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Biogas from Agri-Food and Agricultural Waste Can Appreciate Agro-Ecosystem Services: The Case Study of Emilia Romagna Region

Elena Tamburini *, Mattias Gaglio, Giuseppe Castaldelli and Elisa Anna Fano

Department of Life Sciences and Biotechnology, University of Ferrara, 44121 Ferrara, Italy;
gglmts@unife.it (M.G.); ctg@unife.it (G.C.); fne@unife.it (E.A.F.)
* Correspondence: tme@unife.it; Tel.: +39-532-455172

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Abstract: Agro-ecosystems are intensively exploited environments which are both providers and consumers of ecosystem services. The improvement of both provisioning and regulating services in cultivated landscapes is crucial for the sustainable development of rural areas. Among the provisioning services offered, producing biogas from the anaerobic digestion of residual biomass is nowadays a promising option for decreasing greenhouse gas (GHG) emissions, while avoiding the land use conflicts related to the use of dedicated crops. Based on the available quantitative data at a regional level, provisioning and regulating services provided by the use of agri-food waste, livestock waste and agricultural residues were assessed for the case of Emilia Romagna region, the second biggest biogas producer in Italy. One provisioning service, i.e., bioenergy generation, and three regulating services were considered: (i) air quality improvement by the reduction of odors derived from direct use of waste, (ii) regulation of soil nutrients by reducing organic load and digestate spreading, and (iii) global climate regulation by saving GHG emissions. A potential further generation of 52.7 MW electric power was estimated at the regional level. Digestate spreading on fields may reduce odor impact by more than 90%, while containing a higher percentage of inorganic nitrogen, which is readily available to plants. The estimated GHG emission savings were equal to 2,862,533 Mg CO_2eq/yr, mainly due to avoided landfilling for agri-waste and avoided replacing of mineral fertilizers for livestock waste and agricultural residues. The results suggest that bioenergy generation from lignocellulosic, livestock and agro-industrial residues may improve some regulating services in agro-ecosystems, while helping to reach renewable energy targets, thus contributing to overcoming the provisioning vs. regulating services paradigm in human-managed ecosystems.

Keywords: biogas; agricultural residues; livestock waste; animal manure; ecosystem services; agri-food waste

1. Introduction

Agriculture covers about a half of the world's habitable land [1] and represents the largest human-managed ecosystem [2]. Its continuous expansion and intensification, which faces up to the urgent nutritional needs of burgeoning populations and to bioenergy demand, especially in developing countries, has currently made agriculture the anthropic activity with the largest impact on environment and ecosystem services (ES) [3]. On the other hand, beyond producing food for the billions of humans on the planet, it is a key interface between humans and the natural environment, providing, and at the same time, depending on several fundamental ES [4]. As ruled by the Millennium Ecosystem Assessment (MA) program, which has run since the early 2000s [5] and is by now well-established, the ES are defined as the benefits for human health and well-being that derive directly or indirectly from ecosystems [6]. Agriculture is a provider of ecosystem services, as well as a consumer of them, and the relationship between agricultural practice and impact on ecosystem services is complex. The environmental changes associated with agriculture affect a wide range of ES including water quality and quantity, soil quality, air quality, carbon sequestration, pollination and pest management, as well as biodiversity, habitat loss and degradation [7]. While agriculture uses ES generated by the surrounding territory (i.e., soil fertility, pollination), the increasing food demands have almost restricted croplands as ecosystems, providing mainly provisioning services at the cost of degradation of a significant number of other services, including habitat provision, water quality regulation and sediment transport [8]. Moreover, soil degradation jeopardizes the productivity of agro-ecosystems, resulting in an overall depreciation of the economic value of the ES [9]. Sutton et al. [10] have recently estimated the global annual loss of value of ES caused by land degradation as a consequence of the poor management of natural capital (soils, water, vegetation, etc.) to be about 630 billion USD, corresponding to 9.2% of the total value of ES provided by agro-ecosystems. However, appropriate management can mitigate many of the negative impacts of agriculture without endangering provisioning services [11]. While agricultural landscapes offer a large potential to reach renewable energy targets and support local economies, bioenergies are often envisaged as a controversial solution for sustainable development because of the related competition for agricultural land. Many efforts have been spent to solve such food-energy dilemmas in the last years. Alternative strategies, based on the circular economy paradigm as an unavoidable option for a more sustainable agriculture development, could be planned starting from the exploitation of the large amount of residues yearly produced by agricultural processes [12]. Within this framework, an important issue is represented by bioenergy production from biomass. The use of residual biomass for energy production is one of the most promising alternative sources for renewable energy. In the last decades, it has assumed great economic and environmental relevance and can be used to close material and energy cycles, to preserve environments, recover resources and reduce the impacts and the quantity of waste [13].

In comparison to other biofuels, biogas is versatile and flexible and can be produced from different feedstock [14]. As is well-known, biogas technology enables the conversion of biomass into energy and digestate through the anaerobic digestion (AD) process. Energy can be used for heat and electricity or biomethane, whilst digestate can be used as a biofertilizer, allowing for nutrient restoration in soil and consequently, increasing feedstock productivity [15]. According to Lijò et al. [16], biogas as a potential renewable energy source could represent 25% of all the bioenergy in Europe in the near future because of its several advantages in terms of energy supply security and economic benefits [17], and it will play a key-role in achieving the target for EU 28 target, approved by the Renewable Energy Directive II (RED), of replacing 32% of final energy consumption with renewable sources by 2030 [18,19]. However, negative environmental issues associated with the use of dedicated energy crops for biogas production have been widely reported in the literature [20]. In particular, it was already demonstrated by Tamburini et al. [21] that biogas from maize, in some cases, does not comply with the greenhouse gas (GHG) emissions thresholds issued by the RED II when indirect land use change (ILUC) effects are accounted for (the RED II states that the average GHG emissions of biofuels plants must be less than 33.5 gCO_2/MJ for new biofuels plants or less than 41.9 gCO_2/MJ for plants installed before 2015). On the contrary, biogas from agricultural residues and agro-food waste has been receiving growing interest due to the fact that it is out of the "food versus fuel" debate and that any mechanism of ILUC occurs because food production continues independently [22].

A large variety of feedstock with no commercial value, such as urban and industrial organic waste, sewage, manure and animal waste, and agricultural by-products, together with energy crops can be destined for biogas systems [23]. Quantitative estimates of the feedstock potentials, i.e., of the biomass waste streams suitable for AD, shows that biogas production in the EU could increase from the current level of 14.9 Mtoe (Million Tons of Oil Equivalent) towards 28.8 to 40.2 Mtoe in 2030, depending on the amount of feedstock availability [24].

Within the context of ES, biogas from residual biomass could be a practical approach to reduce the local energy deficit and mitigate problems of environmental contamination [25]. In fact, at farmer scale, the most usual way of handling animal waste is direct spreading in the soil, which produces significant atmospheric emissions of GHG, consumes fossil energy resources and contribute to odors [26]. Thus, biogas generated from agricultural residues and waste can be considered not only an appealing option to reduce GHG emissions but also an energy product with a provisioning service function that, at the same time, sustains regulating services through the closing of agricultural cycles and avoids undesirable effects in the environment derived from other uses of residual biomass. From that perspective, agriculture moves from a productive to a multifunctional function since it leads to a synergy between production and maintenance of ES while becoming itself a source of ES [27].

The aims of this study were (i) to investigate the potential contribution of biogas from agricultural residues and agri-food waste to sustainable bioenergy management in terms of both environmental benefits and GHG emission savings according to RED II and (ii) to evaluate how biogas generated from residual biomass could contribute to lowering the trade-off of ecosystem services provided by agriculture. To this purpose, we have examined the case of the Emilia Romagna region, Italy. In particular, we have attempted to identify which ES could be provided by the generation of biogas from residual biomass. Based on available standardized data at the regional level, we carried out a quantification of the best indicators for describing the potential benefits for the environment and human well-being.

2. The Case Study

The model case for this study is the Emilia Romagna region, located in the north-east of Italy, in the Po valley plain. With an overall extension of 2,245,300 ha, the region is covered for almost half of the territory by plain and for the remaining part by hills and mountains (27% and 25%, respectively) (Figure 1). The Emilia Romagna region represents an interesting case study because, due to the national incentive policies on renewable energy from biomass in the past years, it has become the second largest biogas producer in Italy, which is, in turn, the second largest producer in Europe, after Germany. Furthermore, the regional economy is principally based on agriculture, livestock and the agri-food transformation industry, all sectors producing large amount of residues and waste [28].

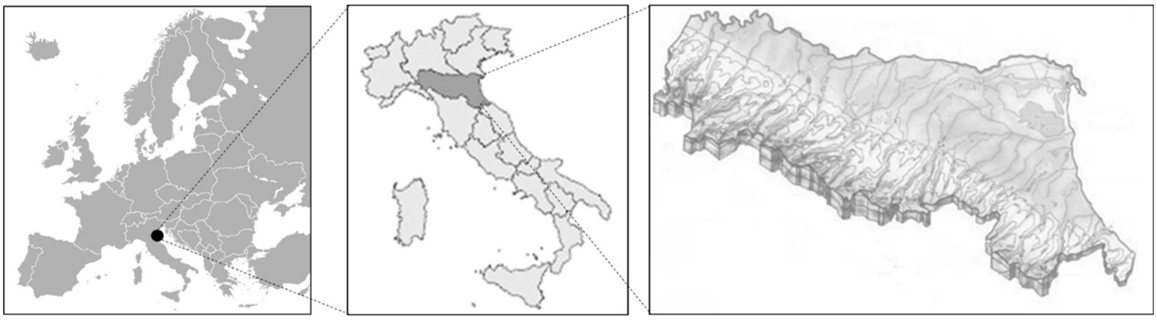

Figure 1. The case study area of Emilia Romagna region, North-East Italy, Europe (modified from [21].

The main urban centers are displaced along the ancient Roman *Via Emilia*, which passes through the entire region in the direction north-west/south-east, ideally dividing the plain zone from the hills and mountains. Agricultural land is principally covered by cereals, such as maize and wheat, and to lesser extent by vegetables and permanent crops, while about 26% is pasture and meadows, which supports the animal farming sector [29].

The Italian energy regulation provides a high level of regional autonomy in adopting local energy policies, depending on the peculiar energy requirements and resource availability of regions. In this regards, the Emilia Romagna region has approved the first Regional Energy Plan

(REP) to 2030, which set the targets and the regional strategy for GHG emissions reduction, energy consumption forecast and bioenergy contribution for the next ten years [30]. In the REP, a notable increase of bioenergy is predicted to come from biogas towards 2030, from the actual 234 megawatts (MW) of installed electric power to 298 MW in a conservative scenario or 320 MW in a best-case scenario. Actually, 215 biogas plants are registered, of which 85% are fed with agricultural and agri-food waste and 15% with the organic fraction of municipal solid waste or landfill gases [31]. Actually, more than 60% of the biogas produced in the region is now based on dedicated crops, with about 31,500 ha of land diverted from food/feed production to bioenergy, originating a cogent question around the land use change effects and the overall sustainability of biogas production [21].

In the plan, the use of agricultural residues (i.e., straws, stalks, cobs, prunings), by-products and waste materials from the sector of agri-food transformation and animal manure is strongly encouraged as an important opportunity to increase sustainability and, indirectly, as a means for farms to increase their own income through the valorization of materials whose disposal currently represents a cost.

3. Materials and Methods

3.1. Ecosystem Services

In this article, the Common International Classification of Ecosystem Services (CICES) classification [32] has been used as a basis for the identification of the ES potentially provided by biogas produced from residual agricultural biomass and from agri-food waste. CICES has adopted a hierarchical framework, where each level provides a more detailed description of the ES. It is indexed in three main categories of services (provisioning, regulating and maintenance, and cultural), and divided in more detailed sections for each of which some indicators have been developed in order to be able to compare ecosystem service supply and demand [33,34]. Starting from previous experiences of Bürhing et al. [27] and Gissi et al. [35], the proposed classification of the ES and possible indicators involved in biogas production from residual biomass and waste are shown in Table 1.

Table 1. Proposal of ecosystem services (ES) involved in biogas production from residual and waste biomass, indicating division, and definition of possible indicators and estimated value in euros (2020).

Section	Division	Definition	Indicator
Provisioning	Energy	Energy production by means of biomass residues and waste anaerobic digestion (AD)	Biomass effective availability as raw material for biogas (Mg/y)
			Biogas/biomethane gross production (Nm^3/y) *
			Potential electric power (MW)
Regulation and maintenance	Mediation of waste, toxic waste and other nuisances	Regulation of air quality by reduction of odors derived from direct use of waste	Perception of odors
	Maintenance of physical, chemical and biological conditions	Regulation of nutrients in soil by reduction of organic load and spreading of digestate	Elemental concentration in digestate (C, N, P, K)
		Regulation of global climate by reduction of GHG emissions	Greenhouse gas (GHG) emission savings ($MgCO_2eq./y$)

* Nm^3 = normal cubic meter.

3.2. Current Regional Biomass Availability and Biogas Yields

Based on data registered by national authorities and local research centers [36–38], the yearly availability at regional level of agricultural residues (animal and vegetal) and agri-food waste has been reported (Table 2). An average percentage ranging from 50% to 70%, depending on the type of material, is already destined to AD or allocated to other uses. For example, milk whey is almost completely used in cattle feeding, as is beet pulp, or used as feeding for AD. Agricultural residues are usually left on field in order to restore part of the organic carbon of the soil or used as animal litter, for animal feeding or buried. The use of straw or wooden agricultural residues as solid biofuels is not yet well-developed in the region, occurring almost only at domestic level, and exploits, at the moment, a small percentage of the overall residues availability [39]. We have assumed that only 10% of straws, cobs and stalks for bioenergy production are collected in order not to compromise the annual organic matter soil balance and nutrient cycling and not to compete with the potential household use of agricultural residues for domestic heating [40]. Residual biomass from pruning has been excluded from the present analysis because it has a better fate as wood-based bioenergy than in biogas production due to its high lignocellulose content and low water content [41]. Average biogas yield and percentages of methane (CH_4) in the biogas have been reported and used for subsequent calculation of gross biogas and biomethane calculations, based on published data available at national and regional level [42,43].

Table 2. Quantity of agricultural residues and agri-food waste produced per year at a regional level, quantity already destined to AD and to other uses, biogas yield and % of CH_4 in biogas (data reported from [42,43]).

Type of Material	Quantity Produced (Mg/y)	Quantity Already Destined to AD (%)	Quantity Already Destined to Other Uses (%)	Biogas Yield (Nm^3/Mg FM)	% CH_4 in Biogas
Cow sludge	4,603,370	70%	-	2.4 ± 0.1	62.5 ± 2.5
Pig sludge	5,099,469	50%	-	10.4 ± 0.4	62.5 ± 2.5
Cow manure	6,282,033	50%	-	63.3 ± 7.5	62.5 ± 2.5
Poultry manure	99,700	70%	-	97.8 ± 6.4	62.5 ± 2.5
Poultry litter	794,755	50%	-	241.6 ± 21.3	62.5 ± 2.5
Total livestock residues	**16,793,329**				
Tomato pomace	109,800	50%	-	101.8 ± 15.2	52.5 ± 2.5
Potato residues	39,000	50%	-	126.8 ± 3.5	51.5 ± 1.5
Vegetable, fruit and legume waste	16,000	50%	-	158.1 ± 18.7	55.0 ± 5.0
Beet pulp	150,000	30%	50%	104.5 ± 13.6	57.5 ± 2.5
Grapes and vinasses	167,654	50%	-	150.0 ± 12.1	52.5 ± 2.5
Slaughterhouse waste	197,493	75%	-	102.5 ± 0.4	62.5 ± 2.5
Milk whey	1,500,000	20%	80%	14.1 ± 0.3	52.5 ± 2.5
Oil press residues	2845	50%	-	301.0 ± 9.3	52.5 ± 2.5
Total agri-food waste	**2,182,792**				
From annual crops (straws, cobs, stalks)	1,138,035	20%	70%	124.4 ± 4.9	54.0 ± 1.0
From perennial crops (pruning)	197,385	-	100%		
Total agricultural residues	**1,335,420**				

FM = Fresh Matter; Nm^3 = Normal cubic meter.

3.3. Estimated Potential GHG from AD Treatment of Livestock and Agri-Food Waste

In order to estimate the amount of GHG emissions savings by using manure, agricultural residues and agri-food waste as biogas plant feeding, the average data reported in Table 3 have been taken as a reference from the literature. As conventional disposal treatment options, landfill for agri-food waste and direct land spreading for livestock waste have been assumed [44,45].

For GHG emissions of biogas units produced from the different input materials, data published by regional authorities have been taken [46]. They are reported as unitary standardized biogas plant (USBP), with an installed power of 1 MW, operating for 8000 h/year and located in Northern Italy. The USBP fed with livestock waste treated 66,000 Mg of raw materials per year (cereal silage, 16% and livestock waste, 84%), whereas the USBP fed with agri-food waste processed 30,000 Mg of raw materials per year (cereal silage, 16% and agri-food waste, 84%). In Table 3, the GHG emissions calculated for the USBP are reported. The small percentage of cereal silage is added to ensure good biomass digestion [47]. These standardized feeding recipes have been used for subsequent calculations.

Table 3. Values of emissions factors used for estimation of GHG emissions of different treatment options of livestock residues and agri-food waste. FM = fresh matter.

Treatment Option	Emissions	Unit	Source
Biogas production from livestock waste *	10	gCO_2eq/MJ	[46]
Biogas production agri-food industry waste **	25	gCO_2eq/MJ	[46]
Agri-food waste landfilling ***	2240	kgCO_2eq/Mg FM	[48]
Livestock byproducts storage and direct land spreading	34.5	kgCO_2eq/Mg FM	[46]

* assuming a standardized feeding recipe: cereals silage, 16% + livestock waste, 84%; ** assuming a standardized feeding recipe: cereals silage, 16% + agri-food waste, 84%; *** without landfill gas recovery.

3.4. Estimated Potential GHG Savings from AD Treatment of Livestock and Agri-Food Waste

For calculating the GHG emissions savings derived from digestate land spreading instead of chemical fertilizers, an average whole digestate composition has been taken as a reference, assuming a production of 0.830 Mg of digestate per 1 Mg of raw waste (Table 4) [46]. Although nearly all nutrients remain in the digestate, we have focused on the main nutrients (N, P, K).

Table 4. Dry matter (DM) content, volatile solids (VS) and main nutrient content of whole digestate from energy crops, manure and agri-food waste.

Parameter	Value	Unit
DM content	5.8 ± 3.0	%
VS in DM	68.9 ± 13.3	%DM
pH value	7.9 ± 0.4	
N-total	10.4 ± 7.4	%DM
NH_4-N	6.4 ± 6.7	%DM
K_2O	5.1 ± 3.2	%DM
P_2O_5	3.7 ± 1.8	%DM

For estimating the GHG emissions saving potential from nutrient recycling via digestate, the average GHG emissions of mineral fertilizer production have been reported [48,49] (Table 5). The values correspond to average GHG emissions calculated considering the production of different N, P_2O_5, K_2O-based fertilizer using different technology processes at a worldwide level.

Table 5. Average estimations of GHG emissions from fertilizers production.

Parameter	Value	Unit
N-based fertilizers	4.20 ± 3.07	Mg CO_2eq/Mg N
P_2O_5-based fertilizers	0.91 ± 0.36	Mg CO_2eq/Mg P_2O_5
K_2O-based fertilizers	0.52 ± 0.02	Mg CO_2eq/Mg K_2O

4. Results and Discussion

4.1. Provisioning Services: Potential Biogas and Biomethane Gross Production and Electric Energy Power

Starting from the yearly production reported in Table 2, the amount of agricultural residues (animal and vegetal) and agri-food waste in the Emilia Romagna region effectively available at regional level has been calculated for each type of material. The effective availability has been calculated from the total amount by subtracting the quantity already destined to AD or other uses and applying a recovery factor of 80% on the remaining fraction (as best-case), expressed in Mg per year. In fact, it would be unrealistic to assume a complete recovery of all residual biomass for biogas production. Based on the assumption that this amount of residual biomass would be properly collected and entirely submitted to AD, a potential further productivity at regional level has been estimated (Table 6). For example, to obtain the effective availability of cow sludge, we started from a total regional availability of 4,603,370 Mg/y minus the 70% (data reported in Table 2) already destined to biogas (resulting as 3,222,360 Mg/y) and applyed a further reduction considering only 80% of recovery (i.e., 1,104,810 Mg/y). Considering a biogas yield of 2.4 ± 0.1 Nm^3/Mg FM, a potential biogas gross production of 2.651 million of Nm^3/y has been calculated, corresponding to about 0.6 MW of potential installed electric power. More details are available in Tables S1 and S2.

Table 6. Potential biogas and biomethane production from agricultural residues and agri-food waste at a regional level, on yearly basis.

Type of Material	Effective Quantity Available for AD (Mg/y)	Biogas Gross Production (mln Nm^3/y)	Potential Installed Electric Power (MW) *	Biomethane Gross Production (mln Nm^3/y)
Cow sludge	1,104,810	2.651	0.6	1.657
Pig sludge	2,039,788	21.214	4.8	13.260
Cow manure	1,507,690	95.440	21.7	59.648
Poultry manure	39,880	3.900	0.9	2.438
Poultry litter	317,902	76.805	17.5	48.003
Total livestock residues	**5,010,067**	**200.007**	**45.5**	**125.005**
Tomato pomace	43,920	4.436	0.9	2.323
Potato residues	15,600	1.965	0.4	1.013
Vegetable, fruit and legume waste	6400	1.012	0.2	0.556
Beet pulp	40,000	4.160	0.9	2.392
Grapes and vinasses	67,062	10.602	1.9	5.566
Slaughterhouse waste	39,500	4.049	0.8	2.530
Milk whey	0	0	0	0
Oil press residues	1138	0.342	0.1	0.179
Total agri-food waste	**213,618**	**26.567**	**5.3**	**14.556**
Straws, cobs, stalks	79,662	9.878	1.9	5.334
Pruning	0	0	0	0
Total agricultural residues	**79,662**	**9.878**	**1.9**	**6.259**
TOTAL	**5,303,349**	**236.453**	**52.7**	**13.658**

FM = Fresh Matter; Nm^3 = Normal cubic meter**;** * the potential installed electric power has been calculated assuming a low heating value (LHV) of biogas of 5.1 kWh/m^3 [50], an electric energy conversion efficiency of 32% [51] and an average working hours per year of 8000.

In terms of ES, the Emilia Romagna region yearly provides an estimated amount of more than 5.0 mln Mg of raw materials potentially deliverable to biogas system, which would give a gross biogas production of about 240,000 mln Nm^3. With respect to the target indicated by REP, this could represent up to 75% of the overall needs in the realistic scenario, or up to 55% in the best-case scenario. It could represent an economic benefit for farmers or producers, at least in terms of avoided costs of disposal. As an example, the actual costs of land spreading of livestock residues or of landfill waste disposal are about 6 €/Mg and 110 €/Mg, respectively. Moreover, according to Porter et al. [52], the value of the ES of provisioning raw material for energy valorization has been estimated in 60 USD (2007)/Mg, corresponding to 59 €(2020)/Mg.

Biogas can be upgraded to about 13,600 mln Nm^3 of biomethane after carbon dioxide removal or converted into 52.7 MW of electric energy ($42.1 \cdot 10^4$ MWh). From the data calculated in Table 5 and considering the energy equivalents of the cubic meter of biogas [53], at the regional level, this could replace about 150,000,000 L of gasoline ($1m^3$ biogas~0.625 L of gasoline) or about 66,700,000 L of diesel ($1m^3$ biogas~0.28 L diesel). As biomethane, it would permit traveling about 230,000,000 km per year, considering an average consumption of 4.3 kg methane/100 km by a popular car (the mass of 1 m^3 of CH4 is 0.671 kg).

Compared with electric energy, the potential biogas production from biomass residues could supply the yearly energy requirements of more than 140,000 houses, considering an average consumption of 2700 kWh of electric energy per year by a domestic unit of 4 people in Italy [54]. Taking into account that the average number of residential houses in the cities located in Emilia Romagna is about 80,000 units [29], biogas produced from biomass residues recovery could provide electric energy to almost 2 cities in the region per year, without using new resources.

Vegetal agricultural residues are usually used as co-substrate in AD, due their high content of lignin, which makes the fermentation as single substrate difficult. They can serve as complementary feeding for biogas plants working with other raw materials rich in promptly fermenting organic carbon [55]. The option of recovering 10% of the annual production of agricultural residues from field to biogas production can ameliorate the overall sustainable strategy of farm management, closing the circular loop with energy production from biomass and still restoring nutrients to soil through digestate spreading [12].

4.2. Regulation and Maintenance: Perception of Odors and Benefits of Digestate on Soil Nutrients

The impact of livestock waste on the environment derives not so much from their chemical composition as from the method of disposal and agronomic reuse [56]. The monitoring of anaerobic digestion plants serving farms demonstrates how these can contribute to the maintenance or restoration of a correct animal husbandry–environment relationship, mainly through the energy enhancement of sewage produced in livestock farms and, secondarily, with the control of malodorous emissions and with the stabilization of livestock waste [57].

Animal manure and slurry contains several volatile compounds, the so-called volatile acids (i.e., isobutanoic and butanoic acid, isobutirric acid and butirric acid, isovaleric acid and valeric acid, propionic acid), along with tens of other organic compounds which are formed as intermediate products during their natural degradation [58]. All of them are characterized by unpleasant odors, which are emitted into the atmosphere and overburden the environment, generating annoyance in the surrounding population. When animal manure is processed through AD, these volatile compounds are themselves taken up by anaerobic microrganisms as substrate to produce biogas. Consequently they are almost completely depleted and the odor impact is reduced by more than 90% [59].

At the end of the AD process, a by-product is obtained, which can be used in an interesting agronomic reuse as it is or as compost, which has the further advantage of easy storage and transportation. The anaerobic treatment does not significantly reduce the nitrogen load of livestock manure; on the contrary, where livestock residue is integrated with energy crops, there is an increase in the organic residue [60]. Therefore, the benefits brought by the biogas supply chains also influence the waste management (the digestate), which, after being treated anaerobically, can be reused in agriculture instead of chemical fertilizers. Investigations carried out on the management of livestock waste through anaerobic digestion have shown how this positively affects the income statement of livestock farms [61]. Compared to untreated sewage, digestate contains a higher percentage of inorganic nitrogen (NH_4-N), readily available to plants [62]. Thanks to its greater homogeneity and fluidity, it penetrates the soil more easily and this can contribute to the reduction of ammonia emissions [63]. The efficiency of use of the nitrogen contained in the digestate can therefore significantly increase compared to that obtainable with agricultural livestock effluents.

During the AD and while the gas is produced, the remaining organic matters are subjected to a biochemical stabilization, namely a selective enrichment of organic compounds, highly recalcitrant against degradation by microorganisms and enzymes. Thus, compounds like lignin, lipids and polyphenols will remain more stable in the soil matrix compared to more labile compounds like polysaccharides and proteins [64]. With the given biogas average yields and methane content in biogas, the remaining carbon in digestate still reaches 30–50% of the initial carbon [65]. During the AD, only easily biodegradable carbon is converted into biogas, while lignin and, in general, lignocellulosic compounds remain in digestate, and the carbon content can be used for carbon as a term for carbon sequestration into soil. Moreover, this carbon has a 20–30% higher capacity for humus formation compared with untreated manure [66].

4.3. GHG Emissions Savings

AD of agricultural residues and agri-food waste is a promising practice to mitigate the GHG emissions in comparison with traditional treatment options of landfill or direct land spreading. Moreover, energy from biogas assures lower emissions than those produced by the same amount of energy produced by fossil fuels because of the closed carbon cycle of renewable energy and the absence of direct and indirect land use change (DLUC and ILUC) effects, which are both as overburden on bioenergy from dedicated energy crops. Summing up, the possible GHG emissions savings can be attributed to:

- valorization of agri-food waste to biogas vs. landfilling
- valorization of livestock waste to biogas vs. direct land spreading
- bioenergy production vs. energy from fossil fuel
- fertilization with digestate vs. fertilization with chemical fertilizer.

In Table 7, an estimation of the GHG emissions avoided by producing biogas from residual biomass effectively available in the region has been presented. Based on USBP values reported above, the regional effective amount of livestock waste + agricultural residues can be sufficient to feed about 90 biogas plants of 1 MW of installed electric power, producing a total amount of 12,800 Mg CO_2 per year. Agricultural residues have been treated as co-substrate for livestock waste AD because both of them derive from farming and can be used as mixed feeding for farms serving biogas plants. Moreover, as mentioned above, vegetal residues cannot be used as single substrate due to their high content of recalcitrant carbon. On the contrary, the overall quantity of recoverable agri-food waste available in the region could be sufficient for feeding about 8.5 USBP, emitting 3185 Mg CO_2 per year. The values reported in Table 7 have been calculated starting from the unitary values reported in Table 3; Table 5, subtracting the GHG emissions deriving from biogas production. Results of detailed calculations have been reported in Table S3.

Table 7. Average estimations of GHG emissions savings, as Mg CO_2eq per year.

	GHG Emission Savings (Mg CO_2eq/y)				
Type of Material	**Avoiding Landfilling**	**Avoiding Direct Land Spreading**	**Producing Biogas and Replacing Fossil Fuel ***	**Producing Digestate and Replacing Mineral Fertilizers**	**Total**
Livestock waste + agricultural residues	-	172,346 **	12.02	2,122,587	2,294,945
Agri-food waste	478,502	-	1.12	89,085	567,588

TOTAL	**478,502**	**172,346**	**13.14**	**2,211,673**	**2,862,533**

* GHG emissions from fossil fuel have been calculated using the value of 83.8 gCO2/MJ as a reference as indicated by the RED II directive for energy produced by fossil fuel; ** only for livestock waste, without agricultural residues.

It is worth noting that the main GHG savings in the case of livestock and agricultural waste are related to the missed chemical fertilizer production, which accounts for more than 90% of the total GHG emissions saving, whereas in the case of biogas from agri-food waste avoiding landfilling leads to a significant reduction in emissions. According to the International Fertilizer Association (IFA) in 2008, the production of N, P and K fertilizer worldwide was linked to an emission of 464,800 Mg CO_2eq [67].

At regional level, the major part of a biogas plant fed with livestock waste and agricultural residues is located in the same area of the farm, being a direct support to waste management, whereas the agri-food waste can be collected at plants located at a certain distance to the place of production. In this latter case, an important factor to be considered in an overall analysis of sustainability should be the maximum distance allowed so as not to overcome the sustainability threshold stated by the RED II. Namely, as mentioned above, renewable energy plants operating after 2015 cannot emit more than 33.5 gCO_2/MJ. This means that an USBP fed with agri-food waste has only 8.5 gCO_2/MJ (33.5 gCO_2/MJ minus 25 gCO_2/MJ for biogas production from agri-food waste, corresponding to 1335 Mg CO_2/y) to be managed for biomass transportation. Considering an impact of road transportation of about 62 gCO_2/Mg-km [68] and the fact that the 213,618 Mg of waste can sustain about 8.5 biogas plants, a maximum distance of 5.88 km between the site of production and the plant has been permitted so as not to overcome the threshold of sustainability.

With regards to the ES framework, biogas production from residual biomass in the Emilia Romagna region could provide a reduction of GHG emissions of about 4 mln Mg per year. Moreover, at these values, the amount of carbon recycled in the soil through digestate spreading has to be considered. A tentative value proposed by US EPA in 2016 [69], associated to the ES of carbon sequestration and storage and based on the approach of the costs of the avoided damage, was of 33.18 €/Mg CO_2 or 101.85 €/Mg C.

Biogas production based on the valorization of agricultural residues and agri-food waste has revealed a great potential for producing sustainable energy, which, without burdening the food vs. energy debate, helps in waste management and is also a source of provisioning and regulating ES. For these reasons, it represents the opportunity to lead the transition from fossil to renewable energy, especially at the regional level, where residual biomass is more easily recoverable and processed at small distances between the place of production and utilization. It can also offer a strategy of sustainable development to rural communities. The capacity of biogas to decrease environmental pollutant load by means of the use of residues and waste, as well as to regulate and provide ES, contemporarily improving the efficiency of the energy supply infrastructure, plays in favor of the development of a biogas system. Therefore, it can be said that biogas from residual biomass has lower trade-offs than other renewable solutions as trade-offs have a key-role in the evaluation of the sustainability of human well-being solutions for the future [70,71].

The inclusion of ES in bioenergy discourse has proved ideal to support bioenergy development. Gissi et al. [35] defined the "sustainable potential from bioenergy" as the fraction of energy potential whose exploitation cause no harms to other ESs delivered by the sources of renewable energy. Based on this assumption, the authors identified and mapped bundles of ES related to bioenergy production, thus providing useful decision tools for energy crop allocation. Growing interest has been payed to the effects of 2nd generation bioenergies (i.e., perennial, lignocellulosic non-food crops) on ES. Longato et al. [72] demonstrated that using agricultural marginal land for wood energy crops may improve ES provision while avoiding any trade-offs with food production. Such conclusions were also confirmed in diverse contexts worldwide [73,74].

Some studies proposed approaches to drive resources allocation toward a balanced target. For instance, Paschalidou et al. [75] proposed a SWOT (Strengths, Weaknesses, Opportunities, and

Threats) analysis to identify strengths, weaknesses, opportunities and threats of producing food or generating bioenergy to better support decision making. Dick and Wilson [76] applied a constrained partial equilibrium model to assess the impact of bioethanol production on Nigerian energy and food security. The authors found that ethanol is profitable only when produced from dedicated crops rather than from cellulosic crop residues. Contrarily, other researchers focused on the development of alternative sources of bioenergy as suitable alternatives to dedicated crops. Different works highlighted the large amount of agricultural residues potentially available for bioenergy generation, while others investigated potential environmental and socio-economic benefits deriving from their exploitation [77,78].

5. Conclusions

Agricultural residues and agri-food waste are a valuable resource that can be used in the regional biogas supply chain. Emilia Romagna region represents a case study of interest, being the second largest biogas producer in Italy, which is in turn among the first producers in Europe. The well-established agri-food system and the high density of agricultural and agri-food production sites lead to a surplus of waste, which puts pressure on the ecosystem and cause impacts on the environment, especially if not adequately disposed. It has been calculated that in the Emilia Romagna region, of the about 20 mln Mg of residual biomass produced annually by agriculture and agri-food industry, more than 5 mln Mg of are available and under-exploited. The use of this as feedstock for anaerobic digestion plants, new or already existing, represents a promising alternative to landfill or direct land spreading. In fact, even limiting the potential recovery of the available residual biomass to not more than 80% could lead to a production of an extra-installed power of 52.7 MW, to be used as electric energy for about 2 medium cities in the region or as biomethane, thereby replacing fossil fuel. In addition, about 3 mln of $MgCO_2$ eq. could be saved, considering the avoided emissions due to traditional residual management, as landfilling for agri-food waste or direct land spreading for livestock waste. The greatest emissions savings would be realized as avoided mineral fertilizers production, due to the release of digestate in soil. Moreover, in order to maintain the overall sustainability, a maximum distance of 5.88 km between the site of production and the plant has been estimated. The use of that biomass to produce biogas can be considered as a sustainable solution because without using any primary resource from the environment, it considerably contributes to provisioning and regulating ES, improving the population's well-being. Including ES assessment in bioenergy discourse requires the identification of the ES involved and their estimation. The present study provides an assessment at regional level of the potential ES improvements which would be due to the use of agricultural residues for biogas production. It demonstrates that, under the framework of ES, the exploitation of such supply chains may overcome some barriers to bioenergy development. Interestingly, the results suggest that bioenergy generation from lignocellulosic, livestock and agro-industrial residues may improve some regulating services in agro-ecosystems. This represent an exceptional case, where provisioning and regulating services are provided synergistically, to represent a trade-off, as usually observed, for the anthropic use of biological resources.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/12/20/8392/s1, Table S1: Calculation of the major parameters related to biogas potential production from livestock residues; Table S2: Calculation of the major parameters related to biogas potential production from agri-food waste and agricultural residues; Table S3: Calculation of the GHG savings, expressed as $MgCO_2eq/y$.

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