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Evaluating Circular Strategies for the Resilience of Agri-Food Business: Evidence From the Olive Oil Supply Chain

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ABSTRACT

In the agri-food sector, the valorization of by-products according to a circular economy (CE) approach can be a viable solution to increase profits and improve business resilience. However, to facilitate its implementation and dissemination, it is necessary to validate the application of CE approaches in real case studies and as well as to verify their economic sustainability. This paper analyses the adoption of different circular paths of real case studies in the olive oil supply chain and assesses their degree of circularity through the Material Circularity Indicator (MCI) and economic sustainability through life cycle costing (LCC). As evidenced in the scientific literature, these methodologies represent the optimal approach to assess the impact of circularity in agri-food processes on companies' sustainability strategies. Moreover, the results can be integrated to facilitate progress toward ever-greater sustainability. Findings show that the degree of circularity varies according to the different strategies adopted, highlighting better economic viability of firms that adopt CE strategies, whose profits are less sensitive to changes in input and output prices and therefore more resilient from an economic point of view when market fluctuations occur.

1 | Introduction

The agri-food sector is facing dramatic environmental impacts because of unsustainable production pathways placing the ecological transition at the forefront of national and international policies (Sabato and Mandelli 2023; De Luca et al. 2023). The effects of climate change, the energy crisis, and the reduction in the availability of raw materials, to name some, have put a strain on the stability of several productive sectors (Heading 2023) that have often to deal with increasing their productivity while

reducing environmental impacts. The agri-food sector does not make any exception playing a pivotal role in the world economy.

The most accredited solution that is gaining significant traction among the suggested solutions for this transformation is the concept of circular economy (CE) (Hoogstra et al. 2024; Ellen MacArthur Foundation (EMF) 2015). The CE is a restorative and regenerative economy that aims to contribute to a new balance between ecological and economic systems. One of the fundamental principles of the CE is the transition from the linear

Short informative: This study carried out an assessment of circular strategies for the resilience and economic life cycle sustainability of agribusinesses. Several real case studies within the olive oil supply chain were analyzed, including an investment analysis and a sensitivity analysis based on price and cost variations of outputs and inputs.

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“cradle to grave” model, which is based on the “take, produce, consume and dispose” growth paradigm, to the circular “cradle to cradle” model (EMF 2015).

In the framework of agri-food production, the transition from a linear to a circular model entails profound changes, encompassing alterations to how food is produced, processed, distributed, and consumed, as well as the broader relationship between people and food (Muscat et al. 2021). Through CE, the “waste” of a production process is gradually transformed into biological and technical “nutrients” (Borrello, Pascucci, and Cembalo 2020).

These conditions lead to a reduction in resource use, making CE one of the solutions to interrupt the direct relationship between economic growth and natural resource consumption (Geisendorf and Pietrulla 2018), especially in the dynamics of agri-food systems, which share many common features with inherently balanced natural systems (Cembalo et al. 2020; EMF 2019).

For instance, the reuse of by-products of a production process, as proposed by the CE model, can enhance economic resilience in the agri-food sector (Cembalo et al. 2020; Giannoccaro et al. 2019), thus reducing the interdependence of agricultural supply chains on virgin raw materials, which in turn allows farms to be less attached in the presence of global shocks and input prices volatility (Volkov et al. 2022). Likewise, reducing material use intensity and waste through CE can generate economic (McLennan 2022) and social benefits, such as increased employment, health benefits, and reduced exposure to pollution (Andooz et al. 2023). An increasing capacity to recover from weather fluctuations such as drought is claimed in the case of reclaimed wastewater reuse in agriculture, which shows greater supply reliability while contributing to CE.

To pursue the most virtuous circular strategies applicable to the agri-food sector, it is necessary to measure their degree (Velasco-Muñoz et al. 2021). Furthermore, to ensure their implementation at the company level, it is essential to verify their adaptability, economic sustainability, and potential benefits. The measurement of the implementation of CE practice, according to some authors such as Blomsma and Brennan (2018), Luthin, Traverso, and Crawford 2024, and Farooq, Chairat, and Gheewala (2024), can take place through the joint use of specific methodologies standardized by ISO standards such as those of the life cycle (LC) group or designed specifically for the measurement of circular processes such as the Material Circularity Indicator (MCI). It is important to note that the relationship between circularity and sustainability is not always clearly defined (Borrello, Pascucci, and Cembalo 2020). Furthermore, although the potential benefits of circularity applications in the agri-food sector are confirmed in the literature (Knäble et al. 2022; Zarbà et al. 2021), the economic quantification of CE approaches in real-world cases is a relatively unexplored area. In fact, most studies in the literature only examine the environmental sustainability of CE applications in the agro-food sector (Alzubi et al. 2024), using for example the life cycle assessment (LCA) methodology as in the studies by Ncube et al. (2024), Restuccia et al. (2022), and Khounani et al. (2021). The necessity of conducting an

economic sustainability analysis is further underscored by the importance of evaluating potential rebound effects on other production and consumption systems or levels (Harris, Martin, and Diener 2021). It is notable that, despite the existence of a range of approaches, methods, and tools for the assessment of CE, there is a consensus among scholars that there is a significant deficit of evaluation of CE performance, its levels, spatial and temporal scales, and dimensions to be measured (Stillitano et al. 2022). Therefore, this study could represent a significant contribution and a novelty in the field.

2 | Theoretical Framework

2.1 | Redesigning the Olive oil Supply Chain Through CE

Regarding the applications of circularity, some authors consider CE as an umbrella concept, focusing on the shared characteristics of the constituent elements (Blomsma and Brennan 2017), whereas others define specific principles (Korhonen, Honkasalo, and Seppälä 2018; Yang et al. 2023). These principles are related to so-called R's, ranging from the popular 3 R's (reduce, recycle, reuse) to broader approaches that include up to 10 R's (refuse, rethink, reduce, reuse, repair, restore, regenerate, reuse, recycle, and recover) (Kirchherr, Reike, and Hekkert 2017; Potting et al. 2017). An intermediate application such as the 6 R's in terms of reduce, reuse, repair, reuse, recycle, and recover is proposed by Moreno et al. (2024) and can be applied to the agricultural sector following circular strategies according to these guidelines: *Reduce* is based on the principle of reducing demand for virgin materials (Kennedy and Linnenluecke 2022) by increasing efficiency and eliminating resource loss (Jackson 2014); *Repair and Reuse* involves actions to preserve the value of resources and products over time. This value can be maintained at the highest level for as long as possible through maintenance and repair (Bocken et al. 2019); *Recycle* is based on the principle of recycling and involves actions that lead to the creation of new value, mainly from the reuse or recycling of discarded materials from the value chain, such as biomass (Forastero (2023) even beyond the LC (Falcone et al. 2022); *Recovery* is based on the principle of recovery and falls under stream regeneration, such as energy recovery, such as anaerobic digestion (Haque, Fan, and Lee 2023) or according to multicycle stream approaches (Stillitano et al. 2022).

The aforementioned strategies linked to the CE concept allow us to rethink agri-food chains, especially in those sectors, which are of great economic importance, where large quantities of by-products are present. The agri-food sector is one of the most resource-intensive sectors, utilizing natural resources such as water and soil in significant quantities. Its operations are highly sensitive to climatic conditions (Castillo-Díaz et al. 2023). Consequently, it is a subject of considerable interest with regard to the potential impacts on the economic and environmental sustainability of farms, human well-being in terms of food quality, access to resources, and rural economies (De Luca et al. 2018).

An example of this is the olive oil sector, in the Mediterranean area alone, where 86% of the world's olive cropping area is

concentrated (Faostat 2022), which has considerable economic, social, and cultural importance and is an integral part of the Mediterranean diet (Donner et al. 2022) and generates a large amount of by-products each year.

In the agricultural phase, it is estimated that 14.8 million tons of pruning residues are generated annually in the Mediterranean region, with an average amount per hectare of 1.57 (García Martín et al. 2020; Pari et al. 2018; Velázquez-Martí et al. 2011). At the industrial/extractions stage, given an average oil yield of 18.14% (IOC 2015) and a 2-year average production of 3,039,472 t (Faostat 2021), the quantity of mill by-products, comprising pomace, vegetation waters, and kernels, was 13.42 million t. This value assumes that two-stage processing plants are considered, wherein there is no addition of water. However, three-stage processing plants are still widely utilized (Restuccia et al. 2022) in the Mediterranean area.

Numerous scholars and among others Stempfle et al. (2022), Berbel and Posadillo (2018), and Donner and Radić (2021) proposed strategies for the valorization of the by-products generated during the olive oil production process, valorizing them as a potential resource convertible into a source of income for the farm, for example, energy, organic matter, fertilizers, and irrigation water. However, there is a particular slowness in the practical implementation of CE (Vulsteke et al. 2024). The main barriers appear to be the cost of technological solutions and the need to understand whether the application of circular strategies increases the economic sustainability of farms (Roos Lindgreen et al. 2022). Because of its complexity, the adoption of circularity is made possible by an alliance of stakeholders such as industry, consumers, policymakers, universities, and their technological innovations and capabilities (Hamam et al. 2021; Moreno et al. 2024). To date, the adoption of circular strategies is not yet widespread in the olive sector, and according to scientific literature, many olive entrepreneurs believe that circular strategies help reduce environmental impacts but are less sure that they increase the economic and social benefits for businesses (Walker et al. 2022). To overcome these limitations, there is a need to increase knowledge and properly measure the sustainability of circularity in real case studies. The comparison of different strategies, properly measured, would support both entrepreneurs and decision-makers interested in promoting circular innovations (Chiaraluce 2022).

Given these premises, the objective of this paper is to assess the degree of circularity and economic sustainability of the application of circular strategies to the olive oil supply chain, also analyzing the degree of resilience of farms in the event of changes in market conditions (input costs and output prices) caused by external shocks.

Starting from an analysis of representative contexts, including ordinary agricultural firms and the fees industry of transformation (mills), located in Apulia, Calabria, and Sicily, the main olive and oil-producing regions of Italy, to investigate the potential of innovative strategies applied, the MCI was employed to assess the degree of circularity, whereas the life cycle costing (LCC) methodology, in conjunction with economic and financial

indicators, was utilized to ascertain the economic long-term sustainability of the abovementioned contexts.

2.2 | MCI and LC Appraisal Metrics

Developed by EMF and Granta (EMF 2019), the MCI is among the most used indicators to measure the degree of circularity of a production process, including the time and intensity of the process. However, this indicator is more focused on material flows and does not return answers relating to sustainability. Consequently, several authors have proposed integrating it with LC methodologies (Stillitano et al. 2022; Luthin, Traverso, and Crawford 2024). LC approaches have long been recognized by the scientific community as tools that allow the identification of potential hotspots in the LC phases of products (Notarnicola et al. 2017; Sala et al. 2017), thereby enabling the formulation of mitigation strategies for more efficient and sustainable management (Ben Abdallah et al. 2022). The LCC methodology is a tool for evaluating the economic sustainability of processes in the context of LC methodologies and can be applied for decision support and to identify economic-managerial critical issues (De Luca et al. 2015), also of circular agri-food production processes (Degieter et al. 2022). From an application point of view, few studies apply MCI and LLC to the agri-food sector at the same time, probably also due to the young age of the CE concept: Rocchi et al. (2021), about poultry production; Rufi-Salis et al. (2021) concerning greenhouse tomatoes; and Alzubi et al. (2024) focusing of the citrus sector. To the authors' knowledge, this is the first work to investigate the degree of circularity and relative sustainability of different olive oil scenarios. Based on these premises, this study aims to answer the following research questions:

H1. *What is the degree of circularity of farms that implement closed-loop pathways?*

H2. *What are the investment and management costs of adopting circular strategies?*

H3. *Does the adoption of circular strategies affect the profitability of the farm and increase its resilience to changes in output prices and input costs?*

3 | Materials and Methods

3.1 | Olive Oil Production Case Studies

Italy is the second largest producer of olive oil among Mediterranean countries, with 315,000 tons (approximately 10.1% of global production) during the 2021/2022 season, trailing only Spain with 1300 tons (IOC 2022). Olive cultivation in Italy is largely concentrated in the southern regions of Apulia, Calabria, and Sicily, which collectively account for approximately 70% of the national olive oil production (ISTAT 2022). In recent years, many olive farms have been characterized by high-quality olive oil production, because of both more efficient farming management and the adoption of product and process innovations, which have been implemented to meet the

consumer's needs and, therefore, to move toward a more competitive market (Hamam et al. 2022; Zanchini et al. 2022).

The operational design of the research, illustrated in Figure 1, involved a contextual analysis aimed at determining the state of the art of the main issues and technical-managerial strategies of Italian olive growing and oil extraction for sustainable production.

The next step was to detect ordinary olive farms and oil mills in the regions of Apulia, Calabria, and Sicily, respectively. Subsequently, in 2023, a questionnaire was designed and implemented for the purpose of obtaining primary input–output data. With respect to each analyzed region, the most representative circular strategies in the most olive-growing areas were identified. These strategies are linked to both firms' organizational aspects and territorial locations. Figure 2 reports schematically the strategies detected and analyzed in this study. The study was continued with the definition of six representative and ordinary scenarios consisting of olive farms and mills (two scenarios from each region). Scenarios in which “circular” strategies were applied were compared with scenarios in which there were no CE-related pathways, thus defined as “linear.” All scenarios analyzed in this study are conducted under a conventional production system and have a medium to high level of mechanization. The main characteristics of the scenarios analyzed are shown in Table 1.

In all the circular scenarios analyzed, during the agricultural phase, the shredding of pruning residues is carried out. In addition to this practice, several applications have been adopted in the regions analyzed and subsequently described. In Apulia, field distribution of digestate from the biogas plant

connected to the farm takes place. The digestate obtained from the two-stage pitted pomace is returned to the soil for a fertilizer function. The industrial processing stage involves the use of electric energy obtained from the biogas plant and thermal energy obtained from the combustion of olive pits extracted from the two-stage pomace. In Calabria, the circular scenario envisioned for the agricultural phase involves spreading in the field one-third of the two-stage pitted pomace produced during oil extraction, to which olive leaves are added. Concerning the extraction phase, the circular scenario envisages the utilization of olive pits extracted from the two-phase pomace to generate the thermal energy required by the mill. In Sicily, the circular scenario involves, for the agricultural phase, the field distribution of all the two-phase pomace produced in the processing phase of the respective extent of the olive grove. In the extraction phase, thermal energy is derived from the combustion of olive pits. In the three regions, for linear scenarios, all inputs related to soil fertilization are acquired from external sources. The residual matter resulting from pruning operations is conveyed to external entities for utilization as biomass. The pomace obtained from the extraction stage is entirely provided to the industrial plant for pomace oil extraction, without the separation of olive pits.

3.2 | Methodology

3.2.1 | MCI

The MCI indicator proposed by the EMF (2015) and Goddin et al. (2019) has a range of values from 0 (100% linear) to 1 (100% circular). It is used to assess the extent to which linear flow has been minimized and remedial flow maximized for its

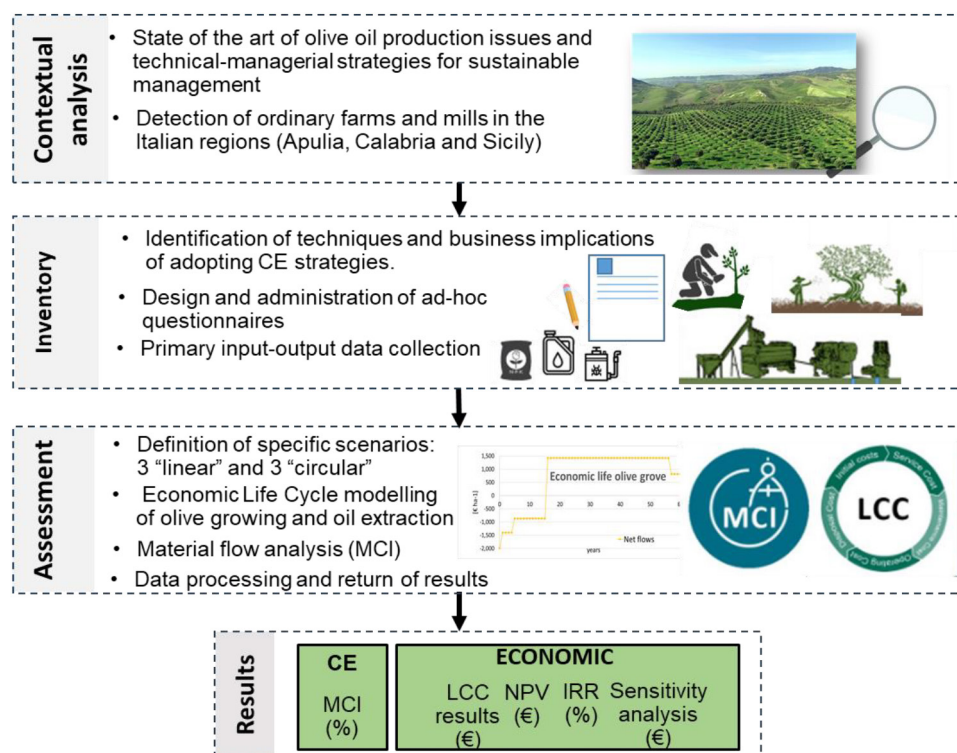


FIGURE 1 | Graphic representation of main procedural steps performed in the study.

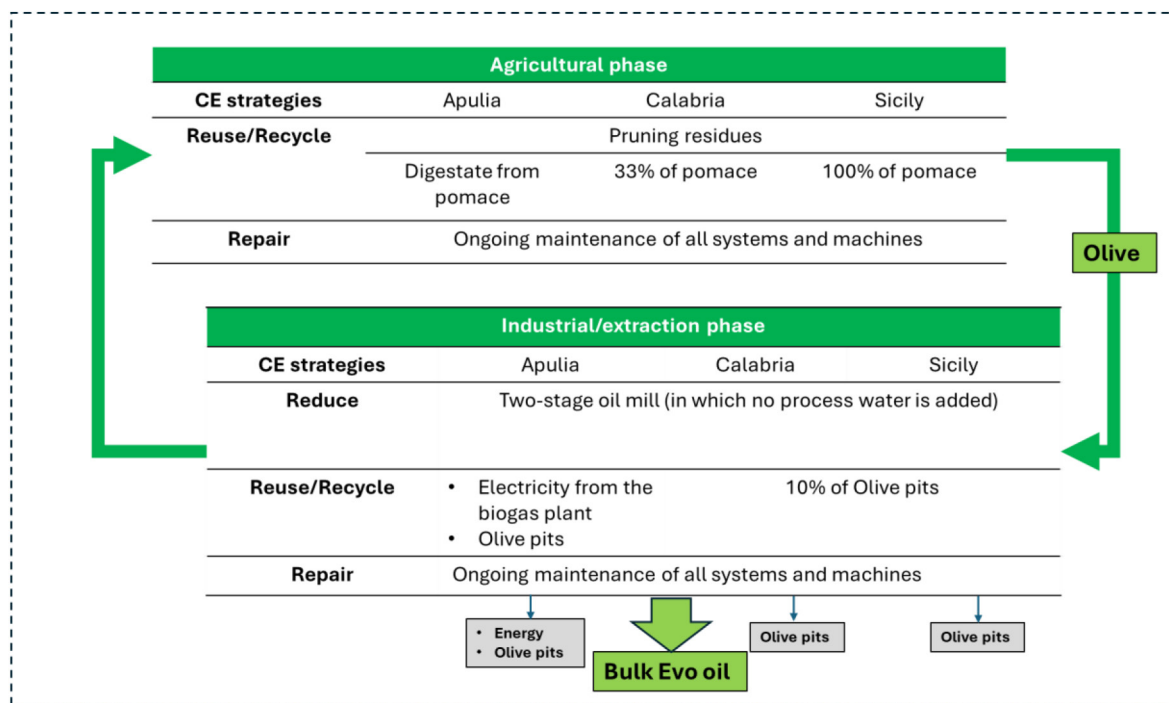


FIGURE 2 | Circular strategies applied in the olive oil system and system boundaries analyzed.

TABLE 1 | Main technical and economic parameters adopted in the study for each scenario.

Agricultural phase						
	Apulia		Calabria		Sicily	
	Circular	Linear	Circular	Linear	Circular	Linear
Province	Bari		Catanzaro		Siracusa	
Olive-growing area (ha)	47	36	100		25	3.89
Cultivar	Coratina		Carolea		Nocellarea Etnea and Carolea	
Planting density (plants/ha)	125	238	240		270	
Life cycle (years)	85		65		65	
CAP subsidies (€ ha ⁻¹)	600.00	800.00	1200.00		500.00	800.00
Olive yield (t ha ⁻¹)	10.0	8.0	9.6	8.4	8.5	6.0
Olive price (€ kg ⁻¹)	0.7		0.6		0.8	
Water resource management	Irrigated		Nonirrigated		Irrigated	
Total olives production for the whole life cycle (t ha ⁻¹)	624.15	657.06	476.96	446.88	367.50	361.76
Industrial/extraction phase						
Life cycle (years)	20					
Oil yield (%)			16		17	15
Bulk EVO oil price (€ kg ⁻¹) (Ismea 2019/2020, 2020/2021, and 2021–2022)			4.30		4.30	5.5

Source: Direct survey to farmers.

components, as well as the duration and intensity of this process (Rocchi et al. 2021). The formula for calculating the MCI of a product is as follows (Equation 1):

$$\text{MCIp} = 1 - \text{LFI} * F(X) \quad (1)$$

The Linear Flow Index (LFI) represents the percentage of material flow originating from virgin sources and ending up as nonrecoverable waste, whereas $F(X)$ represents the utility-constructed factor of the linear component of material flows. The LFI assumes a value between 1 and 0, with 1 representing a completely linear flow and 0 a completely restorative flow and

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 is derived from the following equation:

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

where V is the mass of virgin raw material used in manufacturing, W_0 is the mass of nonrecoverable waste attributed to the product, and M is the mass of the finished product.

Finally, $F(X)$ is defined in the Equation (3):

$$F(X) = \frac{0.9}{X} \quad (3)$$

X represents the utility and incorporates the duration and intensity of the product usage phase. The length component X is obtained from the L/Lav ratio, considering any reduction (or increase) in the waste stream over a given period for products that have a longer (or shorter) useful life (L) compared with the industry average (Lav).

To assess the degree of circularity, inputs and outputs were defined for each scenario. In the circular scenarios, inputs include pruning residues, digestate (Apulia), two-phase olive pomace (Calabria and Sicily), olive leaves, and olive pits, which are “reusable components” in the production process; organic fertilizers from “recycled” sources; and pesticides, water, and fuels from virgin raw materials. Outputs include the residual by-products that are not reused in the production process and other waste from the production process. The linear scenarios include inputs such as pesticides, water, fertilizers, and fuels that are all derived from virgin raw materials, whereas outputs include pruning residues as “recoverable waste” for “energy recovery” and olive pomace and vegetation water as “recoverable waste for other uses.”

3.2.2 | Conventional LCC and Investment Profitability Analysis

The LCC methodology considers initial and operational costs incurred during the LC of a product or production system (Gluch and Baumann 2004), from acquisition to final disposal (Dhillon 1989), allowing for optimal budget allocation over the life of the product/process, as well as improving business performance (Huppes et al. 2004). Specifically, conventional LCC analysis refers to ISO 15686-5:2017 (ISO, 2017a, 2017b), provides guidelines on procedures for calculating and comparing costs, and uses the discounting technique through which all future costs and benefits are reduced to the current value (Woodward 1997).

The analysis was based on the following assumptions:

- The costs of annual inputs, including fuel, fertilizers, pesticides, and water, were calculated based on the quantity effectively used by the farm and the current market prices

(2023), the operating costs related to labor and mechanical operations, which were calculated according to the current hourly wage of workers following the national collective agreement.

- The functional units used in the study are 1 ha of olive grove for the determination of costs in the individual LC phases, whereas in the investment analysis, the results refer to 1 kg of olives in the agricultural phase and 1 L of olive oil in the industrial/extractive phase; for specific operations such as trenching, hole digging, and tree grubbing, the costs of third-party provision were considered as rental costs of mechanical means.
- The interest on advance capital and capital goods was evaluated by applying a rate equal to 4.5% and 2%, respectively.
- The administrative overheads were estimated to be between 2% and 4% of the gross production value, which corresponds to the annual total revenues.

To select a discount rate, the opportunity cost approach in terms of alternative investments with similar risks in terms of typology, market conditions, and times was used (De Luca et al. 2018; Roselli et al. 2020). Here, a discount rate set to 2% and 5% was assumed for the agricultural phase and extraction phase, respectively. During the LC, constant prices by excluding adjustments for inflation were considered (Hussain, Mumma, and Saboor 2005). To perform the profitability analysis of the scenarios under study, all of the costs and revenues were discounted for the entire LC for the agricultural phase and extraction phase, respectively. All scenarios included EU agricultural policy Single Farm Payment (SFP) subsidies. The LCC evaluation included all costs incurred throughout the LC of each scenario. For this analysis, the entire LC of the agricultural phase per scenario was divided into seven main stages, corresponding to the physiological phases of the olive crops defined as follows: planting stage, unproductive stage, increasing production stage, constant production stage, decreasing production stage, senescence phase, and end-of-life stage.

Concerning the olive oil extraction phase, the full LC was split into three stages: the start-up stage, the operational stage, and the end-of-life stage. Within the start-up stage, design and initial investment costs for the extraction component were considered, the operational stage included all operating costs of the olive oil extraction, and in the end-of-life stage, the disposal cost resulting from the removal of the extraction plant was estimated as the residual value of the machinery and calculated at 10% of the cost of construction. The operating costs were divided into two categories: variable costs (material and energy costs, human labor costs, interest on advance capital) and fixed costs (ownership costs of investments in machinery and land, i.e., depreciation, insurance, repairs and maintenance, interest on capital goods, rental shed, taxes, and administration overheads).

Finally, the total revenues for the entire LC of each scenario were evaluated by multiplying the crop yield by its market price. This referred to the average price for the 2019/2020, 2020/2021, and 2021/2022 harvesting seasons. The next phase of the analysis involved the calculation of specific economic and financial

TABLE 2 | Main results of the application of MCI and LCC in the analyzed scenarios.

Production phases	Appraisal approaches	Unit of measure (UoM)	Italian olive-growing case studies					
			Apulia		Calabria		Sicily	
			Circular	Linear	Circular	Linear	Circular	Linear
Agricultural phase + Industrial/extraction phase Life cycle costing (LCC) Agricultural phase	Material Circularity Indicator (MCI)	%	94	54	67	57	91	80
	- Planting stage	€ ha ⁻¹	16,113.24	13,380.27	6886.07	7581.07	9930.88	7847.93
	- Unproductive stage		2647.49	2948.95	2181.93	2262.31	3208.82	2123.29
	- Increasing production stage		3536.03	3853.90	3447.93	3638.89	3502.06	2622.19
	- Constant production stage		4827.05	4811.30	4087.25	4303.31	3697.36	3874.57
Agricultural phase		€ kg ⁻¹	0.50	0.52	0.43	0.45	0.49	0.51
	Incidence % of technical operations cost							
	Soil management	%	10.93	16.39	9.21	8.96	9.44	5.67
	Fertilization		7.36	17.86	18.10	26.10	12.70	19.69
	Pruning		35.77	18.14	27.50	23.99	25.82	25.77
	Harvesting		25.49	34.59	32.06	29.05	32.39	42.59
	Phytosanitary defense		20.46	13.01	13.13	11.90	19.65	6.29
	Incidence % of the cost of circularity applications							
	Quotas	%	4.41	—	5.21	—	17.99	—
	Business-as-usual		95.59	—	94.79	—	82.01	—
Agricultural phase	Manual labour		8.86	—	9.76	—	11.14	—
	Business-as-usual		91.14	—	90.24	—	88.86	—
	Various expenses		11.82	—	3.00	—	12.07	—
	Business-as-usual		88.18	—	97.00	—	87.93	—
	- Decreasing production stage	€ ha ⁻¹	4487.31	4624.95	4055.87	4275.50	3494.95	3421.13
Agricultural phase	- Senescence phase		4296.01	4472.65	4035.07	4207.60	3462.74	3290.63
	- End-of-life stage		9602.00	10,764.86	11,862.86	11,374.86	9382.86	9310.00

(Continues)

TABLE 2 | (Continued)

Production phases	Appraisal approaches	Unit of measure (UoM)	Italian olive-growing case studies					
			Apulia		Calabria		Sicily	
			Circular	Linear	Circular	Linear	Circular	Linear
Industrial phase	Start-up investment cost	€ kg ⁻¹	0.01	0.03	0.05	0.03	0.08	0.05
	Building component							
	Plant component		0.01	0.04	0.05	0.14	0.08	0.09
	Operating cost	%	48.92	70.01	65.02	65.99	58.11	65.76
	Extraction variable costs	%	51.08	29.99	34.98	34.01	41.89	34.24
	Total operative cost	€ l ⁻¹	0.29	0.25	0.49	0.41	0.91	0.53
End-of-life cost (Disposal plant)			0.01	0.01	0.02	0.02	0.06	0.07

Source: Authors' elaboration.

indicators: net present value (NPV) and internal rate of return (IRR). These indicators give the possibility to evaluate the main economic hotspots during the entire LC of the analyzed systems, thus providing ideas for more effective management of long-term sustainability (De Luca et al. 2015).

The NPV is the sum of the discounted net cash flows for all years of the LC. It is a long-term valuation index for selecting the most profitable investment under given market conditions. This index is calculated according to the Equation (4).

$$NPV = \frac{\sum_{t=1}^n \frac{CF_t}{(1+r)^t} - I_0}{\sum_{t=1}^n TP} \quad (4)$$

where t is the time of cash flow (year), n is the duration of the investment, CF is the net cash flow in the t th year, r is the discount rate, I_0 is the initial investment, and TP is the total oil production.

The IRR is a financial metric that measures the profitability and efficiency of investments (Bonazzi and Iotti 2014). It is defined as the discount rate at which the after-tax NPV is zero, meaning that the present value of investment funds is equal to the net present revenues from the operation. Through IRR, it is possible to determine whether a return is minimally acceptable. This index is calculated according to Equation (5).

$$\sum_{t=1}^n \frac{CF_t}{(1+IRR)^t} - I_0 = 0 \quad (5)$$

where IRR is the discount rate, which will make the NPV equal to zero. When the conditions $NPV > 0$ and $IRR > r$ occur, the investment is profitable; otherwise, it should be rejected.

The last phase of the study involved a sensitivity analysis of the NPV obtained for each scenario, modifying the price of the outputs and the cost of the inputs compared with the base scenario, in order to reflect the market's dynamics in which prices are determined by unrestricted competition between privately owned businesses.

4 | Results

4.1 | MCI and LCC Results

The MCI and the LCC results for each phase of the LC for the scenarios under study are reported in Table 2. The studies carried out using the MCI show that the best results are obtained in the circular scenarios, with values of 94% for Apulia, 91% for Sicily, and 67% for Calabria. In the latter region, the difference between the circular and linear scenarios is the smallest, because, although the same circular applications as in the other regions, only part of the pomace is returned to the field as a soil improver. As far as costs are concerned, as shown in Figure 3, it appears that for all scenarios analyzed, the main costs (€ ha⁻¹) are represented by the planting and disposal phases. However, in olive growing, the costs of disposal are largely covered by the

sale of the resulting marketable wood assortments. As regards the planting phase, the highest costs are found in the circulars of Apulia and Sicily, with values of 16,113.24 € ha⁻¹ and 9930.88 € ha⁻¹, respectively. In Calabria, on the other hand, the highest costs are found in the linear scenario, with a value of 7581.07 € ha⁻¹. The constant production phase appears to be the one that covers the greatest number of years in all the scenarios considered, making it the most important phase among the different phases of the LC. The results show a very similar cost between circular and linear for the Apulian scenarios, whereas for the

Calabrian and Sicilian scenarios, the circular scenarios show lower costs of 4055.87 € ha⁻¹ and 3697.36 € ha⁻¹, respectively. However, when analyzing the cost per kilogram of olives produced, the circular scenarios perform the best. The costs are 0.02 € per kilogram lower than the corresponding linear scenarios in each region analyzed. Regarding the percentage incidence of each operation on the total cost, it appears that for all the scenarios considered, harvesting and pruning have a higher incidence, except for the Calabrian linear scenario, where fertilization has a greater impact than pruning.

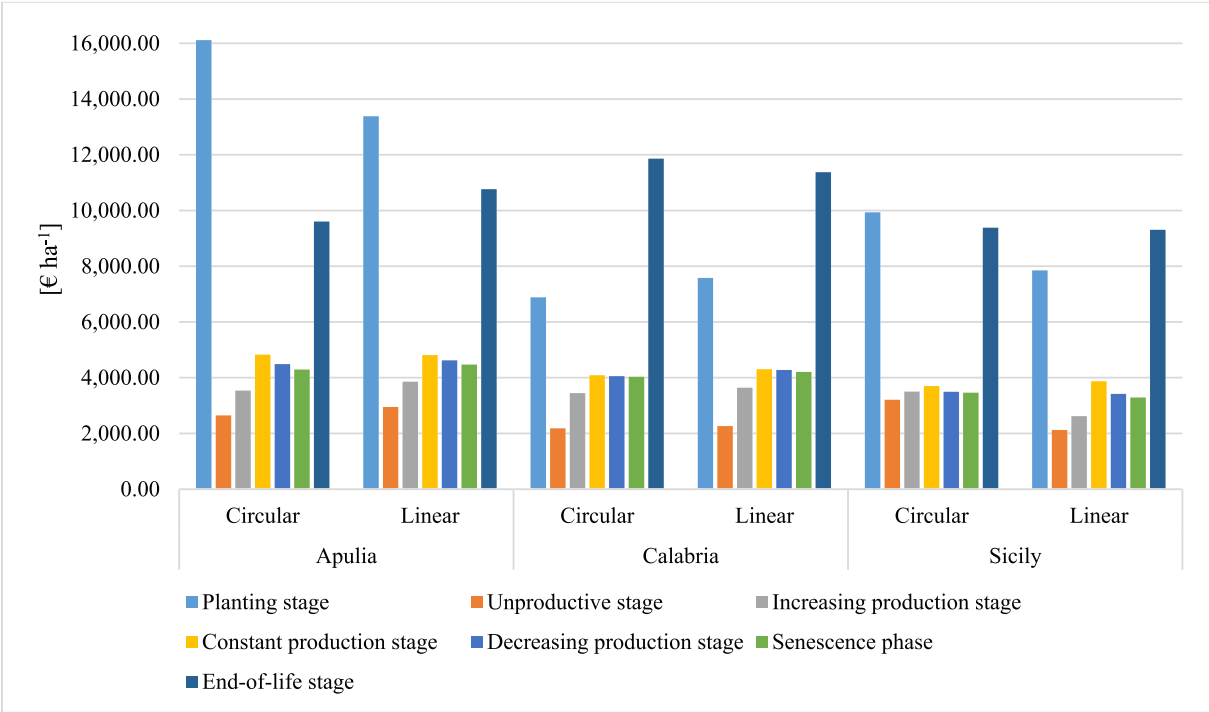


FIGURE 3 | Oil olive production costs through LCC of circular versus linear scenarios by life cycle stages (€ ha⁻¹ year⁻¹).

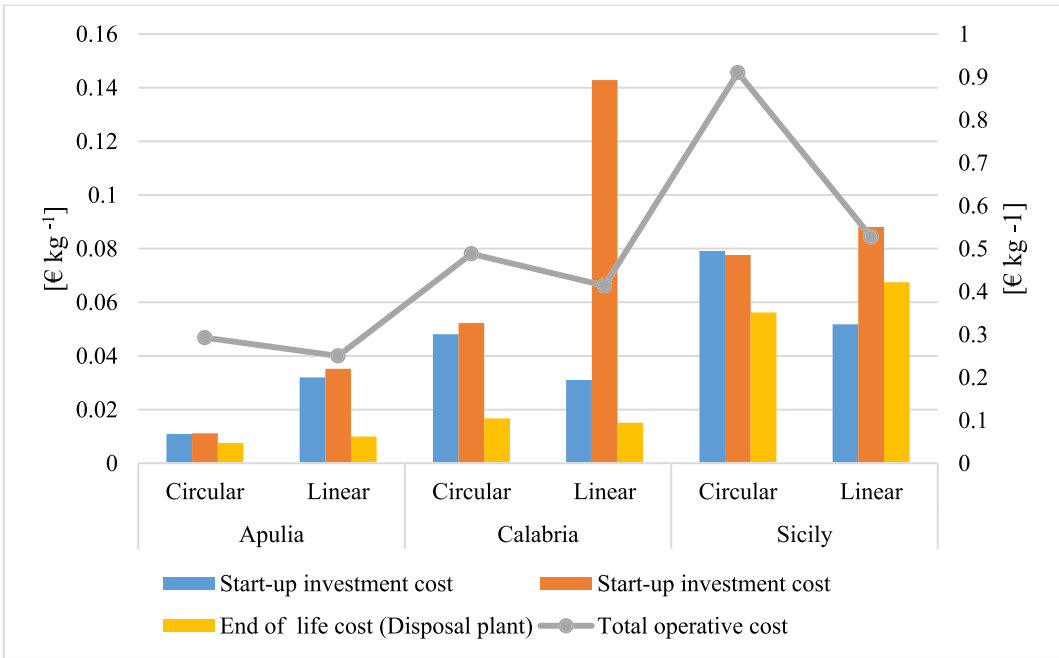


FIGURE 4 | Extraction costs of Evo oil through LCC of circular versus linear scenarios by life cycle stages (€ kg⁻¹).

A common characteristic of all the circular scenarios is the lower incidence of the fertilization item, compared with the linear scenarios, because of the acquisition of recycled or recovery inputs. Concerning the incidence of circularity applications on cost items, it emerges that the quotas and other allocations items for the Sicilian circular scenario have the highest incidence equal to 17.99%, because of the high investments for the acquisition of machines to spread the pomace; for the manual labor, the incidence is quite similar in the three regions, with a percentage between 8.86% (Apulia) and 11.14% (Sicily). The incidence of miscellaneous expenses of circularity applications is obtained in Sicily at 12.07% and in Apulia at 11.82%.

In the industrial extraction phase, as shown in Figure 4, the highest investment costs, expressed in € l^{-1} of Evo oil, are obtained in the Calabrian and Sicilian circular scenarios. The highest total extraction costs are obtained in the circular scenarios and are 0.91 € l^{-1} for Sicily, 0.49 € l^{-1} for Calabria, and 0.29 € l^{-1} for Apulia.

4.2 | Investment Analysis Results

Figure 5 illustrates the results of the profitability analysis in terms of NPV and IRR for the agricultural and industrial phases.

The results of the financial analysis are obtained by considering both the sale of the main products (olives and oil) and of pit by-products that are not reused within the processes. In the agricultural phase, the most profitable NPV is observed in the circular scenarios, particularly in Calabria and Sicily, with a value of 0.03 € kg^{-1} of olives, in comparison with a value of the respective linear scenarios of 0.02 € and 0.01 € kg^{-1} . The most profitable IRR is also recorded in the circular scenarios, with values of 3.85% for the Calabrian scenario, 3.55 for the Sicilian scenario, and 3.00% for the Apulian scenario, versus those of the linear scenarios, which are 3.00%, 2.58%, and 2.16%, respectively. The profitability analysis investments for the industrial

phase indicate that even in this phase, the circular scenarios exhibit the most optimal economic performance. The highest NPV is observed in the Calabrian circular scenario, with a value of 0.54 € l^{-1} , followed by the Apulian and Sicilian scenarios, with NPVs of 0.34 € and 0.27 € l^{-1} , respectively, in the linear scenarios. The Apulian circular scenario exhibits the highest IRR, with a value of 49.49%, followed by Calabria and Sicily with 21.80% and 10.96%, respectively.

A sensitivity analysis (Table 3) was carried out by adjusting the price of outputs (olives and oil) and inputs (total costs) according to a range of $\pm 5\%$, 10% , and 15% . This range was established considering the volatility of output and input prices that can be expected on the market in the current historical context, according to Roselli et al. (2020) and Di Trapani et al. (2014). Sensitivity analysis is particularly useful for studies applied over long periods, such as the LCC case, because it allows us to assess the degree of uncertainty associated with the results (Jansen et al. 2020).

The results show the great variability of the NPV obtained in the scenarios analyzed concerning olive and oil prices and total production costs. The simulations point out that circular scenarios always perform better than linear scenarios, especially in the case of a decrease in the selling price of olives and oil or an increase in total production costs. It is also shown that agricultural scenarios reach negative values before industrial scenarios, because of the lower value of the final product. For example, with a 5% reduction in the production price, both the linear and circular agricultural scenarios in Apulia and the linear agricultural scenario in Sicily reach negative NPV values; with a 10% reduction, only the circular industrial scenario in Apulia and the linear and circular industrial scenarios in Calabria remain positive; finally, with a 15% reduction, only the circular industrial scenario in Calabria remains positive. Regarding the variation of input costs, the values are very similar to those reported for outputs. With a 10% increase in costs, for example, six out of 12 scenarios remain positive, of which four are circular.

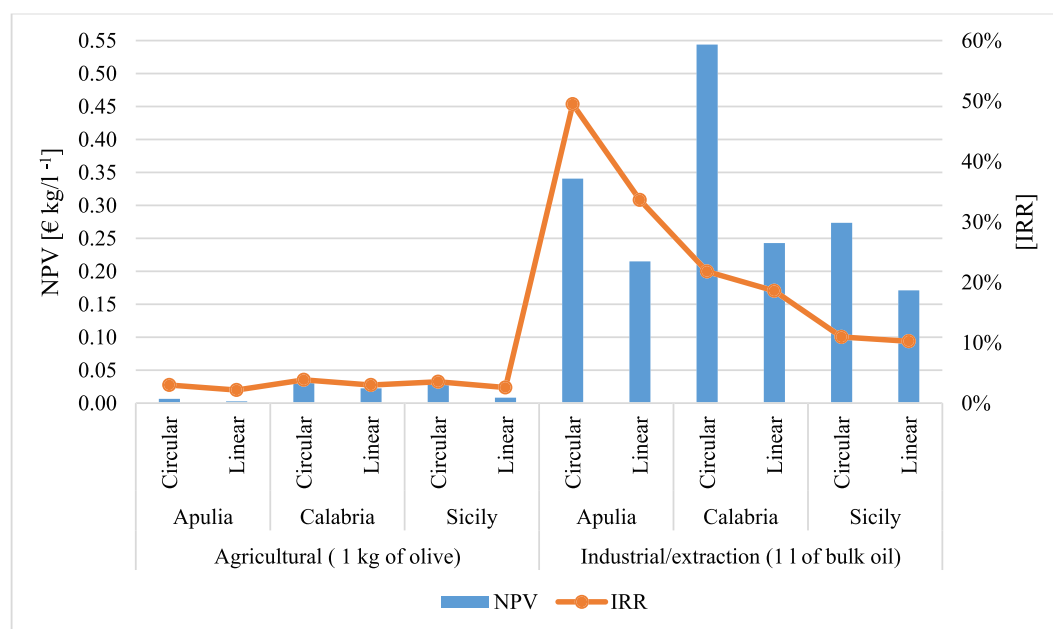


FIGURE 5 | NPV and IRR indicators obtained from the profitability analysis of analyzed scenarios.

TABLE 3 | Results of the sensitivity analysis of NPV with variation in price of outputs and cost of inputs.

	Apulia						Calabria						Sicily					
	Agricultural			Industrial			Agricultural			Industrial			Agricultural			Industrial		
	Circular	Linear		Circular	Linear		Circular	Linear		Circular	Linear		Circular	Linear		Circular	Linear	
Baseline	0.006	0.003		0.341	0.215		0.033	0.023		0.561	0.243		0.033	0.008		0.274	0.008	
Output price	+5%	0.020	0.017	0.488	0.328		0.046	0.035		0.709	0.356		0.051	0.024		0.458	0.024	
	+10%	0.033	0.030	0.636	0.441		0.059	0.048		0.858	0.469		0.070	0.039		0.642	0.039	
	+15%	0.046	0.042	0.783	0.554		0.072	0.061		1.006	0.582		0.088	0.055		0.826	0.055	
	-5%	-0.007	-0.008	0.193	0.102		0.021	0.010		0.413	0.130		0.014	-0.007		0.089	-0.007	
	-10%	-0.020	-0.021	0.046	-0.011		0.008	-0.003		0.265	0.017		-0.004	-0.022		-0.095	-0.022	
	-15%	-0.033	-0.034	-0.102	-0.124		-0.005	-0.015		0.117	-0.096		-0.022	-0.038		-0.279	-0.038	
Input cost	-5%	0.022	0.018	0.472	0.316		0.049	0.039		0.676	0.337		0.070	0.028		0.434	0.028	
	-10%	0.037	0.034	0.603	0.417		0.064	0.056		0.791	0.430		0.089	0.044		0.594	0.044	
	-15%	0.053	0.049	0.735	0.518		0.079	0.073		0.906	0.524		0.107	0.062		0.754	0.062	
	+5%	-0.010	-0.011	0.209	0.114		0.018	0.006		0.446	0.149		0.036	-0.009		0.113	-0.009	
	+10%	-0.024	-0.026	0.078	0.013		0.003	-0.011		0.331	0.055		0.018	-0.027		-0.047	-0.027	
	+15%	-0.053	-0.088	-0.053	-0.088		-0.013	-0.028		0.216	-0.039		0.0001	-0.045		-0.207	-0.045	

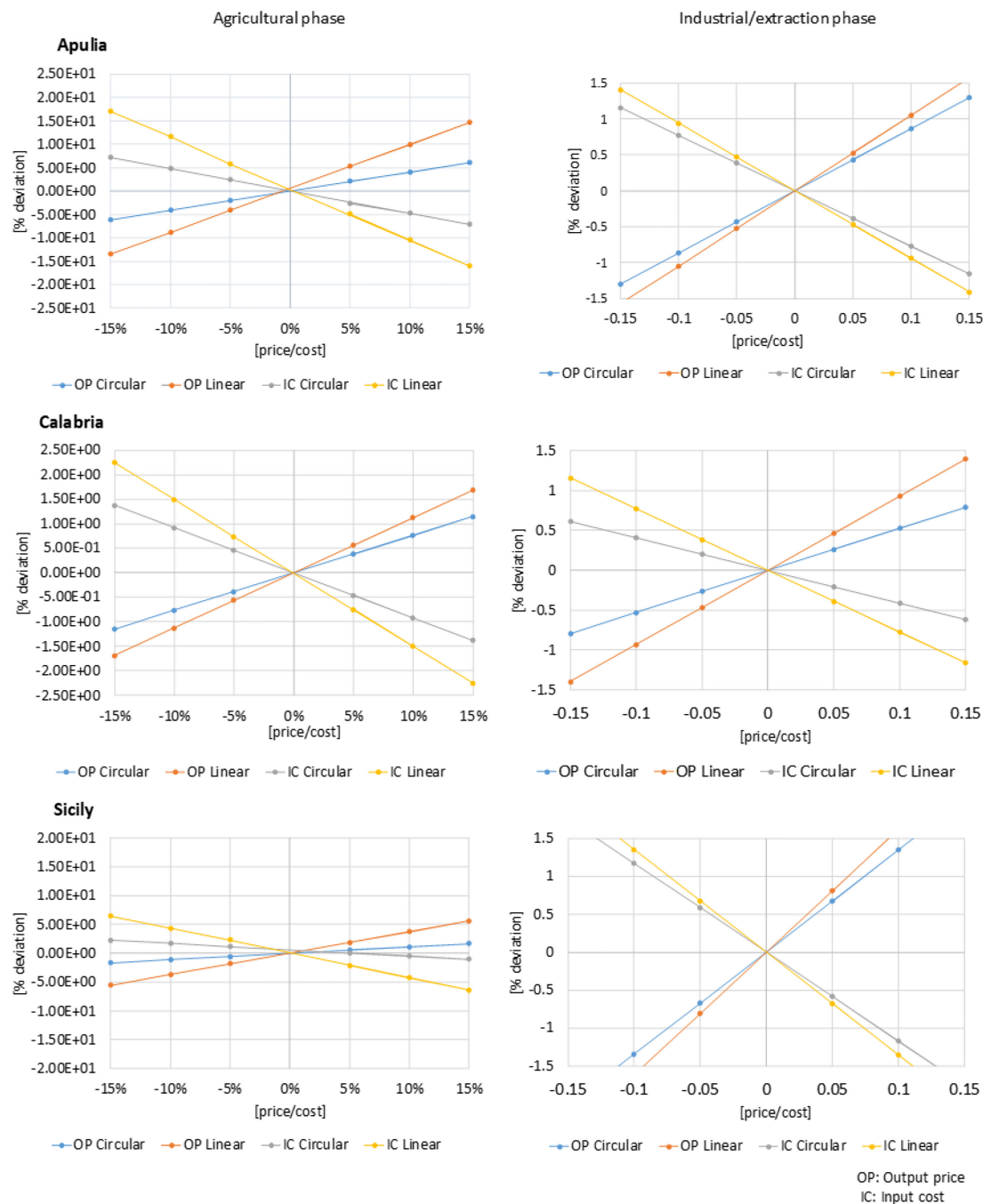


FIGURE 6 | Percentage variations of NPV obtained with sensitivity in the circular and linear scenarios compared with the corresponding basic scenarios.

The analysis of the deviation of the NPV in percentage terms compared with the basic scenario, reported in Figure 6, confirms the lower variability of the circular scenarios regarding the variations considered, resulting in a lower slope of the lines. This condition translates into greater resilience of the circular scenarios concerning the variations considered.

5 | Discussion and Conclusion

Current study results highlight an increase in the efficiency of the farm, supporting the study by Kuisma and colleagues (2017).

The case studies assumed as circular scenarios were able to seize the opportunities offered by embedding the CE paradigm into their production process. By rethinking and innovating their business structure, they have reoriented their approach to creating and capturing value. Their strategies of recovery, valorization, and recirculation of internal resources are now at the core of their business model, rather than being overlooked in linear business-as-usual scenarios. They shifted toward a closed-loop business model (Winkler 2011; Mentink 2014), which are integrated elements of two sustainable business model archetypes: (i) creating value from waste and (ii) substituting with renewables and natural processes (Bocken et al. 2014).

More in detail, organic materials that result as residues or by-products of production processes, conventionally treated as waste, and disposed of outwardly the firm gate, are profitably reused, or recycled as production inputs within the firm system, by means of agronomic application or energetic valorization. End-of-use materials replace virgin and synthetic inputs externally sourced on the market and become new key resources for fulfilling the core business activities. The firms recapture both the ecological and economic residual value of such materials: From one side, they make a restorative and regenerative use of the organic matter reincorporated into the soil; on the other side, they change their structure cost and revenue streams, because internal recycling allows to reduce farming management costs and to enhance economic resilience.

The use of the MCI, in combination with the LCC, made it possible to compare the economic performance of full-LC circular applications, in line with the results of Jansen and colleagues (2020). Taking stock of the approach implemented, it is possible to shed light on the potentials and criticalities of circular approaches, such as high investment costs or high labor requirements to perform certain activities. The evaluation of the economic long-term sustainability of the circular performances of olive growing present in scientific literature is not enough to be able to make comparisons with our results; however, it is possible to find reasoning on economic evaluations of the LC of the olive tree as reported by Castillo-Ruiz et al. (2017), Falcone et al. (2022), Spada et al. (2022), and Stillitano et al. (2016), that report, for linear scenarios, results in accordance with those obtained in this study. In terms of the distribution of fixed and variable costs obtained in the transformation phase, the findings agree with Stillitano et al. (2019). The economic sensitivity analysis shows that all scenarios are influenced by variations in the price of olives or oil production, and by the cost of production factors, as also found in the studies by De Luca et al. (2018), De Gennaro et al. (2012), and Hussain, Mumma, and Saboor (2005). Specifically, it is observed that in circular scenarios, changes in the prices of outputs and inputs are less decisive than in linear scenarios. The circular scenario has a lower variance than the linear counterpart and shows greater economic resilience because of the lower dependence on external resources, which is typical of the circular approach (Haque, Fan, and Lee 2023). However, with variations of 10% or 15%, some of these scenarios also assume negative performances, demonstrating how the volatility of the input and output market strongly influences the olive oil supply chain.

Addressing the first research question posed at the outset of this work—concerning “What is the degree of circularity of farms that implement closed-loop pathways?”—this analysis made it possible to outline that with appropriate applications this can be very high and reach 94% as in the Apulian circular scenario, which therefore can be defined as an almost closed cycle. Regarding the second question—“What are the investment and management costs of adopting circular strategies?”—the work shows, through the application of the LCC, that in circular scenarios greater economic investments are necessary for the acquisition of specific machines that are not always routinely found in agricultural companies, such as the pomace dispenser or the pit separator in the specific case. For this reason, the transition toward this production model needs to be supported by

specific contributions to agricultural companies by national governments and regional policies, as also shown in the study by Donner et al. (2022). In terms of management costs, circular practices require more manual work, for example, spread of by-products. As regards the third research question—“Does the adoption of circular strategies affect the profitability of the agricultural company and increase its resilience to changes in production prices and production costs?”—the results show that in circular scenarios, because of the lower use of virgin raw materials, the cost of obtaining finished products is lower, and despite higher investments, these scenarios show the best economic performance. The lower dependence on external sources in circular scenarios also translates into greater resilience of the agricultural firm, related to the lower incidence of price or cost variations caused by external shocks.

The results obtained can be of great support to entrepreneurs and public decision-makers whose task is to plan in the long term by implementing strategies to pursue sustainable development objectives. First, the higher economic performance reached in terms of NPV and IRR by the circular case studies, both in the agricultural and industrial phases, suggest that adopting circular business models allows to create and capture greater value, leading to cost savings and increased returns on investments. Besides, the results of the sensitivity analysis of NPV also show a greater resilience to external shocks. Overall, business model innovation is believed to be key to business success (Chesbrough 2010), and shifting toward circular business models can generate economic advantage for firms, while delivering positive contributions to societal and environmental sustainability.

Moreover, our findings reveal important implications both for the general nature and for policymakers. The general implication is related to the added value generated by CE strategies in the olive oil sector. This implies optimizing the existing value through interventions in the production model, such as the stimulation of the reuse of by-products or the activation of symbiosis with other companies, as well as the involvement of local communities (Poponi et al. 2023). Regarding the implications at the level of policymakers, it appears that, because of the higher investment costs, shifting to circular business models may not be economically viable at the beginning, although greater revenues can be gained in the medium-long term. So, investment costs can be a relevant economic barrier hindering the adoption of circular strategies, especially for small- and medium-sized businesses with limited access to credit, which however represent a large part of entrepreneurial reality in the agri-food sector. Therefore, policymakers should establish proper policy and market tools (e.g., targeted subsidies or incentives to small and medium enterprises) to help overcome this barrier and thus support a broader transition toward CE in the agri-food sector. This will allow agriculture to continue producing food, address resource scarcity, and adapt to the effects of climate change by promoting its mitigation and preventing environmental risks (Gava et al. 2020).

Although the analysis carried out did not include transaction costs, a further issue to be tackled for transitioning into circular models points to those policies aimed to ease knowledge exchange, enhance capacity building, or raise trust between farmers and other actors along the food supply chain.

In light of the growing attention being paid to environmental aspects by both institutions and civil society in general, integrating this study with an analysis of the environmental sustainability of the impacts of circular strategies would provide a more complete result, thereby enabling policymakers and entrepreneurs to make more informed decisions regarding the planning of agricultural development strategies.

Author Contributions

Emanuele Spada: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Writing—review and editing. **Domenico Carlucci:** Data curation, Investigation, Validation, Writing—review and editing. **Luigi Cembalo:** Funding acquisition, Project administration, Supervision, Writing—review and editing. **Gaetano Chinnici:** Data curation, Investigation, Validation, Writing—review and editing. **Mario D'Amico:** Funding acquisition, Project administration, Resources, Supervision, Validation, Writing—review and editing. **Giacomo Falcone:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing—review and editing. **Giacomo Giannoccaro:** Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing—review and editing. **Giovanni Gulisano:** Supervision, Writing—review and editing. **Nathalie Iofrida:** Conceptualization, Data Curation, Investigation, Methodology, Writing—review and editing. **Stempfle Sarah:** Investigation, Writing—review and editing. **De Luca Anna Irene:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing—review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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