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Research article

Assessment of economic viability and production costs for the innovative microfiltered digestate☆

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ABSTRACT

This paper assesses the economic viability of the production process of an innovative form of digestate known as “microfiltered digestate”, suitable for use as a fertilizer in driplines for permanent crops. A Break-Even Analysis was performed to determine the Break-Even Point which identifies the minimum quantity of products necessary to cover production costs at a certain selling price. Our results show that the production of microfiltered digestate provides positive economic viability for anaerobic digestion managers, providing them with an attractive market outlet and, at the same time, a new form of income.

The experimental study was stated in Sicily, but it is replicable in any territorial context with anaerobic digestion plants. The results are in line with the principles of circular economy and are very current with reference to the use of organic fertilizers instead of chemical ones.

1. Introduction

The biogas production process involves the production of a by-product known as “digestate”. After being divided in two fractions – liquid and solid (Provenzano et al., 2018; Zeng et al., 2022) – the digestate is used in agriculture as a fertilizer or soil conditioner due to its high content of useful nutrients for agricultural crops (Tambone et al., 2013; Nkoa, 2014; Sogn et al., 2018; Stürmer et al., 2020). Solid digestate is usually distributed with the use of traditional manure spreaders. Liquid digestate is instead distributed with manure spreaders or other similar equipment (Monlau et al., 2015; Manetto et al., 2020).

The use of digestate in agriculture fulfills the concept of “circular economy” (Pappalardo et al., 2022) and improves the sustainability of the entire agricultural production process (Coppola et al., 2018).

The use of intensive agricultural models with a massive use of productive factors (phytosanitary products, irrigation water, chemical fertilizers) is causing a drastic reduction of organic matter in agricultural soils, damaging the productive substrate and creating the conditions for a drop in yields (Wang et al., 2019; Alburquerque et al., 2012; Panuccio et al., 2021; Garbini et al., 2022). In this regard, the use of the digestate would ensure the possibility of restoring organic matter (Peng et al., 2020) and improving the structure of agricultural soils, both essentials for a new sustainable agricultural model (Jin et al., 2022).

Despite its benefits, the digestate in agriculture is still not widely used (Selvaggi et al., 2018) both because of its availability linked to the presence of anaerobic digestion plants and its spreading methods still inefficient (Möller, 2015; Plana and Noche, 2016). In this regard, a new and interesting method of digestate distribution concerns the possibility of distributing the liquid part of the digestate through fertigation (Barzee et al., 2019; Guido et al., 2020). This method requires that the liquid digestate undergo preliminary microfiltration treatment to remove coarse solid particles and minimize the risk of dripline occlusion.

The innovative experimental microfiltration plant tested allows to obtain a microfiltered liquid phase that can be used in fertigation with driplines, ensuring the maximum use efficiency of nutrients and water contained in it. The microfilter allows to exclude the particles larger than 50 μm, which could occlude the drip labyrinths of the dripline system, from the microfiltered phase (Manetto et al., 2022). Moreover, it is necessary an additional adjustment of the fertigation system suitable for the treatment of organic and colloidal matrices usually present in the digestate.

In this experimental condition, the microfiltered digestate represents about 60% of the liquid digestate inside the microfilter and retains, on average, 1.5–8.0% dry matter. Within this liquid phase there are many chemical compounds useful for crop fertilization. The most important one is nitrogen in ammoniacal form, in the percentage of 70–90% of the

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total dissolved nitrogen.

Currently, fertigation with digestate mixed with irrigation water is a practice not yet widespread. That is because the chemical-physical characteristics of the digestate cause clogging problems of the dispensers worsening the quality and efficiency of the overall operation.

The so-called "microfiltered digestate" opens new and interesting prospects for the use of the digestate on perennial crops. In fact, fertigation systems with drip distribution are typically used for these crops, with positive repercussions on the environmental and economic sustainability balance of the entire biogas supply chain (Mantovi et al., 2020).

However, the microfiltered digestate is still not widely used because there are currently only few microfiltered digestate production plants that are mainly used for experimental purposes. Moreover, the effectiveness of spreading methods is still uncertain among farmers and the level of profitability is not yet well quantified among plant managers who are expected to produce microfiltered digestate. For the latter, an important role is played by the production cost associated with microfiltration treatment of liquid digestate. Estimation of production costs and profitability margins are a necessary condition for promoting "microfiltered digestate". However, to the best of our knowledge, this aspect has not been thoroughly examined in the scientific literature.

Previous economic studies on the digestate have focused on consumer perceptions and farmers' willingness to pay to buy the digestate instead of conventional fertilizers (Dahlin et al., 2017; Pappalardo et al., 2018). However, an important yet unexplored aspect concerns the economic benefits of producing microfiltered digestate for biogas companies. Microfiltered digestate could be widely used in perennial crops where its use has been very limited due to technical difficulties in distribution.

Assessing the economic viability of producing microfiltered digestate is important for three reasons: 1) to make the production process in agriculture more sustainable and linked to the principles of the circular economy, 2) to improve the profitability of anaerobic digestion plants, and 3) to make anaerobic digestion plants less dependent on public subsidies, promoting diversification of income sources. These aspects are important in the current difficult socio-economic context where agro-industrial companies are at risk of closure due to high operating costs (Murano et al., 2021).

With this in mind, we estimated the profitability of microfiltered liquid digestate production process with the aim to verify the economic viability for anaerobic digestion plants to adopt the innovative microfiltering plant. To this scope, we have preliminary assessed the production costs of microfiltered liquid digestate by referring to the revenues and costs characteristic of its production process. Then, through a Break Even Analysis, we identified the minimum amount of microfiltered liquid digestate to cover production costs (fixed and variable costs). The evidence of the cost-effectiveness of the production process of microfiltered liquid digestate could open up new markets, especially for permanent agricultural crops through fertigation systems.

The experimental activity makes reference to an ongoing research project in Sicily (Italy) which aims to promote the use of microfiltered digestate in Mediterranean perennial crops such as citrus and prickly pear. The results presented in our survey highlight the cost-effectiveness of microfiltered digestate for the anaerobic digestion plants companies. These results can have positive implications for the overall biogas chains since there are no technical limits for the production of microfiltered digestate and it could become a new source of income for the biogas companies. Furthermore, a large-scale production of microfiltered digestate would allow its use in fertigation on permanent agricultural crops, improving the content of organic matter in the soil and the sustainability of the agricultural process. This aspect is very timely since organic matter in agricultural soils has been exploited for decades through intensive agricultural practices and extensive use of chemical inputs.

2. Materials and methods

2.1. Data collection: fixed and variable costs

Data for our survey concern economic information about the production process of microfiltered digestate useable for permanent crops. Our data have been collected in 2021 from an anaerobic digestion plant located in the province of Ragusa (Sicily-Italy). The plant falls within the average technical-economic parameters of typical biogas companies that produce biogas and digestate.

Data collection and processing have been conducted in two phases. The first phase took place at the headquarters of the company through a specific questionnaire which allowed us to detect several technical and economic information regarding the production cost of microfiltered digestate (raw materials, services, equipment and labor).

Data collection began with some basic assumptions about the specific case study being analyzed. The surveyed anaerobic digestion plant annually produces 29,200 m^3 of digestate "as is" i.e. before the separation process between liquid and solid fraction. Net of digestate sold "as is" or reused in the plant following mechanical separation, an average of 20,400 m^3/year of liquid digestate is obtained.

The production of microfiltered digestate involves the use of a specific innovative micro-filtering machine produced with a license by the SEPCOM WAM company, whose purchase cost was equal to 50,950 euros. The depreciation period for this plant has been set at 15 years. For this machinery we have estimated a maximum annual production of microfiltered digestate equal to 12,240 m^3/year, by measuring a separation efficiency equal to 60% and by assuming the microfiltration of all available liquid digestate. The experimental tests conducted at the plant have established the daily working capacity of the micro-filtering machinery equal to 1 m^3 of microfiltered digestate every 6 min. It was also measured that every hour of work there are about 6 min of non-productive time necessary to: 1) filling up the internal tank of the micro-filter, 2) starting the pumps and 3) starting up the system after the filling. In fact, the microfiltration system has its own tank with a capacity of 5 m^3. It must be filled twice within 1 h and each filling takes 3 min. Therefore, the plant examined in our study has enough digestate to work for a maximum number of 170 days per year (8 h per day).

Table 1 shows the variables with the typical units of measure taken into account for estimating the production cost of the microfiltered digestate.

Production costs were evaluated by first identifying and estimating "fixed costs" - the set of costs whose amount is independent of the quantity of final product obtained. Among fixed costs, the depreciation costs related to the purchase and installation of the aforementioned SEPCOM WAM microfiltration machinery and accessory systems were considered. Specifically, in addition to the purchase of the machinery, the following were noticed: 1) purchasing costs, installation and

Table 1
Variables considered for estimating the production cost of microfiltered digestate.

Description	U.M.	Values
Micro-filtering plant tank	m^3	5
Time spent on filling and pumping	min/h	6
Production time of microfiltered digestate	min/m^3	6
Net production of microfiltered digestate, per hour	m^3/h	9
Daily working hours	h/dd	8
Daily net production of microfiltered digestate	m^3/dd	72
CASE STUDY		
Digestate production	t/y	29,200
Liquid digestate production	t/y	20,440
Maximum annual net production microfiltered digestate	t/y	**12,264**
Max working days of micro-filtering plant, per year	dd/y	**170**
Energy price	€/kW	0.15
Water price	€/m^3	1.37
Liquid digestate price	€/m^3	2.00

assembly of a pump for filling the tank of the micro-filtering machinery, 2) purchasing costs of conveyor pipes incoming and outgoing from the micro-filtration plant, 3) electrical panel for energy management and 4) construction of a platform necessary for the micro-filtering machinery positioning. Moreover, the installation of the micro-filtration system requires the purchase of a steel tank for the storage of produced microfiltered digestate, waiting to be delivered to end users. For this purpose, a stainless-steel tank with a capacity of 150 m^3 was installed at the sample company. It therefore ensures the storage of 2 days of production (72 m^3 per day).

Furthermore, labor costs to ensure maintenance and the regular functioning of the micro-filtering machinery were determined. It was estimated a labor requirement equal to 3 interventions per year for a duration of 2 h for each one. In order to quantify the related amounts of the fixed costs, for all the aforementioned transactions the depreciation costs were taken into consideration.

Subsequently the values relating to "variable costs" were identified and estimated, that is the costs that strictly depend on the quantity produced of microfiltered digestate.

First of all, we took into consideration the quantity of raw materials necessary to carry out the process, namely.

- The amount of liquid digestate (m^3) used for the production of the microfiltered digestate, to evaluate the loss of profit for the maneger who would have sold this liquid fraction.
- The amount of water (m^3) used during the production and washing cycles of the micro-filtering machinery.
- The amount of electricity (kW) required to activate the system including the pump to fill up the tank, the motor and the internal pump of the micro-filtering machinery, which are simultaneously activated even during maintenance and washing phases.

For the unit cost of the liquid digestate it was taken into consideration the average selling price adopted by the plant investigated. In fact, it already exists a market for this product and the manager has provided the ordinary average selling price.

For the unit cost of water and electricity the average prices adopted by the companies providing the service were measured and considered.

The values considered for all these raw materials are summarized in Table 1 among the factors of the case study. Finally, it was determined the cost of the labor which involves the use of 1 worker for the entire processing period of the digestate with a daily amount of hours equal to 2. In fact, although the production of microfiltered digestate continues for 8 h, the plant is autonomous and the intervention of the operator is required only for some phases of the production process. The labor costs have been determined by applying the yearly average unit wages of the survey area to the agricultural workers.

2.2. Break-even analysis e break-even point

The data on fixed and variable costs were subsequently used to perform a Break-Even Analysis (BEA) in order to obtain the Break-Even Point (BEP), that is the point of equality between incomes and incurred costs. The BEP defines the time from which an investment generates a positive return since the incomes will be greater than the costs. The BEA represents a simple method for evaluating the combinations of production factors that provide, in a context of uncertainty, the best performance in terms of income, especially in the budgeting phase of the management control (Loevy and Mendlowitz, 2012). The BEA has been used in previous studies to evaluate the economic impact of business choices within farms (e.g. Berry, 1973; Musser and Marable, 1976; Backus and King, 2008; Stobaugh et al., 2018).

The BEP is obtained by applying the following formula:

$$\mathrm{BEP} = P_i \cdot \mathrm{Q}_{\mathrm{BEP}} = P_i \cdot \frac{CFT}{Mdcu_i} \tag{1}$$

where P_i indicates the market price of the good i and Q_{BEP} indicates the amount of production necessary to achieve a balanced budget. This Q_{BEP} value is equal to the ratio between the total fixed costs (*CFT*) for production and the unit contribution margin (*Mdcu*) obtained from the sale of one unit of the good *i*.

The variables used to calculate the BEP of this case study include.

- The market price of the microfiltered digestate. Since there is currently no real market for this product, we have hypothesized three different price levels taking as reference the market prices of similar products (i.e., solid separated digestate and manure) ordinarily used to improve soil fertility in farms with permanent crops. The selling price of solid separated digestate has stabilized at about 10.00 €/ton, as it has entered the same market as manure.

In fact, solid separated digestate is the surrogate commodity in terms of ammonia N content and useable on the same crops (e.g., citrus). The ammonia N content of microfiltered digestate and solid separated digestate is about 4.0 mg/kg on wet basis.

By adopting a precautionary approach, the price levels for the microfiltered digestate considered in this study were 10.00, 8.00 and 6.00 €/m^3.

- The produced amount of microfiltered digestate. For this variable, the minimum production value (1 m^3) and the maximum value that the microfiltration plant can produce (12,240 m^3) were taken into consideration.
- Sales Revenues, obtained by multiplying the selling price by the quantities of microfiltered digestate produced.
- Fixed Costs, that is the costs that remain unchanged for the three market price hypotheses of the microfiltered digestate regardless of the quantity produced, since the working days are always 170 per year.
- Variable Costs, that is the costs that vary according to the quantity of microfiltered digestate produced.
- Contribution Margin, defined as the difference between Sales Revenues and Variable Costs.
- Operating Income, given by the difference between Sales Revenues and total costs (Fixed plus Variable costs).

3. Results and discussion

3.1. Estimation of fixed and variable production costs

The Fixed Costs detected in our study have registered an average value of € 0.645 per m^3 of microfiltered digestate produced (Table 2). Within fixed costs the purchase of the micro-filtration plant is the highest: with a cost of 50,950.00 euros and an amortization period of 15 years, it has a fixed cost of 3396.67 €/year equivalent to € 0.278 per m^3 of microfiltered digestate.

Another element that affects fixed costs is the depreciation of the steel tank necessary to store the microfiltered digestate produced and waiting to be used in the field. In particular, considering a purchase value of € 16,000.00 and an amortization period of 5 years, the fixed cost is € 3200.00 per year and € 0.261 per m^3 of microfiltered digestate.

The other fixed cost items have a lower impact, such as the depreciation cost of other equipment or ordinary maintenance work on the micro-filtration system as a whole.

As regards variable costs (Table 3), the average value per cubic meter of the microfiltered digestate produced is 3.77 €/m^3. The highest cost for this category is linked to the production and acquisition of the liquid digestate. Starting from a micro-filtration efficiency of 60% it has been calculated that to produce 1 m^3 of microfiltered digestate it is necessary to use about 1.60 m^3 of liquid digestate. Therefore, from a purchasing price of the liquid digestate of 2.00 €/m^3 it was calculated a cost of 3.20

Table 2
Fixed costs for microfiltered digestate (170 working days).

Plants and Machinery	Values (€)	Amortization period (year)	Depreciation		Fixed cost (€/m^3)[a]
			U. M.	Values	
Micro-filtering plant SEPCOM WAM	50,950.00	15	€/y	3396.67 €	0.278 €
Electrical system	2150.00	10	€/y	215.00 €	0.018 €
Conveyor Tubes	50.00	2	€/y	25.00 €	0.002 €
Concrete platform construction (30 m^2)	1050.00	10	€/y	105.00 €	0.009 €
Steel tank	16,000.00	5	€/y	3200.00 €	0.261 €
Labor: Maintenance works	n° workers	n° daily hours	Salary		
			U. M.	Values	
	1	2	€/h	9.20 €	0.005 €
Other fixed costs: Microfilter basket	Values	Amortization period (year)	Depreciation		
			U. M.	Values	
replacement	4500.00 €	5	€/y	900.00 €	0.074 €
Total fixed costs				**7850.87 €**	**0.645 €**

[a] In the hypothesis of 12,264 tons/year of microfiltered digestate produced.

Table 3
Variable costs for microfiltered digestate (170 working days).

Raw material	Price		Quantity used to produce 1 m^3 of microfiltered digestate		Variable cost (€/m^3)
	U.M.	Values	U. M.	Values	
Liquid digestate	€/m^3	2.00 €	m^3	1.6	3.20 €
Water	€/m^3	1.37 €	m^3	580	0.06 €
Electrical energy	€/kW	0.15 €	kW	1.64	0.25 €
Labor: Ordinary	n° workers	n° daily hours	U. M.	Salary	
	1	2	€/h	9.20 €/hour	0.26 €
Total variable costs					**3.77 €**

euro to produce 1 m^3 of microfiltered digestate.

As for water, the incidence of this cost per cubic meter of microfiltered digestate produced is € 0.06 while that of the cost for electricity is € 0.25.

Finally, the incidence of labor by the company worker is 0.26 €/m^3.

Overall, the total production cost per cubic meter of the microfiltered digestate is equal to 4.41 €/m^3 (Table 4). In terms of percentage, the variable costs have an impact of about 85% on total costs and the Fixed Costs of the remaining 15%. Assuming that the micro-filtration machinery works for 170 days a year, the production cost of the microfiltered digestate is 39,619.14 €/year.

Table 4
Total costs for microfiltered digestate (Production 170 working days).

Item	Values	%
- Variable costs (€/m^3)	*3.77 €*	*85.37%*
- Fixed costs (€/m^3)	*0.65 €*	*14.63%*
- Total costs (€/m^3)	4.41 €	*100.00%*
- Variable costs (€/year)	*31,722.28 €*	
- Fixed costs (€/year)	*7896.87 €*	
- Total costs (€/year)	39,619.14 €	

3.2. Break-even analysis results

After determining the production costs (fixed and variable), a Break-Even Analysis was performed to determine the Break-Even Point that identifies the minimum amount of microfiltered digestate needed to be produced to cover production costs at a certain selling price.

The BEP was estimated assuming three selling price scenarios of the microfiltered digestate that led to significant differences in the results.

3.2.1. 1st Hypothesis - Selling price: 10.00 €/m^3

In the first hypothesis we assumed a selling price of the microfiltered digestate of 10.00 €/m^3. This resulted in:

- a loss of € 7440.77 corresponding to a single unit of product sold (1 m^3 of microfiltered digestate);
- an Operating Income of € 68,808.20 corresponding to 12,240 m^3 of microfiltered digestate produced in 170 working days of the micro-filtration machinery;
- the Break-Even Point was identified at 1195 cubic meters of micro-filtered digestate produced and sold. This value indicates the amount of product that allows the coverage of the total production costs that will be reached after 16 days of production (Table 5).

3.2.2. 2nd Hypothesis - Selling price: 8.00 €/m^3

In the second hypothesis we assumed a selling price of the micro-filtered digestate equal to 8.00 €/m^3. This resulted in:

- a loss of € 7442.77 corresponding to a single unit of product sold (1 m^3 of microfiltered digestate);

- an Operating Income of € 44,328.20 corresponding to 12,240 m^3 of microfiltered digestate produced in 170 days of work of the micro-filtration machinery;

- finally, the Break-Even Point was identified at 1761 cubic meters of microfiltered digestate produced and sold. This value indicates the amount of product that allows the coverage of the total production costs that will be reached after 25 days of production (Table 6).

3.2.3. 3rd Hypothesis - Selling price: 6€/m^3

As third hypothesis we assumed a selling price of the microfiltered digestate equal to 6.00 €/m^3. This resulted in:

- a loss of € 7444.77 corresponding to a single unit of product sold (1 m^3 of microfiltered digestate);

- an Operating Income of € 19,848.20 for the production and sale of 12,240 units of microfiltered digestate produced in 170 working days of the micro-filtration machinery;

- the Break-Even Point was identified at 3339 m^3 of the microfiltered digestate produced and sold. This amount of product will be reached after 46 days of production (Table 7).

Summarizing the results obtained with the Break-Even Analysis it is possible to state that, in working conditions for 170 days/year and in the best hypothesized scenario (market price of 10.00 €/m^3), the Operating Income is approximately € 68,000 with a BEP between costs and revenues easily reached after only 16 working days.

Even in the more precautionary hypothesis (6.00 €/m^3), the Operating Income is still largely positive with a value of about 20,000 euros. In this case, the BEP between costs and revenues is reached after 46

Table 5
Break Even Analysis outputs - 1st Hypothesis[a].

Digestate production (m^3)	1	1195	12,240
Average selling price (Unit.)	10.00 €	10.00 €	10.00 €
Sales revenues	10.00 €	11,953.45 €	122,400.00 €
Variable costs	3.77 €	4505.15 €	46,144.80 €
Contribution margin	6.23 €	7447.00 €	76,255.20 €
Fixed costs, per year	7447.00 €	7447.00 €	7447.00 €
Operating Income	−7440.77 €	0.00 €	68,808.20 €

[a] Selling price: 10.00 €/m^3 - Variable costs: 3.77 €/m^3 - Fixed costs: 7447.00 €

Table 6
Break Even Analysis outputs - 2nd Hypothesis[a].

Digestate production (m^3)	1	1761	12,240
Average selling price (Unit.)	8.00 €	8.00 €	8.00 €
Sales revenues	8.00 €	14,084.16 €	97,920.00 €
Variable costs	3.77 €	6637.16 €	46,144.80 €
Contribution margin	4.23 €	7447.00 €	51,775.20 €
Fixed costs, per year	7447.00 €	7447.00 €	7447.00 €
Operating Income	−7442.77 €	0.00 €	44,328.20 €

[a] Selling price: 8.00 €/m^3 - Variable costs: 3.77 €/m^3 - Fixed costs: 7447.00 €

Table 7
Break Even Analysis outputs - 3rd Hypothesis[a].

Digestate production (m^3)	1	3339	12,240
Average selling price (Unit.)	6.00 €	6.00 €	6.00 €
Sales revenues	6.00 €	20,036.77 €	73,440.00 €
Variable costs	3.77 €	12,589.77 €	46,144.80 €
Contribution margin	2.23 €	7447.00 €	27,295.20 €
Fixed costs, per year	7447.00 €	7447.00 €	7447.00 €
Operating Income	−7444.77 €	0.00 €	19,848.20 €

[a] Selling price: 6.00 €/m^3 - Variable costs: 3.77 €/m^3 - Fixed costs: 7447.00 €

working days.

The high economic profitability of the microfiltered digestate is due to the low incidence of fixed costs on the total ones. Obviously, the production of microfiltered digestate becomes more and more economically profitable as the produced amount and the working days of the micro-filtering machinery increase.

3.3. Discussion

Our findings reveal how the production of microfiltered digestate is able to guarantee high economic profitability for the anaerobic digestion plants. This result provides economic justification for previous scientific studies that have shown high technical efficiency of the distribution process of microfiltered digestate through fertigation (Guido et al., 2020; Mantovi et al., 2020; Panuccio et al., 2021). In particular, our results show that anaerobic digestion companies can gain a new economic benefit from producing microfiltered digestate and simultaneously decrease their degree of dependence on public subsidies.

Furthermore, our results reinforce what emerged in previous scientific studies, that is the farmers' availability to use the digestate as a fertilizer for agricultural crops (Pappalardo et al., 2018; Selvaggi et al., 2021, 2022). The high economic viability of microfiltered digestate that we estimated could encourage biogas companies to produce it to meet the farmers' demand for it. Our results become even more important when we consider the potential uses of microfiltered digestate also in permanent agricultural crops (e.g., citrus, pome fruit, olive, and Opuntia) through fertigation systems, where it is currently little used. In addition, microfiltered digestate expands the supply of fertilizer by improving the supply of raw materials for farms. The latter is important considering the current economic situation in which prices of inputs such as fertilizer are steadily rising due to recent international crises. The possibility of short-range supply for farmers with farms close to biogas plants could be a considerable competitive advantage.

Even for the environmental issues our results support what has already emerged in previous studies that have analyzed the potential of digestate to promote an agricultural production process more oriented towards the adoption of eco-friendly techniques (e.g. Alburquerque et al., 2012; Barzee et al., 2019; Garbini et al., 2022).

Furthermore, the positive effects that microfiltered digestate could have on public opinion should not be overlooked. In fact, as demonstrated in previous studies (Dahlin et al., 2017), consumers have a positive propensity for digestate to be used in agriculture and this represents a further element that justifies the production of microfiltered digestate. From this point of view, our results could encourage the plant managers to disseminate the use of digestate among farmers and to open up new markets.

In summary, the results of our study show that microfiltered digestate production offers attractive economic opportunities for anaerobic digestion plants by reducing their dependence on public subsidies. Furthermore, farmers can take advantage for using the microfiltered digestate in fertilizing permanent crops as an alternative to conventional chemical fertilizers, and also under organic farming. Finally, an additional aspect concerns the enrichment of agricultural soils with organic matter, which has been gradually reduced in recent years as a result of the adoption of intensive cultivation practices. Digestate comes from the reuse of by-products of agricultural activities, and this makes the production process more sustainable also under the circular economy perspective.

4. Conclusion

Our findings have positive implications for the whole biogas chain as the microfiltered digestate can be used by farms as a fertilizer in permanent agricultural crops through fertigation. However, our results need to take into account some aspects that were not analytically investigated in this study but deserve further investigation in future research. In particular, the economic viability of the microfiltered digestate production process that we obtained through Break-Even Analysis has not taken into account the impact of digestate transportation costs from the anaerobic digestion plant to the farm. The impact of these costs depends on the distance between the place of production and utilization of the digestate, which increases as the distance increases. If these costs are too high, the demand for digestate will decrease, especially in those geographic areas where the number of anaerobic digesters is still limited.

Another limitation of our study could be the scenario assumed with the selling price of microfiltered digestate. Unfortunately, in the absence of an explicit market for this product, we had to consider the average prices of similar products already on the Sicilian market where our study was conducted. In particular, as a reference price for microfiltered digestate we considered the price of manure that is used as a soil conditioner and/or organic fertilizer on farms with permanent crops. However, to confirm the results of our study, it would be desirable for further research to be conducted in other geographical areas.

Credit author statement

G. Pappalardo Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft and Writing – review & editing and Funding acquisition. E. Trimarchi contributes to data curation, Investigation and Writing – original draft. R. Selvaggi Conceptualization, Data curation, Formal analysis, Investigation, Methodology,Visualisation, Writing – original draft, Writing – review & editing and Supervision.

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.

Data availability

Data will be made available on request.

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