



# Performance indicators of circular economy in the agriculture and food industry

Aristea Kounani<sup>1</sup> · Alexandra Pavloudi<sup>1</sup> · Stamatias Aggelopoulos<sup>1</sup>

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## Abstract

Among the main challenges over the past few years has been to capture and analyze the progress made towards the transition to circular economy (CE), since ensuring that the transition is successful requires monitoring progress. As a result of the enormous amount of harmful waste produced by the olive oil industry in the Mediterranean region, monitoring and evaluating circularity has become the basis for economic development measures. An understanding of the degree of circularity is crucial to improving extraction processes. Additionally, this type of measurement could prove useful for driving policies on the topic and improving sustainability, since CE is often used as a potential tool to support sustainable development. This research provides a consistent review of the CE indicators used in agro-industry sector, based on the scientific literature and practice, identifying those who could assess circularity in the olive oil industry. Circularity refers to reducing waste and using by-products in the olive oil industry and in general in the food supply chain. The purpose of this review is to assess the success of CE strategies and to remove some of the ambiguity surrounding CE in practice. Despite the fact that the indicators of circular economy have aroused substantial attention globally, there is not much conceptual and empirical research focusing on the development of indicators in practice.

**Keywords** Indicators of circular economy · Monitoring circularity · Olive oil industry · Ukraine conflict · Pandemic · Systems analysis

## 1 Introduction

In the era of global crisis, humanity not only has to deal with numerous challenges that threaten its survival and prosperity, including the financial downturn, health pandemic, migration flows, climate change, energy sufficiency and food security, but also faces the challenge of ensuring the sustainability of the planet. Therefore, the war between Ukraine and Russia has intensified the energy crisis on the one hand, and put the food security on peril on the other. As a result of their exports of wheat, corn and sunflower oil, which are used in

food processing, Ukraine and Russia account for 30 percent of global exports. The threat to Ukrainian farms and the closure of Black Sea harbors have restricted food supplies at a time when prices are at their highest since 2011, and food shortages have already hit some countries (Tank 2022).

Concurrently, there has been a significant impact on the global economy due to the Covid-19 pandemic. In response to the virus rapid spread, governments around the world have taken extraordinary measures to eliminate it, including temporary closures of businesses and companies that have affected economic markets (Chiaraluce 2021).

In addition to these burdens, many countries have sought innovative policies to address the concerns associated with resource scarcity and global warming (Geng et al. 2012). Directly and indirectly, this situation seems to have influenced the agri-food sector, even though there is an anticipated increase in agricultural demand at a rate of 1.1 percent per year over the period 2010–2050 (Alexandratos & Bruinsma 2012; Berbel & Posadillo 2018). Human societies benefit from agri-food systems (AFS) in multiple ways (food, animal feed, animal traction, clothing, bio-energy,

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✉ Aristeia Kounani  
akounani@yahoo.gr  
Alexandra Pavloudi  
apavloudi@gmail.com; stalex@ihu.gr  
Stamatias Aggelopoulos  
saggelopoulos@ihu.edu.gr; stamagg40@gmail.com

<sup>1</sup> Department of Agriculture, Program of Agricultural Economics & Entrepreneurship, International Hellenic University, P.O.box.141, 57400 Thessaloniki, Greece

construction materials, etc.). In contrast, they alter nutrient cycles and deplete limited resources, specifically phosphorus (P) from mines, which has negative impacts on the environment. Also, the use of non-renewable fossil energy generates greenhouse gases (GHGs) ( $\text{CO}_2$ ), which are responsible for climate change, and release of reactive nitrogen (N) into the atmosphere, causing a cascade of N emissions, increasing greenhouse gas emissions ( $\text{N}_2\text{O}$ ), and increasing atmospheric deposition ( $\text{NO}_x$  and  $\text{NH}_3$ ). This leads to a global acidification of the environment, decreased productivity, inefficient functioning, and eutrophication of natural and cultivated ecosystems ( $\text{NO}_3^-$ ) (Kleinpeter et al. 2023). A number of initiatives have been undertaken recently in the food sector to address perpetual concerns such as food safety, product quality, food loss, waste production, and environmental degradation (Esposito et al. 2020). In this scenario, CE provides avenues for reducing food waste and augmenting valorization of it (Ciccullo et al. 2021). It has become increasingly important to implement CE principles in the food sector, particularly in developing countries, since the food sector is vital for their economic growth (Fukase & Martin, 2020). Considering that the agri-food sector is one of those with the highest environmental footprint, increasing its sustainability is a crucial issue, in order to ensure the sustainability of the planet in general (Ncube et al. 2022). In addition, the agri-food sector, as it seems to be the greater contributor to the production of biomass in a large percentage, is considered the largest biological sector and is therefore one of the main sectors that must focus indispensably on the adoption of the principles of the CE (Duque-Acevedo et al. 2020; Atanasovska et al. 2022). Introducing by-products into the system or creating new processing steps through recycling and reusing would substantially improve the sustainability of the food system (Focker et al. 2022).

The transition to a CE is usually directly associated with stimulating innovation, increasing jobs and investments, as well as added value (Chobanova 2020). For instance, according to an analysis of the Circular Economy and Resource Efficiency Agency of the UK, conducted in 2015, it is estimated that CE has the potential to reduce unemployment rate in EU, since it could create 3 million extra jobs (Kristensen & Mosgaard 2020). While at the same time, according to a IPCC (2014) report, globally, CE could reduce carbon dioxide emissions by 550 Mt  $\text{CO}_2$  equivalent (approximately 33%), or 3/5ths of the projected reduction target for limiting global warming to 2 °C by 2050 (Robaina et al. 2020).

The CE model is the basis for most sustainable development policies and instruments (Yang et al. 2023). In the food sector, CE is considered an idea that can contribute to sustainability goals by supporting regenerative patterns of consumption and production (Friant et al. 2020). According to the UN, CE is associated directly and indirectly with the Sustainable Development Goals (SDGs). Sustainability in

agriculture is a key to achieving zero hunger under SDG 2, cleaner, renewable energy sources are key to SDG 7, sustainable consumption is key to SDG 12. As well as it is specifically emphasized that by reusing and recycling products, food loss can be reduced and resource utilization efficiency can be improved, and climate change is addressed by SDG 13 (Barros et al. 2020; Zhang et al. 2022).

To the best of the authors' knowledge, there have been no comprehensive studies aimed at filling the gaps and addressing the existing lack of an assessment tool to measure and monitoring the CE in olive oil industry. In light of that, the purpose in this review paper is to describe sources of CE indicators for monitoring progress of the agriculture and food industry, by illuminating the case of olive mills, subject to disruption caused for instance by the Ukraine conflict, pandemic, and other stressors. Due to the lack of consensus regarding the CE indicators in the agri-food industry, especially the olive oil industry, an original feature of this paper is that it reorganizes the CE indicators groups, as well as adapts the indicators to fit the olive oil industry. Since the agri-food, and specifically the olive oil industry, has a key role towards sustainable development (Espadas-Aldana et al. 2023), the development of the indicators for measuring or/and monitoring CE in olive oil industry is of great significance in order to detect the level of implementation of CE principles and check the effectiveness of the current policy. To clarify and reach desired outcomes, indicators are generally designed to provide decision-makers with objective, credible information about the state of the olive oil industry. Providing a framework for measuring and/or monitoring the system and ensuring that it evolves towards circularity is an essential component of this paper.

The remaining of this paper has the following structure: Sect. 2 is dedicated to summarize the theoretical background regarding the importance of measuring and monitoring CE in general, as well as to present existing methods and indicators. As a final note, this section gives prominence to implementing CE practices in the olive oil industry sector, and to highlighting the significance of finding indicators and methods that could be used to measure circularity in olive mills. Section 3 is a reference to the methodology this article used to achieve its objectives. A discussion and suggestions of the indicators that could be used in olive mill measurements are then presented in Sect. 4, followed by conclusions in Sect. 5.

## 2 Theoretical background

### 2.1 2.1. Measuring and monitoring of CE

As Peter Drucker describes, “you can't manage what you can't measure”, unless success is defined and tracked, it is not possible for someone to know whether he is successful

(World Bank 2014). The CE is a political goal, which evolves a global one, aimed at combining sustainability with economic growth. The transition from a linear to a CE economy also implies the challenge of assessing this new economy type (Reich et al 2023). Therefore, a fundamental issue in the transition to sustainability is the measurement of CE performance at several levels (Janik & Ryszko 2019), since measuring and reporting progress is essential for a successful CE transition. Nevertheless, there is a lack of detailed understanding of how to assess and monitor progress, particularly at company or product level, making it difficult for producers who want to provide circular products and services in the market, as well as for consumers who wish to compare products and make their decisions considering product circularity (Kristensen & Mosgaard 2020). Since there are a variety of actions, activities, and projects that could be considered “circular,” measuring the “circularity” of a product or service is challenging. Currently, there is no widespread accepted framework for assessing and reporting an organization’s “circularity”. In the CE, this lack of framework represents one of the utmost needs, as well as an opportunity (USCCF, 2022).

It is a complicated task to measure how well a country’s economy or a sector adheres to the principles of the CE, or degree of circularity (EEA, 2016). As part of the monitoring process, key areas of circularity will be identified (sustainable resource management, societal behavior, business operations) and the available indicators will be defined (Chobanova 2020).

Achieving results and targets should inspire action throughout industry and society as well. This requires the development of harmonized, measurable, relevant, and diagnostic indicators (Oswald 2013). As circularity isn’t necessarily synonymous with environmental sustainability (despite often being assumed to be the case), these metrics should also measure environmental performance in addition to circularity. For instance, high recycling rates may result in drastic increases in energy demands, which may offset any environmental gains that are gained from second-hand material recovery (Haupt & Hellweg 2019).

The number of case studies whose primary aim is to evaluate the industrial symbiotic relationship towards CE has increased over the last few years. Such studies could, however, provide insight to those specializing in similar production or business activities or supply chain management processes. These researches use a variety of variables, including economic growth, recycling rates, patents related to SD and CE etc., among others (Cautisanu et al. 2018).

Achieving a circular economy requires providing organizations with tools that measure, monitor, and communicate their progress (Valls-Val et al. 2022). According to several studies in the literature, the lack of a common measurement and monitoring reference point is causing a barrier in CE

development (Poponi et al. 2022). Currently, academia is most concerned with analyzing the transition towards CE, so suitable methods, tools, and indicators are required to gauge the progress (Pavlovic et al. 2020).

## 2.2 Indicators of CE

It has been noted that numerous CE indicators have been developed over the past few years, but there is a lack of consistency regarding their purposes, scopes, and intended applications (Janik & Ryszko 2019). The indicators are typically variables or functions of variables that provide information about circularity (technology cycles) or effects (cause-and-effect models), based on a composite data set of quantitative and qualitative information (Moraga et al. 2019). When designing new products, these indicators allow circularity to be taken into account as a criterion and input for design decisions, as well as allow companies to compare the circularity of different versions (‘what if’ scenarios) of the product. By defining a minimum threshold for their products, the organizations could use the CE indicators to make purchasing decisions (EMF, 2019).

Using the resource productivity (RP) indicator (EEA 2016), which correlates gross domestic product with raw material consumption or domestic material consumption, economic progress can be measured toward a more sustainable economy. The RP measures the overall wellbeing in relative to the resource consumption. A CE transition requires understanding what factors contribute to the different performances of countries in terms of their RP and how they determine a good or poor performance in utilizing resources (Robaina et al. 2020).

CE indicators are typically categorized into micro-level, meso-level, and macro-level, for organizations and products, eco-industrial parks, and cities, provinces, regions and countries, respectively (Pauliuk 2018). A good indicator in CE allows the organization’s performance to be quantified and is a source of relevant decision-making information for managers and entrepreneurs (Walker et al. 2018). Due to the wide variety of sustainability indicators that have been developed, managers were increasingly having trouble grasping their meaning and significance when making decisions and computing the influence of the indicator on their efficiency level. For both company managers and researchers, the assessment of aspects such as environmental footprint, recycling quotas, or environmental impacts of waste management can be challenging, due to its great complexity (Sanchez-Ortiz et al. 2020).

Measurement and monitoring progress towards a circular economy (CE) has been highlighted by a variety of sources, and research into CE indicators has increased (Yang et al. 2023). Table 1 depicts some of the attempts that have already been made during the last decade in

**Table 1** Summary table of the various attempts to identify sets of CE indicators in micro-level

Article title	Year	Description	Authors
Sustainable Development: The Circular Economy Indicators' Selection Model	2016	Analyze a theoretical model for selecting indicators for circular economies	Banaite D., Tamosiuniene R
Measuring circular economy strategies through index methods: a critical analysis	2017	An overview of 17 index-based environmental assessment methodologies is presented, along with a framework that supports the measurement of the adoption of the CE paradigm on four levels	Elita V., Grazia Gnoni M., Tornese F
Circular economy in companies: an analysis of selected indicators from a managerial perspective	2019	Analyzes and compares 19 CE indicators available at the micro level	Janik A., Ryszko A
Circular economy indicators: What do they measure?	2019	Examine existing microscale indicators from the literature and apply the framework	Moraga G., Huisveld S., Mathieux F., Blengini G.A., Alaerts L., Van Acker K., de Meester S., Dewul J
A taxonomy of circular economy indicators	2019	Identify 55 CE indicators and develop comprehensive taxonomy of CE metrics	Saidani M., Yannou B., Leroy Y., Cluzel F., Kendall A
A review of micro level indicators for a circular economy e moving away from the three dimensions of sustainability?	2020	Review 30 indicators of a CE at the micro level	Kristensen H.S., Mosgaard M.A
Circular economy indicators for the food system, CE CENTER Circular Economy, Policy Research Center, pub No 20, p.91	2021	Through a participatory Delphi approach, available academic and policy knowledge about CE and food was brought together and supplemented by stakeholders in Flanders	Vermeyen V., Alaerts L., Arenberg K., Van Schoubroeck S., Van Passel S., Van Acker K
A systematic review for measuring circular economy: The 61 indicators	2021	An overview of 61 CE indicators	De Pascale A., Arbolino R., Szopik-Depeczynska K., Limosani M., Ioppolo G
Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments	2021	Review 38 nano, 14 micro, 6 directed to both levels' indicators related to the sustainability pillars and life cycle stages (take, make, use, and recover) based on their relationship to the sustainability pillars	de Oliveira C.T., Dantas T.E.T., Soares, S.R
Sustainability reports as a tool for measuring and monitoring the transition towards the circular economy of organizations: Proposal of indicators and metrics	2022	For measuring the level of circularity of organizations, 34 indicators were grouped into 10 categories	Ibanez-Fores V., Martínez-Sánchez V., Valls-Val K., Bovea M.D
How to monitor the progress towards a circular food economy: A Delphi study	2022	Defining and prioritizing CE indicator themes to monitor the food system and contributing to a shared vision for a CE for food	Van Schoubroeck S, Vermeyen V, Alaerts L, Van Acker K, Van Passel S
Development and validation of a tool for the integration of the circular economy in industrial companies: Case study of 30 companies	2022	To determine industrial companies' current performance on circularity through the use of a self-improving CE questionnaire	Urain I., Eguren J.A., Justel D
Full length article Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators	2022	Provide 102 indicators for the agri-food sector to guide it towards CE and sustainable development at various spatial levels	Poponi S., Arcese G., Pacchera F., Martucci O
Research gaps and future directions on social value stemming from circular economy practices in agri-food industrial parks: Insights from a systematic literature review	2022	Identify gaps in the three pillars of sustainability by analyzing circularity indicators at nano and micro levels	Atanasovska I, Choudhary S., Koh L., Ketikidis P.H., Solomon A
Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: a systematic literature review	2022	Assess the sustainability of the agri-food sector and, based on the findings, try to understand which indicators are used for what specific purposes	Silvestri C., Silvestri L., Piccarozzi M., Ruggieri A.,

Table 1 (continued)

Article title	Year	Description	Authors
Micro-level measurement of the circularity of organizations: the Italian innovative standardized approach applied to a public sector case study	2023	A critical analysis of the framework of UNI1608856 methodology and its implementation within a public organization is presented in the paper, which focuses on the micro-level of Organisation circularity and improving a specific Organization's environmental performance	Vola P., Cantino G., Gelmini L
Assessing the roles of crops and livestock in nutrient circularity and use efficiency in the agri-food-waste system (AFWS): A set of indicators applied to an isolated tropical island	2023	An AFWS method for assessing nutrient circularity and use efficiency is proposed. An analysis of nutrient flows, a typology of flows, and three indicators are used to characterize (i) circularity between subsystems, (ii) the efficiency of the subsystems, and (iii) the efficiency of the AFWS	Kleinpeter V., Avanitakis M., Vigne M., Wassenaar T., Lo Seen D., Vayssières J.,
Tools for assessing qualitatively the level of circularity of organisations: Applicability to different sectors	2023	Identify and evaluate tools that can be used to measure the level of circular economy implementation in organizations automatically (CE tools)	Valls-Val K., Ibanez-Fores V., Bovea M.D

order to identify the indicators that are measuring the circularity level of companies, organizations etc.

Despite the numerous indicators for measuring the environmental impact or the efficient use of resources, it is relatively rare to find studies that address how to assess circularity in products and supply chains effectively. Currently, there is no generally acceptable method for measuring circularity at a micro-level (Kristensen & Mosgaard 2020). The majority of indicators considered in the literature are based on just one aspect, usually inputs and outputs in the production system, or include just some aspects of CE, despite some attempts to indicate the way to measure CE (Moraga et al. 2019).

With this understanding, the Ellen MacArthur Foundation (EMF) formulated and made available the first-ever “Circularity indicators” project in 2015 in response to the problem of the absence of measuring and monitoring tools of circularity. A major objective of this project was to identify missing indicators in CE and formulate a methodology for evaluating the transition of organizations to circular business models (Pavlovic et al. 2020).

The same year Di Maio & Rem (2015) created the “Circular Economy Index (CEI)”, which encompassed both economic and environmental factors, centered in recycling of materials but not include their recovery. A year later, Scheepens et al. (2016), using LCA, recommended a measurement for evaluating circularity for products, but this method focuses on reducing externalities and not on determining circularity levels.

Banaite & Tamosiuniene (2016) analyze the factors should be considered setting circular economy indicators. In terms of industry-level the following proposal have been drawn:

- Environmental perspectives
- Natural resource use in production: preserving natural resources and making efficient use of water, raw materials and energy
- Level of emissions—both direct and indirect;
- Recycling, reusing, and reclaiming products and materials: reduce waste generation, incineration, and landfilling, and increase material and energy efficiency
- Economic perspectives
- Industrial scale and quality both contribute to the economic benefit of industry
- Social perspectives
- Industry provides social benefits, such as increasing employment and revenue

An analysis of business models based on CE and its effect on efficiency levels by Urbinati et al. (2017) identify two dimensions to measure efficiency: the value network and the customer value proposition and interface.

Elia et al. (2017) show that materials and substance flow analysis and life cycle assessment are the two most promising assessment methodologies for covering four out of five CE dimensions. Moreover, a number of indicators and methodologies based on European Environmental Agency CE characteristics were evaluated, concluding that none of them could be used to monitor all the characteristics independently (Moraga et al. 2019).

A review on the methods for assessing resource recovery from waste in order to implement principles of CE, by Iakovidou et al. (2017) demonstrate that no single method could explain the retention of value in waste resources. So, a comprehensive assessment of CE was needed in order to take into its environmental, economic, social and technical dimensions (Moraga et al. 2019).

Although there are many resources available, Park and Kremer (2017) seek to establish sustainable indicators that could quantify CE's impact on mining efficiency. They organize and categorize the existing sustainability indicators in categories to elucidate their usage and ease their implementation in micro-level: (1) environmental (chemical and release), (2) pollution stemming from waste and emissions due to chemicals' end-of-life and use, and raw material and facility management indicators (Sanchez-Ortiz et al. 2020).

Based on the British Standard Institute's (BSI) BS 8001:2017 standard, Pauliuk (2018) recommends a group of indicators. In spite of its intention to ease CE adoption in organizations and production systems, this standard does not contain mandatory specifications. For assessing the five characteristics promoted by the BSI standard (restoring, regeneration, maintaining utility, maintaining financial value, and maintaining nonfinancial value), existing indicators (climate, resource efficiency, energy and sufficiency) are used along with indicators for complementary characteristics (Moraga et al. 2019).

Along with Mayer et al. (2018), material flow analysis can be used to develop indicators for the EU that will contribute to reducing pressures on the environment caused by resource use. According to EU policy, waste (food waste and waste production) and recycling (Materials recycled and their contribution to raw material demand) should be monitored, as well as economic and social indicators (EC, 2018; Helander et al. 2019).

In the study of Parchomenko et al. (2019), three categories of CE indicators are identified, namely resource efficiencies, stock flows and product-centric indicators. A typical CE metric includes waste disposal, the use of primary versus secondary resources, recycling efficiency, while very few measure value change, value maintenance, and longevity.

According to Haupt and Hellweg (2019), an indicator is designed to measure the environmental impact of value retention in a system, incorporating product life cycle

impacts, value retention processes, and impacts on use phases.

For the practical implementation of CE in companies, Janik and Ryszko (2019) identify 19 micro-level indicators. From a managerial perspective, each metric was evaluated to determine how well it could facilitate CE decision-making. Using technical cycles, Moraga et al. (2019) indicate three types of indicators: indicators of physical properties, indicators of effects, and indicators of ecological, economic, and/or social properties.

Taking a closer look at 30 CE assessment indicators for organizations, Kristensen and Mosgaard (2020) determine extending useful life examined dismantling, maximizing resource efficiency or reusing as less used topics, while recycling, end-of-life management, and regeneration are identified as trending topics. To further improve the contribution of waste management to a CE, governments, industries, and researchers typically use mass-based recycling and reuse goals (Moraga et al. 2019; Haupt & Hellweg 2019).

Assessing an organization's level of compliance with CE requires innovative approaches. For measuring the progress of organizations toward the CE, the EU emphasizes the need to obtain CE indicators. Nevertheless, the EU institutes indicators (Eurostat 2021) at the territorial level, but those for organizations have not yet been developed. Hence, Vinante et al. (2021) argue that the organizational level is particularly important. In order to assess their progress with the CE, organizations must develop their own CE indicators and tools, which make it easier for them to assess and, as a result, improve the transition (Valls-Val et al. 2022).

In their review of CE indicators developed and employed in the academic literature and in industrial practice, Calzonari et al. (2022) provide an overview of supply chain-based CE indicators. As a result, a subset of frequently employed metrics across all sustainability pillars is identified, as well as two prototype composite indicators (CIs) are proposed.

In the meantime, a total of 10 indicators are formulated for sustainable development by UN Environment, while 17 indicators are developed by UNDP, OECD create 25–30 indicators to measure green growth, over 50 indicators are developed by the World Bank regarding sustainable development and environmental protection, and 32 indicators are developed by Eurostat for measuring resource efficiency (Cautisanu et al. 2018). Furthermore, a monitoring framework for CE has been proposed by the European Commission (EC) (EC, 2018). In private consulting, Ellen MacArthur Foundation (EMF) is at the forefront of the CE concept formulation (Ghisellini et al. 2016). However, no common concept of CE has emerged despite these actions (Moraga et al. 2019).

## 2.3 The case of olive oil industry

### 2.3.1 Olive oil industry

Over the past few decades, the production of olive oil has increased steadily due to its high antioxidant and essential fatty acid content (Fig. 1). Olive oil accounts for a substantial portion of the world's trade, and it is widely considered one of the most important trends in dietary trends. Over 3 million tons of olive oil is produced worldwide each year, contributing significantly to the economy and providing employment opportunities. In terms of production volume, Spain accounts for almost one-third of the world's olive oil production. Among the other countries that contribute to the global olive oil production are Italy, Greece, Tunisia, Turkey, and Morocco (Donner & Radic 2021).

In these regions, this food product is highly valued because of its economic importance; however, its adverse effects on the environment have been documented. The cultivation practices followed, as well as the olive oil production practices used, cause adverse environmental effects in the areas where this activity is carried out, related to the disposal of waste, air pollution, the depletion and degradation of natural resources and the degradation of soils (Ncube et al. 2022).

### 2.3.2 Olive mill waste (OMW)

The olive mill waste (OMW) is a solid or liquid by-product of the oil extraction process. It varies in amount and composition, due to the fruit-related factors, production year, microbial treatment, as well as the method of extraction

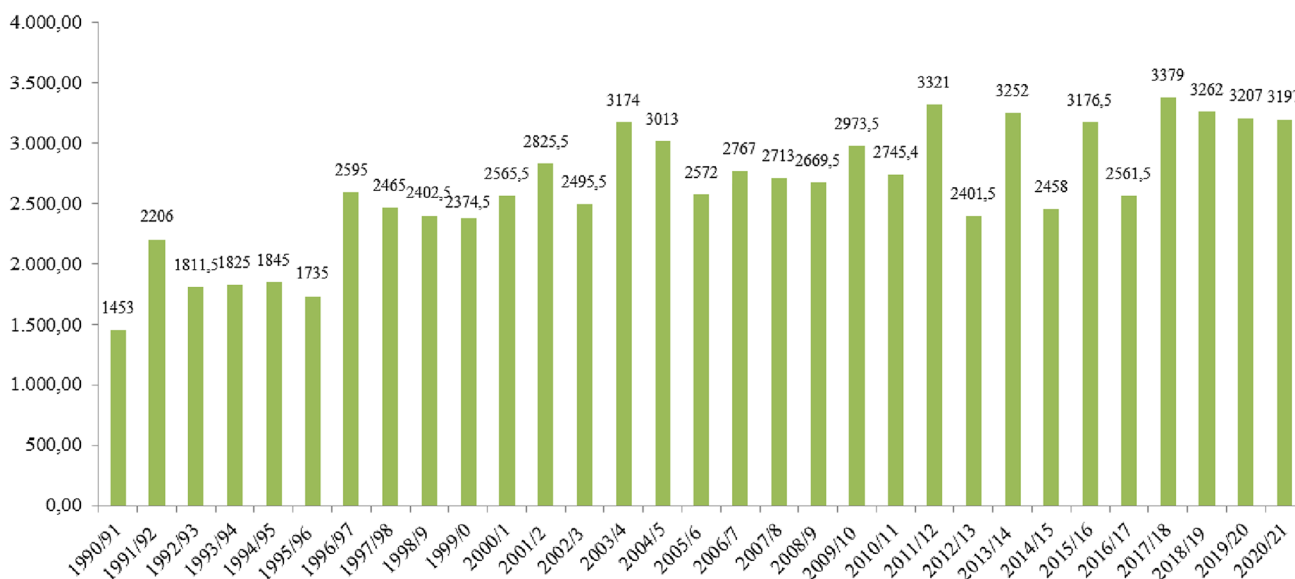
(traditional, three-phase, two-phase). Depending on the extraction process used, the products and by-products are shown in Fig. 2.

The main OMW, aside from olive leaves and olive stones (obtained from separating pulp before or after oil extraction), are the following:

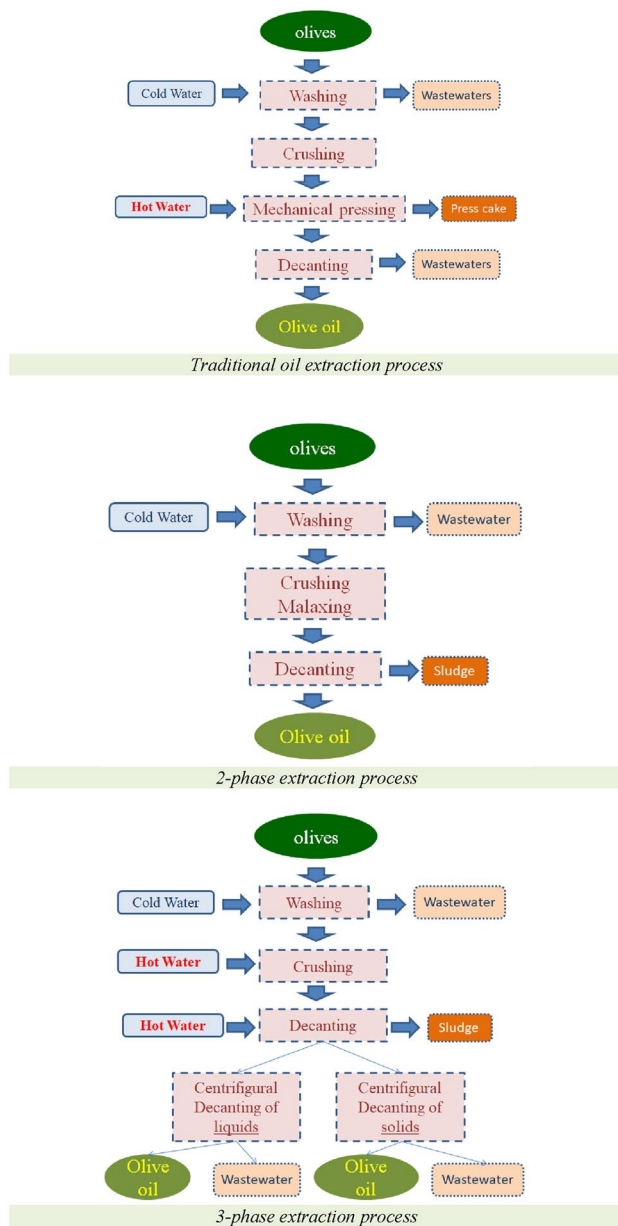
1. Semi-solid waste or Solid (OMSW) from olive mills consists of crushed olive peels, skins, stones, water, and phenolic compounds, including uronic acids and residual oil (Cecchi et al. 2018).
2. Olive mill wastewater (OMWW), a dark-brown liquid composed of 83–92% water (vegetative and process water) and the remainder consisting of a heterogeneous complex of organic matter (pulp and oil residues) (Sciubba et al. 2020). Using a three-phase extraction method, this by-product is generated at the greatest rate, while a two-phase extraction method produces it at much lower rates (Table 2) (Stempfle et al. 2021).

It is especially important to note that, as shown in the Table, the extraction methods differ not only in quantity and quality of extracted oil, but also in the quantity and quality of by-products. While, 3-phase methods use five times as much water as 2-phase methods. Additionally, the Chemical Oxygen Demand (COD) concentration in 2-phase method is 4–6 g/l, while it is 30–200 g/l in 3-phase method. Hence, 2-phase method is widely believed to be less polluting than other methods (Gholamzadeh et al. 2016).

Aside from the valuable minerals and bioactive molecules contained in OMWW, it also has a high phytotoxicity,



**Fig. 1** Total Olive Oil Production (1000 tonnes) (Based on Data received from International Olive Oil Council in December 2021)



**Fig. 2** Products and by-products generated depending the oil extraction process (Khdaïr & Abu-Rumman 2020)

a significant pollutant charge, and low biodegradability (Stempfle et al. 2021). There is considerable environmental concern about untreated olive oil waste in the agri-food industry (Table 3), because of its high toxic load, a PH of less than 7, high COD 110 g/l and a Biological Oxygen Demand (BOD) greater than 170 g per liter. Despite the obvious necessity of waste management-treatment, finding the most efficient and effective method is much more significant (Stasinakis et al., 2008).

OMW also adversely affects the environment, contaminating ground and surface waters, changing the quality of soil, coloring natural water, and causing odors (Danellakis

**Table 2** Quantities of Products and By-Products generated by olive oil mills

Extraction method	Input (volumes)	Output (volumes)
2-Phase	1000 kg Olives 100-120lt Washing Water	<b>247.4 kg Oil</b> 735 kg Pomace <b>200-300lt Wastewaters</b>
Traditional	1000 kg Olives 100-200lt Washing Water	<b>230.4 kg Oil</b> 500 kg Pomace <b>650 lt Wastewaters</b>
3-Phase	1000 kg Olives 100-120lt Washing Water 700-100lt Hot water Add ed	256.4 kg Oil 581.16 kg Pomace <b>1200 lt Wastewater</b>

Source: (Khdaïr & Abu-Rumman 2020)

**Table 3** Pollutants concentration in various industrial wastewaters

Type of Industry	BOD5	COD
Olive oil	<b>10000–150000</b>	<b>37000–318000</b>
Winery	500–40000	500–45000
Meat processing	600–4600	400–11200
Dairy/cheese factory	1400–50000	2000–95000
Sugar mill	4000–7000	3500–10000
Brewery	500–64000	750–80000

Source: (Gholamzadeh et al. 2016)

et al. 2011; Gholamzadeh et al. 2016). The proper treatment of by-products is therefore vital for avoiding negative externalities on the environment and maintaining local resources (energy, water, soil, raw materials).

### 2.3.3 OMW Management-treatment

Over the past few years, researchers have been increasingly concerned about OMW. During the months of October and February, most of the olive oil produced in the world (98%) is produced in Mediterranean countries. The result is more than 30 million m3 of waste being generated each year (Doula et al. 2017) with a high environmental impact (Donner & Radic 2021). Due to the lack of technical and economic solutions for OMW treatment, some mills illegally throw away their waste into the natural environment. Consequently, planning the utilization of natural resources and managing waste efficiently are crucial to reducing the environmental impact of olive oil mills (Khdaïr et al. 2019). Since most olive oil mills are small or medium sized, implementing the majority of management, remediation, and valuation techniques currently available is often too expensive (Doula et al. 2021).

There is a tendency for olive oil mill effluents to end up in evaporation ponds, but they are often discharged into



natural creeks and cause soil contamination (Komnitsas et al. 2016; Donner & Radic 2021). However, this process creates significant odor problems in the area (Zagklis et al. 2015). In this context, it refers to a number of volatile organic acids as well as other low-boiling organic compounds responsible for foul odors. Due to the evaporation of these gases, methane and other pollutants are released into the atmosphere, aggravating air pollution. As well, OMW retains the same organic content and toxicity as before. OMW flooding may also occur if the evaporation ponds fail due to heavy rain. Moreover, their oil content can make the soil more hydrophobic, reducing its ability to retain and filter water (Abu-Rumman 2016), influencing natural phenols, microbial activity, acidity, lipid concentration, nitrogen immobilization, nutrient leaching, salinity and organic acids (Doula et al. 2017). A thick film of OMWW may form on the surface of water bodies and create anoxic conditions, posing a threat to the aquatic ecosystem. However, solid waste discharge has the effect of increasing saturation, water retention, and capillary lift in soil (Khdair et al. 2019). Long-term uncontrolled disposal of raw OMW on soil could adversely influence soil characteristics and lead to contamination of groundwater (Chatzistathis & Koutsos 2017).

A number of studies have been conducted in the last decade on filtration for treating OMW (microfiltration ultrafiltration, nanofiltration and reverse osmosis), which are all effective for recovering antioxidants and phenolic compounds. Before these technologies are widely implemented, however, there are still numerous drawbacks, including membrane fouling, a high cost of energy, and the disposal of concentrates has yet to be addressed (Ioannou et al. 2013; Galliou et al. 2018).

In addition to this, OMW treatment has extensively explored advanced oxidation processes (ozonation, photo-Fenton oxidation etc.). In spite of their effectiveness, these treatment methods presented financial and environmental challenges, such as the production of more toxic compounds. In the case of wastewater with a high organic content, anaerobic digestion should be considered. It has been shown that phenolic compounds inhibit methanogenic bacteria in the case of OMW (Galliou et al. 2018).

There has been a proposal to co-digest organic residues with phenols to mitigate their effect on the anaerobic digestion process (Dareiotti et al. 2010). Despite its promising potential, this technique requires centralized treatment and other feedstocks in the area, such as dung. In general, olive oil production is the primary (or only) farming activity, and therefore the amount of olive oil produced is significantly greater than that produced by other feedstocks (Galliou et al. 2018). As a result, only a relatively small portion of the OMW is suitable for co-digestion. Additionally, infrastructures for storing are needed to mitigate the seasonality of OMW production (Chatzistathis & Koutsos 2017).

Except all the aforementioned, Table 4 proposes some methodologies for valuing the OMW indicatively.

A series of circular paths can be created by recovering and transforming by-products of the olive oil production chain. These paths can prevent new impacts on disposal or provide new products. The proposed circular solutions should also be thoroughly assessed and quantified in order to avoid miscalculations while pursuing sustainability. In spite of the fact that olive oil by-products offer several circular opportunities, very little work has been done to assess their sustainability or compare linear with circular processes (Harris et al. 2021).

**Table 4** By-product value and monetization pathways and mechanisms

By-product	Value and monetization pathways and mechanisms
Olive pomace	A cheap and reliable source of fertilizers, pharmaceuticals, cosmetics, and other products Extraction units: Using solvents or pressurized liquid extraction to obtain additional oil from olive pomace Energy recovery: using pyrolysis, gasification, and combustion Olive oil mills can use biomass boilers to generate steam and electricity or to meet their energy needs Recovery of bio-based chemicals (i.e. antioxidants): Its high polyphenol content necessitates the use of organic solvents or ultrasound-assisted extraction methods Producing compost for later use as fertilizer
Olive pomace-based polyphenol-rich extracts	Used in various chemical, food, and biological model systems
Olive press-cake	Production of olive stone oil or dry fuel
de-oiled pomace (exhausted olive pomace)	Pomace oil is still used for canning and cooking tuna fish in spite of its poor quality
Olive wastewaters	Irrigation water that has been purified (for use in agriculture) fertilizers Molecules (cosmetic antioxidants, tanning agents, and active ingredients for medicines) Fertilizers (OMWW combine minerals, vitamins, and potassium)

Source: (Ncube et al. 2022)

**2.3.3.1 CE in olive oil industry** CE has become increasingly popular in recent years, and practices for immediate integration are being sought. As part of the European Commission's efforts to prevent the uncontrolled disposal of olive mill waste from affecting soil and water resources, PROSODOL, a LIFE project (LIFE07 ENV/GR/000280), was funded in 2009. This project aimed to demonstrate methods for restoring polluted areas and to propose legislative frameworks for countries in the EU to adopt. According to the results of the project, uncontrolled disposal of OMW affects most chemical and physical parameters of soil, permanently or not (Doula et al. 2017).

European Commission created TANNOW project in 2016. As part of the innovation, OMW would be converted from waste into raw material by stabilizing it, promoting the enrichment of highly antioxidant phenols, to be used in tanning steps as a medium in place of water and tannin chemicals, and as a reaction medium to produce antioxidant tanning resins.

In addition, a number of researchers and academics are interested in the topic of implementing CE and sustainability principles. Among the main waste-to-energy conversion pathways of OMSW, Christoforou and Fokaides (2016) also present a basic pretreatment technique for upgrading solid fuels. Several sorts of OMSW were utilized for energy-related purposes in their research, which focused on characterization and utilization of these wastes. Cepo et al. (2018) evaluate the antioxidant activity of dried olive pomace extracts in different food and biological model systems and analyzed the effects of different cyclodextrins. In addition, they outline how cyclodextrin-encapsulation can improve the functionality of complex natural extracts in a simple and cost-effective way. In order to promote a CE in olive oil production, Abu Tayeh et al. (2020) suggest microwave pretreatment as a method of converting OMSW into ethanol and heavy metal sorbents. In Silvestri et al.'s (2021) study, OMWW is incorporated into the brick-making process and proven to be a promising solution, which can reduce greenhouse gas emissions and reduce heat requirements during the ceramic manufacturing process by avoiding impacts related to its disposal. In comparison with conventional bricks, OMWW-based bricks reduce global warming potential by up to 3.1%, as well as abiotic depletion of fossil fuel by 4.3% (Silvestri et al. 2021). Carmona et al. (2023) propose a multi-step circular process for increasing the sustainable production of olive oil by valuing OMW, eliminating waste in virgin olive oil production pipeline, and creating new products of value. Two processes were investigated in order to obtain extracts for nutraceutical purposes from fresh OMW by using natural deep eutectic solvents (NADES) and through the recycling of the dephenolyzed-OMW by vermicomposting to produce organic fertilizer that can be used to make olive oil again. An environmental assessment of olive oil production is proposed by Ncube et al. (2022). In order to

evaluate environmental performance, a variety of scenarios are considered based on a life cycle perspective. To determine the degree of environmental sustainability improved, business-as-usual scenarios, modeled on the concept of biorefineries, are compared with innovative circular scenarios. In the olive oil industry, and more generally in the food supply chain, circularity refers to decreasing waste and utilizing by-products. Instead of merely disposing of food waste to landfills, valuing through recovery is an alternative option where food waste cannot be avoided (Ghisellini et al. 2023). By-products from olive oil production can be used as feedstock for other production processes in order to reduce the environmental impact associated with olive oil production. Olive oil production results in a more equitable distribution of environmental impacts by upgrading by-products into co-products. A number of obstacles limit the valorization of by-products of oil production, including bureaucratic and authorization challenges, as well as seasonality of the supply of feedstock. A more incisive phase of closing the loop in olive oil industry appears to be hampered by economic and organizational barriers (Ncube et al. 2022). Despite a great deal of attention, CE has primarily been used in manufacturing, and recently in agri-food (Atanaskova et al., 2022). However, little research has been conducted on the olive oil industry as a whole. Furthermore, little research has been conducted to determine the current level of CE implementation in the agri-food sector, particularly in olive oil production. The research conducted frequently focuses on evaluating the sustainability, as well as the circularity of various olive oil production practices, the management practices and/or utilization of olive mill wastes. Typical example is Joumri et al. (2023) presenting an overview of thirty-two LCA-related works that have been applied to various scenarios of production involving the valorization of the generated by-products, provide a descriptive review of the LCA applied to the olive oil value chain in order to fill the gaps in the literature. Furthermore, they intend to provide more information on the amounts of water consumed and how the LCA tool assessed the environmental impacts of water consumption (Joumri et al. 2023). A study by Espadas-Aldana et al. (2023) shows how to move from a linear production system to a circular olive production system that recovers materials from organic residues by using the LCA method to support waste valorization to bio-based composite materials in French olive oil circular economy (CE).

### 3 Methodology

Using the last 10 years of research and review articles, a literature review was conducted focusing on olive oil industry CE indicators. The review included the following steps (Fig. 3).

- Step 1. Scopus and Google Scholar databases were searched in the title, abstract or keywords, using the string “indicator” or “metric” or “measuring” or “monitoring” and “circular economy in olive oil industry”.

From the received result, it was ascertained that a little research on this specific issue has been conducted in order to review the specific indicators for this sector.

- Step 2. In addition, a literature search was conducted to identify papers that propose or analyze micro-level circularity indicators. Accordingly, new keywords were added using the string “indicator” or “metric” or “measuring” or “monitoring” and “circular economy in micro-level”.
- Step 3. Based on a screening of the title and abstract, documents that propose or discuss indicators considered that refer to the agri-food sector were selected in order to record the indicators of the sector and to propose the ones that could be used in the measurement of circularity in olive mills.

## 4 Discussion and proposals

In order to examine the circularity of olive oil production, it is essential that CE indicators for measuring and monitoring CE in olive oil mills (OOMs) are defined. Considering that supply chain management integrates environmental sustainability into all of its activities, CE implementation will require changes at several levels of the supply chain (Elia et al. 2020).

Though CE implementation generally involves three levels (macro, meso, and micro), the published indicators are mostly referred to macro- and meso-level. Nevertheless, the role of businesses in promoting CE cannot be underestimated (Geng et al. 2012). There have been several studies that have attempted to measure CE at the micro level by using indicators; however, a few of them have related to the agri-food sector with little reference being made to the olive oil industry (Poponi et al. 2022). While olive oil by-products provide a wealth of circular opportunities, there has not been enough effort put into assessing the viability of lateral production approaches and comparing linear ones to circular ones. Usually, efforts to assess

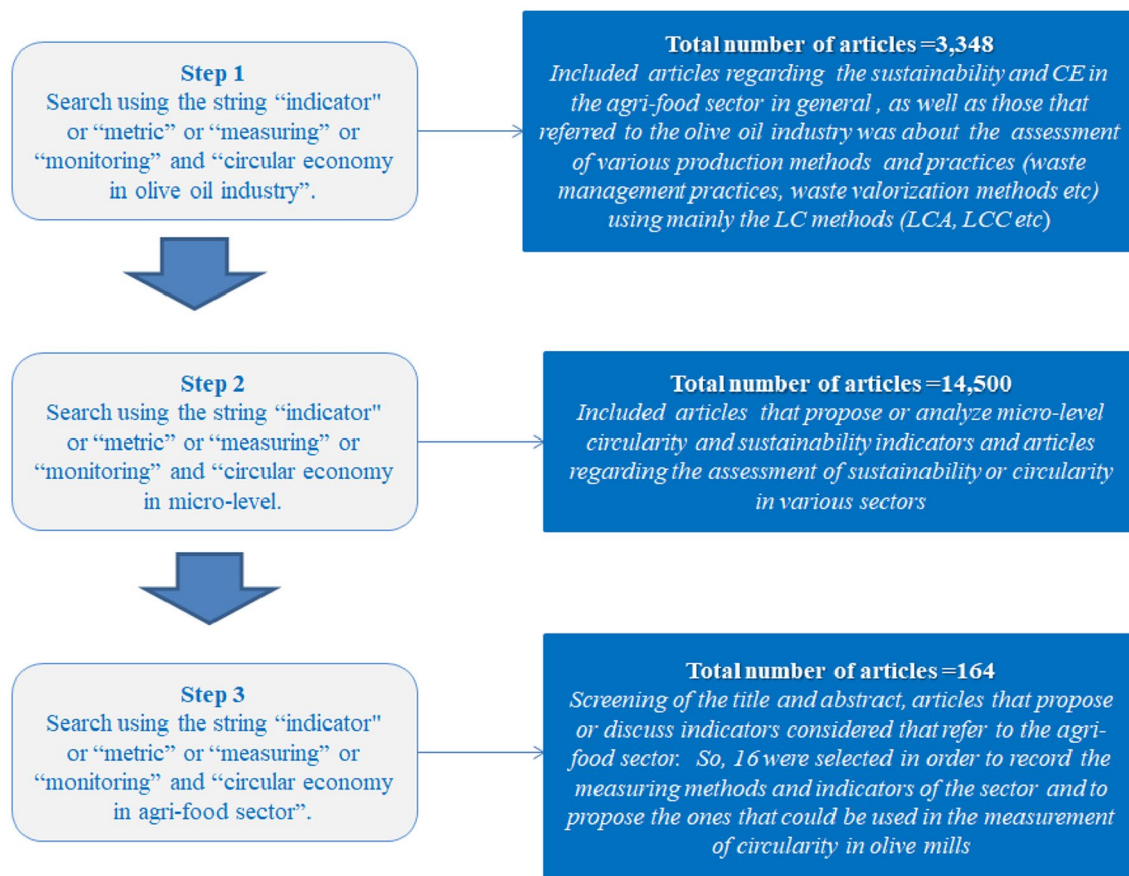


Fig. 3 Steps followed during the literature review

circularity or sustainability in olive oil production focus on production processes, techniques and methods of managing and utilizing wastes and byproducts produced and often use LC methods and not circularity indicators concerning the case of the olive oil industry (Nikkhah et al. 2021; Stilitano et al. 2022; Falcone et al. 2022; Joumri et al. 2023; Espadas-Aldana et al. 2023). Since there are no specific circularity indicators to assess the implementation of the circular economy in olive oil industry, it would be useful to evaluate the existing indicators concerning the agri-food sector in general and adapt them to the olive oil mills. In OOMs, cleaner production can significantly improve the overall eco-efficiency by examining the most promising prospects for reducing internal pollution levels, incorporating processes, and managing waste (Geng et al. 2012).

In order for the olive oil industry to successfully transition to the new economic paradigm, specific CE indicators will be developed and integrated management models will be formulated (Sanchez-Ortiz et al. 2020). Despite their close relationship, sustainability and circularity indicators should view food systems through the lens of preserving functions, products, components, materials, or embodied energy (Moraga et al. 2019), utilizing a linear economy as a benchmark. When assessing CE on a micro level, such as olive oil mills, each sector should formulate a specific set of indicators according to its features, conditions, and problems. Beginning with an analysis of business model of each industry is critical, since a business model explains how it works, and can be used to analyze, evaluate, compare, manage, communicate, and innovate (Osterwalder et al. 2005). Innovation in business models plays a key role in achieving greater social and environmental sustainability. There are eight archetypes of business model recognized in CE, based on whether the innovation was technological, social, or organizational (Boken et al., 2014), most of which could be applied to olive oil mills as well. These eight archetypes were summarized by Sanchez-Ortiz et al. (2020) as follows:

Technological innovations:

1. Ensure maximum material and energy efficiency;
2. Make value out of waste;
3. Use renewable and natural processes in place of current processes.

Social innovations:

4. Focus on functionality rather than property;
5. Become proactive in your role;
6. Increase the level of sufficiency.

Organizational innovations:

7. Maintain a socially responsible company purpose by keeping the environment and society in mind;
8. Design solutions that are scalable

There have been some attempts to fill the lack of indicators gap, but no standardized indicators have been developed (Kristensen & Mosgaard 2020). Vermeyen et al. (2021) attempted to provide sufficient indicators. According to the report, the food system cannot be easily analyzed or summarized due to its high number of indicators. Primary production, consumption, and waste collection and treatment were the three major food chain links examined in the study. It was therefore not possible to develop first-best indicators for all aspects of a circular economy for food. There is a need for further research to address the current gaps, like food processing, and refine the available indicators. Additionally, it is not clear which circular target should be set to achieve for local and global environmental boundaries, even though current inputs are clearly very material intensive and have significant environmental impacts (Vermeyen et al. 2021).

A modification of the material circularity indicator (MCI) (EMF, 2015), among the few tools currently available for measuring circularity, is proposed by Rocchi et al. (2021). Using modified MCI, the results of this study are integrated with life cycle assessment approaches designed for the poultry sector. According to their findings, the modified MCI can be used to evaluate the degree of circularity of a livestock rearing system and to compare different types of animal rearing systems. There is no calculation of how this nutrient contributes to closing the nutrient loop. In agricultural systems, closing the nutrient loop is an important aspect of CE. Modified MCI includes global amounts of feed expressed as quantity without considering origin. Despite its contribution to global circularity, MCI does not valorize food by-products, namely non-edible ones (Rocchi et al. 2021). Thus, such a calculation can be used to measure the circularity of the olive oil industry, but it does not provide sufficient indicators to determine if olive oil mills adhere to CE principles or how close they are to circularization.

A study by Poponi et al. (2022) aim to fill this gap by identifying a possible set of indicators for measuring circularity and sustainability at various levels of application. As a result, 102 indicators are classified according to three sustainability areas (environmental, economic, and social) and spatial dimensions (macro, meso, micro) in the following eight scopes: Air, Water, Soil, Energy, Waste, Cost, Value and Productivity, Equality, and Knowledge and Innovation. According to Poponi et al. (2022) circularity cannot be assessed by monitoring individual indicator. From the indicators discussed in this research, Table 5 lists the indicators considered to be the most appropriate for evaluating circularity in olive mills (Poponi et al. 2022).

Van Schoubroeck et al. (2022) develop a framework for identifying circular economy indicators in the food industry. Using circularity as a metric, the information in this report summarizes the Flanders food system. Despite being intrinsically circular to some degrees, the food system seems to have drifted from the natural cycles underlying it because of industrial intensification and increased consumption. Therefore, there is much room to optimize the circularity of a system on all three fronts: input use, product use, and residual stream use (Van Schoubroeck et al. 2022).

In their paper, Atanaskona et al. (2022) conduct a systematic literature review on the concept of social value generated by circular economy (CE) practices in agri-food eco-industrial parks. It is found that social value associated with CE practices is under researched, providing opportunities for further investigation. Accordingly, Table 6 lists the indicators considered most appropriate for measuring circularity among olive mills based on the indicators discussed in this study.

During their study, Priyadarshini and Abhilash (2023) examine the circularity and efficiency levels in the Indian agri-food sector. Initially, they determine decoupling of energy consumption from economic growth in agriculture at the state level and then develop a Composite Agri-Food Efficiency Index (CAF EI) consisting of 38 indicators, encompassing environmental, social, economic, and governance factors (Priyadarshini and Abhilash 2023).

Based on MCI and LCA as efficient circular and environmental measurement tools, Gallo et al. (2023) aim to suggest an approach that correlates circularity with environmental impacts based on the mentioned tools. In addition, the model is tested and analyzed through the comparison of case studies in order to determine its applicability as a tool for assessing the environmental impacts of products in relation to circularity (Gallo et al. 2023).

In their study, Kleinpeter et al. (2023) develop a methodology that uses quantitative indicators to quantify the role of livestock and crops in the efficiencies and circularity of the agri-food-waste system. An analysis of nutrients flows, a detailed typology of those flows, and three groups of indicators are used to characterize the circularity between subsystems, the process efficiency of the subsystems, and the AFWS efficiency. The nitrogen metabolism of the French Reunion Island AFWS is used to illustrate the method.

According to the literature, CE indicators in the agri-food sector are still in their infancy. The circularity of agri-food is often monitored using different sustainability indicators at different levels (macro, meso, micro), but very few indicators are used to measure circularity in this sector (Poponi et al. 2022). As a consequence, it is necessary to begin measurements in practice in order to certify which of the proposed assesses the circularity effectively in olive oil mills.

## 5 Conclusions

Circular economies have emerged as economically balanced systems that focus on environmental, economic, and social issues, by raising the level of quality of life in overcrowded and impoverished societies due to resource scarcity. Circular economy has become an integral part of society's strategy and policy making and has been recognized as a vital necessity. Since, CE is frequently argued to contribute to sustainable development, an examination of the alignment between the three dimensions of sustainability and the reviewed indicators specifies that economic aspects dominate the indicators, with environmental and social aspects having a lesser role. For different industrial sectors, it may be appropriate to set up specific indicators so that their concerns can be addressed appropriately. A unique and valid common group of indicators for each sector without arbitrariness could be developed to face and manage the complexity of CE transition.

As the CE evolves, the agri-food sector and olive oil industry will have a huge opportunity to manage resources efficiently, valorize and repurpose by-products and wastes, and to generate bio-energy and bio-products by adopting sustainable production practices. It is important, however, to establish strong measures and figures to guide the transition from linear to circular models. A high number of indicators are discussed throughout the literature, making it difficult to analyze or summarize the food system. Different actors in the food system emphasize circularity strategies differently. Therefore, it was not possible to come up with the first-best indicators for all aspects of a CE in the food system. The available indicators need to be fine-tuned to address current gaps, such as food processing.

The olive oil industry is one of the most significant sub-sectors of the agri-food sector, which contributes heavily to the world's biomass production. It has therefore recently emerged as a key component of the bio-economy. Despite its economic importance olive oil has adverse environmental effects, including resource depletion, land degradation, air pollution, and waste production. Circular economy principles are therefore important for the regions that host this kind of economic activity. It is necessary to determine the indicators that will be used to evaluate the degree of CE adoption and implementation in order to draw safe conclusions about the policies that need to be followed.

This study proposed some indicators in order to fill in the current need for a framework around CE for the olive oil industry. Due to the lack of studies that measure the circularity of olive mills effectively, in this paper, indicators regarding the agri-food sector in general, are proposed. Nevertheless, it is extremely important to examine their effectiveness in practice by conducting future research

**Table 5** The most appropriate indicators for evaluating circularity in olive mills

Scope	Description	Indicators
Air	Health risks associated with climate change and indicators of climate change	<ul style="list-style-type: none"> <li>• Agriculture total emission</li> <li>• Global Warming Potential</li> <li>• Ozone layer depletion potential</li> <li>• Photochemical oxidant</li> <li>• Particulate matter formation</li> </ul>
Water	Identify the uses of the resource throughout its lifecycle and their impact on the environment as a result of their production Indicating how much water is used for agri-food practices and what is used in the overall system	<ul style="list-style-type: none"> <li>• Water use</li> <li>• Water scarcity index</li> <li>• Degree of integrated water resources management implementation</li> <li>• Level of water stress: freshwater withdrawal as a proportion of available freshwater resources</li> <li>• Eutrophication potential</li> <li>• Marine eutrophication</li> <li>• Conservation of fish genetic resource (in number)</li> <li>• Freshwater eutrophication</li> <li>• Freshwater ecotoxicity</li> </ul>
Soil	Identify the potential effects of soil pollution on the ecosystem within the context of CE	<ul style="list-style-type: none"> <li>• Proportion of land that is degraded over total land area</li> <li>• Acidification potential</li> </ul>
Energy	Estimate the amount of energy consumed and the performance of the energy system	<ul style="list-style-type: none"> <li>• Energy required</li> <li>• Bioenergy production as a% of renewable energy</li> <li>• Recovery of energy by using waste</li> <li>• Wood fuel production</li> <li>• Energy self-sufficiency indicator</li> <li>• Total Energy consumption</li> <li>• Nonrenewable energy demand</li> <li>• Renewable energy share in the total final energy consumption Use of primary renewable energy</li> <li>• Energy productivity</li> </ul>
Waste	Waste management within the food chain, its impact, and its societal significance	<ul style="list-style-type: none"> <li>• Economic FLW indicator</li> <li>• Recycling rates Waste sent to landfill</li> <li>• Nutrient circularity indicators (carbon, nitrogen and phosphorus)</li> </ul>
Cost, value, and productivity	Analyzing and quantifying the cost of production, the economic value generated, and the results obtained	<ul style="list-style-type: none"> <li>• Total capital investment for CE</li> <li>• Profitability (Assessing the cost-effectiveness of implementing an innovation for the CE)</li> <li>• Gross Value Added</li> <li>• Cost of manufacture</li> <li>• Total labor compensation based on total economic output</li> <li>• Total GVA based on total economic output</li> <li>• Fixed capital investment</li> <li>• Payback period</li> <li>• Value added to the Economy</li> </ul>
Equality	A set of indicators that promote social inclusion	<ul style="list-style-type: none"> <li>• Participation and local democracy (Involvement in the adoption of circular practices)</li> <li>• Social inclusion (Social involvement in the adoption of circular practices)</li> <li>• Employment possibilities (Creation of new job opportunities by adopting a circular model, both in terms of new staff and skills)</li> </ul>
Knowledge and Innovation	Assess the training, knowledge, and innovation development of the sector	<ul style="list-style-type: none"> <li>• Extent of staff training</li> <li>• Availability of latest Technologies</li> <li>• Ratio of investment in research and development in the agri-food sector to the total added value generated Capacity for innovation</li> <li>• Intensity of local competition</li> </ul>

Source: (Poponi et al. 2022)

**Table 6** Incorporating CE practices into OOMs processes

CE practices linked OOMs processes	Practices
Cleaner and circular production and resource efficiency	<ul style="list-style-type: none"> <li>Utilisation of renewable energy sources in production</li> <li>Utilisation of LCA approaches to monitor production</li> <li>Constant production optimization for resource efficiency (i.e., limit overproduction)</li> <li>Circular labelling</li> <li>Facility location optimization to comply with environmental and social value</li> <li>Land use and resource management</li> <li>Utilisation of sustainable and socially friendly transportation</li> <li>Availability of community impact indicators/ metrics (job creation, inequality reduction, food security)</li> <li>Bio-innovation (i.e., adoption of innovative food processing practices, provision of bio-products, technology integration, etc.)</li> </ul>
Recycling, reuse and re-distribution	<ul style="list-style-type: none"> <li>Waste selling to other companies</li> <li>Recycling stream optimization (manufacturing waste reuse)</li> <li>Fertiliser development through recycling and reuse</li> <li>Leftovers are utilised for manufacturing new products</li> <li>Waste and garbage are utilised for manufacturing new products</li> <li>Availability of reprocessing and remanufacturing targets and indicators</li> <li>Utilisation of circular packaging</li> <li>Availability of an internal strategy for the reduction of raw material input</li> <li>Reuse of equipment cleaning material (resources)</li> </ul>
Stakeholder relation and engagement	<ul style="list-style-type: none"> <li>Availability of a sustainable/circular &amp; social supplier/stakeholder selection strategy</li> <li>Environmental and social performance evaluation of supply chain</li> <li>Environmental/circular/social value certification</li> <li>Collaboration with eco-industrial stakeholders to support Environmental/circular/social value deliver training</li> <li>Joint planning and resilience-thinking to maintain environmental/circular/social values</li> <li>Fair competition &amp; pricing for raw &amp; recycled products (i.e. fair inclusion of producer unions, etc.)</li> </ul>
Human resource management	<ul style="list-style-type: none"> <li>Top-management support</li> <li>Mid-management support</li> <li>Employee training programmes</li> <li>Programmes for employee motivation</li> <li>Raising awareness of social and environmental concerns</li> <li>Local/regional employment strategy</li> </ul>

Source: (Atanasovska et al. 2022)

on measuring circularity by using these indicators. CE implementation in olive oil mills is considered a valuable opportunity, as biomass production not only reduces fossil fuel consumption and greenhouse gas emissions, but also creates new green markets and jobs by encouraging waste to be repurposed into value-added products.

**Authors' contributions** AK organized the structure of the paper. AK and Ass. Prof. AP prepared “Measuring and Monitoring the Circular Economy”. AK and Prof. SA prepared the “Introduction” and “Conclusions”. AK conducted the literature review regarding the issue of olive oil mills' waste to highlight the importance of the appropriate management for the sector. Furthermore, AK surveyed the global literature concerning the CE indicators in order to highlight the most important ones that could be used in assessing circularity in olive oil mills. The Methodology was indicated by AK and Ass. Prof. AP. AK and Ass.

Prof. AP revised the manuscript based on reviewers' comments. All authors read and approved the final manuscript.

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## Declarations

**Competing interests** The authors declare that they have no competing interests.

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