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Circular bioenergy from citrus waste: Life cycle evaluation in the Mediterranean context

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ABSTRACT

An effective strategy for enhancing the sustainability of production processes is to adopt a circular economic approach utilising agro-industrial by-products and waste to generate value-added compounds, biofuels, and energy. Citrus processing generates large quantities of orange-peel waste (OPW), and recent research shows that OPW has promising potential for biogas production. Because its availability is restricted to few months of the year for seasonal variations, relying solely on OPW constrains the continuous operation of biogas plants. The inherent volatility of crop yields, coupled with the inhibitory effects of d-Limonene, renders the sole reliance on this substrate a significant risk for anaerobic digestion operations. Within this context, the study aims to analyse the technological feasibility of ensiling OPW to mitigate seasonality, alongside the economic and environmental sustainability of generating electricity from the resulting biogas via anaerobic digestion (AD). This research considers the potential for continuous, year-round use of OPW, both fresh and ensiled. This approach is then compared with two other substrates widely available in the Mediterranean region: two-phase and three-phase olive pomace. Technical feasibility was assessed across all three scenarios. In parallel, the environmental impact was quantified using the Life Cycle Assessment (LCA) methodology, while the financial aspect was estimated through Life Cycle Costing (LCC) at the farm level. The results indicate positive environmental and economic outcomes across all scenarios, findings that are confirmed by sensitivity analyses of these two key dimensions. For example Climate change performance varies across the scenarios, with OPWFE showing the lowest impact (0.316 kg CO_2 eq), while OPWTwPP and OPWThPP exhibit higher impacts by 11% and 17%, respectively, relative to this reference scenario. In contrast, economic performance peaks in OPWThPP (IRR = 23%), with OPWTwPP and OPWFE displaying lower profitability, reduced by 9% and 17%, respectively, compared to the most profitable scenario. The conclusions provide valuable insights for promoting business-oriented strategies that aim to pursue a new ecological transition pathway.

1. Introduction

Driven by the need to address natural resource scarcity and environmental pollution, the Circular Economy (CE) is recognised as a crucial framework for achieving sustainable development. CE requires a fundamental shift from the conventional linear "cradle-to-grave" model to a closed-loop "cradle-to-cradle" approach [1]. In a CE system, waste or by-products are converted into valuable biological or technical inputs, contributing to value creation [2]. This strategy is supported by Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) and key European policies like the Green Deal, which aims for climate neutrality by 2050 through resource-efficient strategies [3,4]. The agri-food sector is a major generator of residues but shares characteristics with natural, balanced systems, making it highly amenable to CE approaches [5]. The citrus fruit sector, globally one of the most cultivated, generates significant quantities of industrial by-products [6]. According to FAOSTAT [7] forecasts, out of an estimated 70 million tons of citrus production in 2023, about 40% is

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processed into juice [8]. With an average yield of 60%, this results in approximately 11.2 million tons of by-products annually. Oranges are the most widely processed citrus fruit, yielding Orange Peel Waste (OPW), consisting of peel, pulp, and seeds [9]. Managing OPW is challenging due to its high-water content and composition. Historically, OPW was used as animal feed, but its low protein content and the high cost of transporting its high-moisture content have limited its economic viability. Consequently, a substantial amount of OPW is disposed of in landfills or directly on soil, leading to severe environmental damage [10]. Improper management results in the production of greenhouse gases (GHGs) like methane and nitrous oxide, odours, and the leaching of organic matter, significantly straining the carbon balance [11]. The adoption of OPW valorisation through CE pathways, such as producing biogas and energy, is key to solving the management problem and creating added value. Biogas production from OPW is achieved through Anaerobic Digestion (AD) of its fermentable matter, involving a series of metabolic reactions. The resulting biogas can be converted into electricity. This approach is recognised as a key decarbonization strategy in many regions of the world, including the European Union, where it contributes directly to the transition towards renewable energy and the zero net emissions target by 2050 [12]. The technical feasibility of OPW digestion has been demonstrated, often employing Co-Digestion (CoAD) with other substrates [13–16] CoAD is vital for mitigating the inhibitory effect of d-Limonene, a compound present in OPW that is toxic to microorganisms, hindering biomethane conversion [17–19]. Cattle manure is considered an effective CoAD substrate due to its wide availability, high biomethane potential, high water content, and buffering capacity that promotes AD stability [20]. A key challenge for industrial AD plants, which require high economic investment, is the seasonality of OPW production (approximately 6 months per year). To ensure year-round operation, the storage of OPW is necessary. Ensiling the fresh OPW has been identified as a viable technical solution to preserve the feedstock [14,21,22]. This process, typically used for forages, involves an initial aerobic phase followed by an anaerobic fermentation phase that lowers the pH, allowing for long-term storage. For closed-loop practices like OPW valorisation to be fully implemented, it is crucial to assess their economic and environmental performance through the simulation of real case studies. This study integrates Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to evaluate both the environmental and economic performance of the process. It also assesses the year-round feasibility of using OPW for anaerobic digestion, including the impacts and costs of storage (ensiling), which is required to ensure continuous plant operation. Previous studies have mainly focused on environmental aspects of OPW use, often in biorefineries or disposal scenarios [[15,23,24]], consistently identifying landfilling as the most impactful option [25].

However, there is a paucity of research evaluating the economic performance and, critically, the sustainability of OPW storage. This lack of specific data hinders the industrial-scale dissemination of these innovations, as both policymakers and entrepreneurs require a preliminary assessment of investment impact [26]. Likewise, the study seeks to validate the technical feasibility and assess the sustainability (environmental and financial) of industrial-scale electricity production using both fresh OPW and ensiled (stored) OPW, and determine the potential spill-over effects of the innovation on the entire production and consumption system by analysing the complete life cycle. Furthermore, to ensure robust, comparable, and technically sound results, this research also includes alternative production scenarios, substituting ensiled OPW with olive pomace which is another abundant and environmentally problematic by-product in the same geographical areas.

2. Materials and methods

2.1. Methodology overview

The LCA methodology is recognised as one of the most effective metrics for analysing environmental issues related to the production of goods and services [[27–29]]. LCA has been standardised within the International Organisation for Standardisation's ISO 14040 and 14044 standards [30,31] and is based on accounting for material and energy flows relating to a functional unit. The objective is to calculate all life cycle flows of a product or service, from 'cradle to grave', and to translate them into impacts, be they risks to human health and safety, environmental impacts, or primary energy use [32].

Furthermore, LCA is one of the most widely used metrics to assess the environmental impacts of AD plants [33,34]. In the contemporary global context of a marked emphasis on ecological transition, this methodology is widely used in ecological design-oriented comparative analyses [35]. The LCC methodology is a robust and well-established technique within management accounting, fundamentally utilising discounted cash-flow analysis [36,37]. Its primary application is in the economic assessment of durable goods acquisition and long-term asset management. LCC provides essential capabilities for investment comparison and optimisation by evaluating the total costs associated with an asset throughout its entire lifecycle, a feature crucial for optimising business performance [38,39].

The LCC methodology is commonly split into three categories, differentiated by the scope of costs considered: Conventional LCC focuses on internal monetary flows experienced by the companies; Environmental LCC that expands the conventional scope by incorporating environmental externalities and translating into a monetary unit; Societal LCC that represent the broadest perspective, examining the full spectrum of costs and benefits experienced by all stakeholders across the product/process value chain and throughout society [40,41].

2.2. Biochemical methane potential (BMP) of OPW, manure and olive pomace

The biochemical methane potential (BMP) values for both fresh and ensiled OPW were retrieved from experimental data generated and previously published by the authors [[13,42–45]] Ensiling and subsequent BMP tests were performed using laboratory glass reactors. These sealed batch reactors allowed for the collection, measurement, and analysis of the biogas produced during the experimental trials. During ensiling, biogas was mainly composed of CO_2, while both CO_2 and CH_4 were present during BMP tests. The ensiling phase lasted from 4 weeks to 2-3 months, while BMP tests were prolonged until the biogas production plateau was reached.

The mass balance was calculated based on the coAD of the two matrices composing each scenario. The input quantities for each scenario were determined using the volatile solids (VS) balance, adopting a 50% allocation (VS/VS), to ensure a balanced supply of degradable organic matter in the digester. This allocation is a common practice, documented by Hartmann and Ahring [46], Aragaw et al. [47], and Riaño et al. [48]. Table 1 presents the characteristics of all the substrates used in the scenarios examined in this paper.

The full set of substrate characteristics required for modelling all scenarios was compiled through a detailed review of scientific literature. The data relating to fresh and ensiled OPW were readily available from the references already introduced, allowing for immediate integration into our analysis. To ensure the accuracy of the co-digestion scenarios, a broad spectrum of sources was consulted for the remaining inputs. Specifically, the characteristic parameters for manure were adopted from the studies conducted by Surenda et al. [49] and Telo and Yigezu [50]. Likewise, information on olive pomace composition was extracted and cross-referenced from the research published by Soldano et al. [51], Sánchez-Sánchez et al. [52], and Rubio et al. [53]. This systematic data collection process establishes the technical basis for the substrate profiles presented in the analysis.

Table 1
Substrate matrix and biogas characterisation.

Scenario	Substrate Matrix	t	Percentage allocation of matrix (%)	Total solids (%)	Volatile solids on total solids (%)	Biogas manure yield (m^3 $kgVS^{-1}$)	Methane content (%)	Biogas from 1 t of matrix(m^3 t^{-1})	kWh
OPW	Manure	1	55.24	20	70	0.25	70	**42.53**	0.26
	OPW	0.81	44.86	18	96	0.30	70		0.31
	Total	**1.81**							**0.57**
Ensiled* OPW	Manure	1	32.66	20	70	0.25	70	**32.91**	0.26
	OPW ensiled	2.06	37.33	11	95	0.30	70		0.31
	Total	**3.06**							**0.57**
* During ensiling for OPW, a 35% reduction in the initial quantity was recorded.									
OPW and Two-phase pomace	Manure	1	62.95	20	70	0.25	70	**42.97**	0.26
	Two-phase pomace	0.58	37.05	26	92	0.23	93		0.21
	Total	**1.58**							0.47
OPW and Three-phase pomace	Manure	**1**	70.33	20	70	0.25	70	**47.42**	0.26
	Three-phase pomace	**0.42**	29.66	36	92	0.23	62		0.21
	Total	**1.42**							0.47

2.3. Anaerobic Co-digestion experiment

Table 2 summarises the key operational characteristics and methane yields reported for semi-continuous anaerobic digestion (AD) systems treating orange peel waste (OPW), comparing small-scale laboratory reactors to a larger pilot-scale system. The study evaluates the Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT) as key process parameters, utilising Continuous Stirred Tank Reactors (CSTR) enhanced with Granular Activated Carbon (GAC).

The comparison of the three studies highlights clear differences between small-scale and pilot-scale semi-continuous anaerobic digestion (AD) setups. Zema et al. [54] operated an 84 L pilot reactor using ensiled orange peel co-digested with poultry manure, achieving the highest cumulative methane yield (0.46 L CH_4 g^{-1} VS) under mesophilic conditions and stable operation at OLR $\leq$1.4 g VS L^{-1} d^{-1}, while thermophilic runs exhibited early inhibition. Fazzino et al. [45] used 1.9 L semi-continuous reactors fed with the solid fraction of ensiled orange peel waste, reaching steady-state yields of 0.23–0.28 NL CH_4 g^{-1} VS_loaded under mesophilic conditions with nutrient supplementation and granular activated carbon (GAC) addition. Unlike our study, in Calabrò et al. [42], it was impossible to establish stable operation in 1.1 L semi-continuous reactors fed with OPW without the addition of nutrients. Across all systems, the addition of nutrients or co-substrates was crucial to prevent acidification resulting from the low nitrogen content of orange peel waste. This issue underline as CoAD with manure is a key factor for the success of ensiled OPW AD. The semi-continuous methane yields were approximately 20–30% lower than those reported in batch biochemical methane potential (BMP) assays, consistent with expected differences between dynamic feeding and static batch operation.

2.4. Economic and environmental analyses

2.4.1. Scenarios description

The subsequent stage of the investigation entailed a comprehensive quantitative assessment of the environmental and economic implications inherent to biogas generation via anaerobic coAD, considering the empirical laboratory data detailed in Table 1,

To effectively bridge the gap between experimental results and industrial applicability, a technical scale-up was systematically implemented. For the ensuing impact analysis, the system considered a full-scale AD reactor designed for biogas production, which is functionally integrated with a dedicated on-site electricity generation unit. This specific configuration enables the valorisation of biogas as a source of renewable energy. A dedicated environmental and economic impact assessment was subsequently executed across the three distinct operational scenarios subsequently delineated.

- OPW fresh and ensiled (OPWFE)

Matrix allocation: For 6 months OPW fresh 44.86% + Cattle manure 55.24%, and for 6 months OPW ensiled 67.33% + Cattle manure 32.66%

- OPW fresh and two-phase pomace (OPWTwPP)

Table 2
Semi-continuous anaerobic digestion test.

Study	Reactor setup	Substrate	OLR (g VS L^{-1} d^{-1})	HRT (days)	Specific CH_4 yield (L CH_4 g^{-1} VS)	Conditions/Notes
Zema et al., [54]	Pilot 84 L semi-continuous CSTR	Ensiled OPW + poultry manure	0.64 to 2.50 (mesophilic conditions) 0.64 to 1.98 (thermophilic conditions)	70 to 18 (mesophilic conditions) 70 to 30 (thermophilic conditions)	Daily: 0.27–1.22; cumulative: 0.46 (mesophilic conditions) Daily: 0.11–0.40; cumulative: 0.12 (thermophilic conditions)	Mesophilic (42 °C) optimal up to OLR ≈ 1.4; inhibition >2.0 g VS L^{-1} d^{-1}. Thermophilic unstable.
Fazzino et al., [45]	1.9 L lab semi-continuous CSTR	Solid fraction of ensiled OPW (4–12 weeks)	1.0	20	Startup: 0.25–0.28; steady-state: 0.23–0.28	Mesophilic (35 °C); added 5 g L^{-1} GAC and nutrient solution
Calabrò et al., [42]	1.1 L lab semi-continuous CSTR	Raw OPW	0.5 – 2.0 start-up 2 regime	13	0.09	Mesophilic (35 °C); very unstable operation (pH drop)

Matrix allocation: For 6 months OPW fresh 44.86% + Cattle manure 55.24%, and for 6 months Two-phase pomace 37.05% + Cattle manure 62.95%

- OPW fresh and three-phase pomace (OPWThPP)

Matrix allocation: For 6 months OPW fresh 44.86% + Cattle manure 55.24%, and for 6 months Three-phase pomace 29.66% + Cattle manure 71.33%

This focused comparative analysis is essential for identifying the optimal operational parameters and feedstock blending strategies that maximise environmental sustainability, economic viability, and financial performance at the industrial scale.

The proportional allocation of the co-digestion matrices was derived from the mass balance calculation, specifically utilising the 50% VS allocation as the governing parameter. This allocation was applied under the constraint of a fixed input of one tonne of manure per batch. Based on this defined blend, the total potential methane yield from the mixture of one tonne of manure and the secondary matrix (comprising fresh OPW, ensiled OPW, two-phase pomace and three-phase pomace) was determined. This yield, which represents the initial laboratory-scale data, is summarised in the previous Table 1. Subsequently, the methane production was normalised and expressed in relation to one tonne of the total input mixture, adhering to the predetermined VS distribution ratio. The current analysis incorporated an annual feedstock quantity of 36,000 tonnes of matrix. This value is consistent with the typical operational range observed in facilities generating up to 1 MW of electrical energy annually, particularly when processing matrices characterised by a medium-to-low energy potential. This consideration aligns with the methodologies and parameters established in prior research by Benalia et al. [55] and Piekutin et al. [56].

2.4.2. Goal and scope definition, functional unit and system boundaries

The same assumptions adopted for life cycle modelling were consistently applied to both the environmental and economic assessments. The purpose of LCA is to evaluate the impact of different possible solutions for the valorisation of OPW, within a realistic context – specifically, a region in southern Italy characterized by significant production of both OPW and olive pomace. Although these two agro-industrial by-products differ substantially in composition and properties, they pose considerable management challenges for local farms. Despite the emergence of a market for olive pomace oil extraction, bioenergy production remains a viable and increasingly attractive alternative. Through comparative analysis, this study explores potential utilisation strategies for these residues, identifying options that may compete with, complement, or even substitute one another, depending on their respective storage and handling characteristics. Since the primary function of the AD plant is to utilize the produced biogas for energy generation, we selected the Functional Unit (FU) as “1 kWh of electricity”.

OPW is normally classified as a waste product from agro-industrial processes. Consistent with the “zero burden” assumption often employed in LCA for waste streams, the system boundaries were defined “from the gate of the agro-industrial company producing the OPW to the generation of electricity”, thereby assigning zero environmental impact to the initial feedstock acquisition. Conversely, olive pomace, driven by the substantial increase in the cost of extra virgin olive oil (EVOO), has recently reacquired a significant market share, suggesting its valuation as a co-product rather than merely a waste stream.

Consequently, since the olive pomace exhibits market value (as noted above), this co-product has been managed using economic allocation within the EVOO extraction process. This methodological choice ensures that the environmental burdens associated with the co-product's initial production are fairly partitioned according to its relative market value, rather than being assigned entirely to the primary product (i.e., EVOO). The foreground data utilised for the Life Cycle Inventory (LCI) are derived from primary sources, specifically direct measurements collected during prototype-scale laboratory experiments. To ensure the relevance of the assessment, this inventory data has been scaled up to model the operation of a full-scale industrial plant. This upscaling procedure was based on the empirical results obtained at the prototype level and involved detailed process modelling of the transition from a laboratory-scale unit to an industrial one.

The model utilises empirical characterisation data from industrial-scale applications to ensure practical relevance. Specifically, the transition from prototype to industrial scale was quantified by measuring TS and VS for each substrate matrix (Manure, OPW, and Olive Pomace). This mass balance integrates specific methane yields and accounts for physical mass reductions, such as the 35% loss recorded during the ensiling process for OPW, and the varying methane concentrations across different scenarios. Furthermore, it is important to note that the subsequent biodigester data reflect real-world industrial plants, ensuring that the model is grounded in verified, operational figures. This data-driven approach ensures that energy outputs (kWh) and biogas production rates are grounded in the biomass's actual stoichiometric and physical potential in a real-world operating environment.

Crucially, the upscaling methodology incorporated adjustments for anticipated process inefficiencies inherent to industrial systems, including an accounting for potential methane fugitive emissions from the AD unit. This approach ensures that the model reflects realistic performance metrics. Finally, the overall analysis considers three distinct scenarios, for which the total annual feedstock input to the AD process remains constant at 36,500 tonnes of matrices, as already mentioned.

2.4.3. LCA methodology and implementation

As previously introduced, the foreground data for the AD process was established using primary data collected directly during the experimental phase. Specifically, the operational parameters, including the matrix input quantities (i.e., feedstock flow rate), the hydraulic retention times (HRT) maintained within the prototype reactors, and the resulting biogas production yields, were directly measured and recorded in-house at the prototype scale. This utilisation of primary, experimentally-derived data ensures a high degree of site-specific accuracy and relevance for the subsequent LCA model, particularly regarding the performance characteristics of the olive pomace matrix. Such an approach significantly minimises the reliance on less representative secondary or literature data for the core bioprocess parameters. The emissions considered in the study include ammonia (NH_3), nitrous oxide (N_2O), and methane (CH_4), along with those arising from the storage of digestate. Emissions of methane and ammonia from digestate storage were estimated based on the methodology outlined by Lovarelli et al. [33]. Additionally, fugitive methane emissions from digesters and post-digesters, as well as losses occurring during biogas processing and combustion, were assumed to be 2%, following the findings of Dressler et al. [57] and emission factors provided by Lovarelli et al. [33]. The data relating to the power plant was taken from the ecoinvent database, as was all the background data.

OPW and manure production and management (including OPW ensiling) were assigned zero environmental impact. The compiled inventory data (presented in Table 3) were subsequently processed using the Simapro 9.6 software package. For Life Cycle Impact Assessment (LCIA), the widely recognised Environmental Footprint 3.1 midpoint method was employed, according to the guidance provided by the European Commission's Joint Research Centre [58]. This rigorous methodological framework facilitated the comprehensive assessment of a broad spectrum of environmental pressures, encompassing the following impact categories: Acidification, Climate Change (categorized by Biogenic, Fossil, Land Use, and Land-Use Change contributions), Ecotoxicity Freshwater (Inorganics and Organics), Particulate Matter, Eutrophication (separated into Marine, Freshwater, and Terrestrial), Human Toxicity (divided into Cancer and Non-Cancer effects), Ionising

Table 3
Inventory primary data.

			OPWFE	OPWTwPP	OPWThPP
Input					
Materials/fuels	Transports	tkm	5.52E-02	4.95E-02	5.24E-02
	Electricity	kWh	6.33E-02	8.20E-02	9.32E-02
	OPWF	Ton	1.51E-03	1.26E-03	1.34E-03
	OPWE	Ton	1.81E-03	-	-
	TwPP	Ton	-	8.39E-04	-
	THPP	Ton	-	-	6.96E-04
	Manure	Ton	2.13E-03	2.46E-03	2.80E-03
Power plant	Digester	p	9.88E-09	8.29E-09	8.77E-09
	CHP	p	9.88E-09	8.29E-09	8.77E-09
	Lubricant oil	kg	2.60E-01	2.60E-01	2.60E-01
	Post Digester	P	9.88E-09	8.29E-09	8.77E-09
Output					
Product	Electricity	kWh	1.00E+00	1.00E+00	1.00E+00
	Heat	MJ	5.16E+00	5.16E+00	5.16E+00
Emissions	Carbon dioxide	kg	1.47E-02	1.39E-02	1.55E-02
	Methane	kg	0.010938	0.011453	0.013628
	Ammonia	kg	1.32E-04	1.59E-04	1.95E-04
	Heat	MJ	1.06E-01	1.00E-01	1.12E-01
Emission from combustion	Carbon dioxide	kg	6.54E-01	6.54E-01	6.54E-01
	Carbon monoxide	kg	3.76E-04	3.76E-04	3.76E-04
	Dinitrogen monoxide	kg	1.96E-05	1.96E-05	1.96E-05
	Methane	kg	1.80E-04	1.80E-04	1.80E-04
	Nitrogen oxides	kg	1.17E-04	1.17E-04	1.17E-04
	NMVOC	kg	1.57E-05	1.57E-05	1.57E-05
	Platinum	kg	5.48E-11	5.48E-11	5.48E-11
	Sulfur dioxide	kg	1.96E-04	1.96E-04	1.96E-04
	Lubricant oil	kg	2.60E-01	2.60E-01	2.60E-01

Radiation, Land use, Ozone Depletion, Photochemical Ozone Formation, Resource Use (distinguished into Fossils, Minerals and Metals), and Water use.

To manage data complexity while maintaining the robustness of the assessment, cut-off criteria were formally established. Specifically, all inventory data flows contributing less than 1% to the total environmental impact were excluded from the final assessment. This standard procedure is a streamlined LCA and primarily applies to minor inputs, such as electricity consumption for supervisory plant control systems (e.g., control computers and low-power monitoring equipment). This approach focuses analytical efforts on the major environmental contributors, in line with ISO 14044 guidelines.

The primary methodological limitation of this study lies in the upscaling procedure. This process inherently assumed a direct and linear proportionality between the production yields obtained in the small-scale laboratory trials and those projected for the full-scale industrial plant. To address these potential limitations, we performed a comprehensive sensitivity analysis covering both economic and environmental dimensions.Recognising that industrial processes could exhibit decreased operational efficiency compared to controlled laboratory settings - due to factors like heat loss, non-optimal mixing, or maintenance downtime - the assumption of linear scaling introduces a key uncertainty. To account for this potential deviation and to test the robustness of the results against technological uncertainty, a comprehensive sensitivity analysis was performed with a variation of the key performance metric, biogas production, by applying both ±10% and ±20% reduction scenarios to the full-scale model. The environmental impacts derived from these scenarios were then normalised against a common reference point, represented by the lowest impact obtained by normalizing the impacts of the different scenarios. This normalisation procedure allows for a direct and explicit comparison, thereby effectively highlighting the magnitude of variation between the modelled scenarios and demonstrating the stability of the conclusions under different operational assumptions.

2.4.4. Conventional LCC methodology and implementation

The conventional LCC analysis is carried out in accordance with the standards ISO 15686-5:2017 [59] and the calculation of fixed capital investments, resulting in deferred cash flows over the asset's lifespan [60]. Additionally, the analysis facilitates the identification of investments in working capital that cover the operating advances required for various production stages, including field cultivation, raw materials processing/transformation, and the eventual ageing or storage of finished products. Assessing the financial sustainability of companies - particularly those in the agri-food industry - is of paramount importance [61].

Once the specific cash flows for each investment are identified, calculated over the investment's entire life cycle, and valued at market prices, the next step is to discount these flows. To complete the analysis, indicators of economic-financial analysis – specifically Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (DPP), and Break-Even Point (BEP) - were used in addition to the LCC methodology.

The NPV (Eq. (1), widely used to evaluate agricultural investments [62,63] is defined as the difference between the total benefits and the total discounted costs, and it represents the maximum amount of willingness to invest without compromising the financial stability. Investment is considered viable when its NPV is positive. The discount rate plays a crucial role in determining NPV: higher rates lead to lower NPVs. When the rate reaches the threshold r_0, the NPV becomes zero; beyond this point, it turns negative. In simple investment scenarios, increasing the discount rate tends to affect the present value of initial benefits (b_0) more significantly than that of initial costs (c_0).

This index is calculated according to Equation (1).

$$\mathrm{NPV} = \sum_{j=0}^{n} \frac{bj - cj}{(1+r)^j} \tag{1}$$

Where:

$\sum_{j=0}^{n}$. indicates that all benefits (*bj)* and costs (*cj)* that may occur from the year $b_j = \sum_{j=0}^{n} \frac{b_j}{(1+r)^j}$

$$c_j = \sum_{j=0}^{n} \frac{c_j}{(1+r)^j}$$

j=0 to year *n* in which the investment ends its production period are discounted

r = discount rate.

The IRR (%) method (Eq. (2)) expresses the value generated by an investment as a percentage return, allowing direct comparison with alternative investment opportunities. Widely recognised in investment analysis, IRR measures the profitability of a project based on debt-free cash flows. It is defined as the discount rate at which the after-tax NPV equals zero.

$$\mathrm{IRR}: \sum_{j=0}^{n} \frac{bj - cj}{(1+r_0)^j} = 0 \tag{2}$$

The DPP (years) (Eq. (3)) is a key indicator commonly used to compare agricultural and agro-industrial investment scenarios [64]. It measures the time required for positive cash flows to offset the initial outlays, with the results expressed in years. Scenarios with lower DPP values are considered more efficient, as they recover the investment more quickly.

$$\mathrm{DPP} = y + \frac{Vcc}{Vca} \tag{3}$$

Where:

y = period before the period in which the cumulative cash flow becomes positive.

Vcc = discounted value of the cash flow of the period in which the cumulative cash flow is ≥ 0.

Vca = absolute value of the cumulative discounted cash flow in period y.

The BEP (kg) (Eq. (4)) constitutes the threshold at which the revenues from a production activity equal its costs. It indicates the minimum quantity - expressed in volume - that must be produced and sold to cover all associated production expenses. Profit is generated only when this quantity is exceeded.

$$BEP = \frac{CF}{PVu - CVu} \quad (4)$$

Where:

CF=Fixed Costs.

PVu = Selling price of a unit of product.

CVu = Variable cost of a unit of product.

To test the robustness of the results and explore the influence of key assumptions in this economic analysis, a sensitivity analysis was performed on the system under study. A selected set of parameters was systematically varied to evaluate their influence on the outcomes. Specifically, the cost of production, the energy price, and the discount rate were adjusted within a ±10% range to observe how changes in these variables affect the results.

Scaling up the experimental results to the corporate level necessitated the adoption of the technical and economic variables subsequently detailed. These data were procured through targeted surveys conducted via interviews with key stakeholders in the southern Italian regions of Calabria and Sicily. According to the findings of the Italian 7th General Agricultural Census [65], Calabria and Sicily collectively represent over 80% of Italy's citrus fruit production, spanning an approximate area of 90,000 ha. The compiled information, in conjunction with the consultation of selected extant agricultural statistics banks (ISMEA, ISTAT), has enabled the formulation of the following methodological assumptions.

- in terms of economic parameters, the annual input costs were computed based on the actual quantity utilised by the farm and prevailing market prices (2025). Operating costs related to labour and mechanical operations were calculated in accordance with the current hourly wage of the workers as stipulated by the national collective agreement;
- the cost of OPW and olive pomace was assumed to be zero, while the cost of manure was assumed to be EUR 2 per tonne. Interest on advance capital and capital goods was evaluated by applying rates of 4.5% and 2%, respectively;
- administrative overheads were estimated to range between 2% and 4% of the gross production value, which is defined as the total annual revenues.

The determination of the discount rate was based on the opportunity cost approach, considering alternative investments exhibiting comparable market conditions and timelines [66] A discount rate of 2% and 5% was consequently assumed for the agricultural and mining phases, respectively. Furthermore, constant prices were adopted across the entire life cycle, explicitly excluding adjustments for inflation [67].

Regarding the industrial-scale scaling-up conducted to compute the full LCC, calculations were performed under the following assumptions.

- Initial investment cost for acquiring:

OPWFE: 3,724,089.97 €; OPWTwPP: 3,672,675.00 €; OPWThPP: 3,570,47.00 €

- Annual methane production:

OPWFE: 963,836.50 m^3; OPWTwPP: 1,085,588.84 m^3; OPWThPP: 1,149,226.87 m^3

- Electricity Energy annual production:

OPWFE: 6,746,856 kWh; OPWTwPP: 7,599,12284 kWh; OPWThPP: 8,044,588 kWh

- Saleable electricity tariff: 0.233 € kWh^{-1}
- Self-consumption of energy: 11%
- Years of plant life: 15 years
- Daily cost of employed workers: 70 € d^{-1}

These parameters were derived from data collected from secondary literature sources [[15,33,55]]. The price of electricity, set at €0.23 per kWh, reflects the current tariff recorded in Italy for energy production from renewable sources, including those utilising agri-food by-products.

This established price is the result of a historical process in which strong public incentives have been granted to encourage the energy transition and the diffusion of AD. In Italy, for example, an "all-inclusive tariff" (electricity sales price + subsidy) of 0.280 € kWh-1 was applied to cogeneration plants commissioned before December 31st 2012 with an electrical capacity of less than 1 MW. The initial incentive was focused on electricity fed into the grid, without considering the use of by-products for heat supply. Subsequently, the incentive was reduced by placing greater emphasis on heat recovery and on the use of by-products. In fact, under the Ministerial Decree of 04/07/2019, installations eligible for incentives were further divided by type, renewable energy source, and category of intervention, thus outlining the current tariff structure [68].

3. Results

3.1. Environmental results

The results compare the three different scenarios: OPWFE (using fresh and ensiled OPW), OPWTwPP (using two-phase olive pomace to replace ensiled OPW), and OPWThPP (using three-phase olive pomace to replace ensiled OPW).

Generally, the analysis reveals that the scenarios incorporating olive pomace (OPWThPP and OPWTwPP) exhibit a higher environmental impact per unit of electricity produced compared to the baseline scenario OPWFE across many of the 27 assessed categories (Table 4). This trend is particularly evident in the highly relevant category of Climate Change (kg CO_2 eq), where OPWFE registers the lowest total impact (3.16E-01), while OPWThPP shows the highest (3.71E-01). This difference is directly linked to the inventory data, which indicates significantly higher Methane (CH_4) emissions in OPWTwPP (0.011453 kg/kWh) and OPWThPP (0.013628 kg/kWh) compared to OPWFE (0.010938 kg/kWh), due to the higher methane production in scenarios that use olive pomace, resulting in higher fugitive emissions and higher emissions from the digestate.

Similar patterns of lower impact for OPWFE are observed in categories related to water and soil pollution. For instance, Acidification (mol H+ eq) is lowest for OPWFE (5.07E-04), and the various forms of Eutrophication, such as terrestrial eutrophication (mol N eq), follow suit, registering 2.03E-03 for OPWFE and 2.76E-03 for OPWThPP. These impacts often correlate with Ammonia (NH_3) emissions, which are minimised in the OPWFE scenario (1552 kg). While OPWFE generally performs better, exceptions exist. Notably, the OPWFE scenario registers the highest impact in Land Use (2.04E-01 Pt), with OPWThPP showing the lowest impact in this category (1.93E-01 Pt). Furthermore, regarding Resource use, fossils (MJ), OPWFE achieves the minimum impact (2.23E-01 MJ), but OPWTwPP exhibits the maximum impact (2.39E-

Table 4
LCA results of the environmental impact analysis (best scenario in green, worst in red, intermediate in yellow).

Impact category	Unit	OPWFE	OPWThPP	OPWTwPP
Acidification	mol H+eq	5,07E-04	6,88E-04	6,40E-04
Climate change	kg CO_2eq	3,16E-01	3,71E-01	3,51E-01
Climate change - Biogenic	kg CO_2eq	2,97E-01	3,50E-01	3,30E-01
Climate change - Fossil	kg CO_2eq	1,90E-02	2,07E-02	2,11E-02
Climate change - Land use and LU change	kg CO_2eq	7,23E-06	8,01E-06	8,11E-06
Ecotoxicity, freshwater - part 1	CTUe	7,91E-02	9,02E-02	8,94E-02
Ecotoxicity, freshwater - part 2	CTUe	2,52E-02	3,08E-02	2,94E-02
Ecotoxicity, freshwater - inorganics	CTUe	6,98E-02	8,41E-02	8,25E-02
Ecotoxicity, freshwater - organics - p.1	CTUe	3,00E-02	3,05E-02	3,14E-02
Ecotoxicity, freshwater - organics - p.2	CTUe	4,50E-03	6,39E-03	4,92E-03
Particulate matter	disease inc.	4,33E-09	5,61E-09	5,28E-09
Eutrophication, marine	kg Neq	3,20E-05	3,88E-05	3,76E-05
Eutrophication, freshwater	kg Peq	3,43E-06	4,32E-06	4,28E-06
Eutrophication, terrestrial	mol Neq	2,03E-03	2,76E-03	2,55E-03
Human toxicity, cancer	CTUh	1,29E-10	1,31E-10	1,35E-10
Human toxicity, cancer - inorganics	CTUh	1,62E-12	1,72E-12	1,75E-12
Human toxicity, cancer - organics	CTUh	1,27E-10	1,29E-10	1,33E-10
Human toxicity, non-cancer	CTUh	7,00E-10	8,06E-10	7,73E-10
Human toxicity, non-cancer - inorganics	CTUh	1,56E-10	1,66E-10	1,69E-10
Human toxicity, non-cancer - organics	CTUh	5,45E-10	6,40E-10	6,04E-10
Ionising radiation	kBq U-235eq	4,43E-04	5,09E-04	5,14E-04
Land use	Pt	2,04E-01	1,93E-01	1,96E-01
Ozone depletion	kg CFC11eq	2,43E-10	2,30E-10	2,41E-10
Photochemical ozone formation	kg NMVOC eq	2,08E-04	2,39E-04	2,33E-04
Resource use, fossils	MJ	2,23E-01	2,33E-01	2,39E-01
Resource use, minerals and metals	kg Sbeq	6,43E-08	6,43E-08	6,57E-08
Water use	m^3 depriv.	1,26E-03	1,35E-03	1,37E-03

01 MJ). The system boundaries specified that OPW was assigned zero impact due to its waste status. At the same time, olive pomace required an economic allocation, which likely influences the burden distribution in the pomace scenarios.

The contribution analysis (visible in the supplementary materials Fig. S1), shows the distribution of the overall environmental burden among the material components within each evaluated scenario. The OPWFE scenario exhibits a relatively uniform distribution of impact between its two primary constituents: the “OPW Fresh” scenario, which accounts for 51.78%, and the “OPW Ensiled” scenario, contributing 48.22% of the total burden.

Conversely, scenarios incorporating olive pomace demonstrate a clear dominance of the pomace component in driving the environmental load. Specifically, the pomace accounts for 64.63% of the total contribution in the OPWThPP and 61.68% in the OPWTwPP scenario. This finding underscores that the specific management and intrinsic characteristics of the olive pomace become the overriding determinant of the environmental impacts once it is introduced into the co-digestion process.

A detailed examination of the contribution of each feed mix component to the environmental impact reveals distinct patterns, as illustrated in Fig. 1.

The components analysed - Emissions, Transport, Electricity, Plant, and Matrix production - demonstrate varying degrees of influence across the impact categories. For Acidification, direct emissions stand out as the primary contributing factor, with electricity being the secondary driver following behind. Conversely, Transport, Plant, and Matrix production register a negligible contribution.

In terms of Climate Change, emissions are once more the dominant factor; however, this is primarily attributable to biogenic CO_2 (originating from biomass), marking a critical distinction from fossil-based sources. Electricity and transport, nonetheless, contribute notably to the fossil-based fraction of the Climate Change impact, while the influence of Plant and Matrix production remains marginal.

Freshwater ecotoxicity shifts the focus to electricity, which exhibits the highest impact, followed by transport. Emissions exert a moderate effect, and both Plant and Matrix production once again play a minor role. Relatively to Human Toxicity (Cancer and Non-Cancer related), emissions are almost negligible in these categories. Transport and electricity show elevated values, though they remain lower compared to their influence in the other categories. Plant and Matrix production continue to exert a minimal influence.

In summary, this analysis provides a clear delineation of impact drivers: emissions constitute the key drivers of acidification and climate change, whereas electricity and transport are more critical for Ecotoxicity and Human Health. Consequently, any strategy aimed at reducing the overall environmental footprint of the process should prioritise improvements in energy efficiency and the optimisation of logistical operations. Furthermore, exploring and implementing technologies that effectively mitigate direct emissions is essential to achieving a meaningful reduction in environmental burden.

3.2. Economics results

The economic inventory, structured by cost breakdown for the two biogas production scenarios under investigation, is presented in Table 5, where the percentage incidence of each cost item is also delineated. A comparative analysis of these financial data reveals that the scenario incorporating OPW ensiling is associated with a greater overall cost, which is fundamentally driven by the necessary expenditure allocated to the ensiling process. This higher cost is compounded by the 35% loss of total solids observed during ensiling, which consequently necessitates the storage of a larger initial product mass to attain the required substrate quantity.

A more detailed examination of the individual cost components yields specific quantitative insights. The investment costs range from 0.042 €kWh^{-1} in the OPWFE scenario to 0.034 €kWh^{-1} in the OPWThPP scenario. During the constant production phase, the OPWTwPP and OPWThPP scenarios exhibit comparable costs, recorded at 0.110 €kWh^{-1} and 0.111 €kWh^{-1}, respectively. In contrast, the OPWFE scenario emerges at the most economical option with a cost of 0.104 €kWh^{-1}. The latter scenario exhibits the lowest percentage incidence on

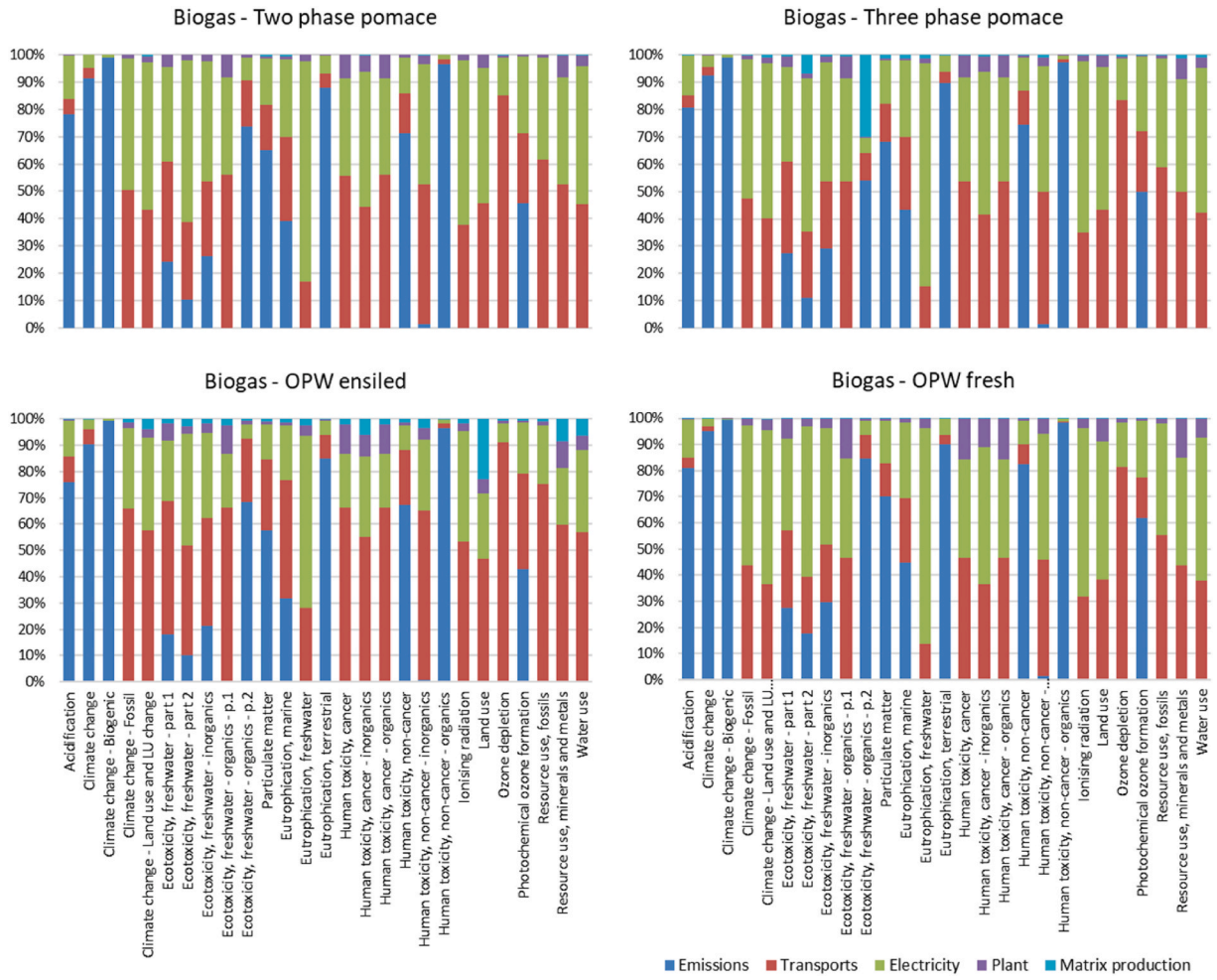

Fig. 1. Contribution analysis for each single matrix considered.

Table 5
LCC results of the analysed scenarios.

Cost Items	Unit	OPWFE -Orange Peel Waste fresh and ensiled		OPWTwPP - Orange Peel Waste fresh and two-phase pomace		OPWThPP - Orange Peel Waste fresh and three-phase pomace	
LCC analysis (15 years)							
Investments	€ kWh^{-1}	0.036	86%	0.032	87%	0.030	90%
Storage		0.006	14%	0.005	13%	0.003	10%
Total start-up phase		0.042		0.037		0.034	
Cost Items (constant production phase)							
Materials and Services	€ kWh^{-1}	0.025	24%	0.040	37%	0.040	36%
Work		0.017	17%	0.016	14%	0.015	13%
Quotas and other allocations		0.061	59%	0.054	49%	0.056	51%
Total production phase		0.104		0.110		0.111	
End of life stage		0.004		0.004		0.003	
Financial analysis indicators							
DGM	€ kWh^{-1} *(15 years)*	0.135		0.126		0.126	
DPP	years	5.6		5.1		4.7	
BEP	kWh	1.92E+06		2.05E+06		1.74E+06	
NPV	€ *(15 years)*	4,117,264.84		4,788,507.91		5,334,111.79	
IRR	%	19%		21%		23%	

the total cost attributed to materials and services, approximately 24%. Concurrently, it demonstrates the highest incidence of quotas and other allocations, at 59%, due to higher depreciation stemming from the significant capital investment, especially for OPW ensiling. The final phase of the project shows highly similar values across the three considered scenarios, ranging narrowly from 0.003 € to 0.004 € kWh^{-1}.

The financial analysis yielded favourable outcomes, with the sale of electricity net of revenues demonstrating significant profitability across all three scenarios.

Regarding DGM, the best performing scenario is OPWFE with 0.135 € kWh, due to the lower cost of materials and services. For this indicator, the other two scenarios have the same value, equal to 0.126 € kWh. In the other two NPV scenarios, it emerges that over a period of 15 years, the best-performing scenario is OPWThPP, with a value of 5.34 million €, followed by OPWTwPP with 4.78 million € and OPWFE with 4.11 million €. The IRR follows the same ranking as the NPV across scenarios, with values ranging from 23% to 19%. The DPP also shows OPWThPP as the most advantageous scenario, with 4.68 years, followed by OPWTwPP with 5.11 years, and OPWFE. The scenario that reaches BEP with the fewest kWh is OPWThPP, followed by OPWFE, and finally OPWTwPP.

3.3. Sensitivity analysis

The main methodological limitation identified in the study is the scaling-up operation, which assumes that industrial production is directly proportional to laboratory results. The sensitivity analysis was conducted to test the robustness of the results against potential

inefficiencies at full scale, by varying the biogas production by ±10% and ±20%.

Fig. 2, presenting the sensitivity analysis results, clearly demonstrates that the normalised impact (per 1 kWh of electricity) varies linearly with changes in biogas production. Since the functional unit is fixed, this linear relationship confirms that the environmental results are susceptible to the actual efficiency achieved at the industrial level. Any reduction in the expected biogas output (e.g., −20%) would lead to a substantial, proportional increase in the environmental impact associated with generating 1 kWh of electricity across all three scenarios, highlighting the critical importance of maintaining high operational efficiency. It is important to note that the two scenarios involving pomace olives only reach the impact levels of the scenario based entirely on OPW (dashed red line), with yield increases of 20%.

Also, for economic results, a sensitivity analysis was carried out for the three scenarios in the study, simulating variations in total operating costs (including raw materials, labour, quotas, and other allocations), the energy selling price, and the total initial investment cost for the plant's construction. Regarding the latter, variations consider a lower cost—potentially due to public funding—or a higher cost resulting from increased market prices. The analysis of the deviation from the baseline scenario was conducted at ±10%, ±20%, and ±30%, with a specific focus on the NPV and IRR.

As illustrated in Fig. 3, which depicts the percentage deviation between the baseline scenario and simulations of overall cost variations, all scenarios exhibit a negative slope, confirming that an increase in operating costs leads to a significant reduction in both NPV and IRR. Conversely, cost reduction enhances performance; however, the analysis reveals an asymmetric response: the negative impact of a cost increase is more pronounced than the benefit derived from an equivalent reduction.

Specifically, a multiplicative effect is observed: for a variation of ±10% in costs, the NPV fluctuates by approximately ±15–16%, signaling high elasticity (coefficient >1). This implies that the system possesses a limited capacity to absorb cost shocks without amplifying the economic impact. The OPWTwPP scenario demonstrates the greatest sensitivity, where a +30% increase in costs results in a −52.70% reduction in NPV and a −35.16% contraction in IRR.

Regarding the energy selling price variable, it emerges as the primary driver of profitability, exerting an even more substantial impact than operating costs. NPV variations exceed ±100% in response to a ±30% price fluctuation, indicating extreme sensitivity to market conditions and incentives. Data analysis highlights critical thresholds where the project loses economic sustainability; indeed, with a −30% price reduction, the OPWFE and OPWTwPP scenarios become negative, with values of -€239,374.79 and -€265,884.53, respectively. In contrast, the OPWThPP scenario is the only one that maintains a positive NPV (€139,488.74) even under highly unfavorable market conditions (−30%), confirming superior structural robustness. Concerning the IRR, it proves to be extremely volatile, with collapses exceeding −80% for the OPWTwPP scenario in the event of price decreases, rendering capital returns entirely dependent on tariff stability.

The third variable considered, namely plant installation costs, shows a less amplified impact compared to current operational variables. Nevertheless, even in this instance, a slightly higher sensitivity is observed in the OPWFE scenario (with an NPV variation of −33.51% for a 30% cost increase), while OPWThPP appears the most stable in the long term, despite requiring the highest initial investment (€5,334,111.79 in the baseline).

4. Discussion

Given the current paucity of scholarly literature that has investigated the economic and environmental sustainability of biogas production specifically from ensiled OPW, the results obtained from this study will be compared with those reported in other works that have analysed energy production from biogas utilising matrices of a comparable nature.

The analysis of environmental results highlights significant findings regarding the environmental assessment of OPW and OP valorisation, particularly in relation to the chosen methodologies.

In this study, the primary finding is that using olive pomace (OPWTwPP and OPWThPP) results in a higher environmental impact per functional unit of 1 kWh of electricity produced, compared to the baseline scenario using only fresh and ensiled OPW (OPWFE). This is specifically linked to the inventory data, which indicates significantly higher Methane emissions in the pomace scenarios. The pomace component itself is confirmed to be the overriding driver of the environmental load in its respective scenarios, contributing between 61.68% and 64.63% of the total burden. The pomace scenarios would only reach the impact levels of the OPWFE scenario if their industrial biogas yields increased by 20%, which is highly improbable (usually scale-up induces a reduction of at least 20% compared to smaller-scale laboratory experiments).

However, this result, suggesting lower performance for olive pomace, contrasts with findings from other LCA studies that analyse optimised conversion pathways for both residues. Ugolini et al. [69], by

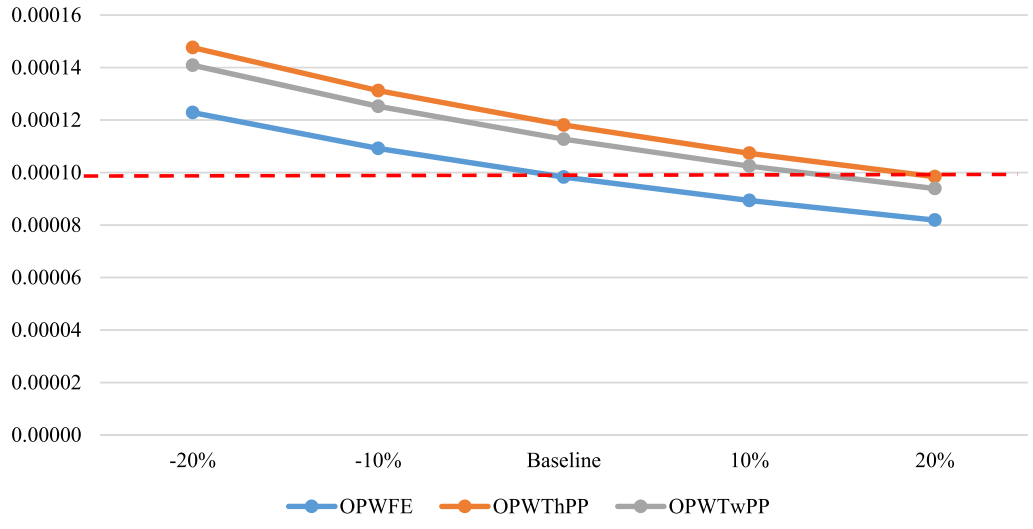

Fig. 2. Sensitivity analysis concerning environmental performance.

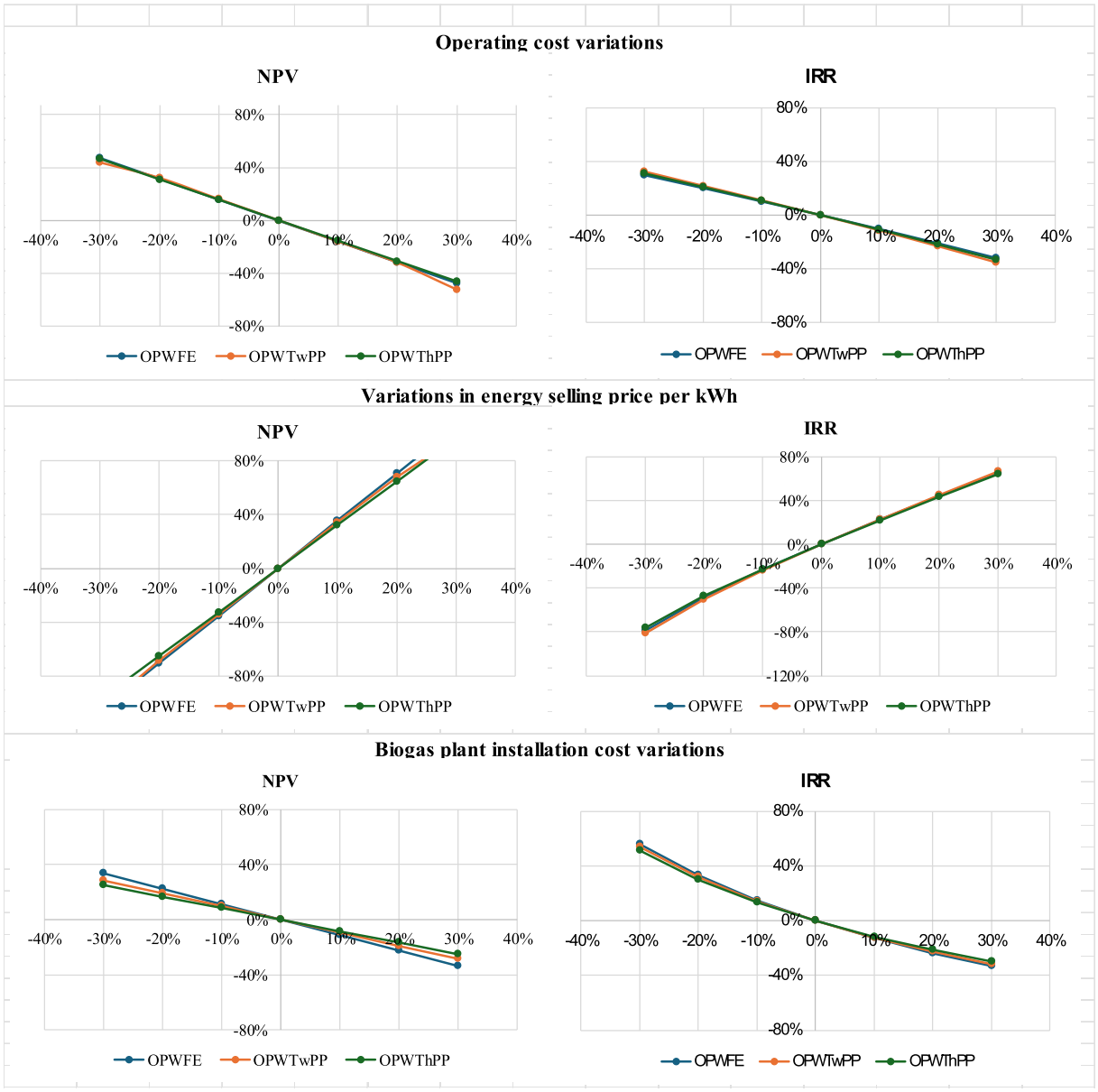

Fig. 3. Sensitivity analysis for economic performance, NPV and IRR *vs* cost variation.

assessing an integrated system of Hydrothermal Carbonisation (HTC) followed by AD, have found that both olive pomace (OP) and orange peel (ORP) achieved extremely beneficial (negative) Climate Change impacts per ton of residue: −1290 kg CO_2 eq t^{-1} for OP and −1301 kg CO_2 eq t^{-1} for ORP. These substantial benefits primarily arise from the effective combination of producing solid bioenergy carriers (pellets) from the solid fraction and biogas from the liquid fraction, along with high credits from avoided emissions through heat recovery [69]. Similarly, another study comparing AD of olive mill solid waste versus Olive Pomace Oil Extraction (OPOE) found that AD was the superior environmental alternative, achieving a global environmental impact reduction of 88.1% compared to OPOE using natural gas [70]. This suggests that while olive pomace may introduce specific process challenges, leading to higher fugitive CH_4 losses in the present study, its inherent potential for environmental savings through bioenergy generation is very high when managed effectively [70,71].

For OPW, existing research provides varied optimised pathways. While some findings support AD for OPW, reducing the Carbon Footprint by around 40% compared to landfilling and coal use [15], other analyses suggest that a complex biorefinery route (producing limonene and citric acid) might not be the most environmentally optimal path. Instead, the most environmentally performant option identified in one study was to stop the process after limonene extraction and use the remaining dried residue as animal feed, achieving negative impacts [24].

The interpretation of these contrasting results depends heavily on the methodological choices adopted in the LCA studies.

The definition of the Functional Unit (FU) varies significantly across the reviewed studies. In the present work, “1 kWh” was selected as the FU, reflecting the primary function of an electricity production plant. This contrasts with the FU of 1 metric ton of residue used by Ugolini et al. [69] and Alonso-Fariñas et al. [70] to compare input waste management, or the 1L of Orange Juice used by Ortiz et al. [15].

A comparison of the results with the national energy mix and Italian biogas-based electricity generation as recorded in ecoinvent shows that electricity from biogas performs noticeably better than the Italian electricity mix (Fig. 4). The national mix has the highest environmental impact, mainly because it still relies heavily on fossil fuels, which drive

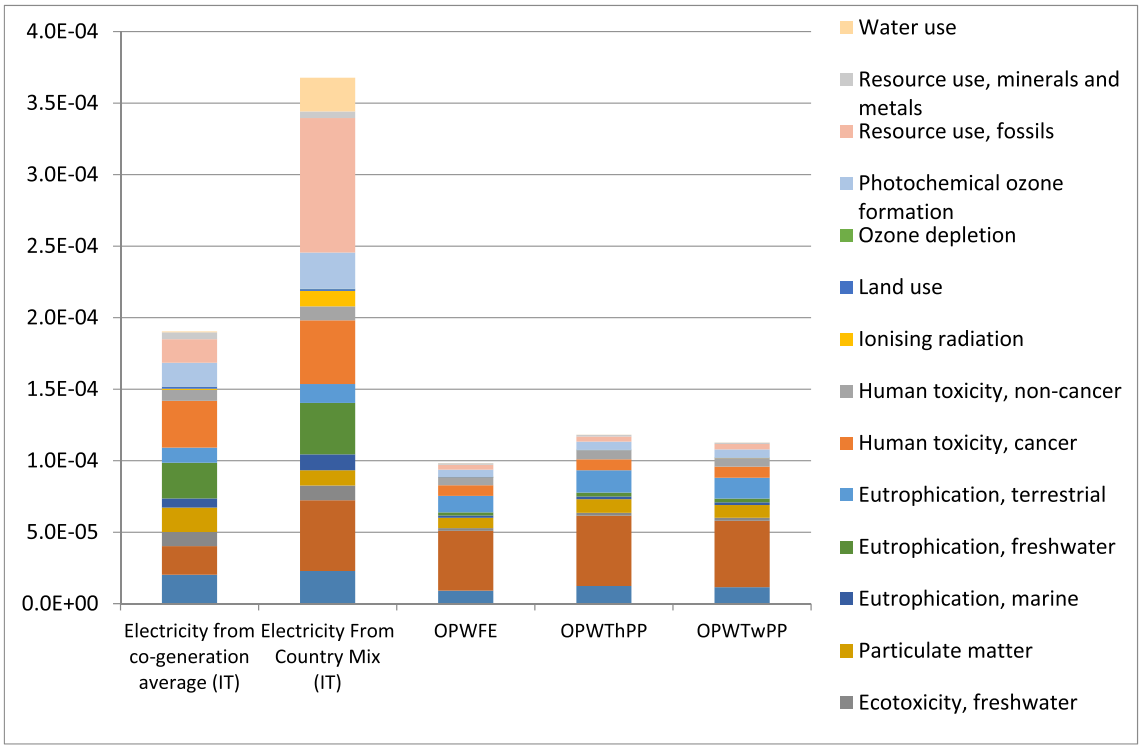

Fig. 4. Benchmarking of scenarios against the national energy mix and the average electricity production from biogas in Italy.

up emissions, resource use, and health-related impacts. Even the average Italian electricity from co-generation does better, but it still carries a relatively high environmental burden.

The biogas options, on the other hand, are less impactful overall. Among them, OPWFE is the best-performing scenario, while the others are slightly higher but still much better than the conventional systems. The biggest advantage of biogas is the strong reduction in climate change impact and fossil resource use.

Biogas is not impact-free. Some effects, like human toxicity and air pollution-related impacts, are still present, mainly due to how the feedstock is handled and how the plant operates, however, it is a good source of energy and an excellent solution for managing agricultural by-products and waste.

A critical methodological difference lies in the treatment of co-products and waste allocation. This work designated OPW as waste, assigning it zero environmental impact for its ensiling and production phases, and defined the system boundaries as "from the digester gate to biogas production'". However, due to the increasing market value of EVOO, olive pomace (OP) was considered a co-product, requiring economic allocation within the EVOO extraction process. Conversely, several external studies addressing multifunctionality (e.g., Refs. [69,70]) have avoided traditional allocation by using system expansion. Through system expansion, these processes received credits for avoiding the need to produce conventional products, such as electricity from fossil fuels, heat, or synthetic fertilisers [70]. The presence of these substantial credits from avoided impacts largely explains why studies employing system expansion often report beneficial (negative) environmental impacts [69].

Finally, the reliability of the data and the challenge of scaling up are crucial methodological considerations. We utilised foreground data derived from direct measurements during lab-scale experiments, which were subsequently scaled up to industrial plant size. The study acknowledged that the scaling-up operation was a limitation, as industrial production might not be directly proportional to lab results. The accompanying sensitivity analysis confirmed that the normalised impact per 1 kWh of electricity varied linearly with changes in biogas production, underscoring that the environmental outcomes are sensitive to the operational efficiency achieved at the industrial level.

The economic performance of the analysed scenarios varies according to the type of plant designed and the matrices used, as demonstrated by Moreira et al. [72].

The operating costs of installing the plant and storing raw materials, ranging from 0.034 to 0.042, are in line with those reported by Sgroi et al. [73], which ranged from 0.065 (<100 kWh) to 0.030 (<999 kWh) for biogas production using giant reed.

In terms of cost items, quotas and other allocations have the highest incidence (49-59%), due to depreciation quotas linked to investment, as also found in the study by Benalia et al. [55] on the AD of olive mill waste.

The cost of raw materials accounted for 37% of the total, as the majority of the matrices were provided free of charge. This incidence is lower than in scenarios where matrices are grown specifically for energy use [74], as in the study by Lovarelli et al. [33], which used corn silage for AD, accounting for 44% of annual operating costs.

The NPV results obtained in this study are consistent with those reported by Bentivoglio et al. [75], who estimated an NPV of €4 million over a decade of biogas production derived solely from vegetable waste. Notably, the DPP was approximately two years.

Lovarelli et al. [33] evaluated biogas production over a 20-year horizon, reporting an NPV of €294,000 for a facility powered by pig slurry and corn silage and a DPP of 13.5 years, and €1,389,000 for a second facility utilising animal slurry with a shorter DPP of 6.5 years.

Similarly, Bacenetti et al. [34] assessed NPV over 20 years under three scenarios differing in proximity to the biomass source, yielding NPVs of €8.1, €8.2, and €7.1 million.

The IRR obtained in this study exceeds the discount rate, corroborating the findings of Lovarelli et al. [33] and Benalia et al. [55]. This outcome highlights the investment's strong profitability potential, albeit with a considerable level of associated risk.

5. Conclusions

5.1. Environmental and economic sustainability

The recovery utilisation of agro-industrial by-products through AD represents a financially sound and ecologically responsible strategy. The ensiling of OPW effectively addresses issues related to seasonal availability, ensuring a stable feedstock supply for AD plants.

From an environmental perspective, the scenario OPWFE, emerges as the most sustainable solution, recording the lowest environmental impact across the majority of the 27 assessed categories.

This superiority is evident in crucial categories like Climate Change, where OPWFE registers the lowest impact due to significantly reduced Methane emissions. A better performance is also noted for Acidification and Eutrophication. The only relevant exception is Land Use, where OPWFE registers the highest impact. However, it should be noted that the differences in overall environmental impact between the scenarios are not overwhelmingly severe.

Consequently, all scenarios (OPWFE, OPWTwPP, and OPWThPP) can represent a viable alternative in the renewable energy production strategy. The analysis clarifies that direct emissions are the main driver for Acidification and Climate Change, while electricity and transport dominate Ecotoxicity and Human Toxicity, guiding future strategies toward energy efficiency and emission mitigation.

From an economic perspective LCC analysis confirms the financial viability of OPW-based AD systems, with an NPV exceeding €4 million over a 15-year period and an IRR ranging between 19% and 23%. The DPP remains below six years, positioning this investment as highly attractive compared to other agricultural biomass-to-energy solutions. Its scalability further supports replication across the Mediterranean basin, where agri-residues and supporting infrastructure are readily available.

The case studies examined suggest a shift toward a closed-loop business model, wherein waste is transformed into value via renewable energy sources and natural processes [76]. This approach enables the direct management of by-products that would otherwise require costly landfill disposal - ranging from €100 to €300 per ton for food industry residues [77], such as OPW. Beyond economic gains, the valorisation process yields significant non-market benefits [78], including reduced environmental impacts, enhanced ecosystem services, and improved biodiversity – elements increasingly imperilled by the accelerating effects of climate change [79,80] Furthermore, establishing a reliable and well-structured management strategy for these by-products is crucial to support sustainable production practices.

The results obtained carry significant implications for both entrepreneurs and policy-makers. For entrepreneurs, the findings illustrate the potential of by-product management as a viable and profitable investment opportunity. However, realising this potential requires the aggregation of by-products from multiple companies to achieve economies of scale and reduce fixed costs. In this contest, conducting a comprehensive inventory of by-products availability across different regions is essential, beginning with an assessment of the factors that may influence stakeholder participation along the supply chain [81].

High initial investment costs remain a substantial barrier, particularly for small and medium-sized enterprises with limited access to credit, despite their prominent role in the agri-food sector. From a policy perspective, the study underscores the importance of designing targeted financial support mechanisms to facilitate the transition to circular economy models, as also emphasised by Donner et al. [82]. Integrating energy production with agro-industrial or farming operations can enhance firms' economic resilience, mitigating the impact of market fluctuations on income and ultimately strengthening their competitive position and profitability.

These results lead to the consideration of significant implications for the implications for the implementation of the EU Green Deal and the Circular Economy Action Plan [83], particularly through targeted incentives for bioenergy derived from agro-industrial wastes. These insights can inform policy development aimed at fostering resource-efficient strategies that integrate renewable energy production, waste reduction, and rural growth – advancing progress toward Sustainable Development Goals 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action).

One of the limitations of the study was that downstream management and agricultural application of digestate were excluded from the modelling, and no substitution credits for synthetic fertilisers were assigned. This boundary was chosen due to the high variability in digestate composition and nutrient availability, which are strongly influenced by local agronomic practices, storage conditions, and treatment methods. Its use in fertiliser production represents a valuable economic opportunity, particularly in light of the persistent and growing demand for agricultural inputs. This potential becomes even more critical during periods of macroeconomic instability, which can disrupt the supply of key materials such as fertilisers, rendering them temporarily inaccessible. Such disruptions are increasingly relevant in today's global context, marked by climate variability, geopolitical crises, market volatility, extreme weather events, and shifting socio-economic conditions – all of which pose tangible risks to the agricultural and agri-food sectors [84]. In this context, the growing complexity of agricultural and agri-food challenges and global issues necessitates the adoption of a holistic and general vision on the path toward sustainability [85].

Future research will focus on a comprehensive LCA to evaluate the sustainability of digestate-based fertilisation as a strategic substitute for external synthetic inputs. Given the current high geopolitical volatility, it is imperative to shift toward models that valorise process outputs as primary inputs for subsequent production cycles. Within this circular economy framework, upcoming studies will also incorporate a quantitative assessment of by-product availability (such as OPW) and related logistics in Mediterranean processing regions. This integrated approach will be essential to inform the optimal sizing and siting of AD facilities, ensuring that the internalisation of nutrient loops effectively enhances the resilience and self-sufficiency of agro-industrial supply chains.

Disclosure use of AI-assisted technologies

During the preparation of this work, the author(s) used AI-assisted technology, Gemini, in order to check the grammar and spell in some sentences. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Emanuele Spada: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Paolo S. Calabrò:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing. **Anna Irene De Luca:** Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – review & editing. **Giovanni Gulisano:** Funding acquisition, Project administration, Supervision. **Nathalie Iofrida:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **Francesco Mauriello:** Funding acquisition, Project administration, Supervision, Validation. **Giacomo Falcone:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing.

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Declaration of competing interest

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

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2026.109515.

Data availability

Data will be made available on request.

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