sustainability challenges related to population growth. An increasing focus on resource depletion and the maintenance of resource value.

There is a growing awareness that we cannot consume indefinitely and that developing and underdeveloped countries should not reach the West's level of exploitation of nature, at least not through the same growth path and with similar rebound effects. According to Blomsma et al. (2017), from 2013 onward there was a different kind of engagement with the concept of CE, which marked the period of a validity challenge. In this period, the new cognitive unit and discursive space facilitated discussion, allowing for more critical engagement that led to different interpretations of the concept. The different interpretations involve different concepts, for example, according to Blomsma the distinction between recycling, downcycling and cascading: there are no established tools to distinguish these strategies quantitatively or conceptually, but circular metrics have already been proposed (e.g., Linder et al., 2017). In this context, the European Union, through the "European Union Circular Economy Package" (EC, 2015) also shows increasing attention to the issue, despite a lack of clarity on resource efficiency targets, which remain focused on (low-quality) recycling. This suggests that there is no fundamental change in policy, which critics say should also include disassembly and reusability. The new idea of CE is celebrated for its potential to decouple growth from resource use (Miller et al., 2011). In this way, it is formulated as a way out of the "resource trap". In his review work, Homrich et al. (2018) report the most frequent research flows referring to the foundation of CE (Table 1). The concept of closed loops is one of the most frequently mentioned aspects related to CE; biological cycles are more aligned with environmental and biological backgrounds, while closed technical circuits are more aligned with economic and industrial prospects.

Table 1. Most frequent research streams that refer to the foundation of CE (Source Homrich et al., 2018).

Training schools	**Definition**	**Source**
Cradle-to-cradle	Products designed to regenerate the ecosystem as biological nutrients or to regenerate industries such as nutrients, components and materials in a 100% closed material loop	McDonough and Braungart (2002)
Industrial ecology	Cyclical resource-use patterns observed in biological ecosystems are used as a model for designing mature industrial ecosystems, whose productivity depends less on resource extraction and waste emission.	Graedel and Allenby (1995)
Biomimicry	Designers are inspired directly by organisms, biological processes and ecosystems	Benyus (2002)
Laws of ecology	They are four: (i) everything is connected to everything Else, (ii) everything must go somewhere, (iii) nature knows best and (iv) there is no such thing as a "free lunch".	Commoner (1971)
Performance economy	It enables entrepreneurs to achieve a higher competitiveness with greatly reduced resource consumption and without an externalization of the costs of waste and of risk.	Stahel (2010)
Blue economy	The need to find a way of meeting the basic needs of the planet and all its inhabitants with what the Earth.	Pauli (2010)
Regenerative design	This means replacing the current linear system of transfer flows with cyclical flows at sources, consumption centers and sinks	Lyle (1996)
Permaculture	It is an integrated evolutionary system of perennial or self-perpetuating plant and animal species useful to man, it is a complete agricultural ecosystem	Mollison and Holmgren (1978)
Natural capitalism	An approach that protects the biosphere and improves profits and competitiveness. Some changes in how to run the business, based on advanced techniques to make resources more	Lovins et al. (1999)

	productive, can yield amazing benefits for both current and future generations	
Industrial metabolism, Industrial symbiosis and Ecoparks	The use of matter and energy in the economic system shows certain parallels with the use of matter and energy by biological organisms and ecosystems. Industrial symbiosis is a merger of two or more different industries, where each industry tries to find optimal access to material components and material elements.	Ayres (1989); Renner (1947)

1.3 Definitions and the "Rs" of circularity

The CE is a relatively young field with roots in various disciplines and schools of thought (Blomsma and Brennan, 2017). Even in the academic world, there is no common agreement on its definition (Rizos et al., 2017). According to Merli et al. (2018), the CE definition is not static and includes several principles and proposals that have been formulated in recent decades by various authors, such as those of "regenerative design" (Lyle, 1994), "performance economics" (Stahel, 2008), "Cradle-to-Cradle" (Braungart et al., 2007) and "industrial ecology" (Erkman, 1997). According to Blosman et al. (2017), there is ample ground for conceptualizing the EC as an umbrella concept. This becomes evident when various structures are compared and contrasted in which circularity plays an important role.

For this reason, Table 2 shows some of the most recurrent definitions of CE from different sources, from 2008 to 2020. The sources of the definitions are both academic and non-academic, such as European Community regulations. According to Geissdoerfe et al. (2017), the inclusion of non-peer-reviewed articles is appropriate because the CE is a new area of research and it has not been widely addressed by peer-reviewed articles.

Table 2. Some definitions of CE reported in the literature.

Source	Definition
Peters et al., 2007	"The central idea is to close material loops, reduce inputs, and reuse or recycle products and waste to achieve a higher quality of life through increased resource efficiency".
Geng and Doberstein, 2008	"Mean the realization of a closed loop of materials flows in the whole economic system."(...)"implying a closed-loop of materials, energy and waste flows".
Yang and Feng, 2008	"Circular economy is an abbreviation of "Closed Materials Cycle Economy or Resources Circulated Economy" (...)"The fundamental goal of circular economy is to avoid and reduce wastes from sources of an economic process, so reusing and recycling are based on reducing".
Xue et al., 2010	"Circular economy is the outcome of over a decade's efforts to practice sustainable development by the international communities ,and is the detailed approach towards sustainable development".
Park et al, 2010	"The CE policy seeks to integrate economic growth with environmental sustainability, with one element relying on new practices and technological developments, similar to the application of environmental modernization technology".

Li et al., 2010	“The concept of circular economy broadly accepts that an economic growth and development system to integrate economy with resources and environmental factors is based on the material metabolism mode of ‘‘resource-product-regenerated resource’‘, which incorporates a mechanism of efficient resource use and waste stream feedback, while its metabolism is compatible with the whole ecosystem. For the system, the reduction of resources, energy, and waste stream through the lifecycle of products and the increase in economic output and effectiveness can be achieved simultaneously by improving resource productivity (or eco-efficiency). There are three principles of circular economy, namely to reduce, to reuse and to recycle. And it is generally achieved at three levels. At the level of enterprises, circular economy mainly focuses on cleaner production. At the regional level, circular economy emphasizes structuring a substance recycling eco-industrial park. At the national level, circular economy represents a new pattern of economic operation and aims to create a recycling oriented society”.
Preston et al., 2012	“A ‘circular economy’ (CE) is an approach that would transform the function of resources in the economy. Waste from factories would become a valuable input to another process – and products could be repaired, reused or upgraded instead of thrown away.”
The Ellen MacArthur Foundation, 2012	“[CE] an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models”.
The Ellen MacArthur Foundation, 2013	“A circular economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times. The concept distinguishes between technical and biological cycles. As envisioned by the originators, a circular economy is a continuous positive development cycle that preserves and enhances natural capital, optimizes resource yields, and minimizes system risks by managing finite stocks and renewable flows. It works effectively at every scale”.
Mat et al., 2014	“A circular economy is a mode of economic development that aims to protect the environment and prevent pollution, there by facilitating sustainable economic development.”
European Community, 2015	“In a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimized, and when a product reaches the end of its life, it is used again to create further value”.
Webster, 2015	“A circular economy is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times”.
Haas et al., 2015	“The circular economy (CE) is a simple, but convincing, strategy, which aims at reducing both input of virgin materials and output ofwastes by closing economic and ecological loops of resourceflows.” “CE, material flows are either made up of biological nutrients designed to re-enter the biosphere, or materials designed to circulate within the economy”.
Gregson et al., 2015	“The circular economy seeks to stretch the economic life of goods and materials by retrieving them from post-production consumer phases. This approach too valorizes closing loops, but does so by imagining object ends in their design and by seeing ends as beginnings for new objects”.
Stahel, 2016	“A circular economy would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimizing waste. It would change economic logic because it replaces production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired”.
Bocken et al., 2016	“Design and business model strategies that are slowing, closing, and narrowing resource loops”.
Ghisellini et al., 2016	"Circular economy is defined by Charonis (2012), in line with The Ellen Macarthur Foundation vision (2012), as a system that is designed to be restorative and regenerative”.

Geissdoerfer et al., 2017	“A regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. Second, we define sustainability as the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations.”
Zotti et al., 2019	The definition we propose postulates economy’s circularity as a positive feature of the economy that consists in the presence of internal circular energy and matter fows. The circularity of flows allows keeping matter and energy within the economy with the consequence of delaying their return to the environment. Notice that this feature is the core principle in the CE as well.
Andreola et al., 2019	The Circular Economy is designed to be able to regenerate on its own, through two types of material flows: biological ones, able to be reintegrated into the biosphere, and technical ones, destined to be revalued without entering the biosphere.
Bressanelli et al., 2019	“An economic system restorative and regenerative by design, implemented by one or more supply chain actors through one or more of the four building blocks (circular product design, servitised business models, reverse logistics and enablers), in order to replace the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes, for both technical and biological materials, with the aim to accomplish sustainable development”.
Tognato de Oliveira et al., 2021	“We define circularity as the alignment of a material or energy flow, product, processes, or system to a set of CE strategies (redesign, product disassembly, recycling, use of renewable energy, etc.), that meet the general CE goals. Therefore, circularity indicators may be understood as analytical tools focused on measuring the degree of association of a system (or part of one) to practices and strategies applied to develop a CE further. In that sense, higher circularity means that a specific item or system is closer to achieving the goals set by the guiding standards of a CE.

In many definitions of CE the terms “reduce, reuse and recycle” occur. These principles are the basis of the circular economy, as opposed to the open linear model of “resources/products/waste” in a cyclical model of “resources/products/waste/resources” (Ghisellini et al. 2016; Al Yu-nan Xue et al. 2019). EC theorists, observing the perpetual cycle of elements within natural ecosystems, suggest that future industries will have to adopt a restoration project to survive in a world where current rates of exploitation of natural resources will be unacceptable.

Feng and Yang (2007) argue that the CE follows the principles of “reducing the use, reuse and recycling of resources” in order to reduce resources.

The 3R framework for a while was considered the most important R framework for CE coding. The three 3R imperatives of "reduce, reuse, recycle" form an accepted notion of CE in theory and practice (Reike ad al. 2018). Over the years, scholars have added several "Rs" to those mentioned above, such as 5 "R" (Sinha et al. 2016) 6 "R" (Sihvonen and Ritola, 2015) 9 "R" (Van Buren et al. ., 2016, Kirchherr et al., 2017 Potting et al., 2017, Reike et al., 2018). Table 3 reports the 9 "R" and the respective definitions present in the literature.

Table 3. Shows the 10 “R” currently found in the literature and the corresponding definition.

“R”	Source	Definitions
Reuse	Blomsma and Brennan, 2017, Geissdoerfer et al., 2017, Ghisellini et al., 2016, Homrich et al., 2018, Huang et al., 2018, Kirchherr et al., 2017, Korhonen et al., 2018, Li et al., 2010, Murray et al., 2017, Preston, 2012, Reike et al., 2018, The Ellen MacArthur Foundation, 2012	Using collected materials, building elements and building materials again to fulfill their original or different function (The Ellen MacArthur Foundation, 2012).
Reduce	Ghisellini et al., 2016, Homrich et al., 2018, Kirchherr et al., 2017, Li et al., 2010, Murray et al., 2017, Reike et al., 2018	Reduction of waste production. (Francis 2003).
Recycling	Blomsma and Brennan, 2017, Geissdoerfer et al., 2017, Ghisellini et al., 2016, Homrich et al., 2018, Kirchherr et al., 2017, Korhonen et al., 2018, Li et al., 2010, Murray et al., 2017, Reike et al., 2018, UE, 2008	Any recovery operation by which waste materials are transformed into products, materials or substances for original or other purposes (UE, 2008).
Recover	Ghisellini et al., 2016, Kirchherr et al., 2017, Reike et al., 2018	Incineration of materials with energy recovery (Kirchherr, 2017).
Rethink	Kirchherr, 2017	Rethinking the replacement of the product in order to increase its efficiency of use. By sharing products or placing multifunctional products on the market (Kirchherr, 2017).
Repair	Blomsma and Brennan, 2017, Geissdoerfer et al., 2017, Kirchherr et al., 2017, Korhonen et al., 2018, Preston, 2012, Reike et al., 2018	Repair and maintenance of damaged products so that they can be used with its original function (Kirchherr, 2017).
Refurbish	Blomsma and Brennan, 2017, Geissdoerfer et al., 2017, Kirchherr et al., 2017, Korhonen et al., 2018, Reike et al., 2018	Restore an old product and bring it up to date (Kirchherr, 2017)
Repurpose	Kirchherr et al., 2017, Reike et al., 2018	Use the discarded product or its parts in a new product with a different function (Kirchherr, 2017).
Remanu-facture	Blomsma and Brennan, 2017, Geissdoerfer et al., 2017, Kirchherr et al., 2017, Korhonen et al., 2018, Reike et al., 2018	Use parts of discarded product in a new product with the same function (Kirchherr, 2017)
Re-mine	Reike et al., 2018	Recovery of precious materials from products destined for landfill (Reike et al., 2018).

1.3.1 The umbrella concept

The umbrella concept is defined by Hirsch and Levin (1999) as “a broad concept or idea used freely to understand and explain a set of different phenomena”. In particular, the use of the umbrella concept can occur when a field or discipline lacks guiding theories or a development paradigm (Hirsch and Levin 1999).

As for the CE, according to Blomsma et al. (2017), umbrella concepts can act as a catalyst in bridging this knowledge gap by creating a new global cognitive unit and a new discursive space. The creation of a cognitive unit is achieved by directing attention to some shared characteristics of the constituent elements of the umbrella concept, thus separating these characteristics from the background and identifying the core of a phenomenon (Blomsma et al., 2017).

Also according to Blomsma et al. (2017) thanks to the umbrella concept, attention is focused on a particular shared quality or characteristic of the concepts it contains, such as the concept of "circularity". Furthermore, thanks to the umbrella concept, relationships emerge between pre-existing concepts that were previously unrelated or unrelated in the way proposed.

1.4 Level of circularity

According to several authors, such as Ghisellini et al. (2016) and Saidani et al. (2019), different levels of circularity are associated with the concept of CE. The CE literature discusses the existence of three system levels: nano (product), micro (company), meso (eco-industrial park) and macro (city, nation or global), with a lack of connection between the levels in terms of indicators.

Macro-level

The concept of macro-level has been defined by various authors even outside the concept of CE. Geels (2007) and Smith (2010) define macro-level form as an exogenous environment, which provides a broader structural context in which changes occur slowly (decades). In this context, landscapes are considered an external context, as actors cannot influence them in the short term. However, the macro level is dynamic, as it is susceptible to slow changes such as climatic ones.

With reference to the CE, Winans et al. (2017), including cities, regions and governments at the macro level. The focus on this level is based on a broad strategy aimed at promoting sustainable development, through environmental policies and institutional influence (Yuan et al., 2006).

Specifically, the development of the CE in cities, provinces or regions involves the integration and redesign of four systems: the industrial system (e.g. increasing the size of businesses, abandoning highly polluting businesses in favor of light economic activities such as related to high-tech industries, tourism or culture); the infrastructural system providing services (transport and communication systems, water recycling systems, clean energy and power lines, etc.), the cultural framework and the social system (Ghisellini et al., 2016).

According to Harris et al. (2021), the method of evaluating circularity at the macro level is the Material Flow Analysis (MFA), followed to a lesser extent by the multiregional input-output analysis (MRIO), LCA, and other methods such as evaluations using a range of indicators and multi-criteria evaluations, dynamic system models, as well as those that calculated mass flows without a full MFA.

Meso-level

Jackson et al. (2007), define the meso-level as a relatively stable arrangement of dominant social, technological, economic, environmental and political structures that shape the system. In the context of the CE, eco-industrial parks or inter-company associations known as industrial symbiosis are included in the meso level (Balanay et al., 2016; Kirchher et al., 2017).

In a study by Harris et al. (2021), it emerges that for the meso level, the most commonly used environmental assessment method in the studies examined is LCA. In the same study, it is reported that most of the articles provide different environmental impact categories for sectoral assessments and industrial symbiosis networks employing LCA (Daddi et al., 2017; Deschamps et al., 2018; Martin et al., 2019)

Micro-level

Relating to the CE, the micro level refers to a single company or product and its components (Franklin-Johnson et al., 2016). Also in this case, the basis is the improvement of its processes and business development (Ormazabal et al., 2016).

Implementing the CE for companies is undoubtedly an advantage, both in terms of cost efficiency and for the positive impact, it creates on their reputation among customers.

Since the micro level has a broad scope, many metrics called micro-level indicators do not cover the complexity of a CE and can lead to different interpretations of what this specific CE level faces during circularity assessments (Lindgreen et al., 2020).

Environmental assessment at the product level at CE level can take place through various methodologies including: carbon footprint-based methodologies, energy analyzes, analyzes based on materials / substances / chemicals, analysis of indicators and LCA (Elia et al., 2017; Saidani et al., 2019; Tanzer and Rechberger, 2019; Tecchio et al., 2018, Harris et al., 2021).

In this context, LCA is considered the most suitable tool to be used to assess the environmental impacts of product design based on circles or system modifications (Elia et al., 2017).

During the time with the LCA analysis, several products were evaluated which returning involving a wide range of CE responses such as recycling, product life extension, reuse and regeneration and product systems as a service. In the literature there are several studies related to this, including: recycling of photovoltaics (dos Reis Benatto et al., 2017; Gallagher et al., 2019), reuse of textile fibers (Landi et al., 2018), the recycling of plywood (Jia et al., 2019) and the recycling or reuse of wine bottles (Landi et al., 2019).

Nano level

According to Saidani, for the reasons mentioned above, the nano level presents itself as a more refined level focused on the circularity of products, components and materials, included in three broader systemic levels, along the entire value chain and during their entire life cycle. This level could serve as a common denominator within the other levels and could allow both to establish links and to examine more closely the actual performance of the CE implementation.

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2. SUSTAINABLE AGRI-FOOD PROCESSES AND CIRCULAR PATHWAYS IN A LIFE CYCLE PERSPECTIVES: WHERE IS APPLICATIVE RESEARCH GOING? [1]

Abstract: This study aims at providing a systematic and critical review on the state-of-the-art of life cycle applications from the circular economy point of view. In particular, the main objective is to understand how researchers adapt life cycle approaches for the measurement of the empirical circular pathways of agri-food systems along the overall lifespan. To perform the literature review, PRISMA protocol was considered to conduct a review by qualitative synthesis. Specifically, an evaluation matrix has been set up to gather and synthesize research evidence, by classifying papers according to several integrated criteria. The literature search was carried out employing scientific databases. Findings evidence that the most common circularity topics are about closed-loop production systems, i.e. nutrient recovery for agricultural purposes, production of renewable energy, valorization of residues and wastes as fertilizers, food waste, and agro-wastes recycling for agriculture. To evaluate the benefits/impacts of CE strategies, Life Cycle Assessment (LCA) proved to be the most common methodology applied by authors, as it can help to meet the main CE requirements slowing and closing resource loops.

Keywords: systematic literature review; agricultural sustainability assessment; circular economy; lice cycle methodologies; agri-food sustainability.

2.1 Introduction

2.1.1 Theoretical background of circular economy

Circular Economy (CE), also intended with the synonymous "circularity", is an expression that, although it is now widely used and known, remains shrouded in an aura of mystery, especially if the intent in its use is to grasp the most practical advantages in its application. For this reason too, but not only, discussion themes about CE are strongly explored at various levels and from different perspectives by researchers,

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[1] This chapter is based on the following scientific article: Teodora Stillitano, Emanuele Spada, Nathalie Iofrida, Giacomo Falcone and Anna Irene De Luca (2021). Sustainable agri-food processes and circular pathways in a life cycle perspectives: Where is applicative research going? Sustainability, 13, 2472. DOI: 10.3390/su13052472. Personal contribution to the article: Emanuele Spada: literature search and analysis; writing-original draft.

academics, politicians, practitioners, and entrepreneurs. The CE concept, which can be dated from the original and renowned idea of "closing circle" [1], has been brought back to the forefront in 2010, thanks to the popular activity of Ellen MacArthur Foundation [2] which reprised, among others, the most recent cradle-to-cradle approach [3]; since then, insights on CE never stopped moving forward. However, as Borrello et al. [4] argued, the originality of new contributions is not always clear and this risks making the concept even more disorienting, although it is shareable to consider CE nowadays as a necessary concept precisely because it is still "essentially contested" [5]. One of the key issues that make the CE's discourse particularly complex is the understanding of the link between circularity and sustainability [4; 6; 7] and, although it is quite shared the vision of CE as an effective way to achieve some of the sustainability goals, often the boundaries of these two overblown terms are not so see-through and this risks to blur their meaning as in a real tangle of buzzwords [8; 9]. In concise and effective terms, the CE model, opposed to the linear economic model, would reduce and/or avoid resource depletion, wastes, and other environmental impacts all over the life cycle of services and products, by preserving and/or improving socioeconomic conditions. Just to provide one among the countless existing definitions, that formulated by Kirchherr et al. [9:224]probably represents the most comprehensive: "*CE describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*". Overlooking the theoretical and conceptual debate, most scholars focus on the need to explore what methodologies, metrics, and indicators are most suitable for evaluating the CE in the light of sustainability principles and/or dimensions, considering that not necessarily a CE's scenario is more sustainable than a linear one regardless [10; 11]. Furthermore, it is not only crucial to appropriately measure the environmental, economic, and social impacts of CE's strategies but also to investigate the implications of CE at different system levels, for several subjects involved by including potential rebound effects that are reflected on other production/consumption systems or other levels [12; 13]. Despite the existence of varied approaches, methods, and tools to evaluate CE, scholars agree that unclearness remains, about defining the meaning of CE performances, its levels, its spatial and temporal scales, its dimensions to be measured. Lastly, one could assume that it is probably forced to refer to a common and valid recipe for all CE contexts, the ultimate goal is probably to figure out how to join forces and use methods and tools, appropriate for specific settings, in a holistic, integrated, and complementary way. As [14] argue, a multidisciplinary cross-combination of methods could be an effective solution for CE, to hybridize different metrics, to extend the scope of the analysis, to conduct predictive estimates of consequences, and by using multicriteria techniques to choose the best alternatives or make trade-off choices under conditions of uncertainty and disagreement.

2.1.2 Circular economy in a life cycle perspectives for the agri-food sector

CE is about the rethinking of the current models of production and consumption, and agri-food systems, which are responsible for the pressure on the living environment as well as for assuring the survival of many farms in rural areas, must necessarily move toward transition pathways. The importance of introducing CE strategies in the agri-food sector is primarily based on the circumstance - regrettably well recognized - that among the main contributors to pollution worldwide are livestock and crops, as well as the waste production caused by downstream links in the food sector. According to EEA [15], the food system could be considered the most defenseless of all, due to the exponential growth of total demand for food, feed, and fiber, against a relentless decline of arable land. The potential interdependencies - direct or indirect - in this context are innumerable, for example in terms of resources competition for food or bio-energy production that requires land, energy, and water resources; but also in terms of food losses and food waste, that entail to a value lost in supply chains in turn linked to avoidable environmental impacts and financial losses [16]. Hence the need to improve the resource efficiency of agri-food system activities also through technical innovations to ensure more sustainable use of renewable resources, the reduction of environmental damages, and the depletion of non-renewable resources. CE application is widespread in agri-food sectors [17], because it tries to solve embedded and systemic problems, such for example the conversion of waste into bio-products, new materials, or products to extending the end-of-life by generating new economic returns or costs reduction and anyway by reducing environmental damage or optimizing the use or resources returning to the original process [18]. Therefore, it is not wrong to say that CE is potentially able to contribute to the sustainability of agri-food systems; it's about understanding how and, also means understanding how CE can help to improve specific social, economic, and environmental aspects of sustainability. Undertaking such different dimensions is methodologically challenging and calls into question the epistemological foundations of sustainability science and CE. One of the greatest concerns is the combination of different assessment methods and merging their results in a suitable and believable way. Furthermore, evaluating CE strategies should require a systemic and synergistic approach by considering the agri-food supply chain as a whole, especially to not incur the risk of making effective only one stage nor only single portions, while neglecting the others [19; 20]. This would mean, for example, to include the analysis of pre-production and consumption stages, but also of co-products markets, and other secondary supply chain articulations. To satisfy these purposes, sustainability evaluation methods and, among them, the life cycle (LC) approaches, are particularly appreciated as a robust, science-based, and useful tool not only to measure, but also to validate CE assumptions, to help the feasibility of its implementation getting feedback for improvements and, finally to communicate innovation strategies [21]. Especially Life Cycle Assessment (LCA) is widely regarded to be the tool “par excellence” when it comes to evaluating the environmental impacts of circular based products or systems [13; 22]. The flexibility of LCA is also well appreciated, principally because allows to incorporate it in several other metrics by demonstrating feasibility and usefulness for CE purposes [23]. However, all LC methodologies, LCA (or eLCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA), while are obtaining a growing consensus in the appraisal of different agricultural and food systems by measuring environmental, economic, and social impacts, separately or jointly, lastly required also to be systemic, multidisciplinary, and multicriterial. In these terms, the use of an LC framework, able to capture potentially all sustainability dimensions, can be adapted to evaluate CE strategies operationally and comprehensively, by shifting from the typically “from cradle to grave” to “from cradle to cradle” circular vision. Furthermore, to avoid partial and compartmentalized analyses in CE context, Life Cycle Sustainability Assessment (LCSA) [24; 25] is also recommended by Niero and Hauschild [19], since it could suggest elements of integration among sustainability dimensions, life cycle stages and interdependent subjects of the supply chains by preventing or avoiding burden shifting.

2.1.3. Goal and scope of the review

To the best of our knowledge, within the extensive scientific literature that investigated definitions of CE, discourse typologies, applications, and measurements, no recent review has explored the use of Life Cycle (LC) approaches to measure the impacts deriving from the implementation of CE strategies in the context of agricultural and food productions. Only two reviews addressed a somehow related theme) [17; 26], but the first is mainly focused on general trends in CE research related to the agri-food sector, while the second is particularly centered on bioenergy agricultural practices. Both the studies mention LC as a tool especially liked and appropriate for CE purposes without arguing about the limitations and advantages of using the tool to explain the impacts of circularity pathways.

Therefore, the originality in the scope and approach of this review is to understand how and how much the LC-based analysis is useful to evaluate if CE strategies are more sustainable than linear/traditional economic models in agri-food production systems. To address this issue, the following research questions will be answered: (1) how researchers apply LC methods to evaluate environmental, economic, and social consequences of agri-food circular processes? (2) How LC methods are combined with other approaches to CE measuring? (3) Have impact results been used to increase understanding of the sustainability implications of CE strategies? This study aims to contribute to the research on CE implementation providing an understanding of the role in life cycle approaches to measure the effectiveness of CE strategies for improving agri-food production processes sustainability. A visual diagram is provided in Figure 1 to summarize how the CE vision, i.e. the well-known butterfly diagram by [2], can be brought back to a life cycle perspective through the necessary flow of data and information to measure environmental, economic and social impacts. The paper framework is the follows: the next section describes the research methodology used in this study to conduct the systematic and critical literature review. Section 3 presents the results in terms of the main criteria used in the analysis. Section 4 and 5 argue the discussions concerning the above-mentioned research questions and by drawing the research conclusions and future research proposals.

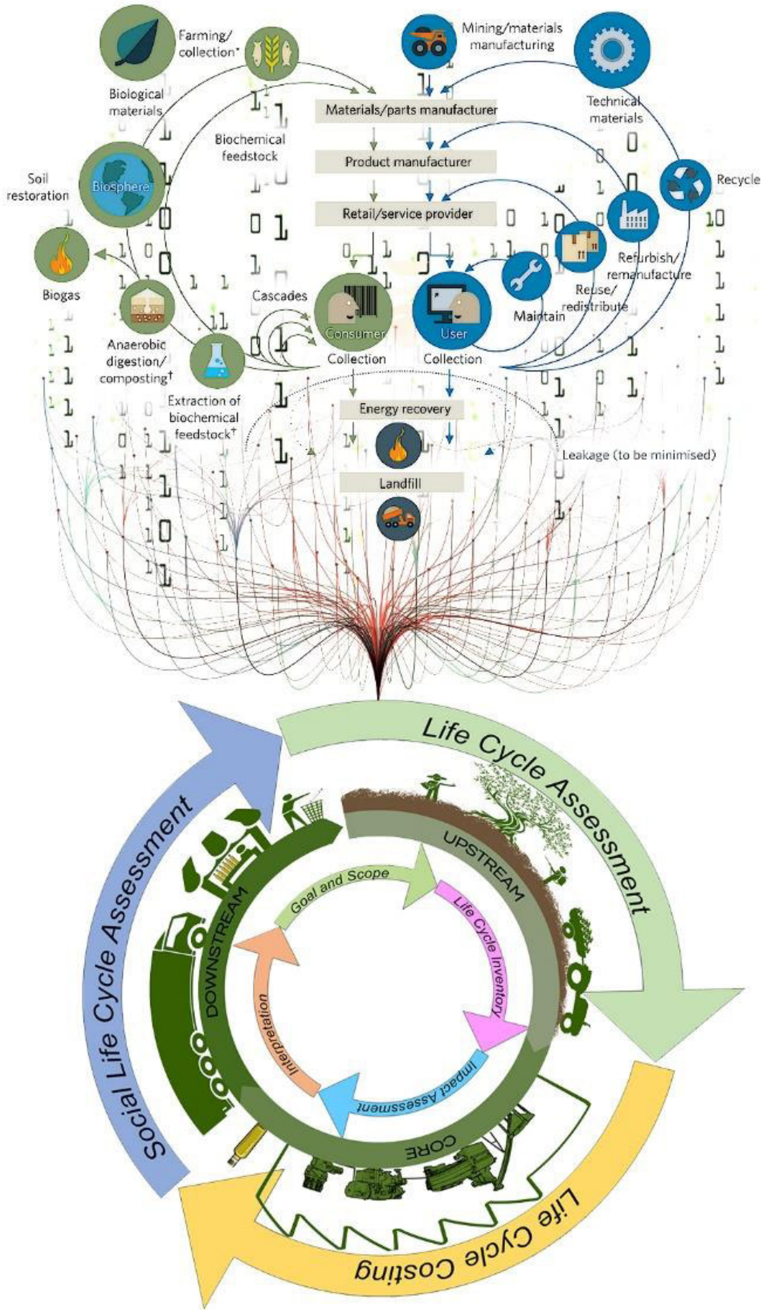

Figure 1. Data flow for the assessment of circular models in a life cycle perspective (our elaboration from Ellen MacArthur Foundation) [2].

2.2 Materials and Methods

2.2.1 Literature search

In order to provide a comprehensive vision on how much and how well life cycle methodologies are suitable to comply with CE requirements in the agri-food sector, a systematic and critical review of the existing scientific literature was carried out. Based on the study conducted by [27], a *critical* review goes beyond a mere description of the literature, but extensively it should evaluate its quality seeking to identify most significant items, analyzing significant components, and synthetizing the main concepts. Embracing the same main characteristics, a *systematic* review differs from the previous one as seeks to systematically search for, appraise, and synthesize research evidence. Therefrom, this study, combining the strengths of these two review typologies, carry out an extensive review employing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [28]. PRISMA was used as a formal systematic review guideline for data collection providing a standard peer accepted methodology, to contribute to the quality assurance of the revision process and its replicability. A review protocol was developed (Figure 2), describing the search strategy, article selection criteria, data extraction, and data analysis procedure.

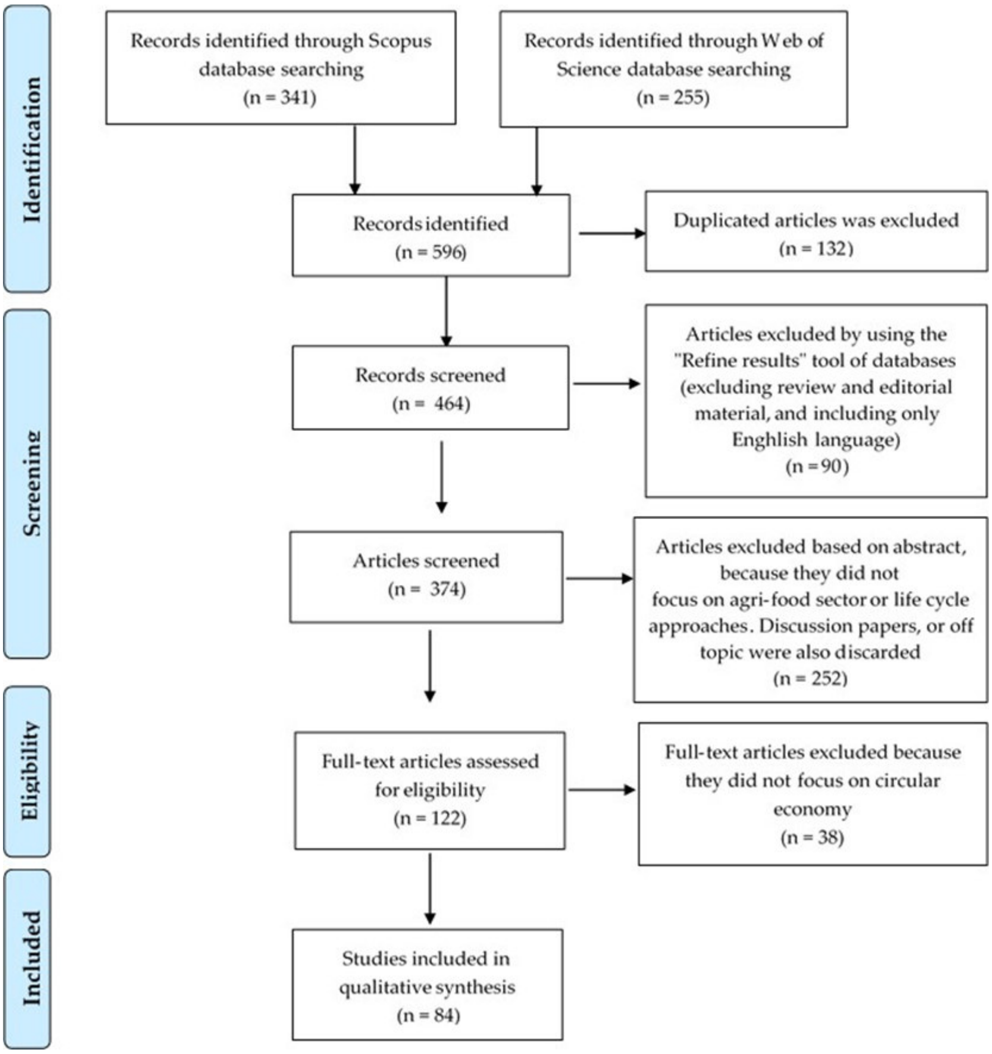

Figure 2. Methodological steps of the literature search process using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram [28].

In the “identification” step of the PRISMA flow diagram (*cf.* Figure 2), a set of keywords was selected based on the question formulation, i.e. the research scope, which consisted of searching for all documents proposing life cycle approaches to measure the empirical circular pathways of agri-food systems. The literature search was performed in Scopus and Web of Science (WOS) databases, through the combination of main keywords using Boolean operators (AND/OR). As shown in Table 1, the following search strings were applied: (“circular economy”), (“life cycle assessment” OR "life cycle analysis" OR LCA), (“life cycle costing” OR LCC), (“social life cycle assessment” OR "S-LCA" OR SLCA OR "social-LCA), ("life cycle sustainability assessment" OR LCSA) combined with (“agr* OR food). The research has been conducted in the fields “title”, “abstract”, and “keywords” for the main keywords, and in “all fields” for the other terms, i.e. agr* or food. The databases were consulted in October 2020 with no time restriction.

Table 1. Query used in database searching.

Database	Search strings[1]
Scopus	(TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY ("life cycle assessment" OR "life cycle analysis" OR "life cycle costing" OR "social life cycle assessment" OR "life cycle sustainability assessment" OR lca OR lcc OR "s-lca" OR slca OR "social-lca" OR lcsa) AND ALL (agr* OR food))
Web of Science	TOPIC: ("circular economy") AND TOPIC: ("life cycle assessment" OR "life cycle analysis" OR "life cycle costing" OR "social life cycle assessment" OR "life cycle sustainability assessment" OR lca OR lcc OR s-lca OR slca OR "social-lca" OR lcsa) AND ALL FIELDS: (agr* OR food)

[1] Last accessed on 29 Oct 2020.

Searches on Scopus and WOS databases led to 341 and 255 articles, respectively, for a total of 596 papers. Duplicate papers were excluded, resulting in 464 documents, which have been subjected to a screening process. A first selection was made by using the “Refine results” tool of the databases used to exclude review and editorial material and include only English language. Then, only applicative indexed references were taken into consideration. A second screening was performed based on the content of abstracts, excluding discussion papers, or off-topic and studies that did not focus on the agri-food sector or life cycle approaches. In so doing, 122 articles were assessed for eligibility by reading the full-text in-depth. Studies not directly focused on the issue of measuring circularity quantitatively were discarded.

Through the above-specified criteria application, the total amount of articles found was reduced to a final portfolio of 84 representative papers that were included in the qualitative synthesis. These articles were read in full and analyzed one by one for the purpose of this study.

2.2.2 Characterization of matrix criteria for the systematic and critical review

According to De Luca et al. [29], an evaluation matrix has been set up to synthesize research evidence, by classifying the selected papers according to several integrated criteria. As shown in Table 2, all reviewed papers have been categorized by bibliometric information (authors, year of issue, title, journal); descriptive statistics that refers to the place where the case-study is applied, field of application (i.e., the area of human activity), the main product under study, circularity topics; and relevant data on circularity assessment methods and circularity indicators. These latter criteria included the differentiation of both the methodologies into “LC tools and other life cycle approaches” and “Other methods different from LC”, and indicators into “Circularity indices” and “CE assessment indicators”. According to Corona et al. [30], the former indicators measure the circularity degree of a system, based on a mere material recirculation and addressed to resource efficiency. The latter assesses the effects (burden or value) of circularity, showing high potential in addressing all the CE goals at the product/service level. Here, we divided the “CE assessment indicators” into “Life cycle based-indicators” and “No life cycle based indicators” (see *3.3 Section* for more details). “Circular strategy application-level” indicates the levels to which the circular strategies or interventions are applied namely: micro level (products, companies or organizations, consumers), meso level (eco-industrial parks), and macro level (regions, cities, countries, or the global economy) [31]. Finally, the last columns of the matrix are focused on the main features that qualify the life cycle approaches, e.g., functional unit, system boundary, database, LC impact assessment method, software, etc. (please see Table S1).

Once the matrix has been completed, the input data were compared and the results were qualitatively and quantitatively extracted to highlight significant information and relationships. The main highlights and conclusions of the selected studies are reported in the following section.

Table 2. Matrix criteria for the critical review of the selected papers.

Criteria	Description
# ID Paper, Authors, Year, Title, Source	Bibliometric information. The sequence follows the alphabetical order of the first author's name
Place	Where the case-study took place
Field of application	What is the context in which the application is implemented
Main reference product	What is the product analyzed in the case-study
Circularity topics	The most common arguments leading the CE literature
Circularity assessment methods	LC tools and other life cycle approaches/Other methods different from LC
Circularity indicators	Circularity indices (measuring the circular degree of a system)
	CE assessment indicators (assessing the effects of circularity) divided into Life cycle based-indicators and No life cycle based indicators
Circular strategy application level	Macro, Meso, Micro
LC approach details	Functional unit, System boundary, Data/Database, LC impact assessment method and/or software, Type of cost, Approach used

2.3 Results

2.3.1 Descriptive statistics

The descriptive analysis was based on the distribution of the reviewed articles over the years and by country (based on the place of case-study application), and their distribution per journal, field of application (resulted from the main argument or topic of study), main reference product (which refers to the product analyzed in the case-study), and the most common topics dominating the CE literature in the agri-food sector.

The selected 84 papers were published from 2014 to 2021, as shown in Figure 3. It should be noted that the papers issued in 2021 were already available online in October 2020. The results revealed an exponential increase in the number of publications regarding the application of life cycle methodologies as circularity metrics in the agri-food sector over the last 7 years. The first publications, starting from 2014 to 2016 (one for each year), concerning energy recovery from dairy farming [32], recycling food waste for use as feed in aquaculture [33], and the waste management with energy recovery in the anchovy industry [34]. Only in the last years, more specifically in 2018-2020, strong efforts were made towards the development of studies to measure the circularity through LC approaches in agri-food systems. In particular, 16 documents were published in 2018, 23 documents in 2019, and 32 documents in 2020. Nevertheless, as mentioned by Barros et al. [35], only a few efforts can be observed towards assessing agricultural systems accounting for sustainability in a circular perspective. Thus, the peak development of this theme has yet to be reached.

According to the place of case-study application, most publications may be traced to European countries (49%), followed by China**,** as it can be seen in Figure 4. Indeed, the five highest-ranked origins of the reviewed articles are Spain (22.6%), Italy (14.3), United Kingdom (UK) (7.1%), China (6%), and Ireland (4.8%). These findings were consistent with results reported by Esposito et al. (2020) [26], who showed the great interest of European scholars towards the development of CE models also in the agri-food sector. Outside the European continent, China represents the major contributor in researching this topic. This is likely due to the Chinese government's request to stimulate actions in favor of the environment also via CE [36]. The interest in using LC tools to analyze CE strategy seems to be growing in Brazil and Sweden with 3 publications each.

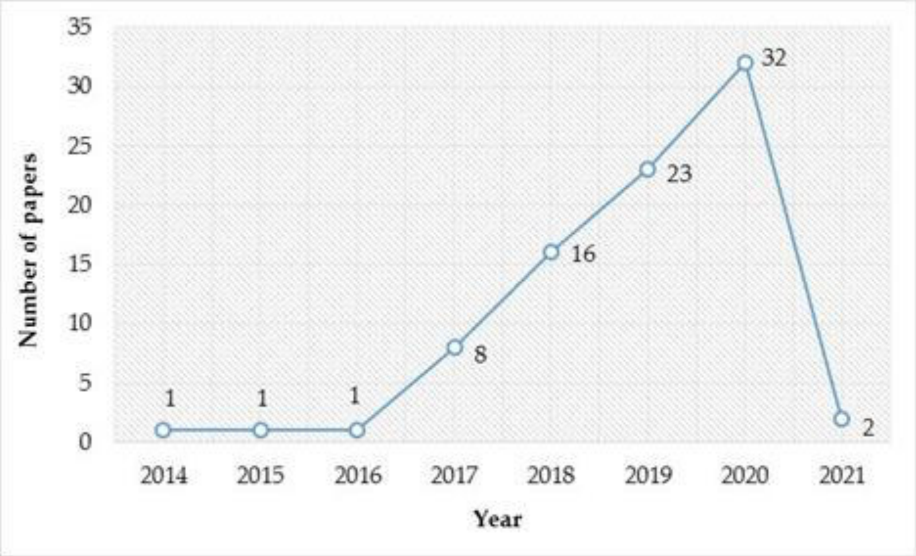

Figure 3. Publication trend by year.

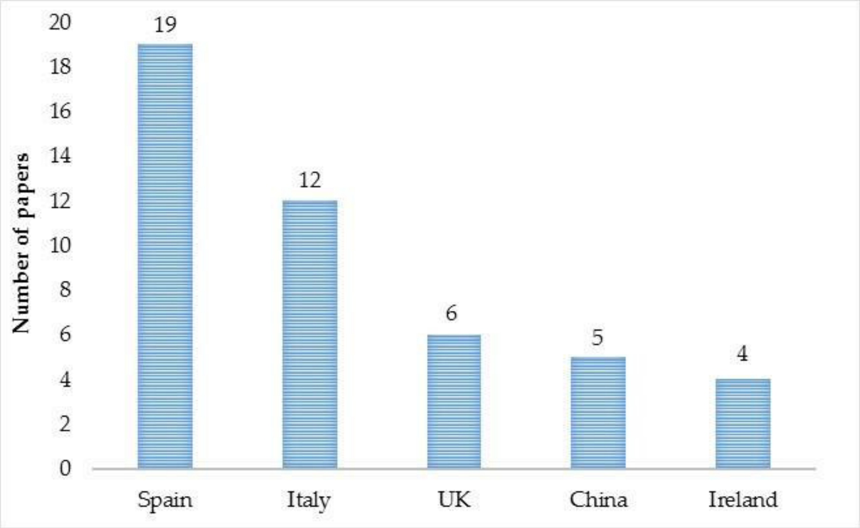

Figure 4. Geographical distribution by top publishing country.

Concerning the type of contribution, 83 articles out of 84 were published in scientific peer-reviewed journals and only one in proceedings of scientific international conferences. The highest-ranked journals were *Journal of Cleaner Production* (21*),* *Science of the Total Environment* (10), *Resources, Conservation and Recycling* (8), *Waste Management* (5), and *Sustainability* (4), with 57.1% of documents considered. This is due to the scope of these journals also related to the theme of the CE. The remaining journals showcased 2 or 1 publications each. All scientific journals were about sustainability topics and environmental issues, only one specialized in agricultural systems and food production (*Agricultural Systems*).

Figure 5 presents the main argument covered in the studies analyzed. In this review, we refer to the area of human activity or context in which the application is implemented. The waste and/or biomass fields of application were the most addressed by the published articles accounting for 55% of the total, of which 24 documents (29%) are strictly dedicated to wastes, 20 (24%) to biomass, and 2 (2%) to the whole of "wastes and biomass". Here, "Wastes" refers to the use and recycling of household wastes [37], wastewater [38], agricultural wastes [39; 40], food waste [41; 42; 43], and organic waste [44; 45], including recovery of nutrients [46], organic compounds, and energy [47]. This field is of great interest to European societies and academics, and constantly under a spotlight due to the recent publication of the waste management directives [48] that fall within the "Circular Economy package" adopted by the European Commission in December 2015 [49]. In the field named "Biomass", several kinds of goods (wood, garbage, crops, fruits, litter, manure, landfills gas, etc.) for energetic purposes (anaerobic digestion [e.g., 50; 51; 52; 53; 54, etc.) were included.

Around 15% of the studies were included in the "Manufacturing" field, which includes product production from raw materials (renewable or not). For instance, the manufacture of biochemicals and bio-based plastics is one of the strategies promoted by the European Union within the Europe 2020 strategy [55], as well as the production of bio-based packaging is an effective and promising climate change mitigation strategy [56]. The "Agriculture" field, accounting for 11% of the total, enclosed production of fruits and vegetables [57; 58] for fresh consumption or industrial transformation [e.g., 59] (raw materials, food, and no food).

Considering the reference product analyzed in the case studies, Figure 6 shows the most common ones in the selected papers. With 11% of the total, "Food waste" is the most represented product category. In this group, the authors were considered a heterogeneous set of products. For instance, [42] attempted to identify the optimal combination of food waste prevention by analyzing the quantity of food waste generated along five different food supply chain (i.e. grain, meat, fruit and vegetables produces, milk/dairy, and seafood). [37] analyzed the avoidable food waste amounts contained in household waste (fruits and vegetables, bread and pastries, fish, meat, dairy products, eggs, meal leftovers,), for waste prevention, energy recovery, or recycling purposes.

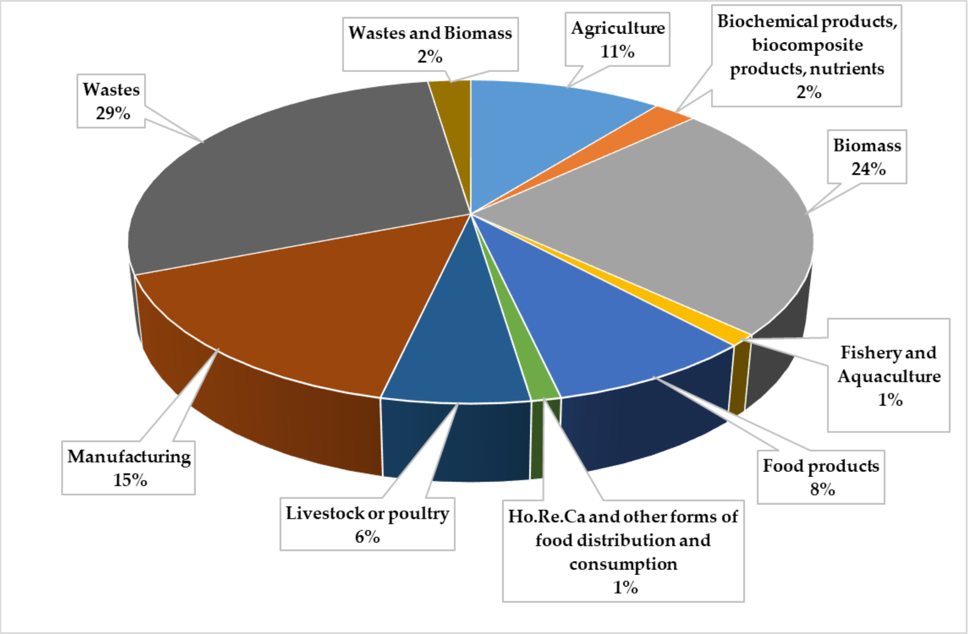

Figure 5. Fields of application.

Other main reference products identified in this review included several agro-industrial products, such as tomato [59; 60; 61; 62; 63], anchovy [34; 47; 64; 65], maize [58; 66], pig [67; 68; 69], olive [70; 71; 72], dairy [32; 73; 74], corn [44; 46; 75] and rice [57; 76; 77], as well as potato [78; 79], poultry [50; 80], beer [81], coffee [82].

The need to recycle nutrients like phosphorus has been widely considered as an important issue of a CE. For instance, [83] and [84] carried out an environmental evaluation of technologies for phosphorus recovery from sewage sludge to be applied on agricultural land as fertilizers (P-based fertilizers). As argued by the authors, phosphorus in wastewater should be utilized to avoid depletion of mineral phosphorus reserves, in line with the principles of a CE.

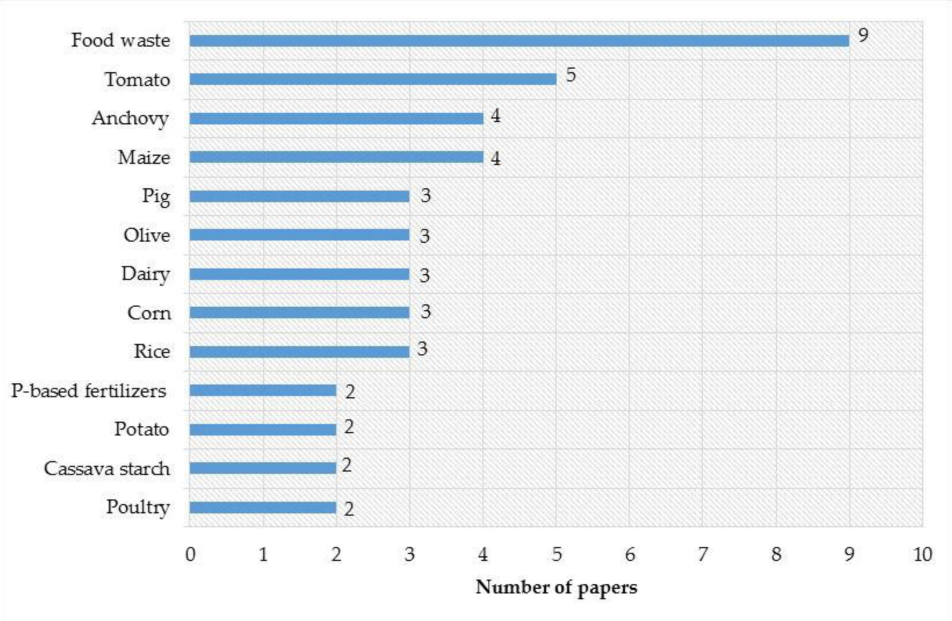

Figure 6. The main reference products in the literature review.

The most common “circularity topics” that emerged in this study’s final portfolio were closed-loop production systems, e.g., nutrient recovery for agricultural purposes, production of renewable energy, valorization of residues and wastes, food waste, and agro-wastes recycling for agriculture, as well as reduction of input, final wastes or product losses (Figure 7). Here, the “Waste valorization” topic, accounting for 32% of the total, is used to indicate retrieve elements from wastes or losses to be used for new purposes, such as extraction of biochemical feedstock and nutrients recovery [e.g, 85; 86; 87; 88; 89]. The second main circularity topic issued in this study refers to Energy recovery, with about 29% of the final portfolio. Incineration of material, usually biomass, with energy recovery [e.g., 90], composting for energetic purposes [e.g., 91], and anaerobic digestion [e.g., 92; 73; 79] were the recurring questions include in this topic.

To follow, the "Recycle" topic was observed in 15% of the total documents. In the present review, we refer to turning an item (products, co-products, by-products) into raw materials that can be used again, usually for a completely new product. For instance, composting and packaging recycling [e.g., 93; 94; 95]. In this topic, energetic purposes are excluded.

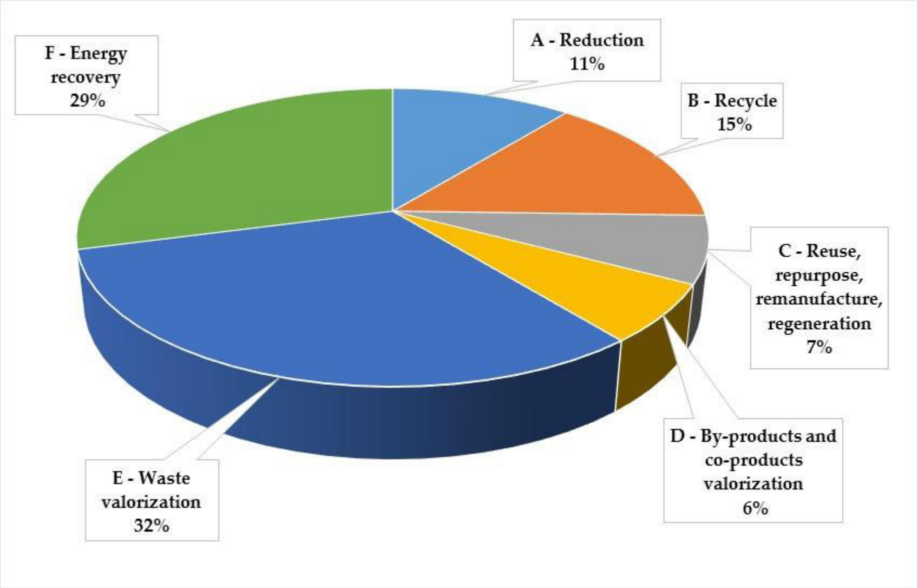

Figure 7. Most common "circularity topics" in the literature review.

2.3.2 Circularity assessment methods based on LC tools and other life cycle approaches

According to the findings shown in Figure 8, the most common LC tool adopted by papers to assess the benefits/impacts of CE strategies is LCA. This review found 52 case studies out of 84 (62% of the total) using stand-alone LCA. LCA is considered by all authors as the most suitable methodology to assess products, services, technologies in a CE perspective, including studies on biomass for energetic purposes, food products as well as biochemical and bio-composite products, waste reduction, and waste valorization also for energy recovery, manufacturing of products from raw materials (renewable or not). Most of the papers were published in 2019 and 2020, pointing out how LCA in the agri-food sector towards CE is a quite recent topic of research.

On the contrary, only 8 studies (9.5%) deal with the LCC methodology combined with other analyses. Of these, 6 adopt LCC combined with LCA [41; 55; 44; 47; 96; 74], 1 paper combine the LCC model with LCA and Material Flow Analysis (MFA) [75], and another with externality analysis in the CE perspective [97]. Finally, no paper deals with the sLCA methodology.

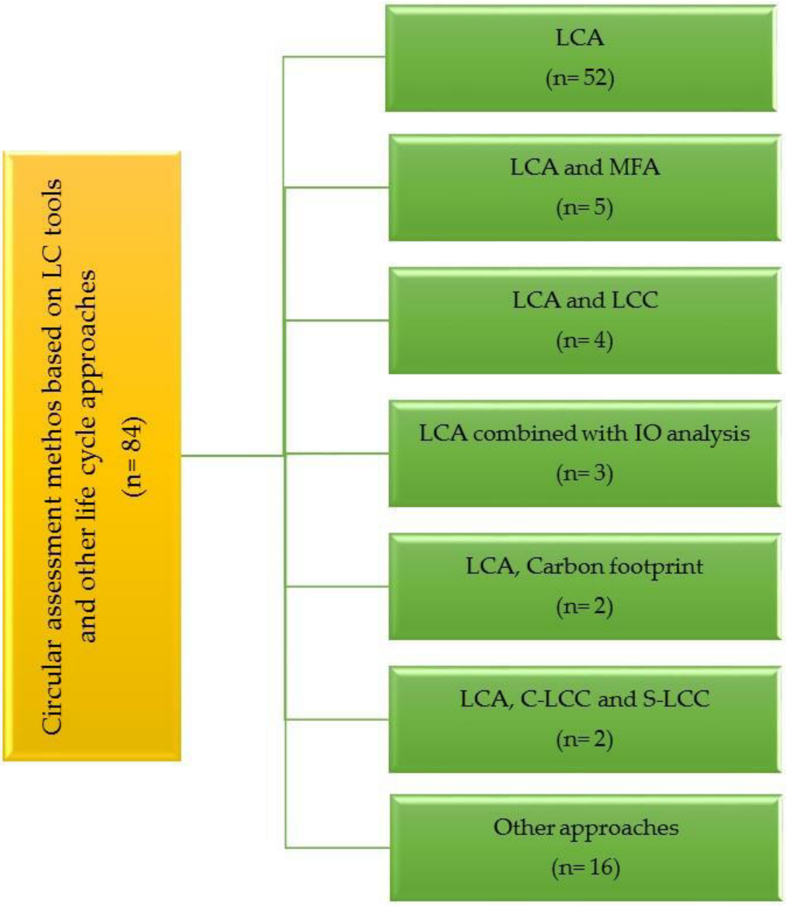

Figure 8. The main circularity assessment methods based on LC tools and life cycle approaches in the literature review. (*LCA=Life Cycle Assessment, LCC= Life Cycle Costing, MFA= Material Flow Analysis, IO= Input-Output Analysis, C-LCC= Conventional Life Cycle Costing, S-LCC= Societal - Life Cycle Costing, Other approaches= LC inventory analysis, Mass and Energy Balances, Cumulative Energy Demand, Energy flow analysis, Life Cycle Protein Assessment (LCPA), LCA-based waste footprint metric, Material flow model, Eco-Efficiency Analysis, Emergy Accounting method (EMA)*).

As described in Table 3, this literature review found 52 case studies applying stand-alone LCA to analyze the contribution of circular strategies to the principle of CE. Most of the reviewed LCA is performed following several impact evaluation methods that include multiple indicators representing up to 16 different impact categories.

In such final portfolio of papers, the most common LCA indicators were Global Warming Potential (or Climate Change or Carbon Footprint) applied in 58 papers (67% of the total), Eutrophication (for marine, freshwater, and terrestrial ecosystems) in 45 papers (55%), Human toxicity in 28 papers (35%), and Ecotoxicity in 25 papers (30%). According to Berti et al. [98], these impact categories have been documented to be the most appropriate for agricultural assessments.

The most applied method was Recipe, accounting for 38.5% of the total papers. For instance, [50], used the Recipe method in the hierarchic perspective to conducted a consequential LCA to examine several scenarios where biogas produced from poultry litter is used to generate heat and electricity or is upgraded to biomethane which can substitute natural gas. Among the impact categories (midpoint level) selected by the authors, climate change, acidification and eutrophication are recommended impact categories for LCA of bioenergy systems. Moreover, these impact categories related to carbon, nitrogen, and phosphorous flows are significant for agricultural systems. The ReCiPe midpoint method was chosen by [51], allowing for the assessment of the contribution of wood-based bioenergy plant, which utilizes local residues from wood industries and forestry operations, through several impact categories, i.e., climate change (GWP), fossil depletion (FD), ecotoxicity (FEP), human toxicity (HTP), photochemical oxidant formation (POFP), etc. [60] and [39] also used the ReCiPe method in a hierarchic perspective and at the midpoint level. In the first case study, the authors conducted a life cycle assessment of different productive uses of rooftops under Mediterranean climatic conditions, while, in the second case study, an evaluation of the environmental burdens of composting as a way to achieve a more circular valorization of wine waste.

The other two most applied methods in the literature review were CML (21.2%) and ILCD (17.3%). [80], for example, assessed four environmental impact categories using the CML method, i.e, global warming (GW), abiotic depletion (AD), acidification (AC), and eutrophication (EUT), to carry out an environmental life cycle assessment of poultry fat, poultry by-product meal and steam hydrolyzed feather meal obtained by rendering poultry byproducts. The CML-IA impact assessment method and eight of its impact categories (global warming potential (GWP100a), human toxicity (HT), fresh water aquatic ecotoxicity (FW), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (AC) and eutrophication (EU)), were applied by [106] for assessing the environmental impact of a redesigned mango food supply chain to improve environmental sustainability.

To evaluate the environmental performance of the animal feed from *Camelina sativa*, [99] used ILCD 2011 Midpoint + considering the following impact categories: climate change, human toxicity, terrestrial acidification, freshwater eutrophication, terrestrial eutrophication, and abiotic depletion. ILCD midpoint characterization method was also adopted by [100], to evaluate the environmental impact of the bioconversion of fruit and vegetable waste into earthworm meal to be used as new food/feed source.

Considering the importance of energy consumption in the agricultural systems, some authors also included in their analyses the cumulative energy demand (CED), an impact indicator that expresses the energy consumption throughout the life cycle of a product or a service [94; 66; 52; 62; 101; 102; 33]. Others focused on the primary energy demand (PED), which represents an appropriate indicator for illustrating the interactions of the food-energy nexus [59; 61; 82; 103; 92; 104].

Table 3. LCA framework in the literature review.

#	Authors	Case studies	LCA application	Impact evaluation method/categories or indicators*
1	Beausang et al. 2020 [50]	Poultry	Consequential LCA	ReCiPe 2016 method (midpoint level)
2	Belaud et al. 2019 [76]	Rice	LCA	ReCiPe 2016 method (midpoint and endpoint level)
3	Boesen et al. 2019 [93]	Liquid food	Streamlined LCA	ILCD 2011 method
4	Buonocore et al. 2019 [51]	Wood	LCA	ReCiPe method (midpoint level)
5	Campos et al. 2020 [80]	Poultry	LCA	CML method
6	Cascone et al. 2020 [94]	Plastic films	LCA	ReCiPe (endpoint level) + IPCC 2013 GWP 100a + CED + WFA
7	Casson et al. 2020 [105]	Street food	LCA	ILCD 2011 midpoint method
8	Chaudron et al. 2019 [85]	Cranberry juice	LCA	IMPACT 2002 + method
9	Colley et al. 2020 [20]	Meat	LCA	ReCiPe (endpoint level) + CML+ TRACI + USETOX methods
10	Corcelli et al. 2019 [60]	Tomato	LCA	ReCiPe Midpoint method
11	Cortés et al. 2020 [39]	Viticulture	LCA	ReCiPe 2016 method (midpoint level)
12	Cristóbal et al. 2018 [42]	Food waste	LCA	ILCD method
13	Eggemann et al. 2020 [54]	Cattle manure and straw residues	Attributional LCA	ReCiPe 2016 method (midpoint level)
14	Gaglio et al. 2019 [66]	Maize-germ oil	LCA	CML-IA baseline method
15	Keng et al. 2020 [95]	Food waste	LCA	TRACI 2.0 method
16	Krishnan et al. 2020	Mango	LCA	CML-IA method + WFA

	[106]			
17	Lansche et al. 2020 [52]	Cassava starch	LCA	CED + DEF + WSI + GWP + OFP + AP + HTP + ETP
18	Laso et al. 2016 [34]	Anchovy	LCA	IChemE, 2002 metrics + AA + GW + HHE + SOD + POF + AqA + AOD + Meco + NMEco + EU
19	Laso et al. 2018b [64]	Anchovy	LCA	Wc + Ec + Pc + Cei + EROI method
20	Liu et al. 2018 [107]	Corn straw	LCA	Life-cycle fossil primary energy and GHG emissions
21	Lokesh et al. 2020 [108]	Corn and sugar-beet	LCA	IPCC GWP + UNEP model + Accumulated exceedance model + EUTREND model - ReCIPe 2008 + USEtox model + CML 2002 + AWARE methods
22	Lucchetti et al. 2019 [86]	Ecological detergent	Partial LCA	EcoIndicator 99 method
23	Martin et al. 2019 [87]	Brewers' spent grains	LCA	CML 2014 method
24	Martinez et al. 2020 [99]	*Camelina sativa*	LCA	ILCD 2011 Midpoint +
25	Monsiváis-Alonso et al. 2020 [45]	Fish oil	LCA	ReCiPe 2016 method
26	Niero et al. 2019 [81]	Beer	LCA	ILCD method
27	Noya et al. 2017 [67]	Pig	LCA	ReCiPe Midpoint method
28	Oldfield et al. 2017 [59]	Tomato	LCA	CML 2001 method + PED
29	Oldfield et al. 2018 [109]	Food waste	LCA	CML midpoint method
30	Pérez-Camacho et al. 2018 [110]	Maize/grass silage and cattle manure	LCA	ReCiPe method (midpoint level)
31	Piezer et al. 2019 [61]	Tomato	LCA	PED + fossil fuels + renewable energy + dissipation
32	Qin et al. 2018 [40]	Tobacco	LCA	TRACI method (midpoint level)
33	Roffeis et al. 2017 [88]	*Musca domestica* and *Hermetia illucens*	LCA	not explicit
34	Roffeis et al. 2020 [89]	*Musca domestica* and *Hermetia illucens*	Attributional LCA	ReCiPe method (midpoint and endpoint level)
35	Rufí-Salís et al. 2020a [62]	Struvite recovery	LCA	ReCiPe 2016 method (midpoint level) + CED
36	Rufí-Salís et al. 2020b [111]	Tomato	LCA	ReCiPe 2016 Midpoint method
37	Rufí-Salís et al. 2020c [112]	Green bean	LCA	ReCiPe Midpoint method
38	Santagata et al. 2017 [113]	Animal waste	LCA	ReCiPe Midpoint method
39	Santiago et al. 2020 [101]	Onion	LCA	CML 2001 method + CED
40	Schmidt Rivera et al. 2020 [106]	Coffee	LCA	Recipe 2016 method +PED
41	Schmidt Rivera et al. 2019 [82]	Raspberries and meat	LCA	Climate change, Depletion of fossil fuels, Depletion of metals + PED
42	Sierra-Perez et al. 2018 [102]	Cork	LCA	ReCiPe 2008 method + CED
43	Slorach et al. 2019a [92]	Food waste	LCA	ReCiPe method (midpoin level) + PED
44	Slorach et al. 2019b [104]	Food waste	LCA	ReCiPe + Thinkstep (PED) methods

45	Smol et al. 2020 [84]	P-based fertilizers	LCA	ILCD 2011 Midpoint+ method
46	Strazza et al. 2015 [33]	Salmon breeding	LCA	IPCC report (GWP) + CED + WSI
47	Svanström et al. 2017 [83]	P-based fertilizers	LCA	ILCD method
48	Tedesco et al. 2019 [100]	Earthworm meal	Attributional LCA	ILCD midpoint method
49	Uceda-Rodríguezet al. 2020 [72]	Olive	LCA	CML 2000 (midpoint level)
50	Vaneeckhauete al. 2018 [68]	Pig	LCA	CML 2010
51	Wohner et al. 2019 [74]	Dairy	Streamlined LCA	ILCD 2018 method
52	Wolsey et al. 2018 [90]	Willow biomass	LCA	not explicit

** (CED= cumulated energy demand, DEF= deforestation, WSI = water stress index, WFA= water footprint assessment, PED= primary energy demand, GWP= global warming potential, OFP= photochemical ozone formation potential, AP= acidification potential, HTP= human toxicity potential, ETP= aquatic ecotoxicity potential, AA= atmospheric acidification, GW= global warming, HHE= human health (carcinogenic) effects, SOD= stratospheric ozone depletion, POF= photochemical ozone (smog) formation, AqA= aquatic acidification, AOD= aquatic oxygen demand, MEco= ecotoxicity to aquatic life (metals to seawater), NMEco = ecotoxicity to aquatic life (other substances, EU= eutrophication. EROI= Energy Return on Investment, Wc= water consumption, Ec= energy consumption, Pc= food, Cei= Climate).*

Few studies used water footprint (WF) indicator [94; 106], known worldwide for the assessment of environmental performance. Among the methods involved in LCA-based water footprint, the authors adopted the Water Footprint Assessment (WFA), a method centered upon computation of the Water Stress Index (WSI) that calculates the water impact on the consumption-to-availability perspective of freshwater deprivation.

As above-mentioned, few studies adopted LCC methodology as a tool for measuring CE strategies from an economic point of view. Table 4 summarizes all the reviewed papers that implemented LCC combined with other approaches. [41] and [55] performed a conventional (C-LCC) and societal (S-LCC) life cycle costing paired with LCA. The first authors used LCC to evaluate the socio-economic impacts of producing wet animal feed, protein-concentrated animal feed, and lactic, polylactic, and succinic acid from food waste. The LCC model implemented was the unit-cost method approach, where the waste management system under study is divided into stages (e.g. collection, transport, processing) and each stage is characterized by its relevant costs, classified into budgets costs, transfers and externalities. As argued by the scholars, LCC provides critical insights into process performance, giving a platform for more targeted technology optimization. The second authors used C-LCC and S-LCC to assess the economic aspects of the use of bio-based plastics in the fruit chain along the whole chain, following the methodological scheme expressed by [114] and [115]. Environmental externalities and their relative monetary value were also identified.

By combining the LCC model and externalities in the CE, [97] analyzed the benefits of using aluminum packaging in the food sector. The approach proposed by [116] was used to evaluate costs and benefit and to externalities. As discussed by the researchers, it is necessary to adopt the LCC approach as a useful economic model to guide the solutions for sustainable manufacturing and the CE vision. [75] and [44] used the economic model derived from SWOLF (solid waste optimization life cycle framework) to perform an LCC analysis to evaluate a waste management system that aims at recovering nutrients from municipal organic waste. [47] performed an LCC analysis based on the approaches described by [116] and [117] to assess the costs related to different waste management alternatives from fish canning industry. The scholars suggest that LCC can help to identify all steps that constitute an opportunity to reduce costs, helping decision-makers to choose a cost-effective project alternative. To estimate the economic implications of recovering energy and material resources from food waste, [92] applied LCC methodology following the guidelines published by [117] and [116]. Finally, [63] used LCC taking the value-added approach (VA) to evaluate the economic aspects of packaging-related food loss and waste of food-packaging systems.

Table 4. Main LCC features in the reviewed papers.

	Authors	**Case studies**	**LCC framework**	**LCC features**		
				Approach used	**Type of costs**	**Data**
1	Albizzati et al. (2021) [41]	Food 'aste	LCA, C-LCC, and S-LCC	Unit-cost method approach	-Budgets costs, transfers, and externalities	Statistic, Literature
2	Albuquerque et al. (2019) [97]	Aluminum and tinplate	LCC and PSILA, Externalities	Approach proposed by Hunkeler et al. (2008)	-Production cost -Overhead Costs -Depreciation	Interviews to stakeholder
3	Blanc et al. (2019) [55]	Berry fruit	LCA, C-LCC, and S-LCC	Methodological scheme expressed by Gluch and Baumann, 2004, and Neugebauer et. al (2016)	-Conventional costs for agricultural operations -Costs incurred for product transformation, sales, consumption, and disposal of waste -Environmental externalities	Face-to-face interviews with different actors
4	Cobo et al. 2020 [44]	Corn and wheat	LCA and LCC	Economic model derived from SWOLF	-Capital costs of the unit processes -Costs associated with the farmers' equipment and land	Data from SWOLF
5	Cobo et al. 2019 [75]	Corn	MFA, LCA, and LCC	Economic model derived from SWOLF	-Waste management costs	Data from SWOLF, Literature

6	Laso et al. 2018a [47]	Anchovy	LCA and LCC	Approaches described by Hunkeler et al. (2008) and Swarr et al. (2011)	-Costs of raw materials -Costs of anchovy processing and manufacturing --Costs of packaging -Management costs of waste treatment Value Added	Literature, Market reports, and actor information
7	Slorach et al. 2019c [96]	Food waste	LCA and LCC	Guidelines published by Swarr et al. (2011) and Hunkeler et al. (2008)	Costs to local authorities, operators of treatment facilities, and consumers	Literature, Statistics
8	Wohner et al. 2020 [63]	Tomato	Streamlined LCA and LCC	Value-added approach (VA)	-Costs to the ketchup producer for purchasing ingredients, energy, and packaging -VA of agricultural production of ingredients, energy and packaging, transports	Ecoinvent 3.5 database

(LCA=Life Cycle Assessment, LCC= Life Cycle Costing, MFA= Material Flow Analysis, C-LCC= Conventional Life Cycle Costing, S-LCC= Societal - Life Cycle Costing, SWOLF= Solid Waste Optimization Lifecycle Framework, VA= value-added).

In many case studies reviewed, CE strategies were assessed through LCA combined with other “life cycle-type” approaches, i.e. methods not directly ascribed to typical LC framework (i.e, LCA, LCC, and sLCA), but that approached the evaluation process in a life cycle perspective. Among the other methodological approaches most applied, there were Material Flow Analysis (MFA), Input-output (IO) analysis, and Carbon Footprint, implemented coherently with principles and methodological steps of an LC-based approach.

Five case studies adopted MFA accounting combined with LCA to evaluate the circularity of systems. Following the MFA modeling principles of Brunner and Rechberger [118], material flows of a system are measured in terms of their mass. [37] compared the environmental benefits of household food waste prevention to the benefits from various waste management strategies concerning recycling rates, energy efficiency, and emission efficiency, by using MFA model combined with published LCA results. The authors suggest that the most effective food waste management strategy seems to be a combination of prevention and recycling strategies. However, for mitigating climate change, the prevention of food waste clearly stood out as the most effective strategy. [119] studied the optimal configuration of a waste management system that valorizes the municipal organic waste (OW) in Cantabria, performing an MFA of the system and an LCA of the unit processes concerning the treatment of solid OW and the land application subsystem. The closed-loop perspective of the system analyzed by the authors is given by the application of products generated from the OW (compost, digestate, etc.) to land, which results in a reduction in the consumption of the industrial fertilizers. Their results indicated that an enhanced circularity of resources does not necessarily entail the decrease of both the overall consumption of natural resources and the emission of environmental burdens of the system. [46] also considered the circularity of nutrients within a system that handles the organic waste generated in Cantabria. They concluded that improving nutrient circularity paradoxically leads to eutrophication impacts, and increasing the source separation rates of OW has a positive effect on the carbon footprint of the system. [91] developed an LCA approach based on MFA to calculate the potential environmental impact of combined energy recovery and nutrient recycling from horse manure through anaerobic digestion in a centralized plant, replacing unmanaged composting. The authors indicated that anaerobic digestion is suitable to reduce potential environmental impact in comparison to unmanaged composting, mainly due to biogas substituting the use of fossil fuels. Finally, [73] propose an approach based on MFA and LCA for measuring the environmental performance of the anaerobic treatment of dairy processing effluents based on the CE principles. Their results showed that the recovered energy from AD provides 20% of the energy requirements of the factory reducing the total carbon footprint emissions by 13% compared to the baseline scenario.

This analysis found three studies applying Input-output (IO) technique combined with LCA. According to Miller and Blair [120], IO analysis uses a top-down, economic method to capture product and service flows from one industrial sector to all other sectors within one country, region, or multi-regions. As argued by Corona et al. [30], such a top-down approach has been applied by the LCA community to compensate for the shortcomings of process-based LCA (e.g., expanding the scope from the product level to national/global level). [77; 78], developed a hybrid life cycle assessment model integrating process-based LCA with IO analysis. In the first study, the authors implemented such an approach to evaluate the feasibility and potential benefits of a novel bio-fertilizer technology that utilizing paddy rice residues through composting. The bio-fertilizer can recycle the nutrients in residues to replace synthetic fertilizer within a circular rice production system. In the second study, the authors used a hybrid IO-LCA model to assess the environmental, social, and economic impacts of modifying conventional bioplastics production with a potato pulp residue left over from starch production to produce biocomposite. [121] also applied an IO-based hybrid LCA model to estimate total waste generation throughout the supply chain in Spain.

Only two studies applied the Carbon footprint of a product by using the LCA approach. [57] used the LCA concept for greenhouse gas emissions (LCA-GHG) to evaluate and compare GHG emissions of large-scale and individual farming in rice production, while [69] used LCA for analyzing carbon footprints in traditional and biogas-based circular economic models of pig farming.

2.4 Reviewed circularity assessment indicators

As shown in Table 5, only 8 articles deal with the CE assessment through specific indicators. As previously stated, in this review we refer to the classification of CE assessment indicators proposed by [30], who identify indicators that measure the circularity degree of a system, based on a mere material recirculation and addressed to resource efficiency, and indicators that assess the effects (burden or value) of circularity. Here, by LC-based indicators, we refer to the life cycle impact categories indicators retrieved from LCA, the LCC indicators when utilized for evaluating CE strategies, and stand-alone indicators based on life cycle approaches.

Purposes and advantages derived by the use of CE indicators have been widely argued in the literature [31; 122; 123; 124]. Due to the complexity inborn in the circularity economic paradigm, CE indicators combining different metrics can deliver simplified results.

Some CE indicators examined in this review were developed to assess the circular degree of a system. Within this topic, [46] developed indicators to study the circularity of nutrients within a system that handles organic waste (OW) generated in Spanish. More in detail, the circularity indicators of carbon (CIC), nitrogen (CIN), and phosphorus (CIP) have been applied to a circular integrated waste management system, which encompasses not only waste management, but also the processing and consumption of the components recovered from waste and the external raw materials. As argued by the authors, enhancing the circularity of these nutrients seems to be a suitable strategy for closing their natural biogeochemical cycles by avoiding the accumulation of nutrients in one of the Earth's subsystems at a rate faster than the ecosystems can sustain. The authors jointly evaluated the main environmental impacts associated with the emissions of these elements by using a set of indicators based on LCA, i.e., global warming, marine eutrophication, and freshwater eutrophication.

[125] used the energy return on investment (EROI) ratio, and a CE perspective, to develop an energy return on investment - circular economy index ($EROI_{ce}$) to quantify the amount of nutritional energy recovered from the food loss in the Spanish food supply chain. The $EROI_{ce}$ index, based on a food waste-to-energy-to-food approach (the energy recovered from food loss is reintroduced into the food supply chain in form of food), was developed starting from the calculation of primary energy demand (PED) of each stage of the food supply chain under study. Here, we consider this index as a "life-cycle based indicator" since it is based on the evaluating of energy flows along the entire food supply chain (agricultural production, processing, and packaging, distribution, and consumption).

Advancements in the assessment of CE strategies at the product level have been suggested by [81], who coupled two sets of indicators via multi-criteria decision analysis, i.e., material circularity based-indicators - namely, material re-utilization score (MRS) and material circularity indicator (MCI) - and a selection of life cycle based-indicators (climate change, abiotic resource depletion, acidification, particulate matter, and water consumption). The MRS is the metric used to quantify material re-utilization developed by Cradle to Cradle Products Innovation Institute (C2C), while the MCI is the main index developed by the Ellen MacArthur Foundation (EMF) and Granta to measure how well a product performs in the CE context. The authors suggest exploring the application of the multicriterial analyses of LC-based indicators (including the socio-economic dimension) to address CE trade-offs and rebound effects. In a complementary manner, [82] proposed a set of indicators integrating techno-environmental and CE criteria to guide the design and development of new food packaging solutions within the new plastics economy. In detail, the authors considered nine indicators based on the CE guidelines developed by EMF, which focus on the materials and energy used in manufacturing as well as on end-of-life waste management, and four LCA based-indicators, i.e., climate change, depletion of fossil fuels, and metals, and primary energy demand to assess the environmental impacts of packaging from cradle to grave. [73] also developed an approach for measuring the material and environmental circularity performance of the anaerobic treatment of dairy processing effluents. Material CE performance was assessed by the “Material circularity performance” indicator (MCPI), suggested by [126], which enables to evaluate to what extent the demand of resource or energy flows reduced when the circularity loops are closed. On the other hand, the environmental performance was estimated by the “Environmental Circularity Performance Indicator” (ECPI) based on the ratio of the total environmental benefits and costs.

Combining LCA (global warming potential, acidification potential, eutrophication potential, and ReCIPE single score) and LCC (value-added) indicators, [47] suggested a method to assess the eco-efficiency of canned anchovy products with the eco-efficiency index (EEI), which enables the translation into economic terms of the environmental damage caused by the manufacture of a specific product.

[108] proposed a new set of hybridized sustainability indicators, drawn from the principles of green chemistry and resource (material and energy) circularity, to evaluate the environmental performance of bio-based products, bio-based packaging films, and mulch films in comparison with their commercial counterparts. These metrics are demonstrated via the application of a comparative LCA, incorporating the hybridized indicators including hazardous chemical use, circular-process feedstock intensity (CPFI), circular-process waste factor (CPWF), process material circularity (PMC), product renewability (PR), and circular-process energy intensity (CPEI). Through a set of LCA indicators, the authors also highlighted the resource and energy hotspots and toxicity to the environment and human health, and the quantification of impacts from the minimization of resources. Last but not least, [127] used emergy-based circular economy indicators (no life cycle-based) to assess the sustainability of the urban eco-system. These indicators were developed by using Emergy accounting (EMA), which accounts for different categories of supporting contribution to the systems, including renewable and non-renewable energy and material resources, information and knowhow, and finally labor and services. The authors consider EMA indicators as valuable tools to evaluate the implementation rate of CE patterns.

Table 5. Classification of reviewed circularity indicators according to Corona et al. (2020).

#	Authors	Circularity Indices (Measuring the Circular Degree of a System)	CE assessment Indicators (Assessing the Effects of Circularity)		CE Application Level
			Life Cycle Based-Indicators	Other (no Life Cycle Based)	
1	Cobo et al. 2018a [45]	– Carbon circularity indicator (CIC) – Nitrogen circularity indicator (CIN) – Phosphorus circularity indicator (CIP)	– Global warming – Marine eutrophication – Freshwater eutrophication	-	Micro
2	Hoehn et al. 2019 [124]	– Energy return on investment-circular economy index (EROIce)	– Primary Energy Demand (PED)	-	Micro
3	Laso et al. 2018a [46]	-	– Global Warming Potential – Acidification Potential – Eutrophication Potential – ReCIPE Single Score (SS) – Value-added (VA) indicator – Eco-efficiency index (EEI)		Micro
4	Lokesh et al. 2020 [107]	-	– Global warming potential (GWP100), Respiratory inorganics, Human toxicity, Cancer, Acidification, Terrestrial and freshwater, Freshwater eutrophication, Water scarcity, Fossil resource depletion. – Hazardous chemical use, Circular-process feedstock intensity (CPFI), Circular-process waste factor (CPWF), Process material circularity (PMC), Product renewability (PR), Circular-process energy intensity (CPEI).	-	Micro
5	Niero and Kalbar, 2019 [80]	– Material Reutilization Score (MRS) – Material Circularity Indicator (MCI)	– Climate Change, – Abiotic Resource – Depletion, – Acidification, – Particulate Matter – Water Consumption	-	Micro
6	Santagata et al. 2020 [126]	-	-	– Emergy Yield Ratio – Environmental Loading Ratio	Micro

				– Renewable fraction of emergy used – Empower Density – Population emergy intensity	
7	Schmidt Rivera et al. 2019 [81]	– Amount of material – Mono or multi-components – Recycling content – Reuse rate – Current waste management – Current recycling rate – Potential recyclability – Use of renewable materials – Use of renewable energy	– Climate change – Depletion of fossil fuels – Depletion of metals – Primary energy demand (PED)	-	Micro
8	Stanchev et al. 2020 [72]	– Material circularity performance indicator (MCPI)	– Environmental circularity performance indicator (ECPI)	-	Micro

2.5 Discussion

Although it is not the only existing circularity indicator, it can undoubtedly be said that the Material Circularity Indicator is one of the most robust tools for assessing the CE, and since the development of the original methodology, published in 2015 by the EMF, the similarities between Life Cycle Assessment and Material Circularity Indicator became evident. Both methodologies use system boundaries that encompass all phases of a product's life cycle, from creation to end of life. What differentiates the two approaches, however, is that the assessment of circularity cannot be limited to one life cycle, as the circular pattern of one will inevitably influence the next. Slavishly quoting the methodology for measuring circularity: "*the economic and environmental benefits from using such materials do not commonly rest with the initial product but instead accrue through the successive use of the product or material over the multiple life cycles that they enable"* [128:13]. So first step to marry these two methodologies should be to extend the boundaries of the system by integrating into the horizon of the analysis product losses, recycling and reuse in the next cycle, transport, and all processes that allow closing the loop of the LCA methodology according to a circular approach.

The literature review found that only 20% of studies use a cradle-to-grave [e.g., 42; 55] system boundary, only three of these explicitly refer to a cradle-to-cradle or system expansion approach [46; 68; 56] and only one of these integrate a circularity indicator [46]. Most studies focus on a partial system boundary and, therefore, life cycle analysis is more limited to assessing the environmental profile of the process or co-product [e.g., 51].

The studies do not, therefore, aim at a true "circular strategy" since circularity is not really measured in most of them. Most articles use indicators relating to the use of material and energy resources but this is not enough to define the degree of circularity of a process or product, just as circularity alone cannot define sustainability.

LCA can assess the environmental impacts of a process and, through an eco-design approach, allows for the implementation of strategies to reduce these impacts, including a reduction in the use of resources and by considering the burden-shifting phenomenon whereby a change in one stage of the life cycle influences another one [129]. What attributional LCA cannot assess are rebound effects, a key element in sustainability assessments because it takes into account changes in production and consumption when the availability of a resource change (positively or negatively) [130].

For these reasons, the assessment of circularity must pass through a multi-component approach that takes into account not only circularity itself but also other characteristic elements. The Ellen MacArthur Foundation identifies as complementary analyses, to the evaluation of circularity, the evaluation of risk factors such as Material Price Variation, Material Supply Chain, Material Scarcity and toxicity, and the evaluation of impact factors such as Energy Usage and CO2 Emissions, Water and Toxicity [128].

The analysis of the papers shows the opposite situation, where the assessment of impact factors becomes the main driver for measuring sustainability [e.g., 57], while circularity rather remains a goal to be achieved but hardly ever explicitly measured.

If we acknowledge the need to expand the boundaries of the system from a cradle-to-cradle perspective, at the same time, we should be aware that stating that a process serves to make the usual business model more circular does not automatically prove that this is the case: it has to be proven.

While the use of classic impact assessment methods, as already mentioned, can give us an assessment of resource and energy use, it does not allow a complete evaluation of circular strategies, which are often based on other fundamental factors such as product lifespan or functional unit, understood as the unit of measurement of product use. We can make the same product, using the same amount of resources but, by increasing the efficiency of those resources by extending the life of the product, we can contribute positively to increasing the circularity of the process. This will probably not be detected by an LCA, especially if it does not take into account the use phase of the product.

This, moreover, may not apply to materials of biological origin, whose shelf life depends on factors not directly under anthropogenic control. However, in the case of food and agricultural products, extending the shelf life of products intended for consumption can make a significant contribution to the circularity of the process, reducing waste and thus increasing production efficiency. Moreover, as the results of the review show, lost food or products of biological origin that are no longer usable can easily be valorized in different ways, returning to the production cycle as fertilizers or generating bioenergy or bio-components with high added value.

The element that, however, appears clear and seems to be unavoidable, is that an LCA complementary to a circularity assessment framework should always assess the whole life cycle of a product and should consider its possible extensions, expanding also the time boundaries of the study by considering at least more than one life cycle.

A “Circular LCA” [128] also take into account a detailed Life Cycle Inventory analysis and consider “resource use” as one of mandatory impact indicator, or use specific supporting methodologies such as Material flow analysis which takes into account the flows and stocks of materials and substances entering and leaving a defined system.

Some works explore the use of methodologies in conjunction with LCA or stand-alone methodologies that take a life-cycle perspective. Above all, material flow analysis is a methodology that lends itself well as a supporting methodology for the assessment of circularity [37; 119]. Other methodologies such as IO Analysis applied to the life cycle of a product allow the assessment of environmental impacts to be integrated with the impacts of positive or negative economic shocks and possible concatenated reactions on the economy [78].

As proposed by Santagata et al. [127] Emergy Accounting can also be a valuable support for measuring circularity. The authors of the paper also point out that conventional analysis methodologies (Life Cycle Assessment, Material Flow Accounting, Cost-Benefit Analysis, among others) do not allow to capture all aspects of CE, proposing emergy accounting as a possible solution, however, this methodology is also at the center of many scientific controversies and does not enjoy a consensus shared by the scientific community.

It might seem that the LCA methodology can make little contribution to the development of circularity metrics, but this is not the case because LCA is a well established and standardized methodology while circularity assessment indicators are in development and their development is not in opposition to LCA but an ideal complement to it.

It should not be forgotten that talking about LCA is probably reductive since it should be part of a multi-objective framework (i.e. LCSA) aimed at analyzing the integrated sustainability of a process, product, system, or organization [29].

In this direction, as already discussed some studies have already explored the possibility of also using the Life Cycle Costing methodology in the assessment of circularity [41]. While the main circularity indicators are essentially based on the increase in the utility of resources within an economic model, an approach that assesses the life cycle value flows of a product, process, system or organization is a fundamental complement to both circularity and sustainability assessment. What has already been discussed for the LCA also applies to the LCC, so the community of experts in life cycle methodologies and the CE must accompany the approach of these methodologies, resolving the technical and scientific issues [21] that have only briefly been discussed so far.

While the methodologies discussed so far mainly refer to environmental and/or economic metrics, the role that the large-scale economic model change will bring to the social level cannot be neglected. Therefore, the efforts of the scientific community mustn't neglect the social sustainability linked to the adoption of a new circular model. And while the LCA and LCC methodologies are now scientifically established, the social counterpart of life cycle analysis, sLCA is still in an embryonic state, so it is essential to manage the growth of this methodology so that it is consistent with new business models.

sLCA is the latest tool developed within the family of Life Cycle methodologies. Since the nineties, life cycle scholars felt the importance and urgency of taking into account social impacts [131], with an implied sustainability approach borrowed from the three pillars model, meaning that sustainability is composed by three dimensions (environment, economy, and society).

However, sLCA is still not definitively codified in an agreed and consensus-based protocol. From its beginnings, a plethora of social impact assessment methods has been proposed for sLCA, paying attention to the most diverse aspects, such as the social performances, the presence of hot spots, the accounting of risks, the consequences of a scenario, the externalities of a system, and the participation of [132; 133]. Moreover, while LCA and LCC are focused on the impacts caused by the functioning of a system (whatever it is a product or a service), very often, in sLCA studies, the focus is on companies' behaviors. This entails, therefore, evaluating a wide range of impacts, also not directly attributable to a life cycle (such as corruption, child labor, collective bargaining, fair wages, among others). This is due to the epistemological eclecticism of social sciences, inevitably reflected in sLCA studies [132]. Recently, the second edition of the sLCA guidelines have been published [134], however, life cycle methodologies are still striving to reach an epistemological alignment, with LCA and LCC approaching impacts assessment in a post-positivist way, quantifying cause-effects relationships, and sLCA mainly devoted to the interpretation of social performances according to stakeholders' perceptions and behaviors.

In general, many academics and scholars describe social sustainability as the most conceptually elusive pillar in sustainable development discourse [135].

Among the papers selected for this review, no one applies the sLCA or another specific methodology for social impacts assessment. Rather, some kind of social impacts are explicitly associated, in some few cases, with economic performances, as it is the case of [41; 55; 77]. [41] and [55] who implemented the societal LCC to evaluate high-value products from food wastes, the former, and bio-based plastics the latter. Societal LCC is a "welfare-economic", meaning that takes into account marketed goods and the effects on the society's welfare caused by exchanges that would otherwise not be accounted for, i.e. by identifying environmental externalities and measuring their relative monetary value [55]. [77], applied a hybrid life cycle assessment model to estimate social-economic impact through a multi-regional input-output database (Exiobase), with engineering process data of conventional and circular rice production systems. The indicators used in this case were "gross value added" and "employment" in each system, therefore, taking into account "the social significance" of economic performance. [45], in their study, defined social issues as "product or process-related aspects of operations that affect human safety and community welfare". The authors illustrated the possible social criteria suitable in the study of chemical/ lipid processing, i.e. the satisfaction of social needs (SN), Work satisfaction (WS), Healthcare security coverage (HcS), Employee turnover (EmpT), Working hours (WH), Employee complaints (EmpC), and Risk Assessment. However, none of these mentioned criteria is calculated in their study. All the other papers reviewed, just mention the importance of considering the social aspects of the life cycle, mentioning sometimes the social acceptance or desirability [51], the social perception [68].

The lack of a specific, stand-alone, social impact assessment method in the papers here reviewed, but very often in sustainability assessments in general, let us make a reflection about the taxonomy and interconnections between "sustainability dimensions". Are they perfectly separable, or are they - at least - partly stackable? Do they have the same importance, or is there a hierarchy among them? These questions still remain open in the academic debate among life cycle scholars and practitioners.

2.6 Conclusions

This critical and systematic literature review provided a picture of the state-of-the-art of applications of the life cycle approach in the assessment of circularity of processes and products. Lights and shadows emerged: the relationship between circularity measurement and life cycle analyses still seem to be primordial, even though these two aspects are absolutely complimentary. CE measurement and life cycle methodologies should be like Manzoni's "The Betrothed" whereas as things stand, they seem almost like the protagonists of an arranged marriage, who are getting to know each other in order to decide whether to continue their lives together or separate.

The methodological development in this field is constantly evolving and new tools are increasingly being tested by the scientific community to identify the most effective ones, as well as to provide a measurement of circularity that takes into account sustainability issues. However, the scaffolding on which this methodological development must be based has already been built, and scholars cannot ignore it because there is a risk of making an irreparable mistake. In particular, experts in life cycle methodologies must strive to adopt some key elements to ensure that the results obtained fit perfectly with the measurements of circularity and that these can even be largely based on a common basis. The effort must also go in the direction of operability of the framework for measuring circularity and sustainability, so that it does not have the opposite effect of an assessment structure that is so complex that it is hardly usable, thus thwarting efforts to create new models of sustainable agri-food production and consumption.

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3. A CUSTOMIZED MULTI-CYCLE MODEL FOR MEASURING THE SUSTAINABILITY OF CIRCULAR PATHWAYS IN AGRI-FOOD SUPPLY CHAINS[2]

Abstract

Circular economy (CE) is claimed to be a promising pathway to achieve the Sustainable Development Goals (SDGs), but a reliable metric is needed to validate closed-loop strategies by measuring sustainability performances together with the degree of circularity. A significant contribution is offered by Life Cycle (LC) scholars in terms of methodological advances and operational tools for different sectors, also those more complex such as the agro-industrial systems that encompass biological and anthropogenic variables at different scales. However, to date, LC methodologies have not yet answered how to model the complexity of circular pathways. LC evaluations are often modelled for cradle to-grave analyses, while a circularity evaluation would require an extension of the system boundaries to more interconnected life cycles, orienting towards a cradle-to-cradle perspective. This research gap led us to propose a multi-cycle approach with expanded assessment boundaries, including co-products, into a cradle-to-cradle perspective, in an attempt to internalize circularity impacts. The customized LC framework here proposed is based on the Life Cycle Assessment (LCA), the Environmental Life Cycle Costing (ELCC) in terms of internal and external costs, and the Social Life Cycle Assessment (SLCA) in terms of Psychosocial Risk Factor (PRF) impact pathway. The model is designed to be applied to the olive-oil sector, which commonly causes significant impacts by generating many by-products whose management is often problematic. Results are expected to show that the customized LC framework proposed can better highlight the environmental and socioeconomic performances of the system of cycles, allowing CE to deliver its promises of sustainability, as the circularity of materials per se is a means, not an end in itself.

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[2] This chapter is based on the following scientific article: Teodora Stillitano, Giacomo Falcone, Nathalie Iofrida, Emanuele Spada, Giovanni Gulisano, Anna Irene De Luca (2021). A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains. Sci. Total Environ. 844, 157229. doi.org/10.1016/j.scitotenv.2022.157229. Personal contribution to the article: Emanuele Spada: Methodology; Investigation; Writing - original draft.

Keywords: Sustainability, Life cycle methodologies, Multi-cycle model, Circular economy, Agri-food sector, Olive-oil supply chain

3.1 Introduction

In line with the 2030 Sustainable Development Goals (SDGs), the global reference framework for sustainable development signed in 2015 by the United Nations, the European Commission prepared, at a macro level, the "Action Plan for Circular Economy" for a cleaner and more competitive Europe, trying to achieve a transition towards the climate neutrality by 2050 and decoupling economic growth from resource use (European Commission, 2020). Rodriguez-Anton et al. (2019), by analyzing the relationship between the CE and SDGs, asserted that an increase in the recycling rate of municipal waste, the recycling of biological waste, the use rate of circular material could significantly improve the sustainability of EU countries.

At a micro level, circularity practices can represent a practical chance to integrate sustainability into corporate goals (Maranesi e De Giovanni, 2020). According to Machin Ferrero et al. (2022), to increase the sustainability of products, Circular Economy (CE) strategies implementation must seek to return to the process as many materials and energy flows as possible by reducing waste and pollution. To measure product circularity performance several methods and tools have been tested (Ellen MacArthur Foundation, 2015; Saidani et al., 2017). However, most circularity metrics focus their analysis on material flows occurring in relation to a process or a product, overlooking the nature of the materials in circulation and especially in not considering the environmental, economic, and social impacts generated by circular strategies. As stressed by Goddin et al. (2019), who update the original methodology for calculating the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2015), to overcome these limitations, a circularity assessment should find its methodological complement in Life Cycle (LC) management tools. Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) have long been recognised by the scientific community as tools that enable comprehensive sustainability assessments (De Luca et al., 2017).

In recent years, LC scholars and practitioners are also making a significant contribution in terms of methodological advances and operational tools to circular economy studies (Niero and Hauschild, 2017; Rigamonti and Mancini, 2021). However, despite these efforts, LC methodologies still have not consensually solved how to model the complexity of closed-loop strategies (Corona et al. 2019). In other words, to fully exploit the potential of LC methodologies, which originally have been conceived mainly for linear processes, should be properly customized for circular systems. Indeed, LC evaluations are often modelled for cradle-to-grave analyses, while a circularity evaluation would require an extension of the system boundaries to more interconnected life cycles, always orienting towards a cradle-to-cradle perspective, to include the reuse of materials, their remanufacture and recycling. Therefore, to combine the two approaches, it is necessary to extend the boundaries of the traditional LC methodologies and assess the likely impacts for each next life cycle, in a continuous or closed process of production, recycling and reuse. However, the difficulty lies in defining at which level, to what extent and from which perspective these loops should be closed. As argued by Liu and Ramakrishna (2021), when comparing circularity indicators with LC approaches, it must be ensured that the metrics are indeed being calculated on an appropriate basis.

Besides addressing the system boundary issue, circularity assessment metrics must also consider the inclusion of biological materials for more complex sectors, such as the agro-industrial systems, that encompass biological and anthropogenic variables at different scales. According to Del Borghi et al. (2020), the agri-food sector is the main consumer of freshwater resources in the world and over a quarter of the energy used globally is spent on the production and supply of food. The application of CE concepts, where conservative practices are implemented between the agro-ecological (primary production) and agro-industrial (commercial food production) subsystems, can mitigate the impact of current industrial agriculture and potentially contribute to the sustainability of the sector. However, as argued by Poponi et al. (2022), although the research progress in the CE field applied to the agri-food sector is constantly evolving, there is no yet a harmonized and shared way of measuring it. As highlighted by Stillitano et al. (2021), who carried out a systematic review of the scientific literature on LC applications from the CE perspective in the agri-food sector, LC methodologies are not fully implemented or exploited to provide a circularity measure in a life cycle perspective. They found that in most of the reviewed studies the circularity is not really measured. Most articles use indicators relating to the use of material and energy resources, but this may not be enough to define the degree of circularity of a process or product, just as circularity alone cannot define sustainability.

These gaps in scientific literature led us to propose the following research question: How can LC methods measure the effects of closed-loop pathways? In answer to this inquiry, the present contribution provides a proposal of a customized life cycle framework adapted to evaluate circular economy strategies, by including biological cycles and being able to capture all sustainability dimensions. Therefore, we propose a model with expanded assessment boundaries, including co-products valorisation, into a multiple life-cycle perspective (cradle-to-cradle) that allows for the evaluation of the environmental, economic, and social effects over time of adopting circular economy strategies. The time horizon is extended for more years following the characteristics of the biological cycles involved and the circular technologies considered, which also means including in the assessment all those cycles and sub-cycles connected with each other. The LC framework here proposed is based on the LCA, the Environmental LCC (ELCC) in terms of internal and external costs, and the SLCA in terms of Psychosocial Risk Factor (PRF) impact pathway. The model is conceived to be tested on the olive-oil sector, with the aim to implement the LC approaches in the agro-ecological (olive growing and harvesting) and agro-industrial (olive-oil extraction) subsystems, which commonly cause significant impacts by generating many by-products whose management is often problematic. Closed-loop strategies within the sector can make it possible to reuse by-products as a possible resource capable to move the system toward a model more sustainable and economically efficient.

To the best of the authors’ knowledge, this is the first study attempting to model a cradle-to-cradle life-cycle perspective by applying epistemologically aligned life cycle tools, to assess impacts of circularity practices including by-product valorization in olive-oil systems. The findings of this study could offer guidance for olive-oil operators in choosing technological solutions for by-products management and help to legitimate firms’ circularity claims.

The paper is structured as follow. Section 2 presents a recent literature overview on LC applications for assessing the sustainability of circular strategies in the agri-food sector. Section 3 introduces the olive-oil sector in terms of sustainability concerns and the mainstream approach for circular life cycle modelling. Section 4 illustrates a new proposal for a customized multi-cycle model in the olive-oil supply chain, and Section 5 argues on the main advantages and limits of the model proposed and concludes the discussion with proposals for further research.

3.2 Methodological advances in circular pathway assessment by Life Cycle tools focusing on the agri-food sector.

3.2.1 Life Cycle Assessment (LCA)

Circularity indicators, such as the most widely used of them, the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation (2015), focus their analysis on material flows occurring in relation to a process or a product, on a microeconomic scale, or in relation to a supply chain or an economic sector, on a meso- or macroeconomic level. The limitation lies in neglecting the nature of the materials in circulation and above all in not considering the impacts generated by circular strategies, in environmental, economic, and social terms.

To overcome these limitations, as highlighted by Goddin et al. (2019), circularity assessment finds its methodological complement in life cycle management tools. Environmental Life Cycle Assessment (LCA) has been the spearhead for the development and diffusion of Life Cycle Thinking (LCT), awakening with force interest also in long-established methodologies such as life cycle costing, used since the 1950s in investment appraisal (Strano et al., 2013). Standardized almost twenty-five years ago, LCA methodology has undergone a process of consolidation from the original norms (ISO, 1997), through a first substantial (ISO, 2006a; ISO, 2006b) and after a minor revision (ISO, 2018), to the latest update (ISO, 2021a; ISO, 2021b) that has overhauled both the methodological framework as well as the requirements and guidelines for its application.

The picture is even more complex if one focuses on biological processes. The agri-food sector is certainly one of the most interested in the development of circular strategies and therefore measuring the circularity of these becomes a fundamental requirement (Chiaraluce, 2021). However, many open questions are still not immediately reflected in circularity assessment methods. The attribution of material flows to the product may be simple for a brick (or for any product resulting from an industrial process), but not at all for an agricultural product. For instance, what proportion of nutrients incorporated into finished products comes from fertilizers applied and what from natural processes? What part of product is strictly linked to cultivation techniques and which one to biological phenomena such as photosynthesis? Is it useful to consider indicators such as lifespan or intensity of use of a product that has a natural shelf life and is inevitably consumed/exhausted during use? On these and other questions the scientific community is debating, trying to find computational solutions that allow an assessment of circularity and environmental impacts using available tools (Rufí-Salís et al., 2021).

In recent years the LCA applications to assess circular strategies, also in the agri-food sector, have skyrocketed, however, most of the applications are limited to assessing only the environmental aspects of new technologies or new "circular" management systems, leaving the assessment of circularity itself out of the objectives of the study. Other studies try to combine the LCA methodology with other customary methodologies such as "Material Flow Analyses" combined with life cycle studies, to provide an assessment of how a product's materials circulate (Stillitano et al., 2021).

Some studies limit the boundaries of the system only to the evaluation of the reuse or recovery process of a waste (e.g. Benalia et al., 2021) and, while this allows the analysis of possible burdens shifting, it does not allow to understand to what extent the valorization of waste can contribute to improving the circularity of the production process that generated it or of the production process that will benefit from its valorization. Apart from purely applicative studies, which are often affected by the aforementioned problems, there is a growing interest in the scientific community in more methodological issues, aimed above all at identifying possibilities for integrating life cycle analysis and circularity assessment methodologies, combining the potential of the two approaches in guiding the ecological transition (Peña et al., 2021). The main issue addressed in these studies is represented by the convergence of the concept of "life cycle" that, while in the usual definition of LCA has a "beginning" and an "end", in the concept of CE itself refers to a continuous or closed life cycle, which is configured as an unceasing process of production, recycling and reuse. Obviously, this represents a generalisation, and many questions remain open; as highlighted by Niero and Hauschild (2017) it is not effortless to define at which level, to what extent and from which perspective these loops should be closed.

3.2.2 Life Cycle Costing (LCC)

LCC is a method for evaluating the economic dimension of sustainability of a product or service, in which monetary costs across its entire life cycle are accounted. There are three types of LCC: i) Conventional LCC (CLCC), also called financial LCC that is synonymous with the total cost of ownership (TCO). CLCC takes into account stakeholders such as consumers, manufacturers, or project managers who are only interested in analysing the cash flows they directly incur; ii) Environmental LCC

(ELCC) where, in addition to the direct monetary flows of the product or service, the monetary value of the externalities (environmental impacts) may also be included. Results of ELCC can be useful for all stakeholders in the value chain or life cycle; iii) Societal LCC (SLCC) that includes the monetary value of externalities corresponding to environmental and social impacts and it should have interesting implications for stakeholders working in the government and other public authorities (Kerdlap and Cornago, 2021). Within the international scientific debate on sustainability assessment, ELCC has long attracted great interest. It has been defined as the logical counterpart of LCA analysis for economic evaluation, which goes beyond mere cost accounting and is entirely compatible with LCA (Klöpffer and Renner, 2008). ELCC allows for the estimation of external costs which are the equivalent monetary values of indirect damages that are not explicitly captured in the market (goods or services without a market). For this component, in 2011 a specific guideline was developed to build consensus for achieving an international standard that is comparable to the LCA's ISO standards. Since both tools consider a life cycle thinking perspective and LCA is well established, it made sense to use the LCA framework when specific guidelines for LCC studies are not available (Swarr et al., 2011). Thus, LCA-LCC integration is accomplished by adopting a common database, considering the same functional unit and system boundaries, and following the same methodological steps. Although the use of such a structure does not guarantee synergy as debated by Heijungs et al. (2013), given the lack of standardization for the integration of LCA and LCC, this practice offers the opportunity for closer alignment between these tools (Rödger et al., 2018).

LCC methodology can be applied to support economic decision-making for products and services in a circular economy. Although activities such as reuse and recycling take place in a circular economy as opposed to a traditional linear economy, the way they are accounted for as costs and revenues in an LCC is not so different. While the main circularity indicators are essentially based on the increase in the utility of resources within an economic model, an approach that assesses the life cycle value flows of a product, process or system is an important complement to both circularity and sustainability assessment. As argued by Bradley et al. (2018), CE and closed-loop can drive new sustainable innovations and an LCC model is needed to achieve a truly sustainable progress. In the context of a circular economy, several scholars attempted to use the CLCC, SLCC and ELCC approaches (Kerdlap and Cornago, 2021). For example, about applicative studies in the agri-food sector, Blanc et al. (2019) and Albizzati et al. (2021) performed the CLCC and SLCC, combined with LCA, to provide critical insights into process performance, giving a platform for more targeted technology optimization. The former analysed conventional costs from cradle-to-grave of bio-based plastics in the raspberry supply chain, followed by an estimate of externalities by using ExA (externality assessment) model to assess the social aspects of the analysed scenarios. The latter calculated budget costs and transfers expressed in factor prices as considered in CLCC, and budget costs and externalities expressed in shadow prices as in SLCC for evaluating the socio-economic sustainability of high-value products obtained from mixed food waste as a feedstock. A broader approach can be found in studies that combine environmental and economic aspects by using LCA and ELCC. In terms of ELCC aligned with LCA analysis, the study proposed by Mayanti and Helo (2022) highlighted the importance of integrated environmental and financial assessment as a key to improve decision-making also in a circular economy environment. The scholars used ELCC in terms of budget costs and transfer cost (excluding externalities) by employing the same assumptions and physical parameters of LCA, to evaluate the environmental and economic implications of bale wrap films collection from the agricultural sector. Based on integrated life cycle analysis, Albuquerque et al. (2019) conducted a cost analysis by combining the product structure based integrated life cycle analysis (PSILA) and externalities by Miah et al. (2017), for evaluating the benefits of closed-cycle food packaging systems. The authors concluded that the LCC approach is a useful economic model to guide the solutions for sustainable manufacturing and the CE vision. In the study by Estévez et al. (2022), an economic evaluation of wastewater management systems to recover nutrients to be used for growing vegetables was carried out by using an ELCC with the estimation of internal costs as Capex (capital expenditures) and Opex (operating expenses), and external costs through monetization of environmental impacts by De Bruyn et al. (2018).

3.2.3 Social Life Cycle Assessment (SLCA)

Social Life Cycle Assessment (SLCA) is the latest LC tool in chronological order; it has been developed to evaluate the social impacts occurring during the life cycle, but it is still not consensually defined, and its process of development is being particularly long and difficult. According to Iofrida et al. (2018a; 2018b), in the process of transposing the impact evaluation method to social impacts, some of the typical elements and procedures of environmental LCA were difficult to hand over, such as choosing the functional unit, defining the system boundaries, setting the cut-off criteria.

Essentially, the intrinsic characteristics of social phenomena are very different from those of natural phenomena. Natural phenomena are studied within the realm of post-positivism research paradigms, which recognize that there is a single reality, which can be quite fully explained using cause-effect relationships, obtaining objective and statistically valid data. Differently, social sciences are multiparadigmatic, and the most diverse epistemological positions are possible (Iofrida et al., 2018a; Saunders et al., 2019).

The epistemological eclecticism of social sciences had repercussions on SLCA literature, leading to diverse methodological approaches proposed in the last years for SLCA, because of its roots in the cultural and scientific heritage of sociology and management sciences. Recently, UNEP (2020) updated the Guidelines for SLCA, providing some guidance for SLCA practitioners. According to the Guidelines, there are two main families of Social Life Cycle Impact Assessment (SLCIA) approaches, each of them responding to different practitioner aims: the Reference Scale Approach (Type I or Reference Scale impact assessment), and the Impact Pathway Approach (Type II or Impact Pathway).

Therefore, in SLCA, both interpretivist and post-positivist epistemological positions are possible (Iofrida et al., 2018a), with the first one evaluating (mostly in a qualitative and normative way) a wide range of impact categories mostly linked to companies' behaviour (e.g., child labour, corruption, fair salary, etc.), and with the second quantifying cause-effect relationships between life cycle functioning and Areas of Protection in an objective and generalizable way.

Recently, some authors analysed how the social dimension of sustainability is considered in circular economy studies, highlighting how social implications are the most disregarded aspect, especially in applicative studies (Geissdoerfer et al., 2017; Moreau et al., 2017; Merli et al., 2018; Schroeder et al., 2019; Padilla-Rivera et al., 2020; Walker et al., 2021; Mies and Gold, 2021).

Geissdoerfer et al. (2017) highlighted that the environmental performances of CE attracted most of the attention of scholars, avoiding a (necessary) holistic perspective of sustainability, focusing the attention on minimising resources input, waste, and emissions, which is an oversimplification of the CE concept. This narrow perspective is even more limited when concerning the social dimension (social well-being, quality of life) in many CE studies: very often social aspects are briefly considered, referring most of the times to impacts on occupation, human health, suggesting that it is not clear how CE could contribute to the improvement of social impacts (Geissdoerfer et al., 2017). This has been confirmed by Moreau et al. (2017:498), affirming that “the lack of thorough analysis of the necessary social and institutional conditions is considered an important barrier to the development of the CE”, mainly because social processes are strictly connected with material and energy flows (Cohen-Rosenthal 2004). Moreover, according to Ayres (1999), the anthropogenic stocks can be considered as a source of renewable flows subject to the availability of renewable energy, expanding the flows and funds model by Georgescu-Roegen (1988) (Moreau et al., 2017).

Social Circular Economy (2017) published a report in which social CE is described as the combination of circular business models (closed-loop production systems) and social enterprises, i.e., firms with a social mission. Therefore, from this source, social CE is considered an effective model to ensure that the economic activities do not harm society or the environment and an operative solution to meet more SDGs at once instead of just the responsible consumption and production, which is met by the CE alone.

However, there is no consensus about how, in practice, social aspects should be considered into CE studies (Padilla-Rivera et al., 2020). Even the Ellen MacArthur Foundation (2015), who is considered one of the main references for a long time, did not report how to measure social issues and how to incorporate these issues into circularity indicators. In a systematic literature review, Padilla-Rivera et al. (2020) found that, in terms of tools and metrics used for social dimension within CE, SLCA can be used to include social aspects of goods and services within a life cycle perspective, to complement environmental and economic dimension of CE.

Concerning applicative studies about social CE in the agricultural sector, very few papers have been published, but the reference to the circular economy consists mainly of a general framework. Aranda et al. (2021) analysed the social impacts of the meat supply chain to prove the versatility and utility of SLCA (PSILCA database) to help companies quantifying and understanding their social performance from a holistic point of view through different social indicators assessed from a life cycle perspective. The study by El Wali et al. (2021) focuses on the issues related to the social sustainability of circular phosphorus economy at regional and global scale, addressing some of the SDGs linked to global phosphorus management. The authors showed that the circular production model contributes to reductions in poverty in middle and low-income regions and it aims to sustain water with a 53% savings worldwide.

However, Mies and Gold (2021) affirmed that SLCA and social organizational LCA (SOLCA) are not sufficient because they mainly focus on workers and health-related issues, even if this is not fully correct, because many different methodological approaches are currently possible for SLCA, making it an instrument adaptable to a wide range of situations.

Table 1. Overview of recent literature on LC applications for assessing the sustainability of circular strategies in agri-food sector.

Authors	**Field of application**	**Circularity topics**	**LC methodologies**			**LC approach used**	**Circularity degree assessment metrics**
Albizzati et al. (2021)	Food waste	Waste valorisation	LCA	CLCC/SLCC	-	- Consequential LCA - Budget costs - Transfer - Externalities by De Bruyn et al. (2018); Friedrich and Quinet (2011); Martinez-Sanchez et al. (2016)	-
Albuquerque et al. (2019)	Food packaging	Reduction	-	ELCC	-	- PSILA life cycle analysis - Externalities by Miah et al. (2017)	-
Aranda et al. (2021)	Meat supply chain	Waste valorisation	-	-	SLCA	- Product Social Impact Life Cycle Assessment (PSILCA) - Eora Database	-
Blanc et al. (2019)	Bio-based plastics in the fruit chain	Remanufacture and regeneration	LCA	CLCC/SLCC	-	- LCA by ISO standards 14040:2006 and 14044:2006 - Conventional costs - ExA (externality assessment) model	-
El Wali et al. (2021)	Phosphorus supply chain	Recycling	-	-	SLCA	UNEP (2020)	Material Flow Analysis (MFA)

Estévez et al. (2022)	Urban farming	Nutrient recovering	LCA	ELCC	-	- LCA by ISO standards 14040:2006 and 14044:2006 - Internal costs as Capex (capital expenditures) and Opex (operating expenses) - Externalities by De Bruyn et al. (2018) - Total costs by Net Present Value (NPV)	-
Mayanti and Helo (2022)	Agricultural plastic waste	Recycling	LCA	ELCC	-	- Consequential LCA - Budget costs - Transfer cost (excluding externalities)	-
Niero and Hauschild (2017)	Beverage packaging sector	Collection and recycling	LCA	ELCC	SLCA	- Life Cycle Sustainability Assessment (LCSA) - Cradle-to-Cradle (C2C) design framework	Material Circularity Indicator (MCI)
Rufí-Salís et al. (2021)	Rooftop greenhouse	Nutrients recirculation and material recycling	LCA	-	-	Attributional LCA	Material Circularity Indicator (MCI)

Source: Authors' elaboration.

3.3 The olive oil supply chain

3.3.1 Major sustainability concerns of the agro-industrial phases in the olive-oil sector

With a total area of around 11 million ha, the Mediterranean basin provides about 95% of the worldwide olive production (FAOSTAT, 2020). The olive oil sector is thus a significant source of income, but it is also one of the main consumer of resources and producer of wastes both in the olive cultivation phase (wood, branches, and leaves) and the processing phase (olive pomace, olive mill wastewater, and olive stones). Only in European producing countries, there are about 9.6 million tons year^{-1} of wastes from the oil mills and 11.8 million tons of additional biomass from the olive pruning process (Berbel and Posadillo, 2018). These wastes, if not properly managed, have a high environmental impact and high costs. Careful management can turn into a benefit for the company in socio-economic terms and environmental impact by being part of the circular economy strategies.

As with other crops, several environmentally harmful issues emerge from the olive cultivation phase. About the core process, among the main environmental and ecological concerns facing agricultural operators, the soil management, in particular with mechanical processes and the chemical control of weeds, is responsible to generate mainly compaction, oxidation of organic substance, destruction of wildlife shelters, pollution of surface and groundwater. Nutrition management, if not properly performed, leads to nitrate and phosphorous leaching, and eutrophication of water (Rodrigues et al., 2019), alterations in soil pH and cation exchange capacity. Mismanagement of canopy can lead to a higher incidence of phytosanitary diseases and vegetative-productive imbalances. Incorrect use of phytosanitary products results in drift with pollution of surface and groundwater, accumulation of heavy metals, reduction of biodiversity, including useful fauna (Calatrava et al., 2021). By way of example, olive harvesting, if mechanically carried out, can lead to phenomena of soil compaction, destruction of shelters for wildlife, and high spread of fungal diseases. Concerning irrigation, which is mandatory in super-intensive plants, the high use of water and the risk of salinization of the soil are, certainly, among the main concerns.

The extraction phase of olive oil generates by-products that, due to their high phytotoxicity, can have a high polluting load, threatening the fertility of the soil and the potability of the aquifers. The quantity and physico-chemical properties of the by-products produced depend mainly on the technological method used for extraction. In fact, according to the most common extraction methods to date, it is possible to distinguish the following typologies: traditional production process producing for a ton of olives between 400 and 600 kg of olive mill wastewater; three-phase production process between 1,000 and 1,200 kg of wastewater; and two-phase production process, which does not produce vegetation water but pomace with high moisture content. Mill wastewater has a high organic load and numerous contaminants (phenolic compounds), which are phytotoxic and poorly biodegradable (Ergüder et al., 2000; Vlyssides et al., 2017). The pomace of the three-phase plants having a low water content can be used for the extraction of pomace oil or sprinkled on agricultural land according to the regulations in force in each country. The wet pomace from the two-stage extraction, on the other hand, has a strong odour and a pasty consistency, making it difficult to manage and transport it.

In addition to the environmental issues, several concerns can affect the socio-economic performance of the olive oil sector, which may depend on the planting system (traditional, intensive, and super-intensive), the farming systems (organic and conventional), the productivity, the level of mechanization, the investments, and the management costs. In terms of economic impacts, the highest costs concern the productive means and the labour, above all in the traditional plants, hill scenarios, and in the farms characterized by a low level of mechanization (Bernardi et al., 2018, 2021). The social impacts may relate to the hours of potential exposure of workers to working conditions that can lead to health problems, the level of employment in this sector for rural populations as a significant source of income, as well as the maintaining the cultural landscape and identity (Iofrida et al., 2020).

3.3.2 Mainstream approach for circular life cycle modelling in the extra virgin olive oil production

The modelling of the life cycle is the cornerstone of a life cycle assessment and, the most commonly used approach involves structuring "the cycle" along with a substantially "linear" scheme that extends from the cradle to the grave of the product. All input and output flows will be referred to the main product, so the management of co-products in the modelling process may follow two different approaches: one, the most widespread, which foresees the definition of an allocation criterion to the co-product of the input and output flows (e.g., economic, or energy); the other which avoids the use of allocation criteria favouring the expansion of the system. This type of modelling is generally based on the attribution of a certain amount of avoided impacts by the production system, thanks to the substitution of some material or energy with the products of the by-product valorisation (e.g., if the co-product will be used to produce energy, the impacts related to the production of energy from fossil fuels will be avoided) (Houssard et al., 2021). Waste generated during the production process is generally considered as a "zero burdens" output product (cut-off approach) or they can be considered in an expansion approach if there is a process of enhancing those (Malabi Eberhardt et al., 2020). This last aspect is particularly connected with the evaluation of circular strategies that can also be based on the saving of raw materials or the improvement of the product in terms of its useful life or intensity of use. However, it also true that in most cases these strategies are based on the valorisation of waste, transforming it into co-products through techniques that foresee its reuse or recycling. Figure 1 shows the mainstream approach for circular life cycle modelling for the extra virgin olive oil (EVOO) production, where the cycle is designed according to a linear scheme. It is possible to distinguish the different phases of production: *i*) agricultural production (upstream processes), *ii*) industrial extraction of EVOO and bottling (core processes), and *iii*) distribution, selling and consuming (downstream processes), from which various by-products are obtained. The main by-products of the agricultural phase are the pruning biomass, which in the context of traditional management is burned in the field (Michalopoulos et al., 2020), with high environmental impacts due to the production of CO_2 (Perone, 2019). Its reintroduction during the agricultural phase by shredding could represent an efficient CE approach. This is a good source of organic substance that through natural mineralization can replace a part of chemical fertilizers. In the industrial processing phase, the following by-products can emerge: leaves obtained from the olive cleaning, vegetation water obtained from the olive washing and the separation phase, pomace (with high water content in two-phase mill), and olive stones. CE approaches could be the use of vegetation water after a settling period as irrigation water for the agricultural phase, the use of decomposed leaves as an organic soil improver, the use of olive pomace and olive stones as fuel to obtain the thermal energy needed for the processing plant (Benalia et al., 2021) or as organic fertilizer after a composting process. Moreover, considering the bottling phase, the possibility of recycling olive oil empty bottles would allow a great saving in environmental terms.

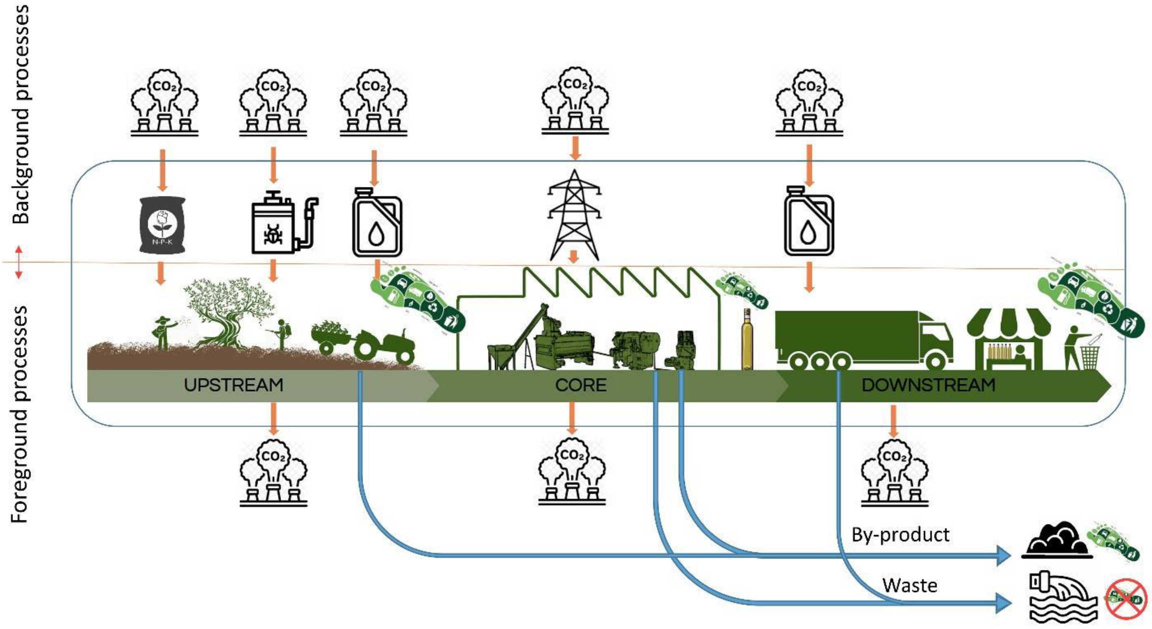

Figure 1. Mainstream approach for circular life cycle modelling in the EVOO production (Source: Authors' elaboration).

To our best knowledge, all recent studies from literature seeking to apply LC tools to assess the sustainability performance of circular strategies implemented along the olive oil supply chain seem to follow traditional linear schemes for life cycle modelling (from cradle to grave). For example, a "cradle-to-grave" approach was used by Pampuri et al. (2021) to perform an LCA analysis for assessing the environmental impact of lab-scale food preparations enriched with phenolic extracts from olive oil mill wastewater and olive leaves. Espadas-Aldana et al. (2021) and Uceda-Rodríguez et al. (2021) applied a "cradle-to-gate" approach life cycle assessment to evaluate the environmental benefits related to the olive pomace valorisation, as reinforcement in polymeric biocomposite materials and as an additive in the manufacture of lightweight aggregates, respectively. A similar approach has also been applied by Nikkhah et al. (2021) and Silvestri et al. (2021), who performed an LCA analysis to evaluate environmental impacts of olive kernel oil production systems and reuse systems of olive mill wastewater for the fired clay brick production, respectively

3.4 A proposal of a customized multi-cycle model in the olive-oil supply chain

Deepening the knowledge developed in the context of the evaluation of remanufacturing and recycling processes, it is possible to find references of a modelling approach that allows going beyond the classical concept of a "cradle-to-grave" life cycle to a broader "cradle-to-cradle" model (Suhariyanto et al., 2017). In particular, through the 6Rs (Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture) concept, it can be devised a life-cycle model based on a *"perpetual material flow in a sustainable multiple product life-cycle system" (*Jaafar et al, 2017: 37). This approach takes the form of a Multi-Life Cycle Assessment, which consists of considering multiple life cycles within the boundaries of the analysis. This modelling approach has not been widely accepted due to the complexity of carrying out such an extensive analysis, and few papers explicitly mention a multi-cycle approach (Suhariyanto et al., 2017). However, the increasing focus on the evaluation of circular economy strategies has given this approach a new lease of life, by addressing one of the main issues related to the interpretation of the concept of life cycle by circularity assessment models. Thus, in recent years, some studies have been published proposing the application of a Multi Life Cycle Assessment to assess circularity scenarios (e.g., Niero and Olsen, 2016; van Stijn et al., 2021). However, all the studies identified in the literature relating to multi-cycle applications refer to technical cycles, citing the nomenclature used by The Ellen MacArthur Foundation.

Considering that, this study aims to propose a multi-cycle modelling approach for the environmental, economic, and social evaluation of a product, adapting it to biological cycles. A life cycle analysis of the EVOO production will be carried out, following the requirements and guidelines for life cycle analyses (ISO, 2021b).

3.4.1 Methodological steps

Guided by the principles of transparency and repeatability of results, LCA is based on an accounting of material and energy input and output of the product life cycle, from the extraction of raw materials to the use phase of the product and its disposal at the end of its function. The ISO 14040 standard (ISO, 2021a) defines four distinct phases of an LCA: Goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. These phases follow an iterative scheme whereby one phase interacts with the other and is interdependent. Basically, the Goal and Scope phase defines the characteristics of the model that will be represented in the next LCI phase and that will be assessed and interpreted in the LCIA and Interpretation phases. The ELCC and SLCA approaches here proposed are meant to be aligned with the ISO 14040 and 14044 for LCA and follow the same steps (Table 2).

3.4.1.1 Goal and scope

The first phase of the analysis includes the definition of the objective and scope. The function of the system under study is the production of Extra Virgin Olive Oil (EVOO), therefore the Functional Unit (FU) chosen will be 1 Litre of EVOO.

The crucial issue will be the definition of the system boundaries, and in particular, the life cycle model is based on the interdependent evaluation of different life cycles. The extension of the system boundaries to several production cycles, enables to consider a closed-loop system for all intents and purposes - in a cradle-to-cradle perspective - even if the distribution, use and disposal phases of the product are excluded from the analysis, since the waste produced during the cultivation and processing phases are included in terms of valorisation and/or recycle, so that it can be reused in the next cycle or other production cycles, generating a reduction in the flow of virgin material from the second cycle onwards. The prerogative to consider within the system boundaries also the processes of waste valorisation allows taking into account possible burden shifting (Figure 2).

The multi-cycle model, in fact, includes within the system under study also the processes of valorisation of co-products and waste, thus making it possible to assess all the impacts generated for their valorisation within the boundaries of the system. In this way, for example, the substitution of fertilisers will not simply be considered as an avoided impact, but the impact of its replacement will be evaluated.

Another factor to be taken into account will be the procedures for attributing impacts to co-products are also a crucial issue to take into account in order to evaluate the multi-cycle scenarios. In this proposal, an effective mixed approach provides for an allocation system for the co-products whose secondary life cycle is interconnected to re-use/recycling processes within the system boundaries (e.g., exhaust pomace), while a System Boundaries Expansion with substitution (SBES) approach will be considered for those co-products whose secondary life cycle will not be interconnected to re-use/recycling processes within the system boundaries (e.g., extraction of polyphenols from leaves).

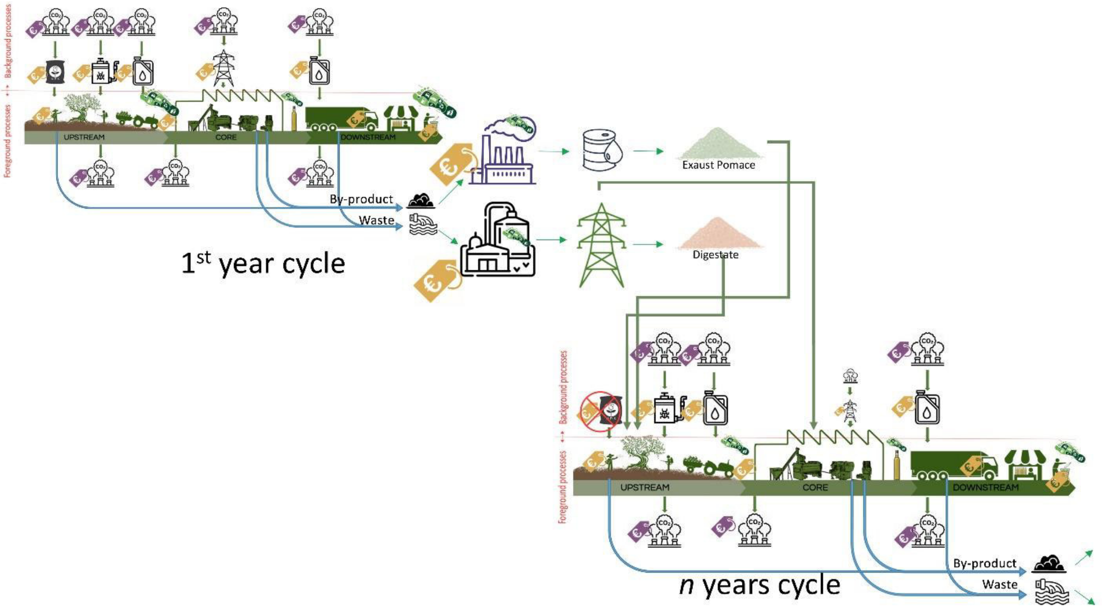

Figure 2. Design of the multi-cycle model to assess circularity pathways in olive-oil chain (Source: Authors' elaboration).

3.4.1.2 Life Cycle Inventory (LCI)

The second step is the creation of the Life Cycle Inventory (LCI). In this regard, it should be specified that the results of the inventory analysis are also used to define the incoming and outgoing material flows and therefore to measure circularity. For the LCA analysis of multi-cycle scenarios, the availability of the widest possible amount of primary data is of utmost importance, with secondary data obtained from the most comprehensive life cycle inventory databases (e.g. Ecoinvent; Agri-footprint; World Food LCA Database), while data relating to emissions generated during production processes and waste and co-product valorisation will be estimated using specific consolidated estimation models, e.g., IPCC (2019) for the estimate of N_2O, Brentrup et al. (2000) for the estimate of nitrate leaching etc.

To accomplish a believable LCC analysis, the accessibility of reliable cost data is crucial. Farm-based data sources, independent data sources (i.e., public and updated statistical databases) and derived data by surveys and interviews, and expert opinions are useful for carrying out the inventory of internal costs, and in particular, also for materials and energy consumption production-related relying on the LCA's inventory analysis. However, the production data are expanded to cover all costs (investment costs, labour costs, and other overhead costs). Data for evaluating external costs are derived from LCA results and Environmental Prices Handbook (de Bruyn et al., 2018).

Concerning the SLCA's inventory analysis, the hours of exposure for each life cycle phase and task (such as planting, pruning, harvesting, input supplying, etc.), classifying the typology of exposure (manual or mechanical work, temperature, exposure to pesticides, noise, etc.) are scrutinized by conducting a scientific literature review on particular working, consuming and living conditions that entail exposure to psychosocial risk factors. Each verified statistical association retrieved from verified sources is classified according to its intensity.

3.4.1.3 Life Cycle Impact Assessment (LCIA)

The assessment of environmental impacts for this multi-cycle proposal will be performed using the ReCiPe (Huijbregts et al., 2017) assessment method, midpoint and endpoint version, for covering the characterisation of impacts as well as the contribution analysis of individual processes within a cycle and individual cycles within the multiple cycle systems (Goedkoop et al., 2013)

From the economic characterization, we will consider the ELCC methodology aligned with LCA to evaluate internal and external costs of the circular olive-oil system under study. Internal costs include the initial investment costs, the costs of materials and energy, labour cost, interests, ownership costs of machinery and land investments (i.e., depreciations, insurance, repairs, and maintenance), and administration overheads. To include external costs in an ELCC, the externalities need to be monetized by putting a specific value on the environmental impacts of a product. To date, the main path for calculating externalities and integrating LCA-LCC is to monetise environmental impacts resulting from LCA studies, struggling to translate environmental impacts into economic impacts. Starting from the LCA results obtained, the Environmental Prices approach (de Bruyn et al., 2018), which expresses the WTP for less environmental pollution in Euros per kilogram of pollutant, is applied through the SimaPro software to evaluate external costs. The environmental prices identified in the environmental prices handbook (de Bruyn et al., 2018) provide average values for the EU28, for emissions from an average emission source at an average emission site in the year 2015 and are distinguished on the environmental categories it values (Durão et al. 2019). Finally, the ELCC approach here proposed also envisages an investment analysis to determine the financial performance of the likely technologies involved in the circular scenarios under study. To carry out this analysis, annual cash flows are normally actualised considering the time of occurrence, as well as dynamic criteria like net present value, internal rate of return, and discounted payback period.

Concerning SLCA, the Psychosocial Risk Factor (PRF) impact pathway (Iofrida et al., 2018c; Iofrida et al., 2019) is applied to assess the social impacts of the olive growing production to highlight specific effects (if any) directly linked to the adoption of circular strategies. This methodology allows quantifying the risk of psychosocial impacts on different typologies of stakeholders, according to the duration of exposure to certain living and working conditions that can lead to health issues. Cox et al. (2000) defined PRF as the aspects and characteristics of work planning and management that can potentially lead to physical or psychological damage. Precisely, the psychosocial risks are measured using odds ratios (ORs), a statistical measure of the intensity of association between two variables, e.g., as the ratio between the odds of exposure for people with a disease and the odds of exposure for healthy people (Szumilas, 2010). Data are retrieved from validated scientific investigations, normally clinical and epidemiological validated studies that examined the relationships between specific living and working conditions and diseases (or disorders). For example, low incomes are strongly associated to myocardial infarction and to stroke (Min et al., 2017), the use of organophosphate insecticides increases the risk of Non-Hodgkins Lymphoma (Kobayashi et al., 2012), and the exposure to sun combined to the use of glyphosate (herbicide) increases the risk of asthma (Salameh et al., 2006).

Measuring the psychosocial risks with the ORs is a retrospective analysis of a phenomenon, expressed with a non-dimensional value, and it can assume values between 0 and + ∞: a value of 1 indicates that there is no association between disease and exposure, while values >1 indicate a positive association (the risk factor can provoke the disease/disorder); higher values show a stronger association between exposure and disease (Bottarelli and Ostanello, 2011).

A PRF matrix, where every condition of exposure that occurred in the scenarios is linked, as retrieved from scientific literature to a physical or psychosocial disease is constructed. The assessment of social impacts is then conducted through the quantification of hours when stakeholders areexposed to particular conditions that represent factors of psychosocial risks.

For the first time, an Impact Assessment Method based on PRFs and integrated into Simapro will be proposed to also allow the assessment of the social impacts of the same life cycle model considered for LCA and LCC analysis.

3.4.1.4 Interpretation of results

The results are interpreted through sensitivity analyses related to the variability of material flows within the closed system.

For example, in LCC analysis, the timing of costs is very important. As commodity prices are much more volatile due to the market mechanisms of supply and demand, costs with high price variability (e.g., fuel costs) must necessarily be subjected to an in-depth analysis to reduce the uncertainty of results in terms of how much a change of the variables, within a pre-established range, can affect them. Additionally, in cases where there is no single correct discount rate, the effect of different discount rates should be investigated through a sensitivity check.

Concerning social impacts, the sensitivity check aims at determining whether and to what extent the results of social evaluation may be affected by the previous methodological steps and assumptions about data, value judgments, activity variables, calculation of the social performance and social impacts (UNEP, 2020). Many methods and tools to support a sensitivity analysis are available for environmental LCA studies; to some extent these can be applied to S-LCA studies too (UNEP, 2020).

Table 2. The methodological framework of the multi-cycle model.

ISO 14040-44 (2021) phases	LCA	ELCC	SLCA
Goal and scope	Functional Unit: 1 Litre of EVOO; System boundary: multiple cycles in a cradle-to-cradle perspective; Allocation procedure: mixed approach/System Boundaries Expansion with substitution (SBES).		
Life Cycle Inventory (LCI)	Primary data: farm-based data sources. Secondary data: Ecoinvent, Agri-footprint, and World Food LCA databases; IPCC (2019) for the estimate of N_2O, Brentrup et al. (2000) for the estimate of nitrate leaching, etc.	Primary data: farm-based data sources. Secondary data: public databases, indirectly derived data (i.e., surveys and interviews, and expert opinions); data from LCA results and Environmental Prices Handbook (de Bruyn et al., 2018).	Primary data: farm-based data sources. Secondary data: literature studies.
Life Cycle Impact Assessment (LCIA)	ReCiPe (Huijbregts et al., 2017) assessment method using SimaPro software.	Internal costs: specific economic and physical parameters to calculate each cost; Investment analysis. External costs: Environmental Prices approach (de Bruyn et al., 2018) using SimaPro software.	Type II: PRF Impact Pathway using SimaPro software.
Interpretation	Retrieving conclusions and recommendations from results		

Source: Authors' elaboration.

3.5 Conclusions

Key issues emerge when comparing circularity and life cycle approaches. As previously mentioned, the main concern stays in the different views of the product life cycle. In the case of impact evaluation, the system boundaries focus on a single life cycle of a product (cradle-to-gate or cradleto-grave analyses); while the circularity evaluation would require a system boundary extension to more life cycles (cradle-to-cradle perspective), to include the reuse of components, their remanufacture and recycling. Therefore, an LC approach complementary to a circularity assessment framework should extend the boundaries of the system in a multi-cycle approach, by integrating into the horizon of the analysis product losses, recycling and reuse in the next cycle, transport, and all processes that allow closing the loop of the LC methodologies according to circular approach.

The assessment of both circularity and environmental, economic, and social sustainability of a system turns out to be even more complex when biological processes are involved. The olive-oil production, which encompasses both biological and technical cycles, is one example. Agricultural process evaluation involves difficulties related to the modelling of phenomena that are not completely under anthropic control. On the other hand, industrial process evaluation involves the difficulties associated with waste and by-product management.

Based on these assumptions, the methodological proposal here shown concerned the design of customized LC modelling, where a circular olive oil system of more interconnected life cycles is considered into a multicycle perspective (cradle-to-cradle), in an attempt to internalize circularity impacts. The model will allow for the evaluation of the environmental, economic, and social effects over time of adopting CE strategies along the entire olive-oil supply chain. In this sense, as example, the impact of chemical fertilizers replacement with by-products will be evaluate within the system boundaries. Specifically, the framework suggests implementing and applying the LCA, the ELCC in terms of internal and external costs, and SLCA in terms of impact pathway assessment to the agro-industrial system, from which many by-products are generated, causing several environmentally harmful impacts, and socio-economic concerns that can affect the performance of the olive oil sector. In this context, closed-loop strategies make potential wastes susceptible to being transformed into by-products, allowing their reuse within the sector or the recycling, enhancing, and adding value to the mand moving to more sustainable and economically efficient production and consumption patterns. Indeed, by using specific technologies, it is possible to manage the by-products as a possible resource capable of being converted into a source of income for the company (e.g., energy, organic matter, irrigation water). This could be useful to provide guidelines for olive farmers and entrepreneurs, who want to invest in technological solutions for the management of their by-products to reduce environmental impacts and increase profitability.

The proposed multi cycle model provides significant assets and advantages. First, it allows the application of three epistemologically aligned methodologies, LCA, ELCC and SLCA, able to target an overall sustainability assessment. The multiple cycle approach also makes it possible to highlight burden shifting among life cycle phases, as it consider within the system boundaries the processes of waste valorization. Our model is designed to be applied to open systems such as agricultural systems, where energy, nutrients, organisms and information constantly cross system boundaries. The multiple life cycle analysis for quantifying net flows among system components and into and out of systems will provide insight into the movements and effects of these processes over the long term. Another contribution of this research is related to the possibility of legitimizing firms' circularity claims, helping to build a framework for developing circular business models.

Future research will be aimed at testing the multi-cycle model here proposed at the micro level to validate its applicability and effectiveness on olive-oil farms, considering that its implementation in the micro dimension can also have extensive effects at the macro and/or meso scale. Analyzing the model in real case studies is therefore crucial to adapt it to the intrinsic complexity of human activities. Furthermore, for analyzing the potential trade-offs, holistic tools such as multi-criteria decision analysis should be used to combine LCA, ELCC and SLCA in order to identify the most effective CE practices in the long term.

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4. ENVIRONMENTAL IMPACTS OF THE OLIVE OIL SECTOR[3]

Abstract

This study aims to provide an overview of the main environmental impacts of the agribusiness sector with a specific focus on the olive oil sector, for which shortcomings of most used technologies and practices in terms of environmental impacts (e.g., waste generated, waste to landfill, recycling rate, GHG emissions, toxicity of materials) at farm and firm level are identified. In a first part of the study, the "Life cycle" that characterizes an olive grove and the various cultivation systems are defined. In the second part, the various techniques that can be used for both the agricultural and industrial processing phases are analysed. For each technical operation in the production process (e.g., fertilization, pest management, in the agricultural phase), the main variables and corresponding environmental impacts are described based on the technical implications. The environmental impacts generated by each technical operation have been traced to the main impact categories and corresponding protection areas.

Keywords: Agri-food sector, Olive-oil supply chain, Life cycle, Environmental impact, Sustainability.

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[3] This chapter is based on the following report: Spada E., Falcone G., Stillitano T., Iofrida N., De Luca A.I. (2021.) Identify shortcomings of most used technologies and practices in terms of environmental impacts at farm and firm level, as part of the research project DRASTIC PRIN 2017.

4.1 Environmental problematic in the olive oil sector

4.1.1 Production cycle and phases

The subdivision of the life cycle of the olive grove into the different physiological phases, to evaluate the environmental impacts through the Life Cycle methodologies, is a hypothesis made by several authors such as De Gennaro et al. (2012), Falcone et al. (2016), De Luca et al. (2018). The years of duration of each phase are linked to numerous variables, such as the cultivar and the type of cultivation. Table 1 shows the phases of the life cycle of an olive tree, the duration in years of the individual phases and the specific cultivation operations for each phase.

Table 1. Cycle duration and physiological phases in different systems of olive grove management.

	Traditional	**Intensive**	**Super-intensive**
Cycle duration (years)	65=<	55	14
Unproductive phase (years) Corresponding to the years in which there is no production, or this has not been taken into consideration, resulting in the collection being unsustainable from an economic point of view.	1-6	1-2	1-2
Technical operations	Breeding pruning; Soil management; Fertilization; Phytosanitary treatments.		
Growing production phase (years) Corresponding to the moment in which the production of the crop begins to be significant, increasing every year even by 100%.	6-11	2-9	2-6
Technical operations	Breeding pruning; Soil management; Fertilization; Phytosanitary treatments; Harvesting.		
Constant production or full production (years) Corresponding to the moment in which the production of the crop, reaching the maximum achievable, stabilizes	11-60	9-48	6-13
Technical operations	Pruning; Soil management; Fertilization; Phytosanitary treatments; Harvesting.		
Senescence phase (years) Refers to the period in which, due to the physiological conditions of the crop, a decrease in production occurs.	61-65	49-55	13-14
Technical operations	Breeding pruning; Soil management; Fertilization; Phytosanitary treatments; Harvesting.		
Disposal phase (years)	65	55	14

Figure 1 shows the production trend of a traditional olive grove with a cycle of 65 years. It is possible to notice the subdivision of the production phases and the duration of the same. In the constant production phase, there is a fluctuating production trend every two years; this is linked to the alternative bearing typical of some olive cultivars and sometimes accentuated by agronomically incorrect practices such as pruning and harvesting.

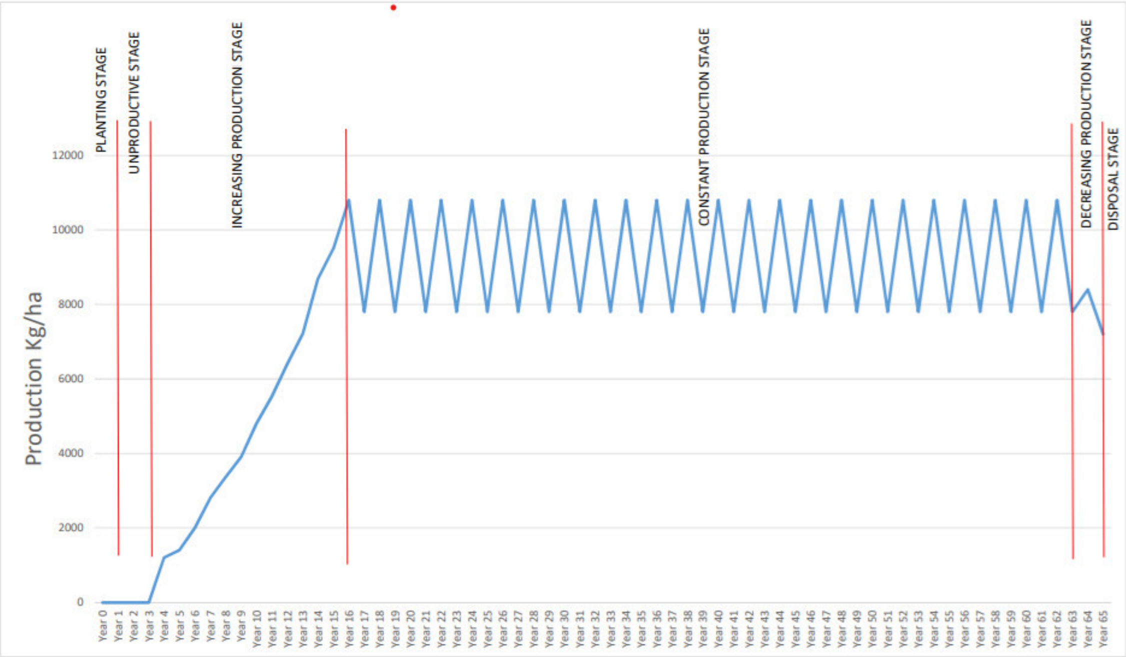

Figure 1. Production trend for the entire life cycle and phases in a "Traditional" olive grove.

4.1.2 *Impact categories*

Within each phase of the olive oil process, there are different technical operations. For each operation, there may be different environmental impacts. Table 2 shows the main impact categories related to the agricultural phase, better detailed in the following chapters.

Table 2. Impact categories of the technical operations in agricultural phase.

Agricultural phase							
Impact categories	*Unit*	*Soil management*	*Phytosanitary treatments*	*Fertilization*	*Pruning*	*Irrigation*	*Harvesting*
Global warming (GWP100):	Kg CO2 equivalent	▨	▨	▨	▨	▨	▨
Acidification	molc H+ eq		▨	▨			
Human toxicity, non-cancer and cancer effects	CTU h		▨	▨			
Mineral, fossil and ren resource depletion	kg Sb eq	▨	▨	▨	▨	▨	▨
Land use	kg C deficit	▨					
Freshwater ecotoxicity	CTU eq		▨	▨			
Formation of particulate matter	kg PM2.5 eq				▨		
Biodiversity loss	PDF ha-1	▨	▨	▨	▨		▨
Marine eutrophication	kg N eq		▨	▨			
Terrestrial eutrophication	Mol N eq		▨	▨			
Water resource depletion	m^3 water eq	▨				▨	

There are also different technical operations in the oil extraction process. For each of these operations there may be different environmental impacts. Table 3 shows the main impact categories related to the industrial phase of oil extraction, better detailed in the following chapters.

Table 3. Impact categories of the technical operations in industrial phase.

Industrial phase					
Impact categories	*Unit*	*Defoliation and washing*	*Malaxing*	*Extraction and separation*	*Pomace management*
Global warming (GWP100):	Kg CO2 equivalent	▨	▨	▨	▨
Acidification	molc H+ eq			▨	▨
Human toxicity, non-cancer and cancer effects	CTU h			▨	▨
Mineral, fossil and ren resource depletion;	kg Sb eq	▨	▨	▨	▨
Land use;	kg C deficit				
Freshwater ecotoxicity;	CTU eq		▨	▨	▨
Formation of particulate matter	kg PM2.5 eq				
Biodiversity loss	PDF ha-1			▨	▨
Marine eutrophication.	kg N eq			▨	▨
Terrestrial eutrophication	Mol N eq			▨	▨
Water resource depletion	m^3 water eq	▨		▨	

4.2 Technical operations in the agricultural phase

4.2.1 Soil preparation, support structures and irrigation

The **soil preparation** consists of deep tillage of the soil before planting to:

- favor the deepening of the roots and the percolation of water also through the removal of any mechanical obstacles;
- improve soil aeration;
- bury soil improvers and materials to correct the chemical composition and pH of the ground;
- complete the removal of root residues from previous crops.
- improve the availability of nutrients;

- mix any different layers of soil.

The execution of the deep tillage particularly important in compact soils, however favor the root development of plants, in which case it is necessary to reach a depth of 80-100 cm. In loose soils, on the other hand, if equipped with a good degree of natural ventilation and no water stagnation, it is sufficient to reach a depth of 50-70 cm.

Figure 2 shows the main environmental impacts related to the preparation of the soil for the cultivation and installation of irrigation.

This technical operation has the same environmental impacts of tillage as reported in the paragraph 4.2.

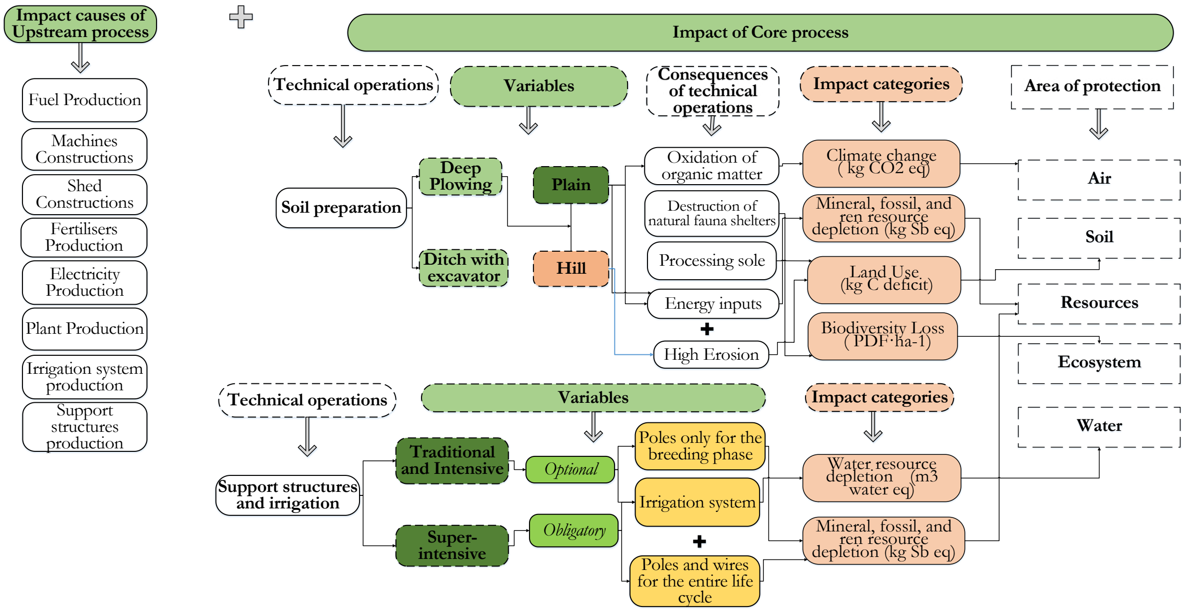

Figure 2. Environmental impact of soil preparation, support structures and irrigation in olive orchard.

Support structures for poles and wires: *Mineral, fossil and renewable resource depletion.*

Support structures are needed for the construction of an olive grove. In the case of an intensive or traditional olive grove, these are only necessary for the first years from the planting and are made up of wooden poles and if present the irrigation system iron wires. In the case of super-intensive plants, on the other hand, these are mandatory for the entire life of the plant.

Irrigation: *Water resource depletion.*

According to Guerrero et al. (2021), high-density olive growing, that requires mandatory irrigation, have been planting in the drier and warmer in which a higher irrigation amount is required. In this sense, year doses usually fall within the 2500-3600 m^3 ha^{-1} interval whereas rarely do they exceed moderate to low doses of 1500 m^3 ha^{-1} in irrigated olive groves with the lower tree.

In the study by De Gennaro et al. (2012), concerning Apulian olive growing, the authors report that the volumes of irrigation water to be provided annually are 480 m3 for intensive olive groves and 800 m3 for high-density olive groves. Such practice will progressively reduce the availability of freshwater (by 2-15% per 2 ° C of heating) and water reservoirs will be critically low, which means that it can endanger crop irrigation in further dry seasons. As the water availability of the aquifers is jeopardized. Furthermore, the energy used to irrigate has an important weight in the environmental impacts of olive groves (Romero-Gámez et al., 2017) and inadequate irrigation can also have negative consequences such as increased compaction and soil erosion.

4.2.2 Soil management

Tillage

The soil management of an olive grove, as in other arboreal and herbaceous systems, requires agronomic practices that allow maintaining in equilibrium the chemical-physical dynamic relationship between plant and soil. In addition, the interventions carried out must take into account the presence and activity of soil and soil communities, which contribute in an indissoluble way to form and constitute together with chemical and physical fertility, that which is the integral fertility of the soil.

Inappropriate soil management and cover lead to soil degradation and loss of productivity; decisive factor in soil degradation under Mediterranean climate is the loss and depletion of natural plant cover that opens the door to soil erosion and other degradation processes (Pascual et al. 2000).

Considering the great variability of the agricultural soil, it is necessary to customize the type of processing according to the environment and the state of the crop. Some variables and environmental impact of soil management in the olive orchard are reported in Figure 3.

In addition, everything is related to the soil moisture conditions, because of precipitation, therefore the periods of execution may vary each year. The soil can be carried out in many ways, usually, by leaving the soil ordinarily without vegetal cover, by working and weeding, or, by permanently managing the vegetal cover, using continuous mowing.

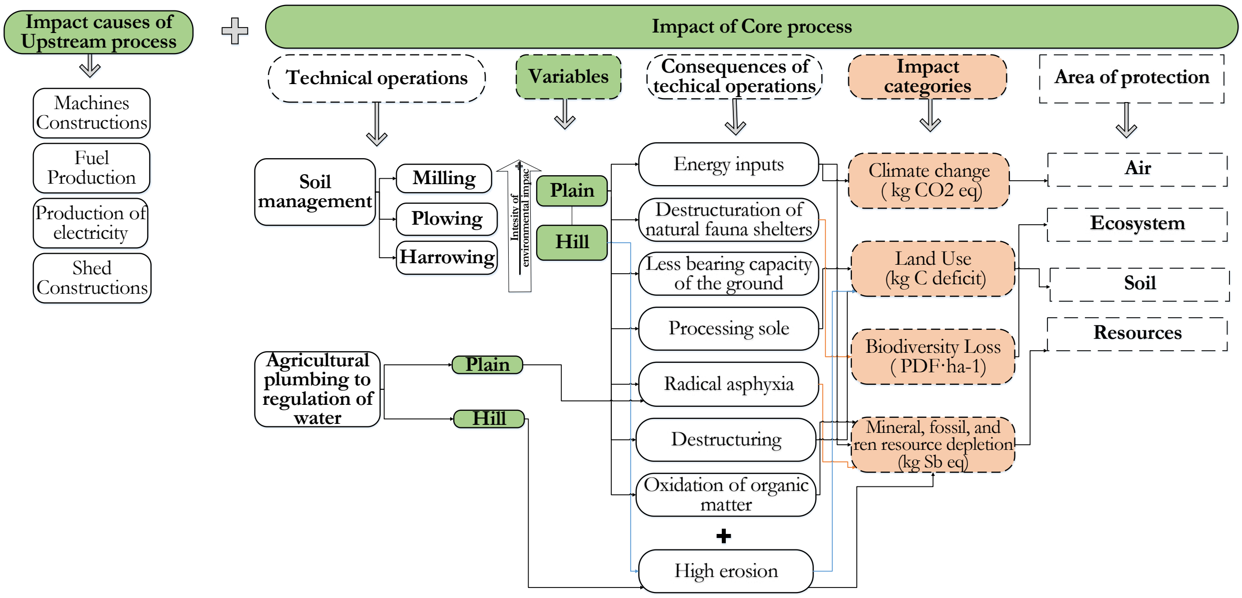

Figure 3. Environmental impact of soil management in the olive orchard.

Among the main consequences of tillage in olive groves that generate environmental impacts, are the following:

- Energy input
- Destruction of natural fauna shelters
- Less bearing capacity of the ground
- Processing sole
- Radical asphyxia
- Oxidation of organic matter
- Destructuration
- High Erosion

Oxidation of organic matter

An environmental problem that derives from the processing of all soils is the oxidation and mineralization of organic matter (Massaccesi et al., 2018). In olive groves, this condition is more evident as the cultivation environments are characterized by an already low content of starting organic matter and for the warm climate. With mechanical processing, there is greater exposure of the soil to air. It concerns all types of soils both weaving and lying (Proietti & Regni, 2019; La Posta et al., 2013), both new plants and secular olive groves for example in Apulia (Simeone et al., 2013).

Destruction of natural fauna shelters e influence on soil microorganisms.

The soil processing in the olive groves through disruptive action destroys the shelters for wildlife, including earthworms (Sanchez-Moreno et al., 2015; La Posta et al., 2013). Moreover, as reported by the studies carried out for olive growing in Campania, the availability for frugivore birds is reduced (Celano et al., 2005). Overall, these conditions are reduced in the reduction of biodiversity, which is an environmental problem Overall, these conditions are reduced to the reduction of biodiversity, which is an environmental problem.

According to Montanaro et al. (2017), soil microorganisms are sensitive to soil disturbances since the soil environment is their habitat. Agricultural fields are managed ecosystems, so external factors (e.g. soil tillage, fertilization, pesticide application) could interfere with the abundance of soil microorganisms and related natural processes and services. According to Simoni et al. (2021), with the mechanical working of the soil in the olive grove, the presence of micro-arthropods that perform important ecosystem functions contributes to the health of the soil and plants through their intersecting roles in decomposition and the nutrient cycle and the direct and indirect suppression of plant parasites.

Processing sole

The development of the "processing sole” occurs mainly with the use of plows and milling. It is a thin waterproof layer that is formed below the processed layer in soils relatively rich in clay or loam, which reduces the infiltration of water into the deep layers of the soil (Proietti & Regni, 2019).

Energy input

Soil tillage in olive groves is a rather expensive land management technique in terms of necessary machines, fuel and labor on average 8-12 hours per hectare per year (Proietti & Regni, 2019).

High Erosion

Soil erosion in olive groves is a particularly serious environmental impact problem caused by the mechanical processing of the soil.

The erosive phenomenon is the result of the combination of many factors, including soil type, slope, atmospheric precipitation patterns, and inadequate agricultural practices

(Camarsa et al., 2010). Caliandro et al. (2005) in their writing “Role of olive growing in the fight against desertification” report that among the most important olive-growing regions of Italy Calabria is the one where erosion affects the most due to the predominantly hilly location. In Apulia, this problem is less widespread due to the spread of olive growing, especially in the plains.

The same problem is found in Campania, especially in inland areas such as those of Irpinia characterized by high slopes, heavy soils, high values of the climatic erodibility factor, determines important erosive processes especially in the spring and late summer, when the rainy events of greater intensity occur (Celano et al., 2005).

Continuous tillage to control weeds and the lack of cover crops make the soil particularly exposed to the typical Mediterranean heavy and intense rainfall in autumn-winter, with an adverse effect in terms of soil and organic matter depletion (La Posta et al., 2012).

Carmarsa et al. (2010) and Proietti & Regni (2019) report that soil erosion is one of the most serious environmental impacts associated with intensive olive cultivation. Erosion reduces the productive capacity of the soil and, therefore, reduces productivity, and this translates into wider use of fertilizers with other environmental effects. With the removal of the soil, fertilizers and herbicides are also often washed away. In the long run, it leads to desertification and land degradation. Sometimes in the hills the severity of erosion and the relative repercussions on the productivity of trees are often not adequately considered, as the continuous leveling of the soil surface implemented with the tillage can mask the phenomenon. Every year it can stress the loss of soil per hectare (in hilly soils the erosion can easily reach and exceed 20-30 t/ ha/year of soil), equivalent and a thickness of several millimeters.

Less bearing capacity of the ground

The mechanical workings reduce the lift, that is the ability of the ground to bear weight without suffering structural damage. Consequently, the transit of the machines when the soil is wet determines the compaction of the same and this prevents the timely execution of the cultivation operations such as pesticide treatments, harvesting, etc. (Proietti & Regni, 2019). The problem of lift is also found in Apulian secular olive groves (Simeone et al., 2013).

Radical asphyxia and Destructuration

According to Alfei et al. (2003) and Proietti & Regni (2019) with the soil tillage and in particular with the use of rotary cutters, excessive shredding is created. With the rains, the smallest particles migrate towards the transition zone between the tillage and the no-tillage, occlude the pores and determine the formation of a compact layer, impermeable to water and air. Ethylene and carbon dioxide accumulate, both toxic for the root metabolism, resulting in a reduction of vigor and productivity, yellowing of the leaves, root rot with an accumulation of toxins. With repeated mechanical processing, the soil structure can be degraded (La Posta et al., 2012).

Operating machines

The intensity of the environmental impacts related to processing changes according to the tools used for them. Tillage maybe with a cultivator, tine-harrow, disk-harrow, or rotovator, or in some cases a plough. The number of passes per year varies considerably, depending on local practice, conditions (e.g. more tillage is needed in the event of high rainfall as this produces more weeds) and the individual farmer. More extensive cultivation systems use one or two passes at the most. Intensive systems use repeated tillage four or more passes per year (Beaufoy 2002).

Among the most impacting machines, there are milling machines (rotary hoes), which favor the spread of weeds and caused the formation of the working sole (Proietti & Regni 2019) and require very high energy inputs.

Other tools used are plows, grubbers or harrows. Plows (except rotary ones) and disc harrows allow the burying of fertilizers, but can lead to the formation of the working sole.

Agricultural plumbing of water

Species such as the olive tree have little resistance to radical asphyxiation due to water stagnation. According to Proietti & Regni (2019) and Alfei et al. (2003), in the plain, the solutions are the ditching or drainage with draining pipes, which must guarantee a cultivation clearance of at least 50-60 cm. Drainage is particularly recommended in the case of high water tables. In the case of clayey soils or where deep stagnation occurs, with the risk of landslides in sloping land due to insufficient natural drainage, the installation of drainage can be useful. Eventually, they will be made in correspondence with any valleys, where water tends to accumulate. Ditching is effective in eliminating water in all situations that cause stagnation, while drainage may not be sufficient in soils with particularly low permeability (eg very clayey); in this situation, the outflow of water towards the drains would be so slow as to make them ineffective. If in the plains drainage and ditching prevent root asphyxiation, in the hills they greatly reduce erosion and all the environmental impacts associated with it.

Grass shredding - Permanent grass (“Inerbimento”)

A permanent turf over the entire plantation that is maintained by mechanical mowing is a widespread practice in some Italian olive growing areas, as some problems of mechanical processing.

However, even in this case, as can be seen in Figure 4, some causes of environmental impact remain as follows:

Reduced rainwater storage

- Use of specific machines and resources
- Accumulation of toxic metabolites.

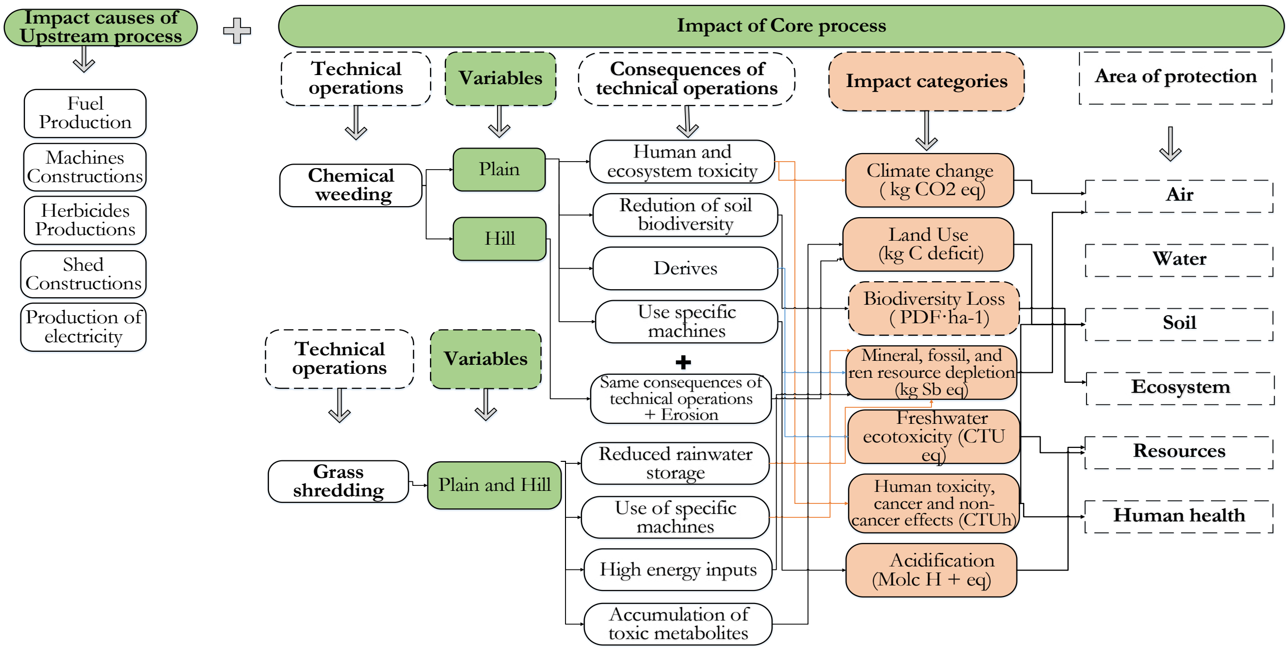

Figure 4. Environmental impact of chemical weeding and grass shredding in olive orchard.

Reduced rainwater storage

Local rainfall can guide the choice of the greening method: with annual rainfall exceeding 700-800 mm and a fair rainfall even in summer, there are no obstacles for permanent (i.e. all year round) and total (i.e. over the entire surface) interventions); with precipitation lower than these levels, but higher than about 600 mm, and/or in the presence of precipitation of at least 150 mm in the four months May-August, partial (i.e.

only in the inter-row) or total, grassing can be practiced, however frequent the mowing. In environments with rainfall below 600 mm/year, grassing involves serious risks due to competition from water and is therefore generally not recommended in the first years of planting (Gucci et al., 2011, Proietti & Regni, 2019).

Proietti & Regni (2019) and Celano et al. (2005) show that the main environmental problem of grassing for the olive grove is the water competition above during fruit set and the first stages of fruit development. Grass cover can consume up to 200 mm of water per year. Therefore, in drought environments and/or in soils poor in organic matter and light, if grassing is used, adequate water availability is also required for irrigation. Grassy ground, compared to bare ground, slows down spring heating, determines higher temperatures during the day and lower temperatures during the night, thus increasing the danger and severity of late frosts.

Furthermore, even in secular olive groves, according to Simeone et al. (2013), grassing does not allow to maximize the available water, increasing the water capacity of the soil and therefore the possibility of "storing" rainwater. and decreasing losses due to evaporation and weeds.

With mechanical working, the macroporosity of the soil is increased and the relative function of the infiltration speed in the surface soil could also be obtained through soil working operations (Montanaro et al., 2017).

Use of specific machines and resources

According to Celano et al. (2005), the need to invest in the purchase of specific equipment not ordinarily included in the company's fleet; the cost of the third party for the shredding and mowing operations, not competitive with that associated with the milling/plowing carried out with the company's machinery.

Furthermore, to compensate for the nutrients absorbed by the turf, for the first years it is necessary to integrate with specific fertilizers.

Accumulation of toxic metabolites

It can cause "allelopathic" effects due to phytotoxic substances produced by the roots of some weeds (e.g., weeds) which, particularly on young trees, inhibit development and production; Green cover does not seem to affect the health situation relating to fungal diseases, except for a higher incidence of verticillosis attacks (Alfei et al., 2003; Proietti & Regni, 2019).

To avoid nutritional stress, which could occur at the beginning of the growing season, in particular as a result of the strong and simultaneous demand for nutritional elements by the olive trees and the turf, it is necessary to intervene with fertilization. Therefore, to favor the action of the demolition microorganisms of the grassy biomass and to compensate for the temporary removal of nitrogen by the same, it is always convenient, as part of normal nitrogen fertilization (Proietti & Regni, 2019).

Chemical weeding

The chemical control of weeds through the spraying of herbicides generates considerable environmental impacts.

Some causes of environmental impact remain as reported below:

- Human and ecosystem toxicity
- Reduction of soil biodiversity
- Derives
- Erosion

"Human and ecosystem toxicity", "Reduction of soil biodiversity" and *"Derives"*

The application of herbicides contaminates the environmental matrices (soil and water), leaves residues in the plants and favors their accumulation in the food chains and the agricultural produce oil and olives (La Posta et al., 2013).

According to Beaufoy (2002) the residual herbicide remains highly concentrated in the top 5-15cm of soil, even after several months, and spreads into untreated areas owing to soil erosion. Where residual herbicides are used widely and intensively, large quantities are washed into streams, rivers and reservoirs with the soil that is eroded in heavy rains

According to Camarsa et al. (2010), the use of herbicides impoverishes the soil from the edaphic community

Erosion

The spraying of herbicides together with the tillage for the control of weeds is reported to cause an impoverishment of the soil and the loss of its structure leading to erosion (Beaufoy, 2002)

According to Bellacicco et al. (2010), the practice of total chemical weeding on the entire plot results in strong compaction of the same both for the passage of machines and for the action of rainwater and triggers erosive phenomena due to runoff.

4.2.3 Pruning

Pruning is a cultivation operation with three specific purposes, balancing the aerial apparatus with the development potential allowed by the resources of the soil and the environment, guaranteeing the illumination of the canopy and concentrating production in particular areas, making harvesting less expensive. Furthermore, it is observed that the drupes from pruned plants contain a higher oil content. In harvesting by vibro-shaking, which appears to be the one practiced in the company and throughout the olive growing area, the efficiency of the operation in addition to innumerable conditions is also linked to the angle of insertion of the primary branches. This must be around 45 ° C, furthermore, it can be seen that as the volume of the tree canopy increases, harvesting efficiency decreases as the vibration loses intensity with the increasing length of the branches.

Also for this cultivation operation there are different variables that generate different environmental impacts, as can be seen in figure 5. Below are detailed causes of environmental impact. Some causes of environmental impact remain as follows:

- Vegetative imbalances
- Energy inputs.

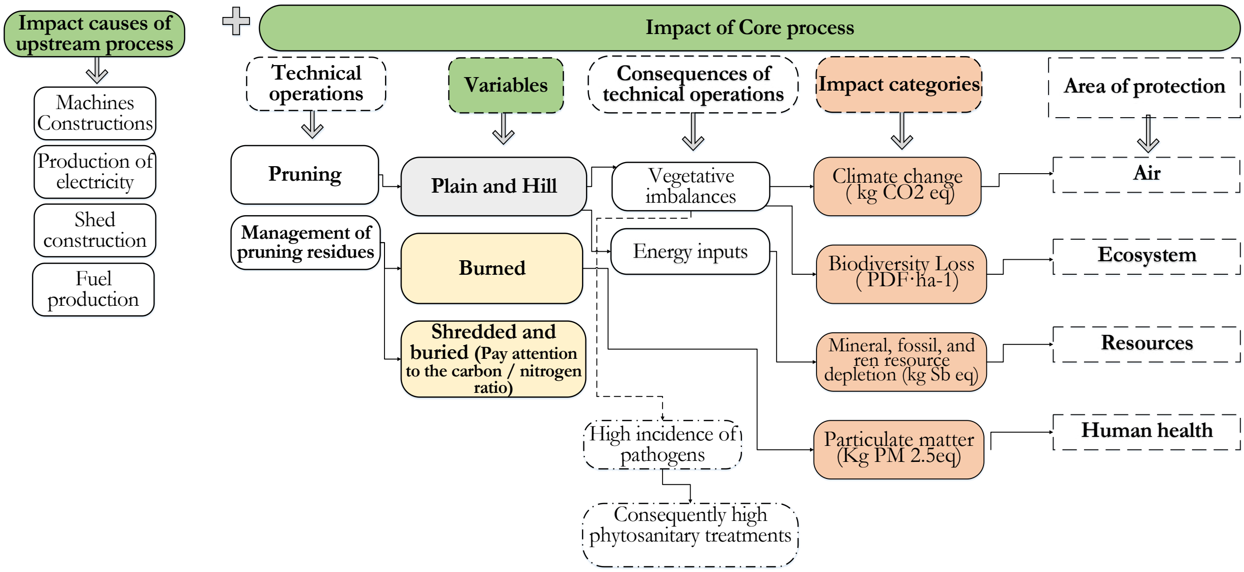

Figure 5. Environmental impact of pruning and pruning residues management in olive orchard.

Vegetative imbalances

According to Simeone et al. (2013), often in olive growing, excessive pruning takes place which determines a reduction in the productive capacity of the plants. Even too light pruning can be harmful, because it can cause excessive shaking in the internal parts of the canopy and a strong consumption of water, creating favorable conditions for the development of pathogens and pests and the possible onset of water stress. In centuries-old olive groves, where pruning is normally performed with a multi-year shift (every 4-6 years), it is important to intervene every year at least to eliminate the suckers to maintain a certain vegetative-productive balance and avoid excessive thickening of vegetation that create the optimal conditions for the development of fungal diseases. The pruning period is also important late pruning removes the reserve substances from the plants. Also according to La Posta et al., (2013) too severe pruning creates a drastic reduction of the foliage and shelters for birds, with damage to biodiversity.

Energy inputs

Pruning is carried out with facilitating tools in traditional and intensive plants, it can be carried out mechanically in super-intensive plants. In the first case it requires a high energy input in terms of work, both for the time necessary to carry out the operation, and because the executing staff must be specialized.

Management of pruning residues

Agronomic practices commonly used in olive growing include annual or biennial pruning operations. The amount of biomass resulting from the pruning operations is extremely variable depending on the variety, the training system, the density of plants per hectare, the pruning timing and the reference geographic area. Generally, the resulting wood residues are burnt on site or chipped and released on the ground or underground. The pruning burned into the field must be considered as a carbon loss by the ecosystem, otherwise if these residues are left into the ground with mulch and fertilizer function, the carbon balance is improved. Another strategy for reduction of the gas emissions in the atmosphere is represented by the use of such residues for energy purposes instead of fossil fuels.

4.3 Fertilization

To achieve good production performance, fertilization must be carried out with attention and rationality. To achieve maximum efficiency of the interventions, both from a technical and economic point of view, it is strictly recommended to carry out the chemical-physical analysis of the soil and the foliar diagnostics. While the former allows to assess the basic fertility of the soil environment, the latter provides elements to know to what extent the plant has the elements present in the soil. The main variables and causes of environmental impact are shown in figure 6 and detailed below.

-Nitrate pollution.

-Denitrification

-Eutrophication,

-Destabilization pH and CSC

-Incidence of pathogens.

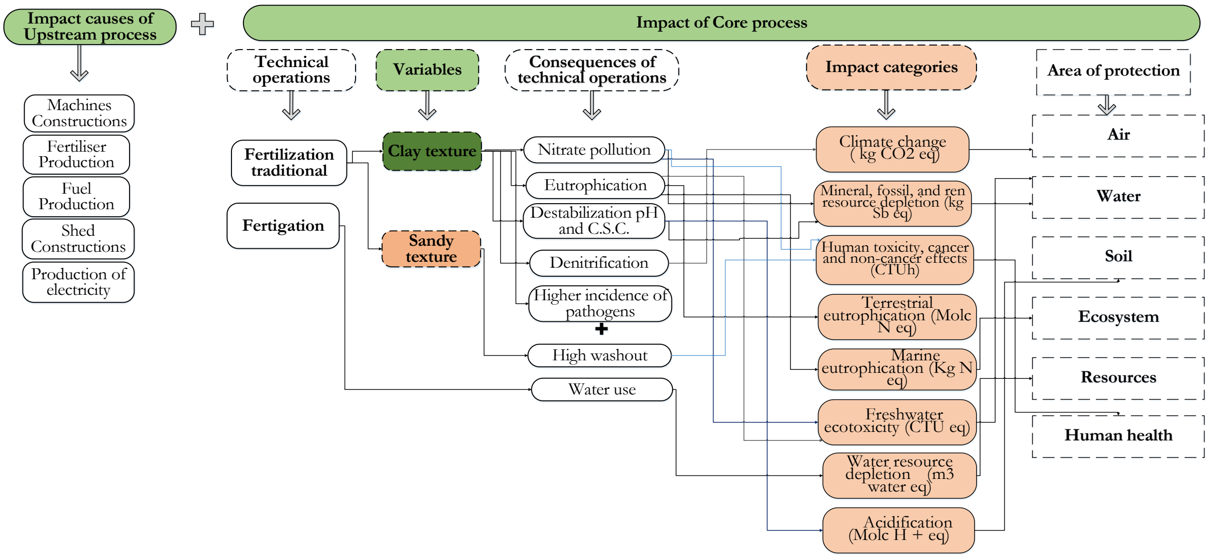

Figure 6. Environmental impact of fertilization in olive orchard.

Nitrate pollution, Denitrification, Eutrophication, Destabilization pH and CSC, Incidence of pathogenes

According to Zipori et al., (2020), nitrogen is applied to olive trees in various ways: direct application to the soil as soluble solid compounds, application of organic matter, or application of a liquid or soluble form by fertigation or foliar spraying. All these fertilization practices can lead to high levels of nitrogen in the soil, mainly in the form of nitrates (NO_3^-). NO_3^- is not adsorbed in the solid phase of the soil, is easily transported below the root zone, and becomes a groundwater pollutant when not absorbed by plants (Rodriguesa et al., 2019; Beaufoy 2002, Camarsa et al., 2010).

Uneaten nitrogen can also be converted into nitrous oxide (N 2 O), a greenhouse gas (Rodriguesa et al., 2019; Zipori et al., 2020). For example one of the most common fertilizers, ammonium nitrate, which it contains up to 33-34% of nitrogen and which, in the most intensive and irrigated systems, can reach levels of about 350 kg/ha, is associated with problems of runoff and eutrophication. According to Beaufoy 2002 one of the causes of nitrogen leaching is also the lack of ground cover crops. According to Zipori et al. (2020), in the Mediterranean climate typical of olive growing regions, organic substances or mineral fertilizers are commonly applied in late winter or early spring, to take advantage of rainy events to transport minerals to the root area. Insufficient rainfall will leave nutrients out of reach of active roots, and excessive rainfall can lead to significant losses of N by leaching or release of gaseous forms of N (denitrification). Nitrogen leaking from agricultural soils can contaminate water bodies causing eutrophication and in the case of contamination of drinking water can cause various human diseases (Rodrigues et al., 2019).

Furthermore, the high quantity of nitrogen exposes plants to more fungal diseases. Many olive cultivars are sensitive to soil fungus. This may, however, be associated more with excessive nitrogen fertilization and high irrigation also favor the fungus Verticillium dahliae Kleb which damages the vascular system of trees and causes leaf wilt (Connor et al., 2014).

The excess of macroelements of phosphorus P and potassium K can also contaminate the soil, surface, and groundwater (Beaufoy 2002, Camarsa et al., 2010).

According to Zipori et al., (2020) due to its poor soil mobility, P rarely reaches groundwater as a pollutant. Most P pollution is caused by mass transport on the soil surface due to soil erosion and runoff of water from fertilized agricultural fields. In this way P can reach water bodies such as lakes and rivers, compromising their biological balance and favoring eutrophication.

As for potassium, excessive fertilization can damage the soil structure. Excessive fertilization with K can indirectly affect salinity since, in general, the source of K is KCl. This practice allows you to accurately dose the amount of fertilizer that the plant must absorb. For phosphorus, which tends not to be washed away, the format that can be used in fertigation is only the soluble one, which is very mobile and pollutes the aquifers. The presence of potassium in the soil affects the Cation Exchange Capacity (CSC).

The use of fertilizers characterized by a basic acitity such as ammonium sulfate, used in soils with already acidic Ph can contribute even more to lowering the pH, the same reverse reaction can occur in alkaline soils with basic fertilizers.

4.4 Phytosanitary management

The maximum expression of the productive potential certainly passes a good phytosanitary status of the plant. Today, especially in Europe, the guidelines of the Community Agricultural Policy increasingly promote the reduction of chemical inputs. The main environmental impacts resulting from phytosanitary management are shown in figure 7 and are detailed below.

- Derives
- Pollution of surface and underground water bodies
- Human toxicity
- Reduction of useful fauna

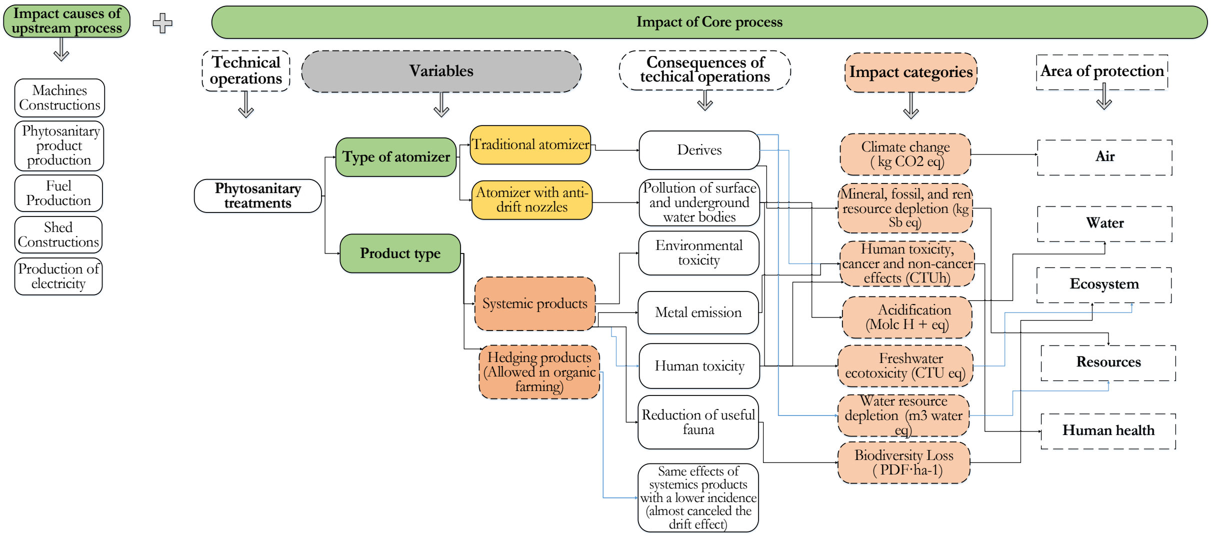

Figure 7. Environmental impact of phytosanitary management.

Derives, Pollution of surface and underground water bodies, Human toxicity, Reduction of useful fauna

During phytosanitary treatments, a fraction of the sprayed product is lost and deposits on the ground or moves away from the site (Calatrava et al., 2021). This phenomenon is called drift and is amplified in the presence of wind.

Undesirable effects of drift include side effects on non-target organisms, pest resistance to active substances, secondary pest outbreaks, or persistence of residues in water, soil and the food chain (Pinheiro et al., 2020).

The pesticides also have a polluting effect on the aquifers (Camarsa et al., 2010) According to Connor et al. (2014), more humidity is present in high-density olive groves, which is why the control of pests and diseases is more critical, in particular for fungi such as Spilocaea oleagina (olive peacock spot), *Pseudocercospora cladosporioides* and Colletotrichum spp. (Connor et al., 2014).

4.4.1 Harvesting and irrigation

The harvesting operation is the one that most affects the total cost of olive oil, so it must be done rationally without neglecting the aspects that allow guaranteeing the quality of the product, therefore one of the fundamental conditions to be taken into consideration. it is the time of harvest, that is the degree of ripeness of the drupes.

Types of harvesting

- **Harvesting tools**: the harvest from the shaft can be facilitated with machines, brought by the operator and applied directly on the canopy, which cause the abscission of the olives by means of activated devices from compressors, small internal combustion engines or electric batteries. The detachment of the fruits occurs both for direct action both, and above all, due to the effect of vibrations induced to the branches.
- **Mechanical harvesting**: the harvesting through the trunk shakers are mechanical means that determine the detachment of the fruits by means of a headboard vibrating applied to the trunk. Trunk vibrators can be brought, when the headboard with the structure that supports it is applied to normal tractors or self-propelled. Trunk shakers can have a structure for intercepting drupes (umbrella) or be part of the collection site: shaker with interceptor nets.
- **Straddle harvester**: continuous harvesting is carried out with straddle machines (modified grape harvesters), which operate astride the row in super-intensive olive groves, taking 3-4 hours / ha (speed of 0.3- 1 km / hour). With plants of adequate size, the vibration of the machines deriving from straddle harvesters is very effective and 90-95% of the fruit is harvested (with resistance to detachment less than 600 g), even for varieties with small fruits and with high detachment force, as the hair is of limited size.

Some causes of environmental impact that can be shown in figure 8, are the following:

- Soil compaction
- Use of specific machines

Soil compaction

This condition generates problems of environmental impact linked to radical asphyxia and the impermeability that the soil assumes.

This condition is accentuated in soils that lack vegetation cover. Compaction is absent in the case of harvesting with facilitators, while it is accentuated in mechanized harvesting.

According to Beaufoy 2002., indirectly, the method of harvesting has important implications for the environment, in particular the question of whether the olives are harvested from the ground or only from the tree. Harvesting olives from the ground requires completely bare and flat land, which is achieved through the intensive use of herbicides and/or mechanical methods. Preparing the soil in this way exposes the soil to the erosion of winter rains as well as removing an element (the grassy layer) in the plantation's biodiversity. This is the normal system in the main producing regions of Andalusia, Apulia, etc.

Use of specific machines

Harvesting machines such as straddle machines can only be used to carry out this operation, therefore very few months a year. A trunk shaker, for example, can be used to collect fruits of other typically Mediterranean species (almond, plum tree). In the case of a solution that involves mounting the shaking pincer on the agricultural tractor, the use of the operating machine is further optimized.

According to Connor et al. (2014), there is a certain risk of disease spread in hedge systems due to transfer during mechanical harvesting because the wounds caused by the harvester facilitate the entry of pathogenic organisms. An example is an olive knot, a disease caused by the bacterium *Pseudomonas savastanoi pv. savastanoi*.

4.4.2 Irrigation

The main environmental impacts that derive from irrigation shown in fure 8, are:

- Water use
- Salinization.

Water use

Thanks to the good quantitative and qualitative results, irrigation of olive groves is becoming an increasingly implemented practice especially in new plants (Camarsa et al., 2010).

Irrigation is mandatory in high-density plants.

As already reported in paragraph 4.1 the regions concerned often have serious problems of water deficit (for example Apulia). In this region, for example, the irrigated olive groves have continued to expand even if the groundwater is severely depleted and affected by salinization, in the case of Apulia Beaufoy 2002.

Currently, there are insufficient mechanisms to ensure that irrigation does not exceed the sustainable capacity of water resources, and therefore an environmental issue linked to the "water resource".

Salinization

Drip irrigation, applied in many intensively cultivated olive groves in the Mediterranean region, can lead to soil salinization, especially along with coastal areas (La Posta et al., 2013).

The exploitation of water resources for irrigation purposes: the productivity of olive trees increases considerably with irrigation, which is used above all for table varieties, where large fruits are desired (Camarsa et al.,). Water is also needed in intensive plantations with rows of high-density olive trees, to maximize production, and also serves to improve the effectiveness of fertilization and pruning. The so-called "localized" irrigation is the most common type in intensive plantations. Although the quantities of water needed per hectare are less than those required for arable land, irrigated plantations cover an increasingly large area, often in regions where water scarcity is already a serious problem in itself. In a study on the intensive cultivation of hedge olive trees, irrigation with RWW caused the accumulation of salt during the summer due to the insufficient irrigation policy adopted, but the salts were leached every year with the winter rains. A negative trend for SAR has been identified. Continuous irrigation with RWW could compromise the physical properties of the soil and measures such as enrichment with Ca ions by calcination should be considered (Zipori 2020).

According to Sala et al., (2019), localized irrigation of olive groves concerns 95% of systems with irrigation.

In some traditional plants, it is still possible to find micro-sprinkling plants that have the advantage of distributing the water over a larger surface area. This method has the disadvantage of having greater losses due to evapotranspiration, of developing a greater quantity of weeds that can compete with the olive grove, aspects that translate into less irrigation efficiency.

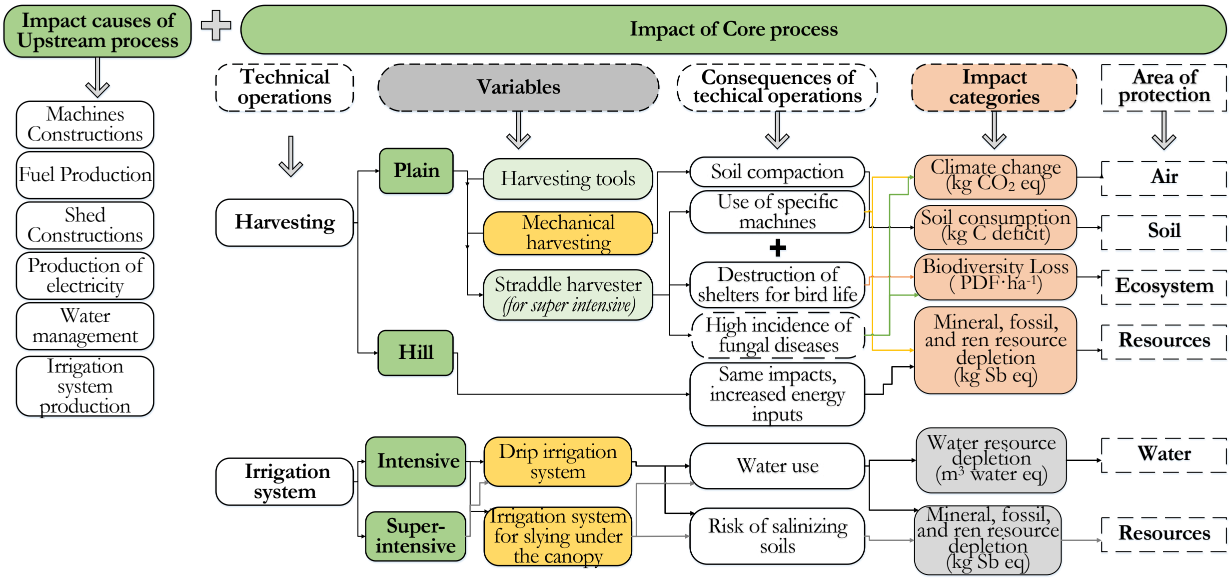

Figure 8. Environmental impact of harvesting and irrigation in olive orchard.

4.5 Technical operations in the industrial phase

4.5.1 Olive oil extraction

Currently, the extraction of extra-virgin olive oil takes place according to three technologies: 1) discontinuous cycle extraction (pressure), 2) three-phase continuous cycle extraction, 3) two-phase continuous cycle extraction.

In Italy, the most common type is the three-phase one. The discontinuous cycle belongs to the past it is found only in the most marginal realities, the two-phase cycle instead begins to spread in recent years. Based on the different types of extraction, the inputs and outputs change. Table 4, elaborated by Caputo et al. (2003), reports the main characteristics of the systems mentioned.

Table 4. Input and output in the industrial phase.

Production process	Input	Amount of input	Output	Amount of output
Discontinuous	Olives	1 t	Oil	200 kg
	Washing water	0,1–0,12 m^3	OH	400 kg
			OMW	400–600 l
Continuous Three-phase	Olives	1 t	Oil	200 kgl
	Washing water	0.1–0.12 m^3	OH	500–600 kg
	Freshwater for decanter	0.5–1 m^3	OMW	1000–1200 l
Continuous Two-phase	Olives	1 t	Oil	200 kg
	Washing water	0.1–0.12 m^3	OH	400 kg
			OMW	85–110 l

Source: Caputo et al. (2003).

According to Caputo et al. (2003), the technology used in the processing of olives, discontinuous pressure or continuous centrifugation systems, the amount of energy consumption, concerning a ton of treated olives, is respectively 40,000-50,000 and 48,000–65,000 kJ.

As can be expected from Table 4, the processing of olives produces large quantities of residues. In discontinuous cycle plants with slightly damp pomace and vegetation water from the mills, in three-phase plants with a continuous cycle with low humidity pomace and with a two-phase continuous cycle plant very humid pomace.

4.5.2 Management of co-products

In Figure 9 you can visualize the environmental impacts related to olive oil extraction and co-products derived. In particular, the main environmental impacts are borne by mill wastewater olives and pomace in the two-phase mill.

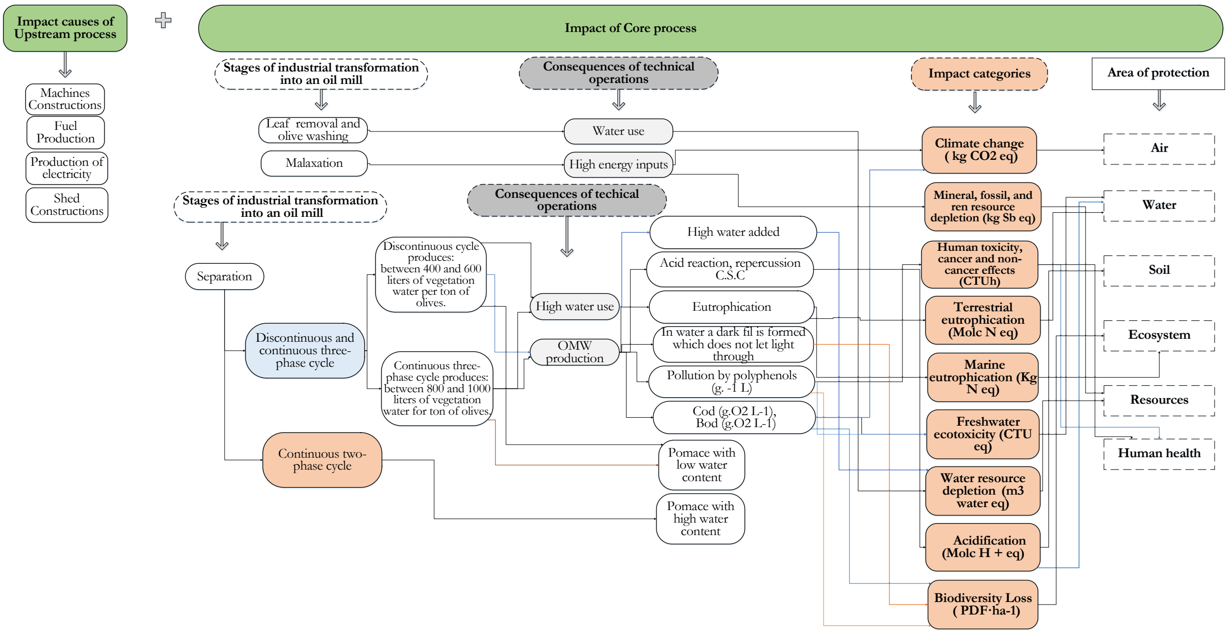

Figure 9. Environmental impact of olive oil extraction.

Olive mill wastewater (OMW)

The wastewater from the mill has a dark color, characteristic odor, low pH and contains high concentrations of fats, oils and fats, organic matter, suspended solids, and polluting compounds, such as polyphenols.

Furthermore, OMW has high values of chemical oxygen demand (COD, 50-180 g L^{-1}) and biochemical oxygen demand (BOD 5, 40-95 g L^{-1}), phytotoxic properties and resistance to biodegradation thanks to the high content of polyphenols and organic content of short-chain fatty acids and antimicrobials (Vella et al., 2003; Saadi et al., 2007). The discharge of unsafe oil mill wastewater into natural water systems can lead to a rapid increase in the number of microorganisms, which, by consuming large quantities of dissolved oxygen in the water, reduce the amount available for other living organisms and could, therefore, rapidly disturb the balance of an entire ecosystem (Camarsa et al., 2010).

The OMW have a high organic matter and contain many complex organic substances which are generally resistant to biodegradation, thus posing negative environmental effects such as the threat to aquatic life, odors, the impenetrable film which harms oxygen transfer, discoloration of the natural waters and toxicity (Yaya et al., 2012 Camarsa et al., 2010). These conditions also determine a reduction in plant growth on the soils of the river banks with greater exposure to erosive phenomena (Camarsa et al., 2010).

The possible negative repercussions of acids, minerals and organic components present in oil mill effluents on the "cation exchange capacity" (CSC) of soils (Camarsa et al., 2010).

Because of these characteristics, OMW management poses serious environmental risks to water, soil and air.

Uncontrolled disposal of oil waste can cause pollution of the water body, soil degradation and odor emissions (Chaari et al., 2015)

There are many ways of disposing of vegetation water, among these, there is the spreading on agricultural land after a period of settling and in the quantities established by local legislation.

The Italian law n. 574/1996, together with the Ministerial Decree of 6 July 2005, defines in 80 and 50 m ^{3} ha^{-1} year^{-1} the maximum quantity of RU tolerated on the fields if obtained in continuous mode (centrifugal extraction system) and traditional (extraction system of the press) processes.

The great complexity of the composition of the vegetation waters has aroused the interest of academics over the years.

According to Mekky et al. (2006) and Pedrero et al. (2020), some components of OMW, are favorable to agriculture since this effluent is rich in organic matter, nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg). The organic fraction of these wastewaters include sugars, tannins, polyphenols, sugar alcohols, pectins, lipids and proteinè. Moreover, OMW is an additional water resource for Mediterranean agricultural areas, affected by a chronic shortage of water (Bombino et al., 2021).

Respecting the limits of the volumes to be spread imposed by the legislation it seems that there are no significant differences in the chemical and biological properties between the control soils and those treated when the distributed quantity was lower than the maximum limit of 80 m ^{3} ha $^{-1}$ year $^{-1}$ established by Italian law (Vella et al., 2016).

This disposal method, if carried out correctly, could solve the environmental problems related to wastewater management (Camarsa et al., 2010).

Pomace

According to Roig et al. (2006), the pomace obtained from the processing of oil extraction is divided into two main categories: 1) pomace from a three-phase extractor and 2) pomace from a two-phase extractor. In the first case, the pomace with a humidity of 50-55% is generally processed in the pomace factory using solvents that allow the extraction of other oil. In the second case, however, the humidity can reach 65%, so it cannot be used by pomace factories, due to the pasty consistency that makes it difficult to manage and transport. The vegetation waters of the olive tree (which in the three-phase systems constituted the wastewater) are now included in the pomace and this characteristic causes the greatest problem for its revaluation due to its high humidity content (65%). This residue has therefore become a serious problem for the mills, because its management requires specific structures (storage tanks with special valves, bulk pumps and tankers). The reduced profitability as a result of this waste compared to pomace has led to a more in-depth study on its new enhancement alternatives.

During the husking of the olives before milling, a limited amount of solid waste is produced (leaves and small twigs). However, these by-products present no management problems as they can be used as animal feed or as a calorie source. Olive leaves are a known source of antioxidant compounds and are marketed as herbal teas with diuretic, antihypertensive and antioxidant effects.

Some mills are equipped with a system capable of pitting the pulp of the olives. This process is often used to improve oil extraction yield. Furthermore, stones, also called pits, are a precious product due to their high calorific value. They are currently used as an energy source, but have been proposed for other interesting uses such as the soilless substrate for hydroponics and for the production of activated carbon.

Figure 10 shows the environmental features in the management of co-products. In particular, these are highlighted with the extraction of pomace oil due to the use of solvents and in the spreading in agricultural soils of pomace obtained from two-phase extraction plants.

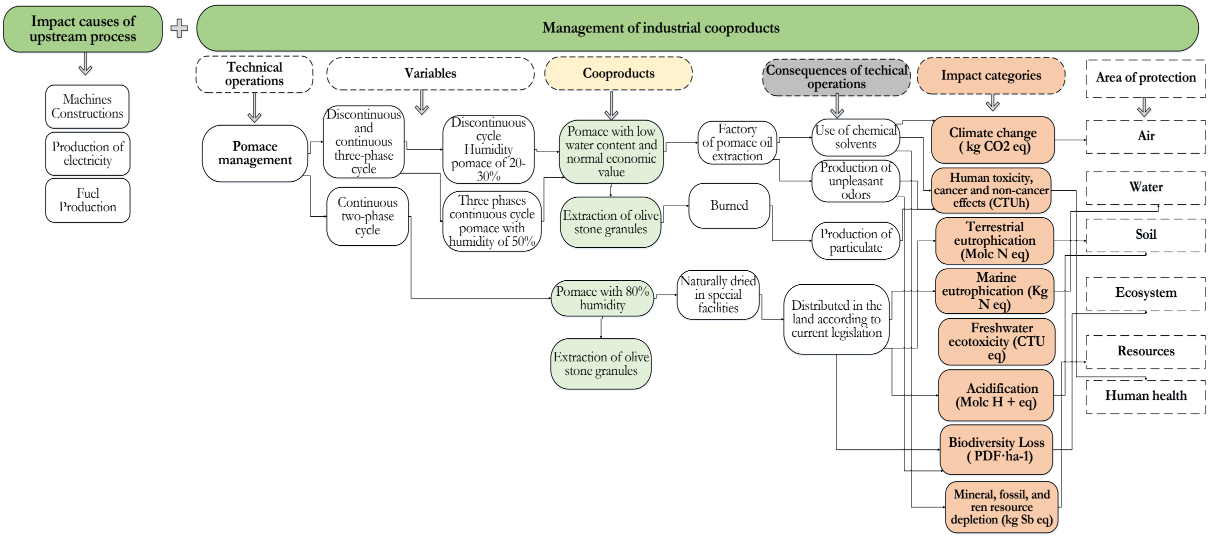

Figure 10. Environmental concerns and impact categories of co-products management.

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5. MEASURING THE SUSTAINABILITY OF CLOSED-LOOP AGRI-FOOD PATHWAYS BY COMBINING LIFE CYCLE AND CIRCULARITY METRICS [4]

Abstract

In recent years, there is a growing interest in the scientific community in identifying the possibility of integrating life cycle analysis and Circular economy (CE) indicators, by combining the potential of the two approaches in guiding the ecological transition. However, there are many open methodological issues addressed above all to the extension of the system boundaries to more life cycles, in order to include the reuse of materials, their remanufacture and recycling. The assessment of both circularity and sustainability of a system turns out to be even more complex when biological processes are involved. The agri-food sector, which encompasses both biological and technical cycles, is one example. Based on these assumptions, this study aims at proposing an application of one of the most robust tools for assessing CE, the Material Circularity Indicator (MCI), to the olive oil sector adapting it to biological cycles and integrating the results with Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies.

Keywords: olive oil sector, circular economy, life cycle assessment, environmental life cycle costing, investment analysis, material circularity indicator.

5.1 Introduction

The benefits associated with improving resources and adopting Circular Economy (CE) practices are increasingly perceived by companies in any manufacturing sector. Despite this awareness, the adoption of circular practices is still lacking due to the presence of

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[4] This chapter is partially based on the following articles:

- Emanuele Spada, Giacomo Falcone, Teodora Stillitano, Nathalie Iofrida, Giovanni Gulisano, Anna Irene De Luca (2022). How can life cycle assessments be combined with other circularity tools to measure closed-loop pathways? An application to the agribusiness sector. XVI Convegno dell'Associazione Rete Italiana LCA, Palermo, 22-24 giugno 2022.
- Emanuele Spada, Giacomo Falcone, Teodora Stillitano, Nathalie Iofrida, Giovanni Gulisano, Anna Irene De Luca (2022). Measuring the sustainability of closed-loop agri-food pathways by combining life cycle and circularity metrics. LVIII Convegno SIDEA, Palermo, 29-30 settembre 2022.
- Giacomo Falcone, Teodora Stillitano, Nathalie Iofrida, Emanuele Spada, Bruno Bernardi, Giovanni Gulisano, Anna Irene De Luca. Life cycle and circularity metrics to measure the sustainability of closed-loop agri-food pathways (2022). *Frontiers in Sustainable Food Systems,* 6:1014228. doi: 10.3389/fsufs.2022.1014228.

several barriers both technical related to the industrial stage and economic related to investments to initiate such practices (Roos Lindgreen et al., 2022). The current challenge lies with the ability of companies to be simultaneously competitive through continuous improvement of their business and attentive to society’s consideration of the cost-benefit ratio related to socio-economic and environmental issues. On the other hand, it is also encountered that not always circular solutions lead to more sustainable outcomes; therefore, it is crucial to assess the sustainability impacts of CE practices before implementing them. To increase knowledge about the efficacy of circular approaches, appropriate measurements of circularity - and its sustainability - in real case studies could be useful to understand both entrepreneurs and public decision-makers who are interested in spreading such innovation. Simultaneous assessment of circularity and sustainability is still uncommon in the scientific literature (Stillitano et al., 2021), probably due to a lack of computational approaches and tools which have yet to be validated by scholars. Starting from these considerations, this study aims to define and apply a methodological proposal based on life cycle (LC) methodologies - Environmental Life Cycle Costing (ELCC) and Life Cycle Assessment (LCA) - and circularity performance indicators, to assess closed-loop pathways by providing comprehensive results on economic and environmental impacts generated by agri-food production systems.

5.2 Theoretical background

Since the CE has become the main topic when firms attempt to increase their business by facing resource scarcity and the need to reduce the environmental impacts, several easy-to-apply indicators have been developed over the years, to assess circularity at the micro-level referring only to the production context. Among them, the most widely used indicator is the material circularity indicator (MCI), which focuses its analysis on material flows occurring about a process or product (Ellen Macarthur Foundation, 2015). However, a limitation lies in neglecting the nature of materials in circulation and overall, in not considering the impacts generated by circular strategies, by quantifying environmentally, economically, and socially with convenient measurement units. Therefore, for a methodological completion, it is necessary to combine the MCI with other sustainability assessment tools such as LC ones (Goddin et al., 2019). CE is supposed to help the re-establishment of a new balance between ecological and economic systems, especially within the dynamics of agri-food systems (Cembalo et al., 2020), if the transition into circularity ensures reconciliation of the triple bottom line principles because not all circular practices are sustainable under all circumstances. Respecting circularity may cause environmental externalities, otherwise, it may not guarantee economic viability, making these two concepts not always interchangeable. So, measuring the effects on environmental, social, and economic dimensions is the *sine qua non* for assuring real sustainability based on the principles of the CE (Silvestri et al., 2022). In their recent review, Stillitano et al. (2021) provided the state-of-the-art of applications of the life cycle approach in the assessment of circularity of processes and products, by arguing that the tools available today are not yet at a level of maturity to overcome critical points for their effective integration. Regarding LCA, this is one of the most applied metrics to measure the sustainability of CE pathways even if its use always turns out to be limited to evaluating only the environmental aspects of "supposed" circular systems, leaving the assessment of circularity out of the objectives of the study. In terms of ELCC and LCA integration, few applicative analyses exist, and the most common practice is to align these tools by adopting a common database, considering the same functional units and system boundaries, and following the same methodological steps. Only three studies have addressed the simultaneous application of LCA and LCC and MCI methodologies in the agribusiness sector, which focused on poultry production (Rocchi et al., 2021), urban agriculture (Rufí-Salís et al., 2021), and beer packaging (Niero and Kalbar, 2019). To the best of our knowledge, this is the first integrated evaluation using life cycle and circularity metrics for the transition to CE in the olive oil sector.

5.3 Materials and Methods

5.3.1 Case study description

To analyse the performance of circular strategies with real data, we took over a "circular" olive oil farm (circular scenario) compared to a "linear" olive oil farm (linear scenario) as case studies. Both farms are located in the province of Catanzaro in Calabria (southern Italy) and share the following characteristics: olive-growing area of 100 ha, *Olea europea* L. cv. Carolea orchards with 40-year-old trees, planting density of about 200 plants/ha, and a high level of farm mechanization. The olive oil production system in both farms was split into two main subsystems: the olive growing and harvesting phase, and the olive oil extraction phase. In the first scenario, circular applications concern the pruning residues are shredded and buried in the soil, the spreading in the field of 1/3 of the stoned two-phase pomace produced during oil extraction, and the use of olive pits extracted from the two-phase pomace to produce the thermal energy needed by the olive mill. In the second scenario, on the other hand, the pruning residues are given to other farms as biomass, the pomace obtained from the extraction stage is entirely given to the industrial plant for pomace oil extraction, without separating the olive pits.

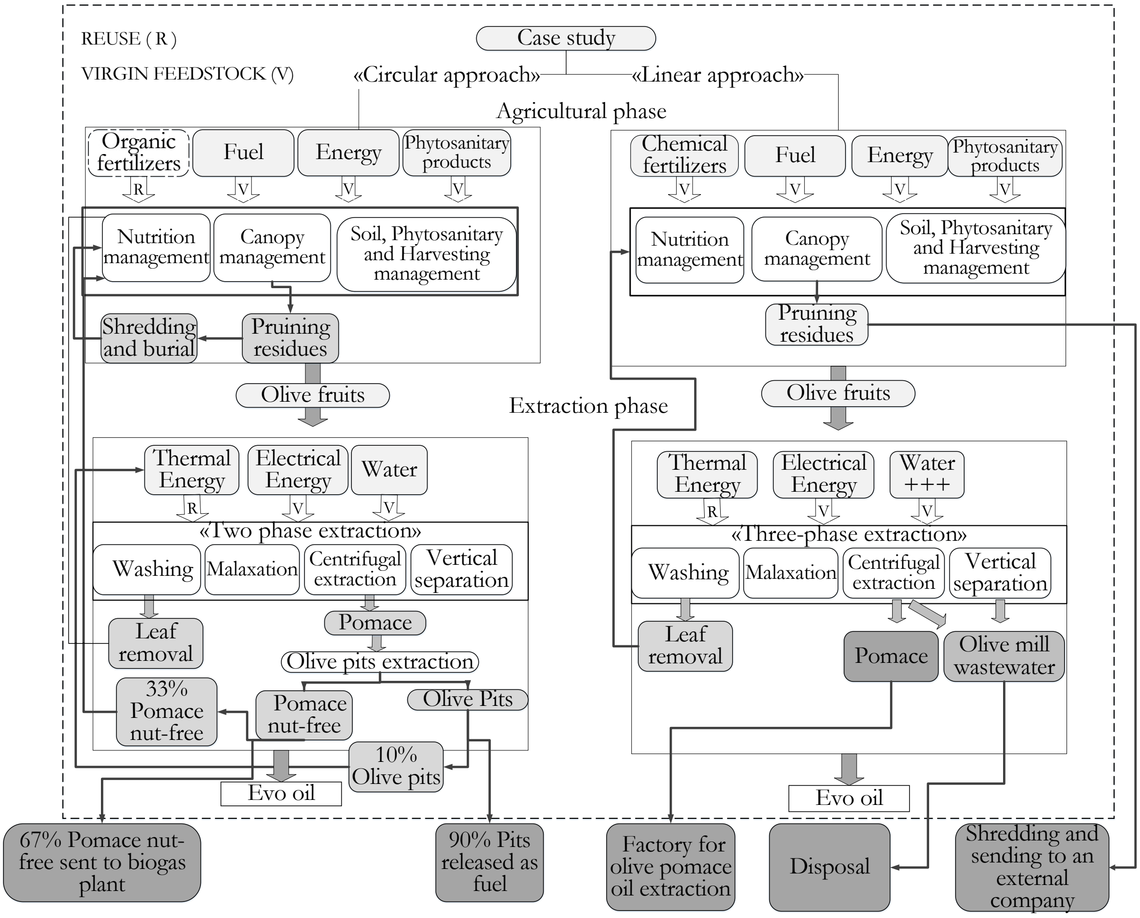

Figure 1. Circular and linear scenarios under assessment (Source: Authors' elaboration).

5.3.2 Life Cycle Assessment and Environmental Life Cycle Costing implementation to the case study

The environmental sustainability assessment was performed using the LCA methodology according to ISO 14040 and 14044 (ISO, 2021a and 2021b). The Functional Unit (FU) chosen was the production of 1 kg of EVO oil. The study was extended from the olive production in the field to obtaining the oil in the mill. The processing data are "primary data" collected directly from the study companies through a specific questionnaire. In particular were collected: data on duration of tillage operation, fuel consumption, maintenance and typology of machinery involved; data on quantity, typology, number of fertilizers and phytosanitary compounds, and the related periods of application; data on yield of olives and wood from pruning. Secondary data on background processes were obtained from Ecoinvent 3.7 (Weidema et al., 2013) and processed using SimaPro 9.2 software (Goedkoop et al., 2013). The results were obtained using the Re.Ci.Pe 2016 Midpoint Impact Assessment method (Huijbregts et al., 2017). All the steps described so far were also shared with the life cycle cost analysis, the inventory of which, however, was realized by monetizing the material and energy flows of the environmental inventory (see Table 1 in APPENDIX).

The economic analysis was carried out through the ELCC methodology, defined as the logical counterpart of LCA analysis for economic evaluation, which goes beyond mere cost accounting and is entirely compatible with LCA (Klöpffer and Renner, 2008). ELCC, aligned with LCA, involves the calculation of internal and external costs. The internal costs were split into variable (material and energy costs, human labour cost, interests on advance capital) and fixed costs (ownership costs of investments in machinery and land, i.e., depreciation, insurance, repairs and maintenance, interests on capital goods, rental shed, taxes and administration overheads). The external costs concern the monetisation of externalities by assigning a specific value to the environmental impacts of a product. To date, the main path for calculating externalities is to monetise environmental impacts from LCA studies, struggling to translate environmental impacts into economic impacts. Thus, starting from the LCA results, the environmental price approach (de Bruyn et al., 2018), which expresses the willingness to pay for less environmental pollution in euros per kilogram of pollutant, is applied through the SimaPro software to estimate external costs. To align ELCC with LCA a common database was adopted, considering the same functional unit and system boundary, and following the same methodological steps.

Subsequently, the total revenues for the entire life cycle of each scenario were calculated by multiplying the product yields (olive and EVO oil) by their market price, which referred to the last harvest season, i.e. 2021/2022, including EU Agricultural Policy subsidies. Table 1 shows the main assumptions made in the study.

Table 1. Main technical and economic parameters adopted in the study.

Agricultural phase	
Life cycle (years)	60
Yield per hectare (t ha $^{-1}$)	9.6
Olive price (€ kg^{-1})	0.50
Daily wage workers (€)	51.00
Extraction phase	
Life cycle (years)	20
Oil yield (%)	16
EVO oil price (€ kg^{-1}) (Ismea 2022)	4.00
Daily wage workers	51.00

As a final step, an investment analysis was carried out by calculating specific indicators, i.e., Net Present Value (NPV), Internal Rate of Return (IRR), Gross Margin (GM) and Payback Period (PBP). These represent the most common indicators used to compare investment options, which are based on the cash flow model (Herbes et al., 2020; Stillitano et al, 2019). Each economic indicator value has been defined for the FU of 1 kg of EVO oil (Table 2).

Table 2. Description of economic indicators.

Code	***Criterion***	***Formula***	***Unit***	***Description***

NPV	Net Present Value	$\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0$	€ kg^{-1}	CF= net cash flow in the t-th year;
				t=time of the cash flow (year);
				n= investment lifetime;
				r=discount rate;
				I_0=initial investment.

IRR	Internal Rate of Return	$\sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - I_0 = 0$	€ kg^{-1}	IRR=discount rate that will make the NPV equal to zero;
				t=time of the cash flow (year);
				n= investment lifetime;
				r=discount rate;
				I_0=initial investment.

GM	Gross Margin	$\sum_{t=1}^{n} \frac{TR_t}{(1+r)^t} - \frac{VC_t}{(1+r)^t}$	€ kg^{-1}	TR_t=total revenue in the t-th year; VC_t=variable cost in the t-th year; *t*=time of the cash flow (year); *n*=investment lifetime; *r*=discount rate.
PBP	Payback Period	$LNC \frac{ADC}{DCA}$	€ kg^{-1}	LNC=last period with a negative discount cumulative cash flow; ADC=absolute value of discount cumulative cash flow at the end of the period LNC; DCA=discount cash flow during the period after LNC.

To perform the profitability analysis of the scenarios under study the following assumptions were made:

- All of the costs and revenues were discounted for the entire life cycle of 60 years (olive grove lifetime) and 20 years (oil mill lifetime), for the agricultural phase and extraction phase, respectively;
- To select a discount rate, the opportunity cost approach in terms of alternative investments with similar risks and times was used (De Luca et al., 2018). Here, a discount rate set to 2% and 5% was assumed for the agricultural phase and extraction phase, respectively;

- During the life cycle, constant prices by excluding adjustments for inflation were taken into account (Hussain et al., 2005).

5.3.3 Material Circularity Indicator implementation in the case study

The circularity assessment was performed by calculating the Material Circularity Indicator (MCI), which measures how much linear flow has been minimized and remedial flow maximized for its components and, at the same time, for how long and intensively (Rocchi et al. 2021). The MCI has a range of values from 0 (100% linear) to 1 (100% circular). According to the Ellen MacArthur Foundation (2015) and Goddin et al. (2019), the formula for calculating the MCI of a product is as follows (Eq. 1):

$$MCIp = 1 - LFI * F(X) \qquad (1)$$

where LFI represents the Linear Flow Index, i.e. the percentage of material flow originating from virgin sources and ending up as non-recoverable waste, while F(X) represents the utility-constructed factor of the linear component of material flows.

LFI is computed by dividing the amount of material flowing in a linear chain by the sum of the amounts of material flowing in a linear and a restorative chain. The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow. The index is derived by the Equation (2):

$$LFI = \frac{V + W_0}{2M} \qquad (2)$$

where V is the mass of virgin raw material used in manufacturing; W0 is the mass of non-recoverable waste attributed to the product, while M is the mass of the finished product. V and W0 are computed by the Equations (3) and (4), respectively:

$$V = M(1 - F_R - F_U - F_S) \qquad (3)$$

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \qquad (4)$$

where FR represents the recycled fraction of the feedstock, FU the fraction from reused sources and FS the fraction of the biological materials used which originate from sustained production; while CR represent the fraction of the product collected for recycling at the end of its use phase, CU the fraction of the product going into component reuse, CC the mass of the product comprising uncontaminated biological materials that are composted and CE the mass of the product comprising biological materials from sustained production used for energy recovery.

Finally, F(X) is defined in the Equation (5):

$$F(X) = \frac{0.9}{X} \tag{5}$$

where the utility X takes into account the length and intensity of the product's use phase. The length component (L/Lav) accounts for any reduction (or increase) in the waste stream in a given amount of time for products that have a longer (or shorter) lifetime (L) than the industry average (Lav). The intensity of use component (U/Uav) reflects the extent to which a product is used to its full capacity, relating the average number of functional units achieved during the use of a product (U) and the average number of functional units achieved during the use of an industry-average product of similar type (Uav). These two components are combined as follows:

$$X = \frac{L}{Lav} \bullet \frac{U}{Uav} \tag{6}$$

For assessing the circularity degree, inputs and outputs have been defined for each scenario. In the circular scenario, among the inputs, we find pruning residues, part of the biphasic pomace, and leaves and olive pits that are "reused components" in the production process; organic fertilizer from "recycled" sources; as well as pesticides, water, fuels, and energy from virgin raw materials. Among the outputs, we find the residual part of pomace and olive pits as "recoverable waste" for energy valorization. In the linear scenario, the inputs such as fertilizers, pesticides, water, fuels, and energy are all derived from virgin raw materials, while the outputs include the pruning residues as "recoverable waste" for "energy valorization", the pomace and vegetation water that represent a waste "recoverable for other uses".

5.4 Results and Discussion

The impact assessment using the Re.Ci.Pe method shows an advantage in almost all impact categories for the circular scenario (Table 3). Only in the categories Stratospheric ozone depletion, Terrestrial acidification, and Marine eutrophication the circular scenario shows higher impacts due to the field emissions. The contribution analysis of impacts (Figure 2) also confirms the fertilisation as the first hotspot related to nitrogen distribution. In fact, the circular scenario uses almost double the amount of nitrogen and this results in higher emissions of N_2O, NO_x, NH_3 and, NO_3, especially for Stratospheric ozone depletion (98.09%), and Fine particulate matter formation (95.87%). In the linear scenario, the impacts related to synthetic fertiliser production are more significant for Ionizing radiation (65.77%) and Mineral Resources Scarcity (66.20%). For both scenarios, the second hotspot is pesticides production, which affects mainly the following categories: Marine ecotoxicity, and Freshwater ecotoxicity. For Water consumption category, the major contribution is due to the milling phase especially for circular scenario. Wastewater disposal only affects the linear scenario using a three-stage extraction system and causes a significant impact in the Freshwater eutrophication (36.38%) and Marine eutrophication (16.66%) categories. It should be noted that wastewater treatment generates a positive impact in terms of treated water available for the ecosystem.

Table 3. Characterization of impacts related to 1 kg of EVOO.

Impact category	Unit	“Circular approach”	“Linear approach”	Circular/Linear
Global warming	kg CO2 eq	1.24E+00	1.76E+00	-29.57%
Stratospheric ozone depletion	kg CFC11 eq	1.86E-05	1.30E-05	**+43.38%**
Ionizing radiation	kBq Co-60 eq	2.59E-02	7.29E-02	-64.51%
Ozone formation, Human health	kg NOx eq	1.53E-02	1.66E-02	-7.61%
Fine particulate matter formation	kg PM2.5 eq	1.77E-02	1.84E-02	-4.00%
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.54E-02	1.67E-02	-7.68%
Terrestrial acidification	kg SO2 eq	2.46E-02	2.20E-02	**+11.73%**
Freshwater eutrophication	kg P eq	2.86E-04	1.17E-03	-75.56%
Marine eutrophication	kg N eq	6.70E-03	5.08E-03	**+31.69%**
Terrestrial ecotoxicity	kg 1,4-DCB	1.93E+00	5.87E+00	-67.04%
Freshwater ecotoxicity	kg 1,4-DCB	1.19E-01	1.94E-01	-38.56%
Marine ecotoxicity	kg 1,4-DCB	1.49E-01	2.22E-01	-32.72%
Human carcinogenic toxicity	kg 1,4-DCB	4.58E-02	9.59E-02	-52.29%
Human non-carcinogenic toxicity	kg 1,4-DCB	2.48E+00	3.46E+00	-28.42%
Land use	m2a crop eq	3.18E-02	6.34E-02	-49.81%
Mineral resource scarcity	kg Cu eq	6.94E-03	2.03E-02	-65.72%
Fossil resource scarcity	kg oil eq	2.36E-01	4.59E-01	-48.70%
Water consumption	m3	2.42E-02	3.75E-02	-35.54%

(Source: Authors’ elaboration).

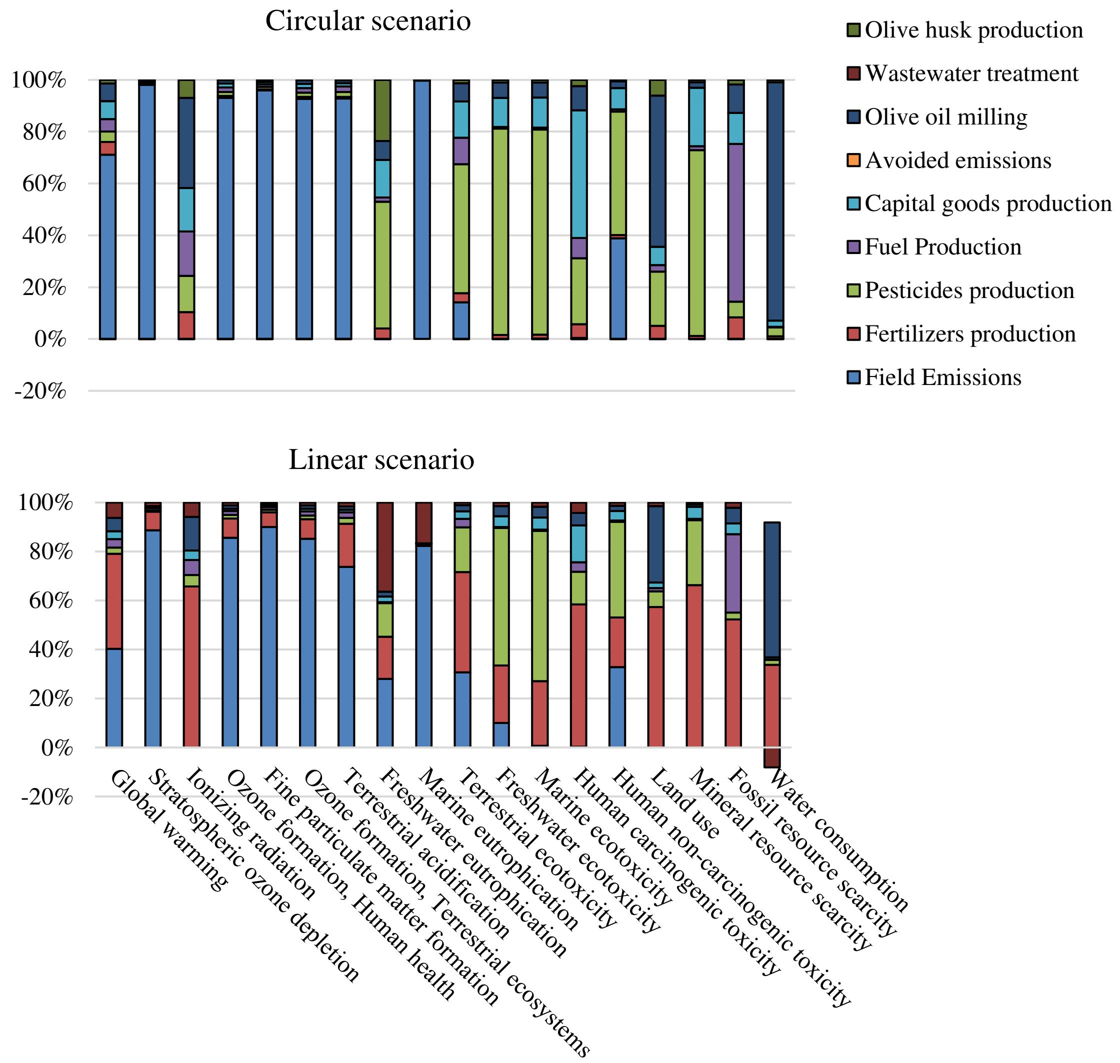

Figure 2. Contribution analysis of EVO oil production (Source: Authors' elaboration).

Table 4 shows the main results of the economic assessment. In line with the proposed methodology, all costs were quantified for each life cycle stage of the olive scenarios. In terms of investment cost in the planting stage, the worst performance is reached by the circular scenario, equal to 7,555.40 € ha^{-1} year^{-1} vs. 7,495.40 € ha^{-1} year^{-1} attained by the linear one. This is due to the higher costs for the purchase of both the pomace spreading and shredding machines. In contrast, focusing on constant production stage, the circular scenario achieves the best performance mainly due to lower fertilizer purchase, because of the reuse of the co-products such as pruning residues, olive pomace and olive pits that return to the production cycle as an input.

Table 4. Olive production costs of the circular vs linear scenario per life cycle stages (€ ha^{-1} $year^{-1}$).

Life cycle stages	Circular scenario	Linear scenario
Planting stage (*year 0*)	7,555.40	7,495.40
Unproductive stage (*1st-4th year*)	2,102.17	2,326.95
Increasing production stage (*5th-15th year*)	3,887.61	3,972.05
Constant production stage (*16th-56th year*)	4,332.28	4,454.09
Tillage (input cost + human labour cost)	*231.07*	*214.80*
Fertilization (input cost + human labour cost)	*779.43*	*827.97*
Disease control (input cost + human labour cost)	*314.90*	*306.40*
Pruning (input cost + human labour cost)	*617.60*	*633.60*
Harvesting (input cost + human labour cost)	*680.00*	*748.00*
Decreasing production stage (*57th-60th year*)	4,418.96	4,298.67
End of life stage (*60th year*)	10,986.67	11,164.86

(Source: Authors' elaboration).

The extraction cost is higher in the circular scenario, with a value of 0.41 € kg^{-1} vs. 0.39 € kg^{-1} reached by the linear scenario. This is mainly due to the higher initial investment costs incurred for the purchase of olive pit separator (Table 5).

In terms of the total production cost of EVO oil, obtained by adding the cost of olive production and the cost of extraction, the results revealed the lower cost for the circular scenario equal to 2.28 € kg^{-1} vs. 2.33 € kg^{-1} achieved by the linear one.

Table 5. Olive oil extraction costs of the circular vs linear scenario.

Item cost	Circular scenario		Linear scenario	
	(€ kg^{-1})	%	(€ kg^{-1})	%
Total Variable Costs (A)	**0.13**	***32.54***	**0.12**	***30.15***
Input cost	0.066	*15.90*	0.062	*15.79*
Human labour cost	0.065	*15.78*	0.053	*13.56*
Interests on advance capital	0.004	*0.86*	0.003	*0.81*
Total Fixed Costs (B)	**0.28**	***67.46***	**0.27**	***69.85***
Machinery and land investment ownership costs	0.081	*19.66*	0.079	*20.07*
Rental shed	0.064	*15.47*	0.064	*16.31*
Interests on capital goods	0.027	*6.60*	0.026	*6.70*
Taxes	0.047	*11.46*	0.047	*12.08*
Administration overheads	0.059	*14.26*	0.058	*14.69*
Total extraction costs (A+B)	**0.41**	***100.00***	**0.39**	***100.00***

(Source: Authors' elaboration).

The findings of investment feasibility analysis by including public subsidies revealed that, in the EVO oil production phase, the circular scenario was the most economically feasible alternative, for all indicators examined (Table 6). The higher profitability of the circular system was positively affected by the lower input costs and the increased revenue from the additional sale of olive pits.

Table 6. Investment analysis of the circular vs linear scenario.

Economic indicator	**Unit**	**Olive production phase**		**EVO oil production phase**	
		Circular scenario	**Linear scenario**	**Circular scenario**	**Linear scenario**
Net Present Value (NPV)	€ kg^{-1}	0.01	0.06	0.91	0.59
Internal Rate of Return (IRR)	%	3.00	4.80	40.30	40.10
Payback Period (PBP)	years	45.28	31.14	2.58	2.71
Gross Margin (GM)	€ kg^{-1}	0.12	0.18	2.98	2.22

(Source: Authors' elaboration).

The results of the evaluation of external costs per scenario are reported in Figure 3. The analysis revealed that the olive production phase is the most impactful compared to the extraction phase in both the circular and linear scenarios. However, the circular scenario showed the best results with a deviation of 3.86% compared to the linear scenario. The impact categories producing the greatest externalities were particulate matter formation with 64.83% of the total (vs. 64.77% of the linear scenario) and terrestrial acidification (17.5% vs 14.0%). The climate change category achieved the lowest environmental costs in the circular scenario (5.96% vs 8.04) due to lower emissions for fertiliser production.

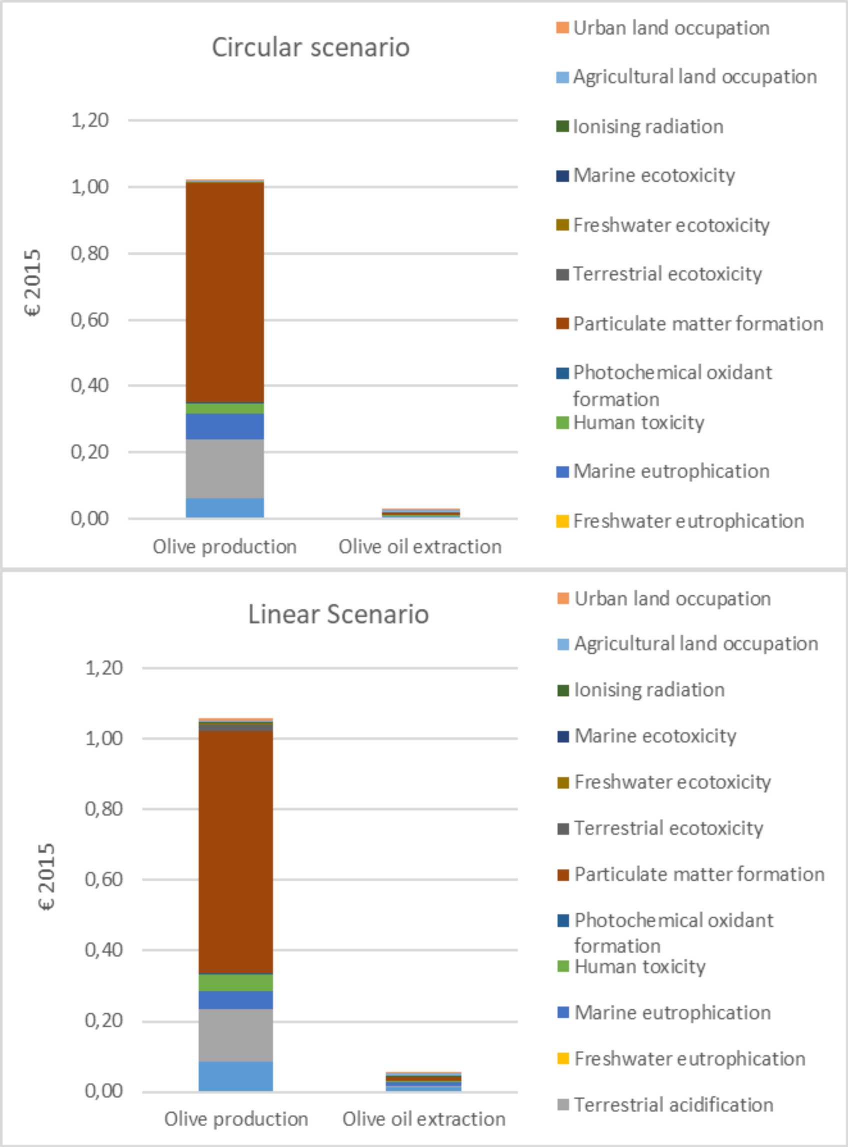

Figure 3. Environmental cost contribution analysis (Source: Authors' elaboration).

The MCI results show that the best performance is effectively achieved by the circular scenario with a value of 0.68 out of 1, unlike the linear scenario in which the MCI reaches a value of 0,53 out of 1 (Table 7). This better result is due to both a lower quantity of virgin raw materials (V), because of the reuse of the co-products obtained in both agricultural and extraction phases, and a lower production of unrecoverable waste (W). Owing to the lack of studies applying MCI to the olive oil system, it is difficult to contextualize its score. The only applications of the MCI to the agricultural system concerned the tomato production in the study by Rufi-Salis et al. (2021), with an MCI value of 0.46 out of 1, and the poultry sector in Rocchi et al. (2021), with a value of 0.48 out of 1.

Table 7. MCI results.

Scenario	V	W	LFI	MCI
	(kg)	**(kg)**	**(0/1 scale)**	**(0/1 scale)**
Circular	1.05	4.11	0.32	0.68
Linear	4.59	8.86	0.47	0.53

Note: V=Virgin feedstock; W=Waste unrecoverable; LFI=Linear flow index; MCI=Material circularity indicator (Source: Authors' elaboration).

5.5 Discussion

The introduction of circular strategies in agriculture undoubtedly represents a crucial challenge in the pathways of ecological transition. In a global scenario with a world population of 8 billion and projections suggesting that it will reach almost 10 billion by 2050 (United Nations, 2022), it is clear that food production will play an increasingly central role. To avoid exceeding the carrying capacity, it will be of growing importance to reduce the consumption of virgin resources, valorizing waste products that would otherwise have to be managed as waste, further burdening the system. The challenge is to grow by reducing resource exploitation, waste and environmental burdens.

The application of the LCA methodology has made it possible to show how much and in which manner the environmental profile of a product is changed for the better or the worse by adopting circular strategies. The subsequent application of the Material Circularity Indicator made it possible to assess the degree of circularity of the innovative scenario compared to the linear one, but without giving any indication of the environmental impacts. It is clear that in the assessment of circular strategies it is not enough to assess only the degree of circularity, just as it is not enough to assess only the environmental impacts: an integrated assessment of the two environmental aspects is required, adding also the assessment of the economic and social aspects. Starting from these assumptions, it is important to first check the robustness of the results. By comparing the environmental profile of the linear scenario with some EPD-certified oils, it was possible to observe substantial comparability for the impact categories in common between the EPD method and the ReCiPe method (Global warming, Terrestrial acidification, Freshwater eutrophication). Considering that one liter of oil is equivalent to 916 grams, simply multiply our results by 0.916 to scale the values to the same Functional Unit used in EPD certifications (1 liter of EVOO). It should also be considered that only upstream and core process impacts should be calculated, excluding bottling impacts. In terms of "Global Warming", the linear scenario has an impact of 1.61 kg CO_2 eq, which is comparable with both "Monini Gran Fruttato" oil (EPD, 2022) which has an impact of 1.88 kg CO_2 eq and De Cecco oil (EPD, 2017) which has an impact of 1.41 kg CO_2 eq.

The impact category “Terrestrial acidification” is the second category that can be compared between the different environmental analyses and has a value of 0.0202 kg SO_2 eq for the linear scenario of the present study, 0.0253 kg SO_2 eq for “Monini Gran Fruttato” oil (EPD, 2022) and 0.012 kg SO_2 eq for “De Cecco” oil (EPD, 2017). The last category “Freshwater eutrophication” has a value of 0.0011 kg P eq for the linear scenario of this study, 0.0653 kg P eq for “Monini Gran Fruttato” oil (EPD, 2022) and 0.006 kg P eq for “De Cecco” oil (EPD, 2017).

These results are also consistent with the literature review carried out by Guarino et al. (2019) who analysed the impacts in terms of “Global Warming” in 18 different studies, using one liter of olive oil as a reference unit.

Having verified the robustness of the results of the linear scenario, a critical comparison can be made with the circular scenario. As can be seen from the inventory analysis, the circular strategies allowed the replacement of part of the synthetic fertilizers with crop residues and by-products from the mill. This provided a double benefit related to the reduction of impacts but also the reduction of waste. If we had expanded the boundaries of the system by considering disposal-related impacts, the results would probably have been even more strongly in favor of the circular scenario.

As was also discussed during the analysis of the results, the adoption of circular strategies does not always bring only benefits, so their adoption must necessarily be evaluated through a life-cycle analysis in order to assess possible burden shifting. An expansion in the adoption of circular strategies could bring further significant benefits. For example, pomace could first be used for biogas production (Benalia et al., 2021) and digestate eventually used as fertilizer. Value could still be extracted from a product that is conventionally considered waste.

In addition to the environmental issues, several concerns can affect the economic performance of adopting circular strategies in olive oil systems. As discussed by Ncbe et al. (2022), the difficulties to start closing the loop in the olive oil production sector appear to be economical and organizational, which, if overcome, become cost-effective paths.

As our study showed, circular techniques necessarily require greater investment in machinery and technology. In the circular scenario examined, more machines are required, i.e. shredding machines for pruning residues, pomace spreading and olive pit extractor, whose use allows the reuse of by-products as input and thus the reduction of chemical fertilizers and thermal energy from virgin raw material. Shredded pruning residues likewise offer an opportunity to improve soil functioning as tangible water and soil conservation measure, also reducing erosion and preserving soil moisture. This agricultural operation allows to reduce the appearance of weeds and thus the application of herbicides, as well as contributes to the improvement in fertility and C sequestration (Gómez et al., 2016; Taguas et al., 2021). The other application that takes part in the reduction of chemical fertilizer use is the spreading of two-stage pomace from olive oil extraction. The use of pomace is also finding increasing application as a soil conditioner and fertilizer due to the decreasing extraction of pomace oil in specific industries. Similar conclusions were reached by the study of Foti et al. (2022), who assert the current use in agriculture of olive pomace as a soil conditioner and fertilizer, as well as in bioenergy production and for the extraction of polyphenols intended for pharmaceutical, food, or cosmetic industries. Until a few decades ago, however, pomace oil extraction carried out with solvents was flourishing and the sale of pomace to processors was profitable. Because of the emergent apprehensions from the public about the use of organic solvents in food processing (Ncbe et al., 2022), pomace has fully lost its economic value and it is ordinary for it to be taken for free by pomace factories.

Olive pit extraction is also considered a circular practice due to its use for thermal energy production (Stempfle et al., 2021). Considering that cold olive oil extraction does not require water at high temperatures, the use of olive pits in the mill is limited. Therefore to a large extent, it is sold as fuel for households, going to be a good source of biomass and income for the enterprise. As argued by Hermoso-Orzáez et al. (2020), olive pits with a high calorific power by thermochemical conversion could be converted into different forms of energy also contributing to the mitigation of global warming.

In addition to high investments in innovative material recovery and extraction techniques, the valorization of the oil by-products is hindered by bureaucratic and authorization challenges, as well as difficulties in planning for the supply and seasonal availability of the raw material (Ncbe et al., 2022).

Financial support from the public sector could help companies in the initial investment of by-product valorization technologies, enabling them to overcome some of the barriers to adopting circular strategies.

In terms of material flow restoration at farm level, our research results showed better performance for the circular scenario with an MCI value of 0.63 out of 1 vs. the linear scenario reaching a value of 0.53. This means that in the circular scenario there is both a lower use of virgin raw material and a lower production of unrecoverable waste. In the former case, the use of virgin resources is replaced by the reuse of the co-products obtained both in the agricultural phase, i.e., pruning residues that are shredded and buried in the soil, and in the extractive phase, where part of the nut-free pomace along with the leaves are used in the organic fertilization of farm soils, and the olive pits to produce the thermal energy needed by the olive mill. The circular system is also characterized by less waste that cannot be recovered (unrecoverable waste) or can be recovered for other uses. Specifically, pomace and pruning residues are not counted in the circular scenario waste. In addition, emissions from LCA results that are lower in the circular scenario were taken into account among the non-recoverable waste. The greater degree of circularity achieved through the application of closed-loop pathways on the olive farm under study represents a means of making environmental improvements and increasing resource productivity.

5.6 Conclusions

This study aims to assess the sustainability performance of circular strategies in the EVO oil production system, applying environmental, economic, and circular metrics at the micro-level. It is well known that olive oil production causes significant environmental impacts and economic concerns due to the production of several by-products that are difficult to manage. The implementation of closed-loop pathways allow reusing, recycling, or enhancing such by-products, moving towards more sustainable and efficient production patterns. Indeed, using specific technologies, by-products can be managed as a possible resource that can be converted into a source of income for the farm (e.g., energy, organic matter, irrigation water). However, the transition to a circular and sustainable model remains a complex challenge needing an approach that includes not only supply chain actors but also public decision makers. In addition, there is a need to overcome the various obstacles, both technical related to the industrial phase and economic related to investments to initiate circular practices. Despite being particularly anthropized, the olive oil supply chain lends itself well to circular modeling, which is instead inherent in natural ecosystems.

The methodological proposal here shown, based on LC methodologies (LCA and ELCC) and circularity indicators (MCI), provides comprehensive results on environmental and economic impacts, and circularity performance of applying closed-loop strategies in olive oil systems. In scientific literature, the integrated applications of LC approaches and circular economy metrics refer to single process components (e.g., agricultural phase, mill wastewater, and olive pomace) rather than to the overall production process. Through the proposed LC model, it was possible to evaluate the sustainability performance of circular strategies along the entire olive oil supply chain.

In terms of environmental assessment, due to not counting energy and transport in the MCI implementation the use of LCA methodology becomes essential for the return of a reliable result and in particular to verify whether the adoption of circular techniques contributes effectively to the mitigation of environmental impact categories and does not instead to burden shifting. For example, the circular scenario was found to allow a double benefit related to the reduction of impacts and wastes, with the replacement of part of the synthetic fertilizers with crop residues and by-products from the olive-oil mill.

From an economic point of view, our study shows how the circular scenario requires greater business investment when closed-loop strategies are implemented. The purchase of machines for separating olive stones or spreading pomace are examples of this. This result highlights how investment outlay is a limitation to circular approaches, which can also be solved through the adoption of specific government-type investment support measures. In terms of profit, circular scenarios achieve better performance related to the reduction of virgin raw materials purchased and the sale of some by-products such as olive pits. From the perspective of external cost evaluation, the circular scenario also shows the best results compared to the linear scenario. The climate change category achieved the lowest environmental costs due to lower emissions for fertilizer production.

Future research will be aimed at extending the analysis here proposed to other olive production areas to validate the applicability and effectiveness of circular strategies on olive-oil farms. In addition, further research development will be concerned with extending the sustainability dimensions by integrating the social-LCA (SLCA) methodology.

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6. Conclusions and Future Perspectives

This thesis work carried out an analytical assessment of the sustainability and circularity of closed-loop olive-growing scenarios, attempting to provide solutions to facilitate the simultaneous coexistence of ecological and economic systems.

The discussion shows that the transition to a circular and potentially more sustainable model remains a complex challenge that requires an approach including not only supply chain actors' good practices, but also the willingness of public decision-makers to effectively promote alternative paths. In addition, there is a need to overcome several obstacles, both technical related to the industrial stage, and economic related to investments to initiate circular practices (Roos Lindgreen et al., 2022).

Despite being particularly anthropized, agri-food supply chains lend themselves well to circular modelling, which is instead inherent in natural ecosystems.

This thesis aimed to contribute to defining a model for evaluating circular practices through the life cycle approach, applying it to real case studies.

Chapter 1 explored the conceptual evolution and the prerogatives that led to the development of CE concept, such as the problems related to the mainstream linear economic model. This chapter also recalled the definitions most commonly found in scientific literature and the current barriers that still hold back the transition to the CE model, despite the commitment of institutional bodies such as the European Commission.

Chapter 2 concerned a critical and systematic review of the literature, which provided an overview of the state of the art of applications of the LC approach in the assessment of the circularity of processes and products. In particular, it was found that circularity measurement and LC analysis are perfectly complementary and integrable, despite still being at a primordial stage. For this reason, it is crucial that experts in LC methodologies adopt the key elements to make the results obtained fit perfectly with circularity measurements and that these can even rest on a common foundation.

In response to these considerations, chapter 3 illustrated the analysis for the integration of LC methodologies with circularity approaches. The main problem with integration lies in the different views of the product life cycle. In the case of LC methodologies, particularly with reference to impact assessment, the system boundaries focus on a single product life cycle (cradle-to-gate or cradle-to-grave analysis); whereas circularity assessment would require an extension of the system boundaries to multiple life cycles (cradle-to-cradle perspective), to include component reuse, remanufacturing, and recycling.

Therefore, a complementary LC approach to a circularity assessment framework would need to extend the system boundaries to a multi-cycle approach, incorporating product losses, recycling and reuse in the next cycle, transportation, and all processes that enable LC methodologies to close the loop according to the circular approach into the horizon of analysis.

For this reason, a methodological proposal has been developed to design a customized LC modeling, in which a circular olive oil system consisting of multiple interconnected life cycles is considered from a multicycle (cradle-to-cradle) perspective in an attempt to internalize the impacts of circularity.

Through this model, it will be possible to assess the environmental, economic and social effects over time of adopting CE strategies along the entire olive oil supply chain.

Moving to the application study of the thesis, chapter 4 analyzed all the production stages that lead to the obtaining of extra virgin olive oil with their respective environmental impacts. For each stage are reported, all possible alternatives currently found in Mediterranean olive growing, with their related impacts. These impacts, after a general description using bibliographic sources, have been reduced to the impact categories and protection areas typically used in the LCA.

Chapter 5 illustrated the evaluation of circular practices of real case studies through the LC approach.

After a theoretical deepening of the LCA, ELCC methodologies (already partially carried out in the third chapter), and MCI indicator, the integration of these methodologies to the scenarios considered is conducted.

Finally the main results obtained from the analysis are reported by highlighting that the application of closed-loop strategies presented the best results in terms of circularity, as measured by the MCI indicator.

Also in terms of environmental impacts measured by LCA, the closed-loop scenario has the best environmental performance for almost all impact categories, with an average reduction of 40%. The most representative categories include the following impact reductions: 67 % for Terrestrial Ecotoxicity, 65 % for the Mineral Resource Scarcity, 64 % for Ionizing Radiation, and 30 % for Global Warming. The circular scenario, on the other hand, has higher values for the categories Stratospheric Ozone Reduction +43%

Marine Eutrophication 31.7% and Terrestrial Acidification 11.73% due to the higher amount of distributed nitrogen. These results demonstrate the critical importance of measuring circularity with methodologies such as LCA to highlight criticalities and even in what conceptually may seem the most sustainable directions, as in the case of circular approaches. Starting from the criticalities mentioned, specific corrections can be put in place.

From an economic point of view measured with LCC, it emerges that circular scenarios require a greater outlay in terms of investment. In a specific case, for example, for the purchase of machines for separating stone olives or spreading pomace. This result highlights how investment outlays are a limitation to circular approaches, which can also be solved through the adoption of specific government-type investment support measures. In terms of profits, circular scenarios achieve better performance related to the reduction of virgin raw materials purchased and the sale of some by-products such as olive pits.

Different could be the future developments of the research:

- extend the boundaries of the study system to include oil bottling, distribution and packaging management;
- moving the modeling from the farm scale (micro) to the territorial scale (meso) and - analyzing from the collaboration of different actors the marketing and communication strategies towards consumers in order to verify their preferences;
- analyze other circular directions by verifying their greater likelihood of adoption in particular contexts, based on the preferences of socio-economic actors, specific characteristics of the environment, as well as environmental benefits that can be maximized at the local level.

In this direction, given the economic, social and environmental dimensions of olive cultivation, a paradigm shift toward the adoption of circular practices could be a path toward sustainable development and ensure economic, environmental and social sustainability, as well as conservation of biodiversity and productivity over time of agroecosystems and help ensure food security.

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Appendix 1.

Table 1. Simplified Environmental and Economic Life Cycle Inventory.

Process	**Input**	**Unit**	**Circular scenario**	**€ kg^{-1}**	**Linear scenario**	**€ kg^{-1}**
Fertilization	Organic fertilizer (N 11%)	kg	0.735	0.294	//	-
	N 11%, P2O5 22%, K2O 16%	kg	//	-	0.441	0.265
	Organic leaf fertiliser (N 9%)	kg	0.007	0.017	0.004	0.011
	Self-produced wet pomace	kg	1.250	-	//	-
	Leaves and twigs	kg	0.222	-	0.221	-
	Boric acid 11%	kg	0.002	0.018	0.002	0.018
Pest control	Cupric oxide 75%	kg	0.003	0.033	//	-
	Kaolin	kg	0.029	0.088	//	-
	Soy Lecithin	kg	0.000	0.004	//	-
	Bacillus thuringiensis Berliner var. Kurstaki	kg	0.000	0.007	//	-
	Spinosad	kg	0.002	0.055	//	-
	Copper Oxiclorid 37,5%	kg	//	-	0.004	0.031
	Fosmet (200 g/l) SPADA 200 EC	kg	//	-	0.002	0.028
	Acetamiprid 200	kg	//	-	0.001	0.074
Technical operations	Diesel fuel for tillage	kg	0.018	0.015	0.018	0.015
	Diesel fuel for shredding pruning residues	kg	0.007	0.005	-	-
	Diesel fuel for spreading leaves and twigs	kg	0.005	0.004	0.005	0.004
	Diesel oil for pomace spreading	kg	0.005	0.004	-	-
	Diesel fuel for fertilization	kg	0.007	0.005	0.007	0.005
	Diesel fuel for pest control	kg	0.024	0.019	0.023	0.019
	Diesel fuel for harvest shaker	kg	0.013	0.011	0.013	0.010
	Diesel fuel for pre-harvest rolling	kg	0.039	0.032	0.039	0.031
	Gasoline for chainsaw and brushcutter	kg	0.005	0.004	0.005	0.004
	Oil	kg	0.004	0.039	0.004	0.039
	Grease	kg	0.003	0.011	0.003	0.010
Work	Tillage	h	0.002	0.064	0.002	0.064
	Shredding pruning residues	h	0.003	0.027		
	Spreading leaves and twigs	h	0.003	0.043	0.002	0.032
	Pomace spreading	h	0.002	0.032		
	Fertilization	h	0.001	0.011	0.001	0.021
	Pest-control	h	0.001	0.064	0.001	0.064
	Pruning	h	0.012	0.263	0.012	0.260
	Arrangement of pruning residue for the chipper machine	h	0.011	0.143	0.010	0.142
	Transportation and handling	h	0.007	0.045	0.007	0.044
	Rolling pre-harvest	h	0.002	0.013	0.002	0.013
	Cleaning borders with brush cutter	h	0.003	0.045	0.003	0.044
	Harvest shaker	h	0.010	0.080	0.010	0.079
	Moving nets for harvesting	h	0.010	0.336	0.010	0.332
Agricultural products	Olives	kg	6.250	-	6.250	-
	Wood	kg	0.368	-	0.368	-
Oil milling	Electricity for moving olives	kWh	0.003	0.001	0.003	0.001
	Electricity for washing	kWh	0.021	0.007	0.011	0.004
	Electricity for milling	kWh	0.024	0.008	0.028	0.009
	Electricity for malaxing	kWh	0.006	0.002	0.008	0.003
	Electricity for horizontal separator	kWh	0.123	0.040	0.125	0.040
	Electricity for oil centrifugation	kWh	0.023	0.007	0.034	0.011
	Electricity for pit separator	kWh	0.028	0.009	-	
	Water	m3	0.002	0.003	0.003	0.006
	Heat	MJ	0.392	-	0.392	0.059
Work	Milling, moving and cleaning	h	0.002	0.027	0.002	0.027
	Surveillance	h	0.003	0.022	0.003	0.022
Industrial products	EVOO	kg	1.000		1.000	
	Pomace	kg	6.156		3.094	
	Husk	kg	0.750		//	
	Wastewater	l	//		4.519	