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Biomethane and Compost Production by Anaerobic Digestion of Organic Waste: Suggestions for Rural Communities in Southern Italy

Christian Bux [1,*], Federico Cangialosi [2] and Vera Amicarelli [1]

[1] Department of Economics, Management and Business Law, University of Bari Aldo Moro, Largo Abbazia Santa Scolastica, 70124 Bari, Italy; vera.amicarelli@uniba.it
[2] Tecnologia e Ambiente (T&A), Via Mummolo 13, 70017 Putignano, Italy; federico.cangialosi@icloud.com
* Correspondence: christian.bux@uniba.it

Abstract: The sharp increase in rural tourism brings, on the one side, economic and social benefits among rural communities but, on the other, contributes to environmental challenges, specifically waste generation and natural resource consumption. From the ecological perspective, several pathways have been developed from local and global communities, such as prevention, reuse, recycling and energy recovery. The present research, by considering the need to boost separate collection and valorize organic waste among rural communities, evaluates the performance of a combined anaerobic digestion and composting plant in Southern Italy. The purpose is to investigate the advantages and disadvantages of collecting organic waste in rural areas and recovering it into biomethane, digestate and compost. First, the research develops the material flow analysis of a real, accessible and available anaerobic digestion and composting plant in Southern Italy. Secondly, on the basis of the results obtained, the research calculates the biomethane, digestate and compost potential in Southern Italy, considering the amount of organic waste produced in 14 rural communities identified as the most beautiful villages in Italy. Last, the research compares the advantages and disadvantages of producing biomethane through anaerobic digestion or resorting to community composting in rural areas. It results that the biomethane and compost potential through anaerobic digestion is 423,854 kg and 954,896 kg, respectively, but significant financial investments must be allocated in order to allow the municipalities to enhance the logistics and the separate collection facilities. The research highlights possible strategies under the circular economy lens to boost sustainability in rural areas, focusing on biomethane and compost production and providing policy implications in light of the National Recovery and Resilience Plan (NRRP) and the Common Agricultural Policy (CAP).

Keywords: biomethane; digestate; compost; rural areas; organic waste; anaerobic digestion; National Recovery and Resilience Plan; Common Agricultural Policy

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1. Introduction

The sharp increase in rural tourism brings economic and social benefits among rural communities but contributes to environmental challenges, specifically waste generation and natural resource consumption [1], due to the overcrowding of public places and facilities, disruption in residents' lives and overuse of resources [2,3]. The upsurge in waste (and organic waste) negatively impacts the environment, due to greenhouse gas emissions into the atmosphere [4], as well as plastics, leachates and other emissions into the soil and water bodies [5,6]. From the managerial perspective, rural communities are undermined by the lack of suitable waste collection systems [6], which leads to the increase in the volume of waste piled up in landfills, as well as to the loss of several valorization opportunities associated with separately collected organic waste, namely reuse, recycling (i.e., waste-to-biomaterials), recovery (i.e., waste-to-bioenergy) and composting, making incineration and landfilling an extrema ratio [7].

It is estimated that each year, more than 1.3 billion t of organic waste is generated on the global scale, which represents about 13.8% of the entire food production [8] and is expected to increase up to 2.2 billion t by 2025 [9]. In Europe, it results that approx. 931 Mt of organic waste is generated, and Italy generated 8 Mt in 2020 [10]. In the Apulia region (Southern Italy), an amount of municipal solid waste of about 1.1. Mt has been estimated, of which 0.24 Mt is organic waste from household kitchens, canteens or catering services. Specifically, 98% of the organic waste comes from hospitality activities, namely hotels, restaurants and food services [11]. However, this amount is not entirely committed to sustainable waste management, since about 31% is recycled, 27% is incinerated with energy recovery, 16% is composted or addressed to anaerobic digestion, and 26% is incinerated or landfilled [12]. These trends underline the need to implement efficient organic waste valorization practices, which could have benefits at an environmental, social and economic level [13,14].

Specifically, waste coming from rural areas is mainly composed of organic waste, such as kitchen and food waste, but also rubber and plastics [1]. It results that waste in rural areas ranges from 0.17 to 0.9 kg per person per day, as outlined by previous studies on the topic [15]. On the global scale, it results that villages in Southwest China generate about 0.17 kg of waste per day [16], whereas rural areas in Iran produce from 0.3 to 0.6 kg per capita per day [17,18]. Higher peaks have been recorded in rural areas in Indonesia, where roughly 0.9 kg of waste per person per day has been recorded [19], of which more than 50% is organic waste [20]. In Romania, it is reported that young people living in rural environments throw away about 0.42 kg of food per day [21], whereas in Norway, it results that rural households waste about 2/3 of the volume generated by urban households [22], which highlights rather comparable food waste amounts worldwide. On average, in terms of solid waste generation, rural areas appear to be more sustainable than urban ones, as the latter generate over 70–80% more waste compared to rural realties [23].

Although food waste prevention represents the first option in the waste management hierarchy [7,24], the European Union has enacted several strategies to enhance sustainability in the hospitality industry and in the entire tourism sector, to reduce the withdrawal of natural resources, energy consumption and waste generation [25]. Considering the alternative waste management options [24], Papargyropoulou et al. [26] highlighted that organic waste prevention has great potential for improving environmental and socioeconomic outcomes at the community level but is also challenging. However, energy recovery activities, such as the production of biogas or biomethane [27,28], as well as composting activities [29], have been discussed in the field of organic waste, representing one of the best solutions to avoid organic waste from being landfilled. In general, anaerobic digestion and composting are alternative organic waste valorization pathways, and the choice between them depends on the scale of the operation [30]. However, as outlined by Vieira and Matheus [31], concrete comparisons are complex, due to different system boundaries, applications and models, as well as attributional and sequential life cycle approaches. On the one side, Murphy and Power [32] discussed that composting is more economically advantageous compared to anaerobic digestions at scales less than 20,000 t per year. On the other side, anaerobic digestion should be preferred because of the low carbon emissions, as well as the reduced amount of secondary pollution, low operating costs and large-scale plants. Further, anaerobic digestion allows for the production of bioenergy and biomethane, boosting energy independence among communities [33–35].

In recent years, the European Commission has implemented the roadmap for the adoption of the Communication on a Long-Term Vision for rural areas "towards stronger, connected, resilient and prosperous rural areas by 2024" [36], which aims at "ensuring a fair standard of living for the agricultural community" and tackling negative environmental externalities, low income, emptying of the countryside and improvement of tourism. Tourism should be considered as an alternative business together with local circular economy activities and renewable energy production [37]. The development of biogas and biomethane production activities based on anaerobic digestion of organic waste could boost more sustainable waste management, but investments to increase separate collection infrastructures are required. The current take–make–waste paradigm requires astronomical investments to reduce emissions, which can be avoided by converting current systems with the adoption of anaerobic digestion and composting plants of organic waste [37]. In this context, Italy represents a fertile area to enhance rural tourism and the production of renewable energies, also considering that it counts about 1655 anaerobic digestion plants, mainly located in rural areas, and represents the second European market soon after Germany and the third on the global scale after China [38,39].

Previous studies [12,40] have highlighted that organic waste, namely waste coming from household and other anthropogenic sectors [41], as well as from kitchens, canteens and gardens, is currently sorted in the organic fraction (if separate collection is available) and treated in composting plants to produce high-quality compost, as well as addressed to anaerobic digestor plants to generate biogas. Biogas represents the most widespread fuel obtained from biomass (also organic waste) and is currently defined as a secondary renewable resource, which can either decrease air and soil pollution related to organic waste disposal or increase the production of high-quality fertilizers. Further, biogas production through anaerobic digestion plants can increase the amount of renewable energy [33,34]. From the technical perspective, biogas can be burnt in conventional boilers and transformed into heat or utilized as a fuel for the production of both electricity and heat (i.e., cogeneration). Also, it can be converted into chemical compounds [20]. Specifically, biogas obtained from anaerobic digestion plants contains on average CH_4 (65%) and CO_2 (35%), as well as traces of hydrogen sulfide, water vapor, ammonia and siloxane depending on the feedstock and the digestion process [42,43]. Considering that the presence of CO_2 and other gases can reduce the economic value of the biogas, it should be treated for the removal of hydrogen and other not valuable components according to the so-called "biogas upgrading". Such an upgrading process allows for the production of biomethane, which can either be transported as fuel or injected into the natural gas grid [29].

The purpose of the current research is to investigate the advantages and disadvantages of collecting organic waste in rural areas and address them to anaerobic digestion and composting in Southern Italy. The authors investigate the performance of a combined anaerobic digestion and composting plant, with the aim to measure under the quantitative and qualitative perspective the opportunities associated with the production of biomethane, digestate and compost from organic waste in the rural areas of the Apulia region. Specifically, the research estimates the biomethane, digestate and compost potential of 14 rural communities, namely Alberobello, Alberona, Bovino, Cisterino, Locorotondo, Maruggio, Monte Sant'Angelo, Otranto, Pietramontecorvino, Presicce–Acquarica, Roseto Valfortore, Sammichele di Bari, Specchia and Vico del Gargano.

First, the research develops the material flow analysis of a real, accessible and available anaerobic digestion and composting plant in Southern Italy. Secondly, on the basis of the results obtained, the research calculates the biomethane, digestate and compost potential, considering the amount of organic waste produced in 14 rural communities identified as the most beautiful villages in Italy. Last, the research compares the advantages and disadvantages of producing biomethane through anaerobic digestion or resorting to community composting in rural areas. The current work adds an extra step to the previous academic literature on the topic [39,44] by developing an original material flow analysis, useful for clarifying technical, practical and strategic aspects related to anaerobic digestion and composting in rural areas. Moreover, the research links its insights to the novel proposals of the National Recovery and Resilience Plan (NRRP) and the Common Agricultural Policy (CAP) at the local and international levels.

The research is structured as follows: (i) the description of the research context, including the definition of the study area and the technical characteristics of the anaerobic digestion and composting plant under research; (ii) the illustration of the materials and methods with a focus on the material flow analysis approach; (iii) the presentation of the results by distinguishing among biogas, digestate and composting production; and (iv) the discussion of the results and conclusions.

2. Research Context

2.1. Study Area

In Italy, the association "I Borghi più belli d'Italia", on the initiative of the Tourism Council of the National Association of Italian Municipalities (ANCI) to enhance the heritage of history, art, culture, environment and traditions present in the small Italian towns, has developed a list of the 100 most beautiful villages. Among the several admission criteria to obtain the quality label, it is required that (i) the population in the ancient village or the historic center does not exceed 2000 inhabitants; (ii) the population of the entire municipality does not exceed 15,000 inhabitants; (iii) the village must have at least 70% of historic buildings prior to 1939; and (iv) the village offers a heritage of quality, which is appreciated under urban and architectural planning (i.e., concrete facts, valorization policies, development, promotion and animation) [45].

In the Apulia region (Southern Italy), 14 villages were selected, as follows: Alberobello, Alberona, Bovino, Cisterino, Locorotondo, Maruggio, Monte Sant'Angelo, Otranto, Pietramontecorvino, Presicce–Acquarica, Roseto Valfortore, Sammichele di Bari, Specchia, Vico del Gargano. Figure 1 illustrates the 14 villages in the Apulia region, their geolocation and the number of inhabitants.

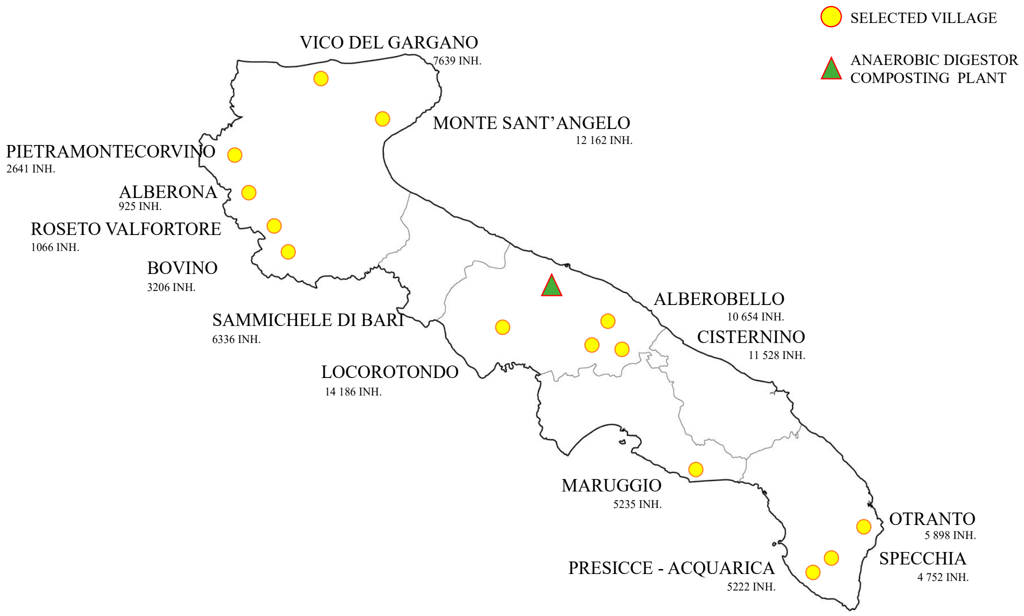

Figure 1. List of the selected 14 villages in Italy, their number of inhabitants and anaerobic digestion and composting plant. Note: INH. = inhabitants. Source: Personal elaboration by the authors on Istat [46].

Considering the definition of "rural area", which states that the population density of rural areas is very low [47]—on average 150 inhabitants per km^2 [48]—the selected 14 villages could be considered as rural communities. Specifically, the lowest population density is recorded in Alberona (17 inhabitants per km^2), followed by Roseto Valfortore (19 inhabitants per km^2) and Pietramotecorvino (34 inhabitants per km^2), whereas the highest values belong to Locorotondo (287 inhabitants per km^2), Alberobello (250 inhabitants per km^2) and Presicce–Acquarica (224 inhabitants per km^2). Out of the 14 selected villages, it results that the average population density is 123 inhabitants per km^2, making them suitable examples of rural communities.

2.2. Characteristics of the Anaerobic Digestion and Composting Plant

The plant under research is powered by raw materials listed in the Decree 10 October 2014 and in the subsequent applicative procedures included in the Ministerial Decree 2 March 2018, namely "raw materials and fuels that give rise to biofuels that can be accounted for as advanced". Considering its definition, the anaerobic digestor plant treats "biodegradable waste from gardens and parks, food and kitchen waste produced by households, restaurants, catering services and retail outlets and similar waste produced by the food industry collected separately" [49]. The produced biomethane, defined as "advanced biomethane", is fed into the natural gas network and destined for the automotive sector, according to the circular economy principles.

The theoretical anaerobic digestion and composting plant is sited in a rural (and central) area in Southern Italy (on average, far from the selected 14 villages about 157 km), as illustrated in Figure 1. The landscape is characterized by calcareous plains, mild gradients with pinkish-white limestone outcropping (grayed by lichens and moss) and the widespread presence of sinkholes, with a rare presence of wooden trees and vegetation. From the economic perspective, scarce areas are cultivated, whereas others, characterized by outcropping rocks, are destined for grazing and animal breeding. Although the area has somewhat been transformed by agricultural activities, which have replaced woods, olive oil fields, vineyards, orchards and arable land, it is still part of the rural areas characterized by downy oak woods and reforestation with pines and cypresses, as well as little household and agritourism complexes. Specifically, the area does not present high construction works, neither residential nor non-residential, whereas some abandoned farmhouses, ruined stone artifacts and agricultural warehouses are present. Within 1 km, there are no residential households, no schools or hospitals, no sports or recreational facilities, no water intake work intended for human consumption, no streams (or lakes or sea), no public sewer, no methane pipelines, gas pipelines, aqueducts or oil towers and no electrodes with a power greater than or equal to 15 kW. On the other hand, there are some productive activities, communication infrastructures and nature reserves, parks and agricultural areas.

The capacity of the theoretical anaerobic digestion and composting plant is equal to 100,000 t/year, of which 90,500 t/year (90.5%) of organic waste and 9500 t/year (9.5%) of green fraction used as a structuring agent in the composting process. As regards the operational data, the supplying of organic waste considers a period or reception of 261 days per year and 8 h of operation per day, as well as the mechanical pretreatment of the organic waste. In the field of the anaerobic digestion process, the period of reception is 365 days per year and 24 h of operation per day. Last, the digestate treatment considers a period of reception of 351 days per year and 8 h of operation per day.

Specifically, the anaerobic digestion and composting plant consists of the subsequent plant sections: (i) reception and mechanical pretreatment of inbound waste; (ii) anaerobic digestion process; (iii) dehydration of the digestate; (iv) aerobic stabilization and composting; (v) liquid digestate process and water treatment; (vi) biogas treatment and valorization; (vii) biomethane production.

Figure 2 illustrates the functioning of the anaerobic digestion and composting plant. Inputs identified under the section "feedstock" correspond to the admissible waste, as highlighted by the CER codes illustrated in the EER (Elenco Europeo Rifiuti) [50].

Several steps characterize the anaerobic digestion and composting plant. First, the mechanical pretreatment regards an evaluation process, which separates the organic fraction (composed of organic waste, wood and paper) from the non-organic fraction (composed of plastics, glass and metals). If the non-biodegradable fraction is higher than 10%, the supplied solid waste should be rejected. Non-organic waste is additionally sent to drying and compacting systems in order to reduce their amount and maximize the recovery of organic material and recyclable components. The organic fraction is sent to the polishing system for the removal of its pollutants, which takes place by using the hydro-cyclone and the decanter for sand removal. Soon after evaluation and storage, the organic fraction is subject to a first mechanical treatment, which transfers waste into a specific machine, which shreds waste into small pieces and homogenizes them in terms of size. Subsequently, such a fraction characterized by an average water content of 70% is pressed to reach a water content from 50 to 60%. The anaerobic digestion process encompasses three different tanks, namely (i) the hydrolysis tank, which starts the metabolization; (ii) the digestor tank, where a minor degradation takes place to generate biogas with a composition of approx. 60% of CH_4 and 40% of CO_2, as well as an additional purification from sulfur; and (iii) the digestate tank, in which liquid and solid digestate are separated. The solid digestate is sent to a composting process, whereas the liquid one is addressed to the wastewater treatment plant.

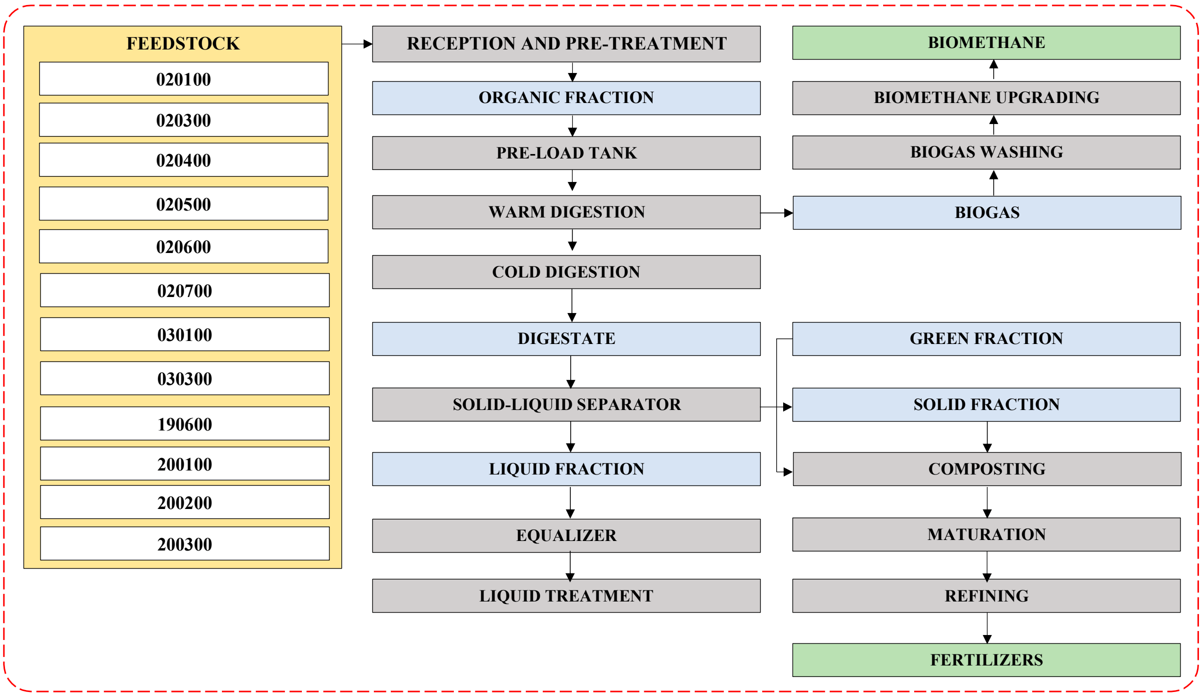

Figure 2. Flow diagram for the anaerobic digestion and composting plant. Note: Dashed lines illustrate the system boundaries. Gray blocks identify processes, blue blocks identify semi-finished products, and green blocks identify finished products. Source: Personal elaboration by the authors.

As regards the inputs entering the anaerobic digestion and composting plant, it is possible to distinguish among (a) the organic fraction coming from the separate collection, addressed to pretreatment, anaerobic digestion and composting; (b) pruning waste from public and private green areas and wood-cellulosic residues, addressed to composting after shredding of the lignocellulosic waste in the treatment line; and (c) the residual organic biodegradable fraction. As to be admissible to the anaerobic digestion plant, the organic waste fraction should respect the subsequent parameters: (i) humidity (105 °C), constant weight from 70 to 85%; (ii) solid organic waste (105 °C), constant weight from 10 to 30%; (iii) volatile solids from 75 to 100%; (iv) content of contaminants, less than or equal to 15%; and (v) BMP value (after removal of overgrown sand and aggregates) more than or equal to 164 Nm^3/t.

3. Materials and Methods

3.1. Research Strategy

First, the research develops the material flow analysis for the anaerobic digestion and composting plant described in Section 2.2, which represents a current reality in Southern Italy. Secondly, on the basis of the results obtained from the theoretical assessment of the described anaerobic digestion and composting plant, the research calculates the biomethane, digestate and compost potential in Southern Italy through anaerobic digestion, considering the amount of organic waste produced in 14 villages. Last, the research compares the advantages and disadvantages of producing biomethane through anaerobic digestion or resorting to community composting in rural areas.

3.2. Material Flow Analysis of the Anaerobic Digestion and Composting Plant

Data are analyzed according to the material flow analysis, which is defined as a "systematic assessment of the state and change of materials flow and stock in space and time" [51]. Such a tool has been successfully applied in the literature, demonstrating its utility in evaluating single products, industrial sectors or entire countries' socio-economic metabolism [52–54]. The current material flow analysis considers several material streams associated with biogas and biomethane production (Section 4.1), digestate production (Section 4.2) and compost production (Section 4.3).

The research develops the material flow analysis for the anaerobic digestion and composting plant described in Section 2.2, to provide a transparent and clear model of a real system [55,56]. Calculations were performed through the STAN 2.7.101 software, developed by the Institute for Water Quality, Resources and Waste Management at the Vienna University of Technology. Such software, which balances flows throughout the anaerobic digestion and composting plant, was updated in February 2022. The functional unit corresponds to the theoretical carrying capacity of the anaerobic and composting plant, namely 100,000 t/year, of which 90,500 t/year (90.5%) of organic waste and 9500 t/year (9.5%) of the green fraction used as a structuring agent in the composting process. The system boundaries start with the reception and pretreatment of the organic fraction and end with biomethane and compost production (Figure 2).

Secondly, the research calculates the biomethane, digestate and compost potential in Southern Italy, considering the amount of organic waste produced in 14 villages, namely Alberobello, Alberona, Bovino, Cisterino, Locorotondo, Maruggio, Monte Sant'Angelo, Otranto, Pietramontecorvino, Presicce–Acquarica, Roseto Valfortore, Sammichele di Bari, Specchia, Vico del Gargano (Table 1).

Table 1. Municipal solid waste per village in Southern Italy per year, focusing on the organic fraction (kg).

Village	Sorted w.	Unsorted w.	Total w.	Procapite w.	Organic Fract.
Alberobello	3,524,957	1,551,460	5,076,417	476	775,491
Alberona	-	-	-	-	-
Bovino	543,830	494,560	1,038,390	324	119,643
Cisternino	4,366,101	1,211,500	5,577,601	484	960,542
Locorotondo	3,967,259	1,396,910	5,364,169	378	872,797
Maruggio	3,277,640	1,281,480	4,559,120	871	721,081
Monte Sant'Angelo	2,511,265	2,261,320	4,772,585	392	552,478
Otranto	14,832,58	3,858,360	5,341,618	906	326,317
Pietramontecorvino	587,360	252,120	839,480	318	129,219
Presicce–Acquarica	2,631,333	1,330,060	3,961,393	759	578,893
Roseto Valfortore	224,153	70,680	294,833	277	49,314
Sammichele di Bari	2,011,558	695,580	2,707,138	427	442,543
Specchia	545,085	1,159,950	1,705,035	359	119,919
Vico del Gargano	2,167,345	1,237,160	3,404,505	284	476,816
Total	27,841,144	16,801,140	44,642,284	488	6,125,052

Note: w. = waste; fract. = fraction. Source: Personal elaboration by the authors on Regione Puglia [11].

3.3. Data Collection

Primary data related to the anaerobic digestion and composting plant were retrieved from a theoretical plant located in Southern Italy, combining the investigation of official documents and reports with observations of the anaerobic digestion plant and personal communication with key people involved in the process, namely project managers and engineers.

As regards data collected on the waste streams in the 14 villages, secondary data were retrieved from the Regione Puglia [11]. Specifically, data distinguish between sorted and unsorted municipal solid waste. As regards the organic fraction, it results that out of the total amount of solid waste generated in Apulia (approx. 1.1 Mt), about 22% is organic waste coming from households, kitchens and canteens, and the research applies such a coefficient to estimate the organic faction sorted in each village [11].

Table 1 summarizes the municipal solid waste per village in 2022. Out of the 14 selected villages, data related to one village are not available (i.e., Alberona), whereas data related to two villages refer to 2020 (i.e., Pietramontecorvino, Specchia). It appears that the waste per capita per year ranges from 224 to 906 kg, which means about 0.62 to 2.51 kg per person per day, in line with previous studies conducted in rural areas [15]. However, the highest peak is recorded in Otranto, which represents the largest village. On average, it results that 1.35 kg of waste per person per day is generated in the selected areas.

In the field of the comparison between anaerobic digestion and community composting, the research relies on secondary data retrieved from Rashid and Shahzad [57], considering their economic and environmental assessment of organic waste recycling into compost, and De Boni et al. [12], who conducted a life cycle assessment of community composting. Specifically, Rashid and Shahzad [57] evaluated a transformation coefficient of the organic fraction into compost of 25% in Saudi Arabia, whereas De Boni et al. [12] evaluated a transformation coefficient of the organic fraction into compost of about 30% in Italy.

4. Results

4.1. Material Flow Analysis for the Biogas Production

Figure 3 illustrates the material flow analysis for the biogas production. The biogas production system is composed of five main processes and several input and output streams. First, it results that 90,500 t of organic waste and 171,599 t of well water are required to begin the process. Once the water has been taken from the well, it circulates into the anaerobic digestion and composting plant: 142,532 t is recovered from the solid–liquid separator (Figure 4), and 19,067 t is obtained from ultrafiltration. Organic waste and other inputs are first addressed to bag openers, magnetic separators and ECS (eddy current system for nonferrous metals) separators. The entire number of mixed materials is addressed to the non-organic fraction separator, from which it results that 9099 t of non-reusable fraction and 6286 t of additional organic fraction are obtained. In the pre-load tank, through a sand trap, about 2197 t of sand is intercepted and collected. The (diluted) organic fraction, which amounts to 250,803 t, is addressed to the anaerobic digestor and is transformed into two main outputs, namely (i) biogas, for an amount of approx. 14,918 t, and (ii) digestate, for an amount of 235,885 t.

From the energy consumption perspective, it results that the average electricity consumption is 1490 MWh and about 7290 MWh in terms of thermal energy.

It results that approx. 14,918 t of biogas could be produced starting from 90,500 t of organic waste (rate of efficiency at 16%). Once the biogas is produced, it is sent to purification through desulfurizer and activated carbon and then addressed to upgrading. The quality of the biogas is supposed to have a 58% methane content and a 99% transformation efficiency. Hence, the production of biomethane after upgrading could theoretically be up to 8652 t. Specifically, the highest calorific value of the generated biomethane is estimated from 34.95 to 45.28 MJ/Sm^3, with an O_2 content of less than 0.6 %mol, a CO_2 content of less than 2.5 %mol, a H_2S content of less than 5 mg/Sm^3 and a sulfur content of less than 20 mg/Sm^3. The quality parameters of the generated biomethane are suitable for injection into the distribution/transport network via direct connection to the methane pipeline and are in line with the compliance identified by the UNI/TR 11537:2016 and UNI EN 437:2021.

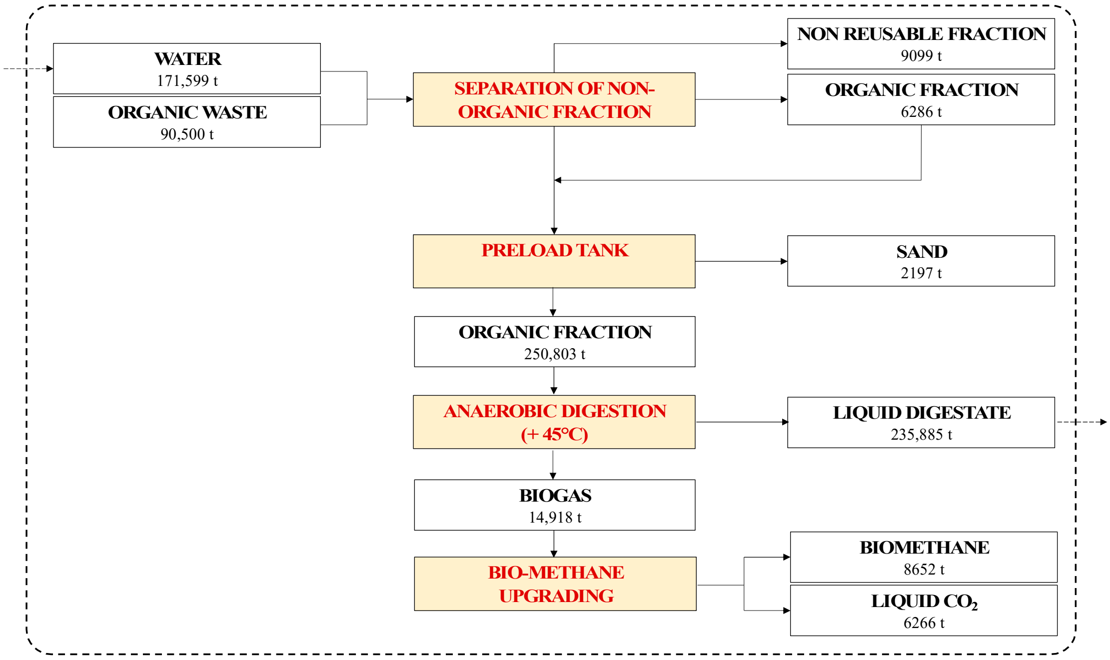

Figure 3. Material flow analysis for biogas production (t). Source: Personal elaboration by the authors using STAN 2.7. Calculations are based on primary data.

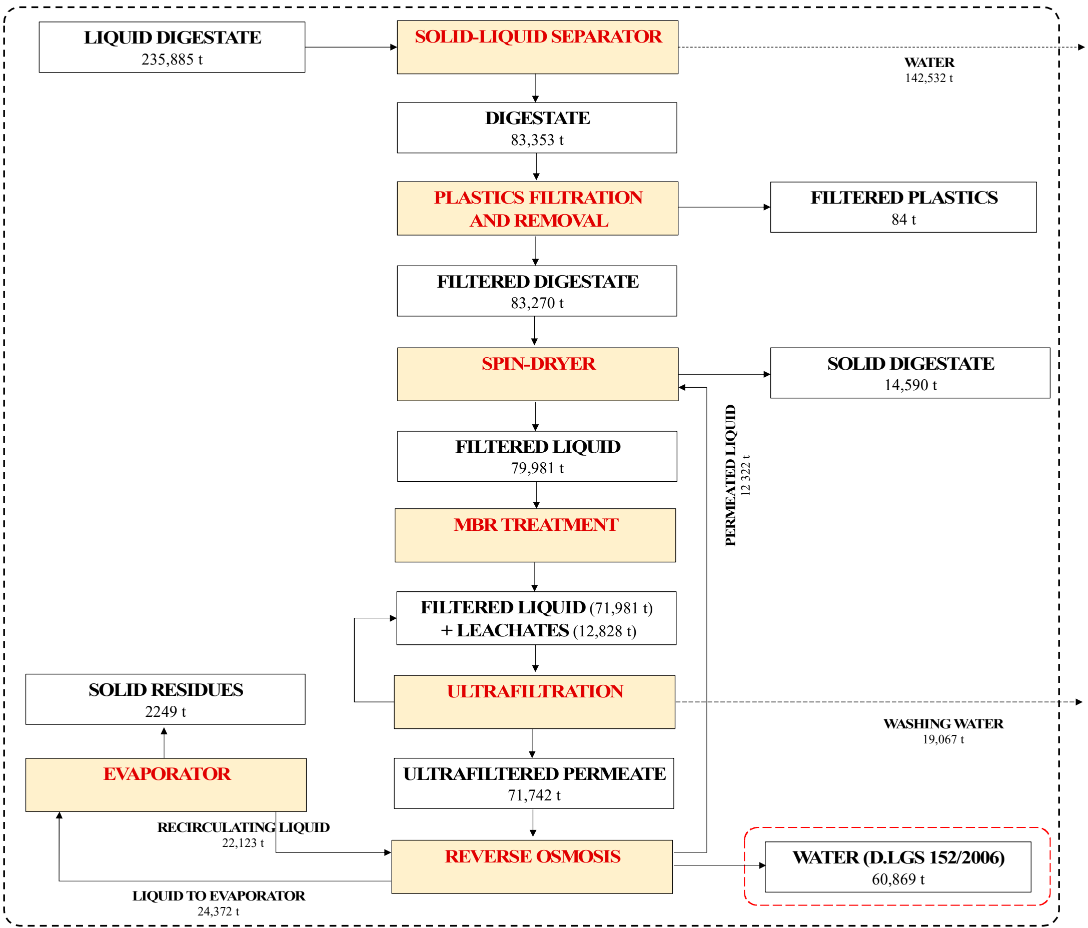

Figure 4. Material flow analysis for digestate production (t). Source: Personal elaboration by the authors using STAN 2.7. Calculations are based on primary data.

4.2. Material Flow Analysis for the Digestate Production

Figure 4 illustrates the material flow analysis for the digestate production. The substrates that have reached the end of the anaerobic digestion process (235,885 t) are sent to solid–liquid separation, plastic filtration and a spin-dryer system, where the solid fraction of the digestate (14,590 t) is separated from water (142,532 t), plastics (84 t) and the filtered liquid (79,981 t). Subsequently, the filtered liquid is sent to purification through a membrane bioreactor (MBR) treatment, as well as ultrafiltration and reverse osmosis. In the reverse osmosis plant, the liquid to the evaporator (24,372 t) and the water according to the D.Lgs 152/2006 on "Emission limits for urban and industrial wastewater to be released to the ground" (Annex 5, part III)" are generated (60,869 t) [58].

Through the MBR treatment, as well as through the ultrafiltration and the reverse osmosis process, the treated water can achieve the pre-established parameters for dispersion in subirrigation. The outbound effluent from the liquid digestate treatment must comply with the quality limits identified by the Legislative Decree No. 152/2006 (and subsequent amendments and additions) on the emission limits for urban and industrial wastewater that is discharged into the ground [58].

From the energy perspective, it results that 3690 MWh of electricity and 4920 MWh of thermal energy are required to feed the entire digestate production.

4.3. Material Flow Analysis for the Compost Production

It is possible to consider the combined production of compost from the anaerobic digestor, as outlined in Figure 5. Starting from the introduction of green fraction (9500 t) as a structuring agent and 14,590 t of solid digestate, which represents an output from the spin-dryer process in the digestate production (see Figure 4), into the mixer, it is possible to obtain 32,885 t of the blend fraction. Such a fraction is addressed to biocells, with an efficiency of 80%, which help mature waste for an amount of 26,308 t. During curing, which has an efficiency rate of 90%, it is possible to obtain additional recyclable overstock (8419 t) and intermediate compost, which accounts for 15,259 t. Last, the intermediate compost is introduced into a winnowing process, with an efficiency rate of 95%, to produce approx. 14,495 t of compost.

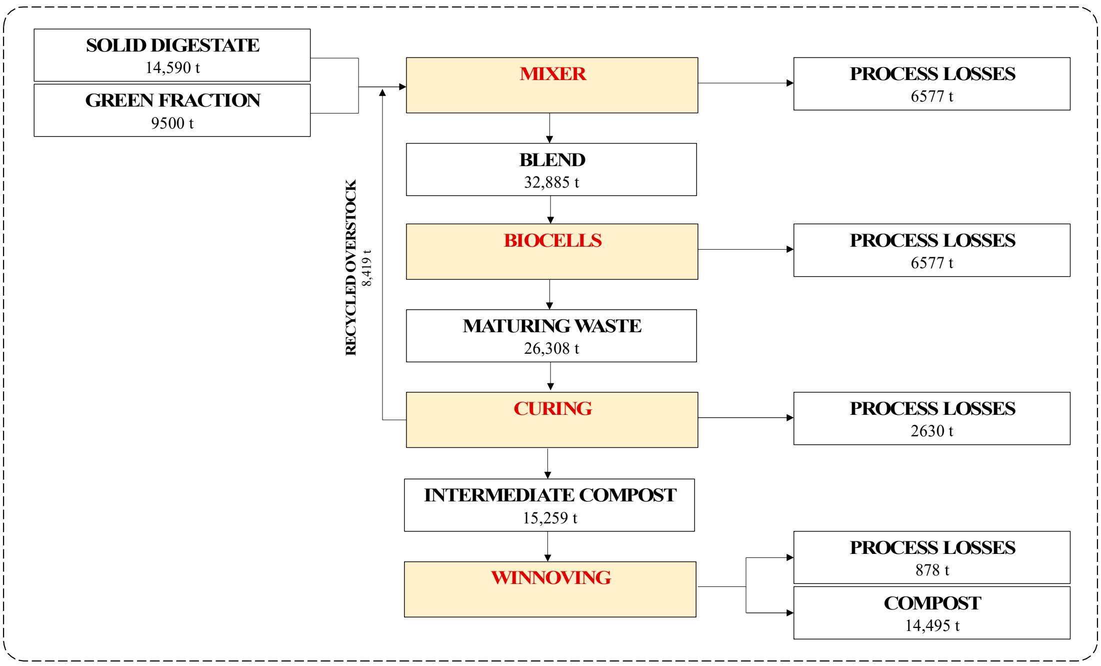

Figure 5. Material flow analysis for compost production (t). Source: Personal elaboration by the authors using STAN 2.7. Calculations are based on primary data.

Of course, if the humidity, pH, organic c, organic nitrogen and other hygienic parameters do not allow for considering the compost as "absolute non-hazardous" (EWC Code 19 05 03), it must be reprocessed at the beginning of the compost section, repeating the entire process.

4.4. Biomethane, Digestate and Compost Potential through Anaerobic Digestion in Southern Italy

As outlined by Table 1 (Section 3.2.), the average rate of separate collection of municipal solid waste is 62%. Its peak is recorded in the village of Cisternino (78%), whereas the lowest peak is in the village of Otranto (28%). It must be pointed out that the amount of organic fraction available for biomethane, digestate and compost production depends on the amount of sorted waste, unsorted waste being mainly addressed to incineration for energy recovery or landfilling. Therefore, one first consideration concerns the need to increase separate collection rates, in order to also increase the amount of substrate (i.e., organic waste) available for anaerobic digestion and composting processes.

In the light of Figure 1, it results that the selected 14 villages are concentrated in three main areas, namely six in the North of the Apulia region (i.e., Vico del Gargano, Monte Sant'Angelo, Pietramontecorvino, Alberona, Roseto Valfortore, Bovino), four in the Center of the Apulia region (i.e., Alberobello, Cisternino, Locorotondo, Sammichele) and four in the South of Apulia (i.e., Otranto, Specchia, Presicce–Acquarica). These areas generate approx. 1,327,470 kg in Northern Apulia, 3,051,373 kg in Central Apulia and 1,746,210 kg in Southern Apulia, for an amount of 6,125,052 kg. Table 2 illustrates the biomethane, digestate and compost potential in Southern Italy, by distinguishing it per each village.

Table 2. Biomethane, digestate and compost potential per village in Southern Italy (kg).

Village	Organic Fraction	Biogas	Biomethane	Digestate	Compost
Alberobello	775,491	127,801	53,664	120,899	119,271
Alberona	-	-	-	-	-
Pietramontecorvino	129,219	21,295	8942	20,145	19,874
Vico del Gargano	476,816	78,579	32,996	74,336	73,334
Roseto Valfortore	49,314	8127	3413	7688	7584
Bovino	119,643	19,717	8279	18,652	18,401
Sammichele di Bari	442,543	72,931	30,624	68,992	68,063
Cisternino	960,542	158,297	66,470	149,748	147,731
Locorotondo	872,797	143,837	60,398	136,069	134,236
Maruggio	721,081	118,834	49,899	112,417	110,902
Otranto	326,317	53,777	22,581	50,873	50,188
Presicce–Acquarica	578,893	95,402	40,059	90,249	89,034
Specchia	119,919	19,763	8298	18,695	18,444
Monte Sant'Angelo	552,478	91,048	38,231	86,131	84,971
Total	6,125,052	1,009,409	423,854	954,896	942,033

Note: It should be considered that per 1 t of organic waste entering the anaerobic digestion plant, 1.68 t of dilution and 0.21 t of water are required. In the composting plant, per 1 t of solid digestate entering the plant, additional 0.67 t of green fraction (as a structuring agent) is required. It results that the rates of efficiency are (i) for biogas, approx. 16%; (ii) for biomethane, 9.40% (55% of biogas); (iii) for digestate, about 16%; and (iv) for compost, 15%. Source: Personal elaboration by the authors.

Considering that the entire amount of organic fraction generated in the selected 14 villages is about 6,125,052 kg per year, which represents about 6% of the estimated amount required in the theoretical anaerobic digestion plant, it could be possible to obtain 569,755 kg of biomethane and 918,758 kg of compost for local communities. On the contrary, if the selected villages resort to community composting, it would be possible to obtain from 1,531,265 to 1,837,515 kg of compost, which represents about 40–50% more than the amount of compost obtainable in the theoretical anaerobic digestion plant. However, if local communities adopt community composting strategies, this will imply the absence of biomethane and digestate production.

From the environmental perspective, the theoretical anaerobic digestion and composting plant is far (on average 157 km) from each selected village, which means that organic waste must be transported with EURO4 7.5—16 t lorry trucks [48]. It results that the main shortcoming is related to the transportation of organic waste to the anaerobic digestion plant, since transportation must take place with a certain frequency, with organic waste being subject to rapid degradation. However, keeping transportation out of boundaries, it should be highlighted that the anaerobic digestion treatment presents the best environmental performance among different valorization pathways of organic waste [59]. Indeed, the anaerobic digestion and composting plant includes an upgrading system for the production of biomethane and the pressure swing adsorption (PSA) system to separate CH_4 from CO_2, which opens paths for carbon neutrality due to the production of biomethane without carbon dioxide emissions. Hence, although direct emissions associated with anaerobic digestion and biomethane production are on average 66 kg of CO_2eq per t of treated waste [60], namely 404 t of CO_2eq in the field of the selected villages, such an amount can be reduced up to zero by using upgrading and CO_2 liquefaction plants. Therefore, the only emissions would be associated with transportation.

Conversely, the adoption of community composting would reduce the amount of CO_2eq emissions associated with the transportation of organic waste. As outlined by De Boni et al. [12] and Mondello et al. [60], collecting organic waste from neighboring municipalities would reduce the paths and fuel consumption for collection and transportation, with community composting plants being far (on average about 15 km). By considering data from De Boni et al. [12], which estimated the emissions associated with transportation (using diesel vehicles), waste collection, composting process and water consumption, the average emissions associated with organic waste composting are about 12.59 kg CO_2eq per t of treated waste. The use of community composting would generate approx. 77 t of CO_2eq, which is a small amount compared to the emissions associated with anaerobic digestion (404 t of CO_2eq emissions), landfilling (about 1243 kg CO_2eq per t of treated waste, namely 7613 t of CO_2eq) and incineration (about 822 kg of CO_2eq per t of treated waste, namely 5034 t of CO_2eq) [12,60].

5. Discussion

The current section presents policy implications in the light of the NRRP and the CAP (Section 5.1), the environmental consequences of biomethane and compost production in the field of waste-to-energy and waste-to-bioproducts (Section 5.2) and the economic implications of implementing an anaerobic digestion plant (Section 5.3).

5.1. Policy Implications

The development of anaerobic digestion and composting plants in Southern Italy should be read in the light of the interventions implemented by the NRRP and the CAP as well as considering that one of the main challenges in implementing such plants in rural areas is the high capital construction costs and the large engineering volumes required.

The NRRP, which is a EUR 750 billion package [61], aims at allowing a green, ecological and inclusive transition by promoting the circular economy, the development of renewable energy sources and more sustainable agriculture [61], and organic waste valorization (i.e., waste-to-energy, waste-to-bioproducts) should be included in such strategies. In the field of circular economy and waste management (i.e., Mission 2, so-called "Green revolution and ecological transition"), the NRRP includes interventions to enhance the separate collection networks, the material treatment and the recycling plants by developing infrastructures and facilities of organic waste [62]. As regards the CAP, which is defined as a "partnership between agriculture and society, and between Europe and its farmers" [63], its goals regard the maintenance of rural areas and the landscapes across Europe, as well as keeping the rural economy alive by promoting jobs in farming, agri-food industries and associated sectors. In addition, the CAP aims to mitigate and adapt to climate change, including the reduction in greenhouse gas emissions, the improvement of carbon sequestration, the promotion of sustainable energy and the reduction in chemical dependency [64]. In the light of the results, the adoption of the anaerobic digestion and composting plant should be considered as an adequate technology to achieve environmental, economic and social sustainability, in line with both the NRRP and the CAP requirements.

Though the valorization of organic waste is an essential aspect of achieving environmental and economic sustainability, food waste prevention represents the most desirable solution from the waste management perspective [24]. Especially in the tourism sector, in which an increase in waste is estimated as a result of numerous variables such as divergent socio-demographic factors and food consumption habits, such as food neophilia [65]. In Europe, several initiatives have been launched to minimize food waste in tourism and hospitality, such as the "Zero Waste Tourism" campaign in Slovenia or the EU Life Foster Project in Malta [65]. As outlined by previous research on the topic [66,67], there are new and innovative ways to manage and minimize food waste through digital platforms and mobile apps, which can help local hotels or bed and breakfasts to sell unsold food or food surplus at discounted prices. In addition, strengthening the education of tourists represents a necessary means to reduce food waste, chiefly for young tourists [68].

5.2. Environmental Implications

It has emerged that from 27,841,145 kg of solid waste, of which 22% is represented by organic waste, it is possible to generate 423,854 kg of advanced biomethane, 954,896 kg of digestate and 942,033 kg of compost, with an efficiency of 9% in the field of biomethane and about 15% as regards compost production.

From the environmental perspective, biomethane and compost production represent one suitable intervention in the field of waste-to-energy and waste-to-bioproducts [7,8], allowing for the reduction in the emission into the soil, atmosphere and waterbodies associated with organic waste disposal. Further, such interventions could permit the production of organic compost, as well as renewable energy sources (i.e., bioenergy, advanced biomethane), to be used by local farmers to cultivate lands and power their facilities (e.g., tractors, transportation vehicles, machinery). The reduction in the withdrawal of raw materials from the soil and the chance of fertilizing the lands with organic fertilizers (rather than chemical ones) allow farmers to preserve the biodiversity of rural agricultural areas and promote sustainability. Such an aspect, namely the supplying of foods grown according to seasonality, locality and sustainability characteristics, represents a key objective of the CAP and can boost food and gastronomic tourism [69]. Last, the increase in the production (and the use) of biomethane could indirectly influence the achievement of Mission 3 of the NRPP, which requires the development of infrastructures for sustainable mobility [70,71].

Theoretically, considering 1 t of organic waste, the life cycle impact assessment related to the anaerobic digestion highlights a negative environmental performance (-39 kg CO_2eq) by including credits applied for the displacement of grid electricity and mineral fertilizers [72]. Specifically, the combined anaerobic digestion and composting have several environmental benefits due to the potential for energy generation by using biogas as a fuel and by substituting mineral fertilizers with digestate. In addition, since organic waste is treated in a completely closed system, it helps reduce odors and control biogenic emissions from the composter and the digester, unlike the windrow community composting [73,74].

5.3. Economic Implications

From the economic and social perspective, anaerobic digestion and composting plants could generate direct value by creating job opportunities (i.e., separate collection logistics, industrial plants) and high-added value products (i.e., advanced biomethane) [70] and indirect value by reducing CO_2 emission pricing [12]. In the field of CAP financial support, it results that about EUR 60 billion have been distributed to farmers in 2019, of which 23% (EUR 14.17 billion) in terms of rural development [63]. Specifically, the CAP defines several strategies to boost rural community development, protect natural resources and create jobs linked to farming. Among others, several interventions are directly linked with the development of anaerobic digestion and compost plants, such as sustainable fuel and organic fertilizer production (i.e., so-called jobs in the "upstream" sectors of the agricultural sector).

The economic performance of the anaerobic digestion and composting plant represents an interesting field of discussion. It was theoretically considered in the current research, but future research requires an in-depth investigation of the topic, specifically a technical-economic analysis of the plant under investigation. In the light of the previous literature [75], the construction of an anaerobic digestion plant with an annual capacity of 40,000 t requires an initial investment of about EUR 35 million with additional operating costs of EUR 1.3 million per year. A total saving/income of EUR 6 million per year is estimated, with a payback period of approx. 5 years. Considering the annual revenue, it results that the output of the anaerobic digestion (i.e., biomethane, digestate) has an average selling price that is higher than the compost one, but profitability should be calculated as a function of CO_2eq saved and not only as a function of kWh or m^3 produced, and subsidies by public authorities are also required [76]. On the contrary, on the basis of a plant that treats 240 t of organic waste, equivalent to 72 t of compost, composting requires an initial investment of about EUR 234,900 (i.e., composting plant, hopper, shredder, trucks, etc.), to which additional EUR 42,000 must be added in terms of variable costs, due to labor, energy or fuel consumption [12]. The cash flow is estimated on the basis of EUR 1 per kg of compost; then, a minimal return year for an investment in community composting for rural areas is estimated between 6 and 7 years [12,77]. Economic benefits are associated with the total earnings from the sale of compost per year and the cost of the avoided landfilling.

6. Conclusions

The research represents an extra step toward the sustainability of rural areas in the field of organic waste minimization and valorization. First, it developed the material flow analysis of a theoretical anaerobic digestion and composting plant. Secondly, the research evaluated the theoretical biomethane, digestate and compost potential of 14 selected rural communities in Southern Italy. From the environmental perspective, biomethane and compost production represent one suitable intervention in the field of waste-to-energy and waste-to-bioproducts, allowing for the reduction in the emission into the soil, atmosphere and waterbodies associated with organic waste disposal. However, huge financial investments are required by public authorities to enhance logistics and separate collection facilities, as well as to construct anaerobic digestion and composting plants.

Although the research is limited to one theoretical anaerobic digestion and composting plant, it was selected since it represents a real, accessible and available example of technology in Southern Italy and is comparable and replicable in space and time. Several benefits are associated with anaerobic digestion plants. On the one side, these renewable secondary raw materials can reduce air and soil pollution associated with organic waste disposal and can increase, on the other side, the production of high-quality fertilizers. In other words, the general aims of sustainability can be reached by reducing the amounts of organic waste sent to landfilling and incineration by increasing the amount of renewable energy, which can even minimize the withdrawal of virgin natural resources to produce energy.

Considering that the research regards 14 selected rural communities, future research direction should enlarge the evaluation of the biomethane, digestate and compost potential by considering the organic fraction generated by tourists. Further, such an analysis could be enlarged to the selected list of the 100 most beautiful villages in Italy, to provide a theoretical snapshot of the entire Italian reality. Last, a technical-economic analysis of the plant under investigation is required, to complete the environmental analysis (conducted with the material flow analysis) with the economic analysis (conducted with the material flow cost accounting).

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