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Economic assessment for vegetable waste valorization through the biogas-biomethane chain in Italy with a circular economy approach

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The current geo-political framework and the environmental concern about pollution and global warming are leading Europe to rethink its energy production, moving forward to the incentivization the renewable energy market. In this scenario, the use of waste from the agri-food sector shows a huge potentiality to enhance the transition in line with the circular economy principles. Biogas production represents an environmental friendly strategy to successfully recover large amounts of waste and by-products to produce renewable energy. Furthermore, in light of the rising need of green biofuels, biogas can be converted into biomethane, allowing the implementation of a full circular model. The objective of this paper is to perform an economic assessment to evaluate whether the upgrading of an existing biogas plant, in which the diet includes also vegetable waste from a plant producing frozen vegetables, could be profitable considering different scenarios, to reach a sustainable circular model. The analysis will be conducted through the Discounted Cash Flow method, considering four main indexes: NPV, DPBT, IRR, and PI. The results highlight the unprofitability of the biogas-biomethane chain if the upgrading system is performed maintaining the same characteristics of the starting plant. On the other hand, if changes in the digester's diet occur, the investment becomes immediately profitable in the considered time-span. The circular economy model is not completely accomplished, as profitability can only be reached if silage maize is partially kept as feedstock. Moreover, the conversion of the plant is not economically feasible if an adequate subsidy is not provided. The economic assessment of the upgrading system for biogas to biomethane is an essential element to be provided to the agribusiness entrepreneurs, as they need all the relevant economic aspects to decide to invest and adopt this solution to establish an innovative circular business model in agriculture.

KEYWORDS

circular economy, vegetable waste, biogas upgrading, biomethane, sustainability, economic analysis, renewable energy, Italy

1. Introduction

The global concern about climate change, fossil fuel depletion, and the increasing prices of energy have resulted in an augmented pressure on national economies, leading policy makers to focalize on alternative innovative ways to produce energy, such as renewable fuels (Barbera et al., 2019; Khan et al., 2021; Naquash et al., 2022). Despite the increased interest in producing green energy, Europe is still not able to declare independence from energy imports of oil, gas, and solid fossil fuels. This situation, combined with the instable political framework, should lead to a reconsideration of the energy system as a whole. In the past, commercially available biofuels were produced from energy crops, creating a controversial condition where most of the feedstock were also important globally traded food commodities (Finco, 2012; Bentivoglio et al., 2014). To try to overcome this problematic, an alternative sustainable energetic feedstock could be represented by biomass residues and waste products from agriculture, agro-industries generated waste, forest by-products, and municipal solid waste (Ambaye et al., 2021). In addition, it is necessary to follow eco-friendly and carbon-neutral approaches in order to encourage the transition from the traditional linear model to the circular one, to overcome the current energy crisis and support the sustainable market position of renewable energies (Abokersh et al., 2021; Cusenza et al., 2021; González-Arias et al., 2022; Jain et al., 2022), in line with the Sustainable Development Goals and the European Green Deal. According to the Ellen MacArthur Foundation (2013), "circular economy represents an economic system based on closed loops, in which raw materials and products keep their quality and value for the longest time as possible, and systems are fueled by renewable energy sources".

In this scenario, the agri-food sector has a huge potential in the context of a circular economy, from the efficient management of resources, valorization and reuse of by-products and wastes, as well as the production of bioenergy and bioproducts through the adoption of sustainable production models (Teixeira, 2018; Chiaraluce et al., 2021). There is a general consensus on the fact that reducing food waste has great potential to enhance food security, strengthen the sustainability of the systems and reduce the economic costs (Vilariño et al., 2017). According to the circular approach and the waste hierarchy, waste management should not only focus on waste prevention, but since some types of processing waste are inevitable, they should be recovered and valorized for alternative solutions like nutrients extraction, animal feeding, or renewable energy production, thus reducing the dependence from fossil fuels (Volpe et al., 2016; Valenti et al., 2017a). However, the implementation of a circular model is feasible only if it brings economic, environmental, and social benefits (reducing pressure on the environment, improving the security of the supply of raw materials, boosting economic growth, and creating jobs), pointing out the need for an economic return on investment to provide a suitable motivation to companies (Ghisellini et al., 2016; Chiaraluce, 2021).

When it comes to circular approaches in agri-food, biogas production represents an environmental- friendly strategy to successfully recover large amounts of waste and by-products to produce renewable energy, as it ensures both pollution control and energy recovery (Valenti et al., 2017b; Fagerström et al., 2018; Barros et al., 2020; Mistretta et al., 2022). According to GSE (*Gestore dei Servizi Energetici*), in 2021 there were 2,200 biogas plants producing electricity in Italy, and 80% of them used biomass from the agricultural sector. The anaerobic digestion (AD) consists in a process where the organic matter breaks down naturally in absence of oxygen through biochemical reactions performed by specific bacteria (Mezzadri et al., 2010). The main product of the AD process is biogas, an extremely useful source of renewable energy; an important secondary product is the digestate, a highly valuable biofertilizer that can be used to offset the financial as well as the environmental costs associated with the use of mineral fertilizer (Sagagi et al., 2009). Farms have the potential to implement a regenerative management system through the exploitation of by-products and waste and to produce biogas from biomasses of different origin, mainly slurry and manure from livestock farming, but also olive pomace, slaughter residues, food wastes from the transformation industry (Zarbà et al., 2021). Among the different supply chains, fruit and vegetables accounted for approximately 14% of the total value of the European agricultural production, representing a fundamental sector for many Member States (Rossi, 2019). On the other hand, vegetable wastes are produced in considerable amounts in agricultural activities and transformation processes (Pavi et al., 2017); it is estimated that around 20–22% of fruit and vegetable is loss from post-harvest to distribution (FAO, 2019). The seasonality and geographical localization of vegetable waste set the focus on how to manage them in a sustainable way from a technical, economic and environmental point of view. The valorization of vegetable waste deriving from the transformation process through AD allows to daily manage high quantities of these matrices, guaranteeing the safety of the food chain by moving them away from the factories continuously, even during the moments of mass production. Moreover, anaerobic digestion plants have the logistics, facilities and expertise for storing vegetable waste to be used as feedstock, according to the current best management techniques (Garuti et al., 2021).

Nevertheless, in light of the need of sustainable green biofuels, biogas can be converted into biomethane through a process of purification (consisting of dehydration, desulphurization, removal of ammonia gas, and others) and upgrading (removal of carbon dioxide; Ryckebosch et al., 2011). According to the European Biogas Association, in 2021 Europe had 1,023 biomethane production plants. France, Italy and Denmark are the countries with the highest growth rate of new plants. While Italy counts 27 biomethane plants on its territory, the upgrading of biogas is just started to spread, thanks to the Biomethane Decree of 2018, which boosted the sector. Biomethane is currently considered promising for applications in the transport sector or to be injected in the gas grid, also because Italy is the European leader in terms of natural gas vehicles, representing three quarters of the European fleet (Eyl-Mazzega and Mathieu, 2019). Even if its production generally brings environmental benefits, because the biogas-biomethane chain is considered carbon negative, the conversion process is not always perceived as beneficial, due to the upgrading process costs and energy demand (Molino et al., 2013). However, the biogas-biomethane chain permits the recovery of some resources, such as manure, agricultural waste and agro-industry waste, and OFMSW (Organic Fraction of Municipal Solid Waste), which can be converted into energy (D'Adamo et al., 2019), allowing the implementation of a full circular model (Yazan et al., 2018).

Several studies about the production of biomethane from waste are already available in literature. Browne and Murphy (2013) assessed the production of biomethane from different food waste, showing that food waste has the potential to provide almost 3% of renewable energy for transport. Valenti et al. (2018) exploited the potentiality of the co-digestion of mixtures of by-products and agricultural residues through biomethane potential tests, demonstrating that all the studied feedstock-mixtures could be potentially used for renewable energy generation. Zhu et al. (2019) analyzed the European policy regarding biogas production and utilization to increase biogas/biomethane production. They highlight that a clear strategic vision is required, with multiple policy supports that are constantly being reviewed and revised, evolving to reflect market and regulatory circumstances. Similarly, Murano et al. (2021) analyzed the European and Italian regulations for producing biomethane, underlining the critical issues and opportunities. They also considered three case studies to study the incentive scheme, showing that biomethane is considered a promising opportunity for biogas producers. Throughout a SWOT and PEST analysis, Piechota and Igliński (2021) investigated the biogas-biomethane chain in Poland, identifying in high investment costs, long lead times and a strong energy lobby as the main barriers, and the environmental aspect as the most important advantage. Pappalardo et al. (2022) estimated the potential production of biomethane in Southern Italy, using the Land Use Efficiency index, calculating the environmental sustainability of the biomethane potential of the study area. The authors estimated the number of biomethane plants that could be built, without detracting from the agricultural land area traditionally used to produce food and feed. Furthermore, to overcome uncertainty in the biomethane production and facilitate its implementation to encourage the circular model, it is important to consider the economic profitability of such system. Cucchiella et al. (2015) applied the net present value and discounted payback time for the evaluation of profitability of biomethane plants, in function of the feedstocks used (energy crop, livestock slurries, OFMSW), the plant dimensions and the firm configuration. They found out that profitability is reached only if certain conditions are satisfied, in particular when using by-products in the feedstock. The authors firmly stated that the adoption of incentives is determining to make an investment profitable. The key-role of subsidies is highlighted also in another study by Cucchiella et al. (2019b), performing an economic analysis regarding both biogas and biomethane plants that use several typologies of animal residues. The profitability is reached for 300 kW biomethane plants fed with sheep/goats, by-products and poultry as substrates. Ferella et al. (2019) aimed to determine whether the upgrading of an existing biogas plant could be profitable and in which specific conditions. The considered substrates were maize silage, by-products and OFMSW. According to the results, the upgrading to biomethane never accomplishes profitability, while the profitability can be reached installing new biomethane plants with a capacity of 250 m^3/h using the OFMSW as substrate. Baena-Moreno et al. (2020) evaluated the profitability of the whole biogas-biomethane chain for three different biomethane capacities (50, 100, and 150 m^3/h) in South Spain, using strawberry extrudate as feedstock. The authors found out that the investment in the three scenarios is not economically feasible, and they confirmed the necessity of incentives in order to promote and boost the production of renewable and sustainable energy. Hoo et al. (2020) investigated the role of policy instrument to facilitate upgrading of biogas (produced palm oil mill effluent, food waste, chicken manures and cattle manures) to biomethane in Malaysia, finding that biomethane injection into the grid is economically unsustainable without policy and institutional support. To conclude, Gupta et al. (2022) compared the economic feasibility of four different upgrading technologies to produce biomethane from food waste and cow slurry in the UK. The profitability of a plant is strongly dependent on the upgrading technologies, and adequate carbon taxes should be established to guarantee an economic viability of the biomethane production. Since most of the studies consider OFMSW, by-products and animal slurries as feedstock, as far as the authors know, there are no papers dealing with the economic profitability of the biogas-biomethane chain implemented with vegetable processing waste. To fill this gap, the objective of this paper is to evaluate whether the upgrading of an existing biogas plant, in which the diet includes also vegetable waste from a frozen vegetable plant, could be profitable considering different scenarios. The analysis, conducted through the Discounted Cash Flow (DCF) method, will emphasize if the production of biomethane represents an opportunity for agribusiness entrepreneurs, with the overall aim of reaching a sustainable circular model. The production of green energy from waste and the utilization of the digestate as fertilizer will close the loop of the frozen vegetable processing chain. The reminder of the paper is organized as follows: "Section 2" introduces the policy framework; "Section 3" presents the case study and the economic analysis; "Section 4" shows and discusses the main results. Finally, "Section 5" proposes some remarks and conclusions.

2. Policy framework: From biogas to biomethane

In Italy, the biogas sector expanded significantly in the last decade due to generous government incentives (Benato and Macor, 2019). By contrast, biomethane production has a limited diffusion, substantially derived from the lack of effective subsidies (Banzato et al., 2018). The history of biomethane started in 2011, with the Legislative Decree (LD) 3 March 2011, no. 28, which is considered the reference standard introducing the definition and the urge to incentive its use in transportation. The regime of subsiding was introduced with Ministerial Decree (MD) 5 December 2013. The decree required to use waste and by-products for, at least, 50% of the final weight of the feedstock, and the incentive perceived by the producer was dependent on the final use and guaranteed for 20 years. However, this policy was unsuccessful, and the real start of the sector was reached with the MD 2 March 2018. In line with the provisions of the EU Directives on the promotion of energy from renewable sources, the DM endorses the use of biomethane in the transport sector. The new incentive system was based on the release of CIC (*Certificato di Immissione al Consumo* - Certificate of Emission of Biofuel in Consumption), and the objective of the incentive is to ensure a fair remuneration for the investment and operating costs. There are no limitations concerning the plant size, and the value of subsidies is equal to 375 € for a CIC. One CIC is assigned for 10 Gcal (single counting), and the unitary incentive is equal to 0.305 €/m^3. A premium is recognized for some substrates (as by-products and waste), entitling the producer to receive one CIC per 5 Gcal (double counting). Consequently, the value of the incentive in this case will be equal to 0.61 €/m^3. Furthermore, entrepreneurs who produce biomethane to be used as fuel are entitled to receive of a number of CIC increased by 20%. The incentive system is valid for all new plants that will come into operation by 31 December 2022, for a maximum volume of 1.1 billion Sm^3 biomethane per year. After 10 years, the value of the CIC will change according to market demands. Finally, on 18 December 2018, the new Renewable Energy Directive (RED II) came into force, which obliged the European Member States to request binding proof of sustainability for the generation of electricity and heat from solid and gaseous biomass fuels such as biogas and biomethane, by July 2021 at the latest. In 2021, Italy has issued the LD 8 November 2021 no. 199 which not only implemented the RED II, but also promote a series of interventions to realize the NRRP (National Recovery and Resilience Plan) and encourage the production of renewable energies, like biogas and biomethane. The legislative decree introduces new rules on incentives for the production of biomethane, through the recognition of an equal tariff for both transport and other uses, some clarifications related to feed used in biogas plants that partially convert the production into biomethane, and simplified authorisation procedures referring in particular to infrastructures.

3. Materials and methods

3.1. Case study description

The biogas plant chosen as case study belongs to a frozen vegetable industry located in Central Italy. It is a consortium agricultural company, consisting of 500 farmers operating in Marche, Umbria, Abruzzo and Emilia Romagna, and the total cultivated area is about 6,700 hectares. The cultivation of the raw materials (almost 42,000 t/year) is carried out both under organic (for a 10–15% of the total) and integrated schemes. The company's average production is 35,000 t/year of frozen products, mainly peas, leafy products (spinach, chard, chicory), borlotti beans, French beans, tomatoes and cherry tomatoes, vegetable soup ingredients (celery, Savoy cabbage, leek, pumpkin) and herbs (parsley and basil). The company produces about 6,700 t/year of vegetable wastes (representing 16% of the initial raw material). Table 1 shows the frozen vegetable mass balance for the year 2021.

The main features of the biogas plant are illustrated in Table 2. The electric capacity is of 1 MWe, working for almost 360 days per year. The main substrate is represented by the maize silage, produced by the members of the cooperative, and the diet is generally composed as follows:

- 70% maize silage
- 10% chicken manure
- 20% by-products from the frozen processing (the presence and actual quantity depend on the processing seasons).

For the maximum efficiency of the digestion, the feed should be arranged so as to provide the maximum yield in biogas in the shortest period of time. Energy crops, such as maize silage, present the best productive potentialities, and their presence is essential to guarantee a standardized activity of the plant (Adani and D'Imporzano, 2008; Rath et al., 2013). Since the amount of by-products is scarce, maize silage is implemented as the main component of the digester feed, to standardize the operability of the plant. From the anaerobic digestion, 15,600 t/year of digestate is obtained as secondary product.

3.2. Economic analysis

To understand whether the upgrading of an existing biogas plant could be cost-effective, a profitability analysis, based on the

TABLE 1 Frozen vegetable supply chain mass balance (data from 2021).

	Cultivated surfaces (ha)	Raw material (t/year)	Frozen product (t/year)	Waste (t/year)	Waste (%)
Peas	4,719.80	17,679.76	14,625.99	3,053.77	17
Leafy vegetable	635.10	10,693.23	8,839.41	1,853.82	17
Beans	154.00	654.33	736.25	−81.92*	−13
French beans	439.06	2,853.88	2,498.83	355.05	12
Soup ingredients	157.75	3,725.18	2,789.74	935.44	25
Tomatoes and cherry tomatoes	523.99	4,790.62	4,450.82	339.80	7
Herbs	93.20	1,468.77	1,307.83	160.94	11
TOTAL	6,722.90	41,865.77	35,248.85	6,698.83	

*The borlotti beans' production yield is around 110-115%: for this reason, the waste amount is a negative value.

TABLE 2 Biogas plant characteristics (data from 2021).

Plant capacity (MWe)	1.00
Working time (hours/year)	8,640.00
Biogas (m^3/year)	4,090,975.00
Digester feed (t/year)	20,917.00
Maize silage	15,000.00
Vegetable by-products	3,417.00
Chicken manure	2,500.00
Incentive (€/kWh)	0.280
Digestate (t/year)	15,600.00

DCF method, was performed. The chosen capacity of the final biomethane plant is 250 m^3/h. The definition of the plant size was chosen as a function of the actual biogas plant size. It was not hypothesized an increase of the capacity. The needed data were obtained both experimentally and throughout literature review. The chosen indicators are Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Time (DPBT), and Profitability Index (PI). NPV is the discounted sum of all cash flows, positive and negative, in a certain time horizon; a project is profitable when NPV is positive. DPBT is the time required to recover the invested capital. IRR is the discount rate that makes the net NPV equal to zero. PI represents the ratio between the NPV and the initial investment; a higher PI means that a project will be considered more attractive. Equations (1–4) describe the parameters used to calculate each indicator.

$$NPV = \sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t} \tag{1}$$

$$\sum_{t=0}^{DPBT} \frac{I_t - O_t}{(1+r_d)^t} = 0 \tag{2}$$

$$\sum_{t=0}^{n} \frac{I_t - O_t}{(1+IRR)^t} = 0 \tag{3}$$

$$PI = \frac{\sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t}}{C_{inv}} \tag{4}$$

I_t = cash inflows
O_t = cash outflows
r_d = discount rate parameter
n = lifetime of the project (set in 10 years)
t = time
C_{inv} = total initial investment

For the purpose of the study, the following costs were considered:

- Cost of investment (upgrading system, compression, distribution)
- Operative costs (OPEX) for the biogas-biomethane chain
- Diet cost.

3.3. List of assumptions

This work evaluates the profitability of a biomethane upgrading system based on four different scenarios. Starting from the business-as-usual scenario, Case 1, Case 2, and Case 3 were hypothesized to improve the circularity of the system. The four situations are detailed below:

- Business-as-usual scenario: the upgrading is performed on the current biogas plant, without any changes in the basic features.
- Case 1: only 30% of maize silage is used for the digester's diet, to reduce the amount of dedicated energy crop.
- Case 2: only by-products and waste are used for the digester's diet to eliminate the dependance upon the maize silage.
- Case 3: an investment in a distribution point for the biomethane for transportation is included, but 30% of maize silage is kept in the feedstock.

The investment's cost for the biomethane production depends upon the upgrading technology implemented. Starting from the actual biogas plant, we chose pressure swing adsorption technology (PSA) among the different upgrading systems. The advantages of this technology consist in the simplicity of construction, compact and small size, and the possibility of use in small plants (up to 250 Nm^3 of unrefined gas treated per hour; Mezzadri et al., 2010). In Case 3, the distribution plant initial investment was also included, and considered equal to 600.00,00 € (European Commission, 2018).

The OPEX include costs for service, labor, maintenance, energy (if required), and other costs (Stürmer et al., 2016). As the analysis is performed on an existing plant, we do not consider any changes regarding the operative costs of the biogas production, and they remain valid throughout the useful lifetime of the project.

The diet cost is dependent on the maize silage price; for the analysis, in Business-as-usual scenario, Case 1, and Case 3, the purchase cost was 50 €/t. The costs have been increased 2% every year, considering the average fluctuations of the market prices as evidenced from the OECD and FAO forecasts (OECD/FAO, 2021). It was considered a null value for vegetable by-products and chicken manure in all the four hypotheses, but in Case 2 a transportation cost to collect the required waste was considered, and estimated equal to 5.50 €/t.

The profit deriving from the biomethane was calculated based on the incentives provided by the Italian Government. Following the last available decree (MD 2018), to the producer are due the so-called CIC, dispensed by the GSE. As the MD 2018 guarantees the incentive for 10 years, this time span was used in the economic analysis. For the purpose of the study, the value of the CIC will be considered in cubic meters. For the business-as-usual scenario, the CIC is equal to 0.305 €/m^3, as the diet remained chiefly composed of maize silage. In case 1, the CIC is considered with the double counting (0.610 €/m^3) for 70% of the produced biomethane, and with the single counting (0.305 €/m^3) for the resting 30%. In case 2, the CIC is equal to 0.610 €/m^3, as only by-products are used in the digester. Finally, for case 3, the CIC is increased by 20% and equal to 0.366 €/m^3, as the plant produces and distributes biomethane for transportation. In this last case, also the distribution and selling of biomethane is included in the final income of the plant, and the price of biomethane is assumed equal to 0.390 €/m^3 (Consorzio Monviso Agroenergia, 2018). In all the four considered scenario, it was estimated to sell part of the produced digestate as fertilizer.

Table 3 summarizes the main features of each hypothesis.

4. Results and discussion

The profitability of the investment in the upgrading system from biogas to biomethane was assessed in four different scenarios. Table 4 presents the results related to the four indicators (NPV, DPBT, IRR, PI). The analysis indicates that the profitability of the biomethane plants is verified only under certain scenarios.

In the business-as-usual scenario, we took into consideration the investment in the PSA technology without any changes to the basic features of the biogas plant. In this setting, the NPV is negative (-6,748 k€), as well as the PI (-4.67) and the DPBT is >10 years. IRR cannot be calculated in this scenario. These values demonstrate that, at these conditions, the considered timeframe is not sufficient to recover the initial investment and dampen all the costs. The profit made with the produced biomethane and the selling of the digestate is not sufficient to cover the investment, the OPEX and the increasing costs of the feedstock. The current incentive is not adequate to sustain the conversion of a small biogas plant produced especially from energy crops (70%). In fact, with the current policy framework,

TABLE 3 Main characteristics of each hypothetic scenario.

		Business-as-usual scenario	Case 1	Case 2	Case 3
Investment	€	1,445,500.00	1,445,500.00	1,445,500.00	2,045,500.00
Diet cost	€/year	750,000.00	225,0000.00	115,043.50*	225,000.00
CIC	€/Sm^3	0.305	0.305 (30%) 0.610 (70%)	0.610	0.366

*Unitary cost of transportation equal to 5.5 €/t.

TABLE 4 Profitability analysis for the 4 hypothetic cases.

		Business-as-usual scenario	Case 1	Case 2	Case 3
NPV	€	−6,748,603.68	1,509,074.37	4,082,428.71	4,487,217.14
DPBT	Year	>10	3	2	2.5
IRR	%	–	23	48	40
PI		−4.67	1.04	2.82	2.19

European Union aims to limit the share of biofuels originating from food crop-based feedstock, promoting the use of waste and by-products in light of the circular economy approach. This limitation is motivated by concerns about the risk of the so-called indirect land use changes, due to an expanding market of biofuel crops which may lead to displacement from food crop production and the cultivation of new arable land (Börjesson et al., 2015).

To overcome the problematics emerged in the business-as-usual scenario, Case 1 was hypothesized. In this situation, the company decides to rebalance the digester diet by reducing to only 30% the amount of maize silage used. The remaining 70% is composed of by-products and waste. In this second setting, the NPV is positive (1,509 k€), as well as the PI (1.04), and the DPBT is of almost 3 years. The investment becomes profitable starting immediately from year one, as the incentive provided by the GSE is doubled for 70% of the produced biomethane, following the principle of the double counting. Following this approach, the biogas-biomethane chain becomes more sustainable, and the system resembles more to a circular one. However, it is not enough to simply reduce the quantity of maize silage to full the circular principles, as its production still exploit natural resources like land and water, detracting agricultural land to produce food.

To make the process as circular as possible, we hypothesized in Case 2 to remove maize silage from the digester's diet, and use only by-products from the vegetable processing plant and agricultural wastes to produce biogas. The costs for the feedstock are related to the gathering and transportation from the nearby (max. 50 km) companies. Thus, the NPV is positive (4,082 k€), as PI (2.82), and the DPBT is approximately 2 years. The profitability of the plant is connected not only to the absence of cost for the energy crop, but also to the double counting CIC, equal to 0.610 €/m^3, for using 100% of waste substrates, as provided by the MD 2018. The situation improved compared to the previous two scenarios, both for the economic and circular balance, since there are no more constrains related to the use of the energy crop. Nevertheless, if removing the component which standardizes and guarantees a continuous production of biogas, so of biomethane, it is fundamental to rebalance the diet, ensuring a consistent supply of by-products to make the plant working in full regime. In this sense, relationships among agri-business entrepreneurs and the creation of companies' net should be encouraged, favoring the industrial symbiosis where the waste of one becomes the resource of another. In this hypothesis, the cost of the diet is null, in a kind of mutualism/favor where the biomethane producer does not pay the feedstock of the digester, and the "supplier" has no costs related to waste management. It is not unrealistic to consider that, in the future, if this system proved to be profitable, it would also be possible to envisage a remuneration for purchasing the agricultural waste, by paying at an agreed rate or by supplying digestate to farms. It is worth to remember that, with the Legislative Decree 21 March 2022 n. 21, the Italian Government has officially recognized digestate as equivalent to chemical fertilizers. This action contributes to promote circular economy principles, spread ecological practices, and reduce the usage of chemical inputs in agriculture, while increasing the supply of organic matter in soils and limiting the production costs. Furthermore, the Legislative Decree 17/2022 improved the already existing list of agro-industrial by-products employable for the anaerobic digestion, such as coffee silverskins and brewer's grains. The implementation of the usable feed list is a significant step further into making the food industry most circular, allowing to produce more renewable energy and higher quantities of digestate, valorizing a wide spectrum of agri-food by-products, and favoring the industrial symbiosis.

In order to work in perspective of the European objectives outlined in the Green Deal, to reduce net emissions by at least 55% by 2030 and to become the first climate-neutral continent by 2050, the new LD 2021 aims to support the production of advanced biomethane to be used for transport. For this purpose, Case 3 presents an additional investment for the realization of a distribution point for biomethane as transportation fuel. NPV is positive (4.487 k€), PI is positive (2.19), and the DPBT is of 2.5 years, since the CIC is increased of 20% and, in the calculation of the revenue, a sales price to the distributor of 0.39 €/m^3 (1.2 €/kg) was taken into account. Nonetheless, we decided to keep 30% of maize silage into the diet. The whole situation is economically positive, and the payback time reasonable; so, in these terms, it is convenient to invest in the upgrading system of an already existing plant. Following this investment scheme, it is possible to comply with the EU's renewable energy programs, and with the circular economy principles. As for Case 1, circularity is not fully reached as we are still exploiting the energy crop. This minimum amount is maintained to guarantee a standardized and continuous supply of the biofuel to the pump.

In summary, Figure 1 represents the evolution over time of NPV for the four hypothetic scenarios. From the graph, it is evident the inconvenience in investing in the business-as-usual scenario. On the other hand, Case 3 represents the most profitable situation; in fact, even if the initial investment is higher compared to Case 1 and 2 (due to the realization of the distribution point), the production and sale of biomethane as vehicles fuel is able to cover the costs and make viable the plant for the considered period.

Notwithstanding, it is important to make some considerations:

- The decree implementing the RED II for the new incentive schemes has not yet entered into force, so at this time there is no certainty about the duration of the incentive or its amount. However, on the basis of the LD 2021, it will be of the same magnitude for the use of biomethane

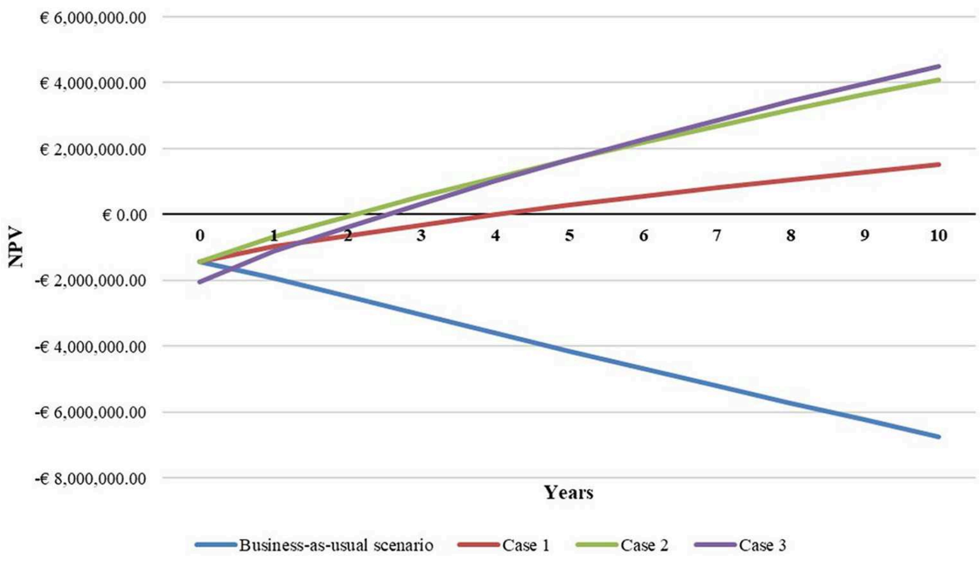

FIGURE 1
NPV values in the 10 years of investment for the four scenarios.

both as vehicles fuel and for other uses. The production of biomethane is strongly dependent upon incentives, that should be calibrated to ensure a fair remuneration to the producers. Baldino et al. (2018) estimated that policy incentives equivalent to 1.50 €/m^3 would be necessary to support a significant amount of renewable methane production using sustainable feedstock.

- The incentive will definitely be linked to the matrices used in the digester, so an optimal balance of the diet is needed to ensure high performances with minimal environmental impact. It is fundamental also to consider the availability of the matrices. Vegetable waste are produced in massive quantities during the specific campaign of each product, and they are not available in the same amount throughout the year. A correct and continuous functioning of the plant requires a standardized diet, both in quality and quantity. To overcome this limit, a winning strategy could be the adoption of cooperative structures, in which more than one producer commits its vegetable by-products to a common plant (like the one taken under consideration in this study) to produce energy. As vegetable waste could not be enough to satisfy the necessities of the digester, the use of other kind of food industry by-products, as well as animal slurries and OFMSW (Cucchiella et al., 2019a), could integrate the diet guarantying a continuous activity of the system. Until now, waste recycling was insufficiently considered in energy system models. To overcome this criticality and encourage the transition to a cleaner renewable energy, collaborative models should be developed to join the energetic system and the production of material, for a more cohesive and interdisciplinary sustainable development (Kullmann et al., 2021).
- The rebalancing of the diet will also be crucial to fully achieve the circular model, which to date is only partially implemented due to the use of energy crops. In this regard, it will be important to define a circular business model to assess the longevity of the project in the long term, and use the produced waste as new production inputs instead of being disposed of in the landfill (Yazan et al., 2018). Nonetheless, the use of waste as input could allow economy of scale. Although circular economy is still at the early stages of development, it provides a reliable framework to radically improve the current business models toward preventive and regenerative eco-industrial development, run by renewable energy directly produced by the waste of the supply chain (Ghisellini et al., 2016).
- With a perspective of sustainable development, and following the dictates of the LD 2021, it will be important to set targets in terms of reduction of GHG (up to 65%, according to the decree). In this regard, biomethane, produced with suitable advanced matrices, can contribute to these results. In addition, the LD 2021 provides that, by 2030, a share of 8% of biomethane will be present in fuel stations.

5. Conclusions

Our study investigates the profitability of upgrading an existing biogas plant to biomethane. The four scenarios highlighted that, if the upgrading is performed maintaining the basic characteristics of the biogas system, the investment is not profitable. This is linked to the high costs of the maize silage, that, from one side, guarantees a continuous activity and production of energy, but, on the other side, does not allow the implementation of a full circular model. Considering this as a starting point, the other three cases propose alternative solutions to cope with the high costs of the investment while give a nod to increase the sustainability and circularity of the production. In all the three hypotheses, the investment is fully recovered and profitable in the considered time span. It is worth to remember that all these arguments are based on the diet costs and not on the incentives, assumed as provided by the current Italian laws. The circular economy model is not completely accomplished as economic feasibility can only be reached in some scenarios with particular conditions. However, as the existing literature suggests, the authors consider it appropriate to rethink the subsidies system, as it is essential to encourage the production of biomethane from waste in order to properly apply the fundamental circular principles, such as the reuse of materials and nutrients, limit the production of waste, produce renewable energy and advanced biofuels.

In general terms, the results show that the cost of running is strongly dependent on the type of upgrading system implemented, which determines the initial investment, and typology of agricultural substrate used in the digester. Moreover, the conversion of the plant is not economically feasible if an adequate subsidy is not provided, as the costs of production are not competitive with the price of natural gas yet. One limitation of the present work is the amount of vegetable waste: the hypotheses were made on the basis that the required amount of vegetable waste is always available. As we know that the quantities of vegetable by-products are limited throughout the year, according to the harvesting and processing period of each crop, the author suggests to implement a cooperative system to collect the agri-food wastes from different companies and farms. In this way, the integration of vegetable waste with animal residues, agricultural scraps and other food processing waste could represent a constant supply of raw material for the digester. Moreover, as many authors suggest, the collection and addition of OFMSW could represent a winning strategy to get rid of a consistent amount of waste while implementing the circular principles to produce renewable energy. Another limitation could be related to the geographical localization of the considered biogas plant. Even if the study is limited on a specific area of Central Italy, findings can be useful to encourage the installation of biogas-biomethane chain plants to favor the ecological transition in Italy, as the produced waste used as feedstock are common for all the vegetable processing plant. In this sense, it would be beneficial to implement the national policy strategy on renewable energy, thus helping to overcome the current energy crisis. Finally, the last limitation is related to the absence of technical specifications regarding the changes in biogas, thus biomethane, according to the different proposed diets. After assessing the profitability of such investment, it could be interesting in the future to test and verify how actually the performance of the plant is affected by the various feedstocks, together with experts in the field. The economic assessment of the upgrading system for biogas to biomethane is an essential element to be provided to the agribusiness entrepreneurs. As they are waiting for the Italian law converting the energy LD, that will establish the incentives and the parameters that will regulate the market, they need all the relevant economic aspects to decide to invest and adopt this solution to establish an innovative circular business model in agriculture. Thanks to the energy production from agri-food waste, the agricultural sector could overcome the current critical situation, limiting the costs, while greening their productive systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GC and DB made the conception and the analysis and interpretation of data. GC drafted the manuscript, tables, and figure. AF revised the work critically and made a contribution in the interpretation of the results. GC, DB, and AF contributed in the acquisition of data and the design of the work. All authors have accepted the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abokersh, M. H., Norouzi, M., Boer, D., Cabeza, L. F., Casa, G., Prieto, C., et al. (2021). A framework for sustainable evaluation of thermal energy storage in circular economy. *Renewable Ener.* 175, 686–701. doi: 10.1016/j.renene.2021.04.136

Adani, F., and D'Imporzano, G. (2008). *I Fattori Che Rendono Ottimale la Razione Per il Digestore*. Available online at: https://air.unimi.it/bitstream/2434/131906/1/razioni-digestore.pdf (accessed June 30, 2022).

Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., van Hullebusch, E. D., Rtimi, S., et al. (2021). Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives. *J. Environ. Manage.* 290, 112627. doi: 10.1016/j.jenvman.2021.112627

Baena-Moreno, F. M., Malico, I., Rodríguez-Galán, M., Serrano, A., Fermoso, F. G., Navarrete, B., et al. (2020). The importance of governmental incentives for small biomethane plants in South Spain. *Energy* 206, 118158. doi: 10.1016/j.energy.2020.118158

Baldino, C., Pavlenko, N., Searle, S., and Christensen, A. (2018). *The potential for low-carbon renewable methane in heating, power, and transport in the european union.working paper 2017–26. International Council on Clean Transportation* (ICCT). Available online at: https://theicct.org/sites/default/files/publications/Renewable_Gas_EU-28_20181016.pdf (accessed June 21, 2022).

Banzato, D., Canesi, R., and D'Alpaos, C. (2018). Biogas and biomethane technologies: an AHP model to support the policy maker in incentive design in Italy. *Green Energy Technol.* 22, 319–31. doi: 10.1007/978-3-319-75774-2_22

Barbera, E., Menegon, S., Banzato, D., D'Alpaos, C., and Bertucco, A. (2019). From biogas to biomethane: a process simulation-based techno-economic comparison of different upgrading technologies in the Italian context. *Renewable Energy* 135, 663–673. doi: 10.1016/j.renene.2018.12.052

Barros, M. V., Salvador, R., Francisco, D. E., and Piekarski, A. C. (2020). Mapping of research lines on circular economy practices in agriculture: from waste to energy. *Renewable Sust. Energ. Rev.* 131, 109958. doi: 10.1016/j.rser.2020.109958

Benato, A., and Macor, A. (2019). Italian biogas plants: trend, subsidies, cost, biogas composition and engine emissions. *Energies* 12, 979. doi: 10.3390/en12060979

Bentivoglio, D., Finco, A., Bacchi, M. R. P., and Spedicato, G. (2014). European biodiesel market and rapeseed oil: what impact on agricultural food prices. *Int. J. Global Energ. Issues* 37, 220–235. doi: 10.1504/IJGEI.2014.067667

Börjesson, P., Prade, T., Lantz, M., and Björnsson, L. (2015). Energy crop-based biogas as vehicle fuel—the impact of crop selection on energy efficiency and greenhouse gas performance. *Energies* 8, 6033–6058. doi: 10.3390/en8066033

Browne, J. D., and Murphy, J. D. (2013). Assessment of the resource associated with biomethane from food waste. *Applied Energ.* 104, 170–177. doi: 10.1016/j.apenergy.2012.11.017

Chiaraluce, G. (2021). Circular Economy in the agri-food sector: a policy overview. *Ital. Rev. Agric. Econ.* 76, 53–60. doi: 10.36253/rea-13375

Chiaraluce, G., Bentivoglio, D., and Finco, A. (2021). Circular economy for a sustainable agri-food supply chain: a review for current trends and future pathways. *Sustainability* 13, 9294. doi: 10.3390/su13169294

Consorzio Monviso Agroenergia (2018). *Verso il Biometano*. Available online: http://www.monvisoenergia.it/wp-content/uploads/2018/04/SPECIALE_BIOMETANO.pdf (accessed July 15, 2022).

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2015). Profitability analysis for biomethane: a strategic role in the Italian transport sector. *Int. J. Energ. Econ. Policy* 5, 440–449.

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2019a). Sustainable Italian cities: the added value of biomethane from organic waste. *Appl. Sci.* 9, 2221. doi: 10.3390/app9112221

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2019b). An economic analysis of biogas-biomethane chain from animal residues in Italy. *J. Clean. Prod.* 230, 888–897. doi: 10.1016/j.jclepro.2019.05.116

Cusenza, M. A., Cellura, M., Guarino, F., and Longo, S. (2021). Life cycle environmental assessment of energy valorization of the residual agro-food industry. *Energies* 14, 5491. doi: 10.3390/en14175491

D'Adamo, I., Falcone, P. M., and Ferella, F. (2019). A socio-economic analysis of biomethane in the transport sector: the case of Italy. *Waste Manage.* 95, 102–115. doi: 10.1016/j.wasman.2019.06.005

Ellen MacArthur Foundation (2013). *Towards the Circular Economy: Opportunities for the Consumers Goods Sector*. Available online at: www.ellenmacarthurfoundation.org/publications (accessed June 17, 2022).

European Commission (2018). State Aid SA.48424 (2017/N) – Italy - Support scheme for the production and distribution of advanced biomethane and other advanced biofuels for use in the transport sector. Available online at: https://ec.europa.eu/competition/state_aid/cases/269927/269927_1973623_186_2.pdf (accessed July 15, 2022).

Eyl-Mazzega, M. A., and Mathieu, C. (2019). *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy; Etudes de l'Ifri, Ifri: Paris, France*. Available online at: https://www.ifri.org/sites/default/files/atoms/files/mathieu_eyl-mazzega_biomethane_2019.pdf (accessed June 17, 2022).

Fagerström, A., Al Seadi, T., Rasi, S., and Briseid, T. (2018). *The Role of Anaerobic Digestion and Biogas in the Circular Economy*. Cork: IEA Bioenergy.

FAO (2019). *The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction*. Rome: FAO.

Ferella, F., Cucchiella, F., D'Adamo, I., and Gallucci, K. (2019). A techno-economic assessment of biogas upgrading in a developed market. *J. Clean. Prod.* 210, 945–957. doi: 10.1016/j.jclepro.2018.11.073

Finco, A. (2012). *Biofuels Economics and Policy: Agricultural and Environmental Sustainability. Biofuels Economics and Policy*. Milano: Franco Angeli.

Garuti, M., Soldano, M., Tonolo, A., and Piccinini, S. (2021). Sottoprodotti vegetali utili a produrre biometano. *L'informatore agrario*. 1, 44–48.

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi: 10.1016/j.jclepro.2015.09.007

González-Arias, J., Baena-Moreno, F. M., Pastor-Pérez, L., Sebastia-Saez, D., Fernández, L. M. G., Reina, T. R., et al. (2022). Biogas upgrading to biomethane as a local source of renewable energy to power light marine transport: profitability analysis for the county of Cornwall. *Waste Manage.* 137, 81–88. doi: 10.1016/j.wasman.2021.10.037

Gupta, R., Miller, R., Sloan, W., and You, S. (2022). Economic and environmental assessment of organic waste to biomethane conversion. *Bioresource Technol.* 345, 126500. doi: 10.1016/j.biortech.2021.126500

Hoo, P. Y., Hashim, H., and Ho, W. S. (2020). Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff. *J. Clean. Prod.* 270, 122160. doi: 10.1016/j.jclepro.2020.122160

Jain, A., Sarsaiya, S., Awasthi, M. K., Singh, R., Rajput, R., Mishra, U. C., et al. (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: current research trends, challenges, and future outlooks. *Fuel* 307, 121859. doi: 10.1016/j.fuel.2021.121859

Khan, M. U., Lee, J. T. E., Bashir, M. A., Dissanayake, P. D., and Ok, Y. S., and Ahring, B. K. (2021). Current status of biogas upgrading for direct biomethane use: a review. *Renew. Sust. Energ. Rev.* 149, 111343. doi: 10.1016/j.rser.2021.111343

Kullmann, F., Markewitz, P., Stolten, D., and Robinius, M. (2021). Combining the worlds of energy systems and material flow analysis: a review. *Energ. Sust. Soc.* 11, 1–22. doi: 10.1186/s13705-021-00289-2

Mezzadri, M., Antonini, E., and Francescato, V. (2010). *Purificazione e Upgrading Del Biogas a Biometano*. Available online at: https://www.venetoagricoltura.org/upload/Bioenergie/Purificazione_upgrading_biogas_in_biometano.pdf (accessed June 20, 2022).

Mistretta, M., Gulotta, T. M., Caputo, P., and Cellura, M. (2022). Bioenergy from anaerobic digestion plants: energy and environmental assessment of a wide sample of Italian plants. *Sci. Total Environ.* 843, 157012. doi: 10.1016/j.scitotenv.2022.157012

Molino, A., Nanna, F., Ding, Y., Bikson, B., and Braccio, G. (2013). Biomethane production by anaerobic digestion of organic waste. *Fuel* 103, 1003–1009. doi: 10.1016/j.fuel.2012.07.070

Murano, R., Maisano, N., Selvaggi, R., Pappalardo, G., and Pecorino, B. (2021). Critical issues and opportunities for producing biomethane in Italy. *Energies* 14, 2431. doi: 10.3390/en14092431

Naquash, A., Qyyum, M. A., Haider, J., Bokhari, A., Lim, H., Lee, M., et al. (2022). State-of-the-art assessment of cryogenic technologies for biogas upgrading: energy, economic, and environmental perspectives. *Ren. Sust. Energ. Rev.* 154, 111826. doi: 10.1016/j.rser.2021.111826

OECD/FAO (2021). *OECD-FAO Agricultural Outlook 2021-2030*. Paris: OECD Publishing.

Pappalardo, G., Selvaggi, R., and Pecorino, B. (2022). Biomethane production potential in Southern Italy: An empirical approach. *Ren. Sust. Energ. Rev.* 158, 112190. doi: 10.1016/j.rser.2022.112190

Pavi, S., Kramer, L. E., Gomes, L. P., and Miranda, L. A. S. (2017). Biogas production from co-digestion of organic fraction of municipal solid waste and fruit and vegetable waste. *Biores. Technol.* 228, 362–367. doi: 10.1016/j.biortech.2017.01.003

Piechota, G., and Igliński, B. (2021). Biomethane in Poland—Current Status, potential, perspective and development. *Energies* 14, 1517. doi: 10.3390/en14061517

Rath, J., Heuwinkel, H., and Herrmann, A. (2013). Specific biogas yield of maize can be predicted by the interaction of four biochemical constituents. *BioEnergy Res.* 6, 939–952. doi: 10.1007/s12155-013-9318-3

Rossi, R. (2019). *The EU Fruit and Vegetable Sector. Main Features, Challenges and Prospects. EPRS. European Parliamentary Research Service, 2019. PE 635, 563*. Available online at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/635563/EPRS_BRI(2019)635563_EN.pdf (accessed June 17, 2022).

Ryckebosch, E., Drouillon, M., and Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass Bioenerg.* 35, 1633–1645. doi: 10.1016/j.biombioe.2011.02.033

Sagagi, B., Garba, B., and Usman, N. (2009). Studies on biogas production from fruits and vegetable waste. *J. Pure Appl. Sci.* 2, 115–118. doi: 10.4314/bajopas.v2i1.58513

Stürmer, B., Kirchmeyr, F., Kovacs, K., Hofmann, F., Collins, D., Ingremeau, C., et al. (2016). *Technical-Economic Analysis for Determining the Feasibility Threshold for Tradable Biomethane Certificates-Report*. Brussels: European Renewable Gas Registry, 1–24.

Teixeira, J. A. (2018). Grand challenges in sustainable food processing. *Front. Sust. Food Syst.* 2, 19. doi: 10.3389/fsufs.2018.00019

Valenti, F., Porto, S. M., Cascone, G., and Arcidiacono, C. (2017b). Potential biogas production from agricultural by-products in Sicily. A case study of citrus pulp and olive pomace. *J. Agric. Eng.* 48, 196–202. doi: 10.4081/jae.2017.727

Valenti, F., Porto, S. M., Selvaggi, R., and Pecorino, B. (2018). Evaluation of biomethane potential from by-products and agricultural residues co-digestion in southern Italy. *J. Environ. Manage.* 223, 834–840. doi: 10.1016/j.jenvman.2018.06.098

Valenti, F., Porto, S. M. C., Chinnici, G., Cascone, G., and Arcidiacono, C. (2017a). Assessment of citrus pulp availability for biogas production by using a GIS-based model: the case study of an area in southern Italy. *Chem. Eng. Trans.* 58, 529–534. doi: 10.3303/CET1758089

Vilariño, M. V., Franco, C., and Quarrington, C. (2017). Food loss and waste reduction as an integral part of a circular economy. *Front. Environ. Sci.* 5, 21. doi: 10.3389/fenvs.2017.00021

Volpe, R., Messineo, A., and Millan, M. (2016). Carbon reactivity in biomass thermal breakdown. *Fuel* 183, 139–144. doi: 10.1016/j.fuel.2016.06.044

Yazan, D. M., Cafagna, D., Fraccascia, L., Mes, M., and Pontrandolfo, P., and Zijm, H. (2018). Economic sustainability of biogas production from animal manure: a regional circular economy model. *Manage. Res. Rev.* 41, 605–624. doi: 10.1108/MRR-02-2018-0053

Zarbà, C., Chinnici, G., La Via, G., Bracco, S., Pecorino, B., D'Amico, M., et al. (2021). Regulatory elements on the circular economy: driving into the agri-food system. *Sustainability* 13, 8350. doi: 10.3390/su13158350

Zhu, T., Curtis, J., and Clancy, M. (2019). Promoting agricultural biogas and biomethane production: lessons from cross-country studies. *Ren. Sust. Energ. Rev.* 114, 109332. doi: 10.1016/j.rser.2019.109332