agronomy

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Replacing Agricultural Diesel Fuel with Biomethane from Agricultural Waste: Assessment of Biomass Availability and Potential Energy Supply in Piedmont (North-West Italy)

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Abstract: Agricultural and livestock wastes are an important resource for the production of renewable fuels such as biomethane, and the effective management of the components of supply chain, such as available biomass feedstock, are critical to the transition to a low-carbon circular economy. Considering that more than half of the emissions (CO_2eq) generated in agriculture come from the use of fossil fuels to power tractors and other agricultural machinery, replacing diesel fuel in tractors with biofuels produced within the agricultural supply chain could contribute to greenhouse gas emissions reduction and to energy self-sufficiency for the local agricultural sectors. This study evaluated, at the regional level (Piedmont—north-west Italy), the potential production of biomethane from local agricultural wastes (crop residues and livestock manure), the potential energy supply to power tractors and the potential CO_2 emission reduction by replacing diesel fuel. Based on mean annual available agricultural wastes over the last seven years (2015–2021) in the Piedmont region, the annual potential biomethane yield of 910×10^6 m^3 $year^{-1}$ was estimated, equivalent to a thermal energy of 30.1×10^9 MJ $year^{-1}$, which is 3.8 times higher than the energy requirements for the regional tractors' fleet. The estimated potential CO_2 emission reduction is about 93.8 t of CO_2 $year^{-1}$, corresponding to 16.8% potential reduction. The study demonstrates the potential of local agriculture to replace diesel fuel with biomethane from waste to meet energy needs and carbon neutrality.

Keywords: biomethane potential; biofuels; anaerobic digestion; agricultural waste; circular economy

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Citation: Assandri, D.; Bagagiolo, G.; Cavallo, E.; Pampuro, N. Replacing Agricultural Diesel Fuel with Biomethane from Agricultural Waste: Assessment of Biomass Availability and Potential Energy Supply in Piedmont (North-West Italy). *Agronomy* **2022**, *12*, 2996. https://doi.org/10.3390/agronomy12122996

Academic Editors: Sung-Cheol Koh and Baskaran Stephen Inbaraj

Received: 20 October 2022
Accepted: 24 November 2022
Published: 29 November 2022

1. Introduction

An increasing interest in renewable energy sources such as wind, solar and biomass has been observed in recent years, supported by several policies and strategies designed by international institutions at global and/or local levels. Indeed, in 2015, 195 countries met at the United Nations Framework Convention on Climate Change (UNFCCC) 21st conference of the Parties (COP21) [1] in Paris and with the "Paris Agreement" set the long-term goal of keeping the increase in the global average temperature to "well below" 2 °C above pre-industrial levels and pursuing efforts to limit it to 1.5 °C [2]. In line with the Paris Agreement, the European Union (EU), one of the main actors within the international context, adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for moving towards a climate-neutral economy by 2050, the so-called "European Green Deal", recently regulated by the European Climate Law (Regulation 2021/1119 of the European Parliament and of the Council) [3]. As part of the European Green Deal, the EU adopted an intermediate action plan, a 2030 Framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030: (i) reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels; (ii) ensuring at least 32% share for renewable energy; (iii) improving the energy efficiency of at least 32.5% [4]. These intermediate targets aim to help the EU achieve a more competitive, secure and sustainable energy system and to meet its long-term objective of making the EU climate-neutral by 2050.

Under this framework, renewable energy sources may be considered key players in future growth in the energy sector to ensure sustainable energy security and mitigate the adverse environmental impact of fossil fuels [5]. With this regard, in recent years, anaerobic digestion (AD) of organic waste and residues has become one of the most attractive renewable energy pathways [6]. Indeed, the AD process represents a suitable alternative to conventional management of organic waste, such as livestock manure, sewage from water treatment plants and agro-food waste. Moreover, this process is one of the most efficient methods for the conversion of biomass to methane (CH_4). In particular, AD is a sequence of biochemical processes occurring naturally in oxygen-free environments where consortia of bacteria [7] degrade complex organic matter. Biogas is the main result of the AD process and consists of approximately 50–75% methane (CH_4), 25–50% carbon dioxide (CO_2) and 1–2% other trace substances including hydrogen (H_2), hydrogen sulfide (H_2S) and ammonia (NH_3) [8]. Moreover, a digested fraction, called digestate, is produced in the anaerobic digester, which is an excellent quality bio-fertilizer [9,10], and is an example of carbon sequestration and circularity.

Biogas can be combusted in boilers to produce heat, or used in combined heat and power (CHP) plant gas engines generating heat and electricity [11]. Through the biogas upgrading process (e.g., purification and pressurizing), CO_2 and other impurities are removed, and biomethane ($BioCH_4$) is produced. Biomethane is an alternative fuel that can replace fossil fuels in heat and power generation and can be used as a vehicle fuel [12]. Indeed, biomethane has similar chemical properties to natural gas and thus can be fed directly into the existing gas grid, transported via tankers to large off-grid users, or dispensed as a vehicle fuel at fueling stations [11,13]. Moreover, vehicles running on natural gas can use biomethane without any technical change [14]. Finally, due to reduced environmental impact and lower GHG emissions, biomethane can be considered a valuable solution contributing to the decarburization of the transport sector, supporting the objectives of the European Union towards "carbon neutrality" [6].

Furthermore, biomethane certainly represents a great opportunity for implementing the circular use of resources, promoting the reuse of "waste" materials, such as municipal solid wastes, sewage sludge and many other industrial and agricultural waste feedstocks. Moreover, within a circular economy scenario, thanks to the development of farm-scale biogas upgrading technologies [15], biomethane from agricultural wastes could be used as a fuel in the agricultural sector, thus contributing to decarburization objectives. Indeed, agricultural machines in general, and tractors in particular, are primarily diesel-powered, and its gradual replacement with alternative renewable fuels—such as biomethane—could represent an interesting support to foster sustainability in agricultural production [16].

To achieve the EU goal of carbon neutrality by 2050, the potential energy and environmental value of biomethane produced from agricultural wastes should be reconsidered [17]. When considering a circular supply chain for biomethane production from agricultural wastes, it is necessary to optimize the use of local resources and ensure the sustainability of agricultural production [18]. Moreover, it is essential to develop technologies and alternative domestic fuels that are available, renewable, environmentally friendly [19] and at the same time not competing with food production. The effective management of the components of the biomethane supply chain is critical for the transition to a low-carbon circular economy (CE). When assessing the energetic potential of the agricultural sector, evaluation of biomass available within a specific territorial context should be examined first. In this way, companies are able to reorganize their production processes and feed the anaerobic digester with the biomass available locally without changing the stock production of food and fodder [20]. Indeed, several international studies in recent years are focusing on the estimation of biogas and or potential biomethane production from crop residues [17,20–22].

Furthermore, in line with the policies and strategies pursued by other European and non-European countries [23], the European Renewable Energy Directive 2018/2001

(RED II) [24] prioritizes low indirect land use change risk bioenergy production, supporting biofuels from by-products, residues and lignocellulosic biomasses. Some EU countries, such as Italy, implemented these directives through national regulations [25], urging companies to focus on residual biomasses and waste as feedstock for biomethane production.

Moreover, paying attention to energy use in agriculture and in particular to the use of fossil fuels could offer significant opportunities for on-farm mitigation actions directly focused on CO_2 [26]. With this regard, the reduction of fossil fuels, together with the increasing use of energy sources which are not petroleum based, represent two of the key factors for the development of energy security and the achievement of carbon emissions reduction in agriculture [16,27]. Under these premises, the present study analyses, at the regional level (Piedmont region, north-west Italy), the possibility of replacing diesel with biomethane from agricultural wastes as an alternative fuel in tractors, evaluating the potential energy and CO_2 emission reduction. To achieve this objective, the following aspects have been evaluated: (i) the composition of the tractor fleet and the fuel consumption; (ii) the CO_2 emission from agricultural fuel consumption; (iii) the available quantity of livestock manure and the available quantity of crop residues for biomethane production; (iv) the potential biomethane yield and related energy content; (v) the potential CO_2 emission reduction by replacing diesel fuel with biomethane in the regional fleet of tractors.

2. Materials and Methods

To achieve the objective of the present study, a preliminary examination of the studied area—the Piedmont region—and of common agricultural practices was pursued. In this context, the agricultural tractors fleet, the diesel fuel consumption and the available quantity of different types of agricultural wastes (livestock manure and crop residues), were estimated at the regional level.

Most of the data were obtained from the official Agricultural Information System of Piedmont region (SIAP), a regional data warehouse service that provides statistical information on the entire agricultural sector of the region. Within this system, the "Agricultural Register" is the integrated database that manages the data on farms, crops and livestock [28].

2.1. Description of the Study Area

The analysis was pursued in the Piedmont region (45°4′0″ N, 7°42′0″ E), one of the most relevant agricultural areas located in the western part of the Po Valley (NW Italy), which is also the largest agricultural area in Italy and one of the most productive at the European level, as a result of high water and nutrient abundance, soil fertility and favorable climate conditions [29]. This region has a total agricultural area (AA) of about 1234 thousand hectares and a utilized agricultural area (UAA) of 917 thousand hectares, composed mainly of plain area (55%) and mountains (27%). The main crops are arable and permanent fodder crops, which occupy 52.6% and 34.8% of the total UAA, respectively. The fruit trees, with 49.6 thousand ha, and the vines, with 42.3 thousand ha, mainly destined to produce wine grapes, represent about 10.6% of the total UAA [28].

In addition to its agricultural vocation, the Piedmont region is a very pertinent study area for being among the first Italian regions with a number of agricultural biogas facilities [30]. Currently, approximately 2000 anaerobic digestion plants (ADP) are running in Italy, 68.3% of which are located in the northern regions: Lombardy (29.7%), Veneto (14.3%), Emilia Romagna (12.7%) and Piedmont (11.7%). More specifically, the Piedmont region has a total of about 235 ADP: 46.0% with an installed power greater than 600 kW, 30.6% have a power between 100–600 kW, while the remaining 23.4% have a power of less than 100 kW [31].

2.2. Fuel Consumption by Agricultural Machinery and Related Carbon Dioxide Emissions in the Piedmont Region

The "Agricultural Motors Users" online database of the Piedmont region [32] was used to determine the mean annual consumption of diesel fuel for agricultural tractors. In detail, the quantification of fuel consumption was calculated by averaging data over the last six years, excluding the year 2020, characterized by an outlying value, probably related to the effects of the COVID-19 pandemic.

To estimate the amount of CO_2 emissions from agricultural tractors, the method described by Shin and Kim [33] was adapted. This method estimates the total CO_2 emitted by tractors based on the amount of fuel consumed each year. However, as highlighted by Janulevičius and Čiplienė [27] in their study, indicators of fuel consumption and CO_2 emissions are strongly interdependent, and CO_2 emissions directly depend on fuel consumption. For this reason, as fuel consumption increases, CO_2 emissions increase proportionally. More specifically, the following equation has been utilized:

$$\text{kg of } CO_2 \text{ emitted} = FC \times SG \times EF \quad (1)$$

where FC is the average diesel fuel consumption (liter); and SG and EF are the specific gravity (0.85 kg L^{-1}) and the CO_2 emission factor (3.12 kg kg^{-1}) of the diesel fuel [33], respectively.

2.3. Crop Residue Yield and Available Crop Residue Yield

The literature proposes several methods to evaluate the potential theoretical production of crop residues, whose availability can vary significantly based on climatic conditions and local agricultural practices. Hence, the first step consisted of identifying Piedmont's main crops. Three categories of crops were considered for the calculation of residues: cereals, industrial crops and horticultural crops. The first category comprises grain maize (monoculture and double-cropping, which were calculated separately and summarized), rice, common wheat and barley, which, respectively, occupy 15.2%, 13.2%, 8.9% and 1.8% of the total UAA. Among industrial crops, soy, sunflower and canola were considered together, and they account for 2.4% of the UAA. Finally, horticultural crops occupy 1.1% of the total UAA.

The theoretical production of crop residues can be estimated based on the cultivated area, or on the agricultural production of each crop with average product/residue ratios or on residue yields derived from the literature [34]. Specifically, in the present work, this estimation was made through the harvest index (HI). Initially defined for cereals as the ratio of grain yield to the total aboveground biomass, later, the HI has been adapted to other crop species as well [35]. The average annual crop yields over the last six years (2016–2021) were obtained by extrapolating data from a publicly available official statistical database [28].

Thus, the available crop residue yield was calculated according to Equation (2):

$$\text{Available crop residue (t)} = \sum \text{Harvested biomass}_a \times [(100 - HI_a)/HI_a] \times CF \quad (2)$$

where a is the crop type and HI is the harvest index of each crop [36]. A crop residue collection factor (CF) of 80% [37] was applied, considering that not all the amount of residue can be collected. Indeed, a certain amount of stubble remains in the field after harvesting crop residues and biomass losses may occur during the management of crop residues (e.g., cutting, pressing, transport).

2.4. Number and Type of Animals Reared in Piedmont and Relative Effluent Production

The determination of the amount of livestock manure (t) was carried out using data relating to the type and number of housed livestock and the analysis of the live weight of heads present in the farms, according to annex 1 of the Regional regulation 29 October 2007, n. 10/R [38].

Specifically, this calculation has been made according to Equation (3):

$$\text{tons of manure (t)} = \sum \text{Number of heads}_a \times \text{live weight (t)} \times \text{tons of manure/slurry produced per tons live weight}^{-1} \times \text{CF} \quad (3)$$

where a is the livestock category and CF is the collection factor, set to 90% in line with regional statistics related to the number of housed animals. Indeed, this quantity cannot be collected and used entirely to produce biomethane, due to agricultural practices that do not involve the housing of animals (e.g., extensive farming, alpine pasture, grazing). The tons of produced slurry were obtained by applying a density equal to 1 (1 m^3 = 1 t).

2.5. Assessment of Potential Biomethane Production in the Piedmont Region from Agricultural Wastes

The potential biomethane ($BioCH_4$) yield, based on the organic carbon content (% dry matter), was calculated using the equation reported by Sun et al. (2021) [17], Equation (4):

$$\text{BioCH}_4\ (\text{Nm}^3) = \text{available biomass}_a\ (\text{t}) \times \text{TS}_a\ (\%) \times \text{OC}_a\ (\%\text{TS}_a)/12.01\ (\text{g mol}^{-1}) \times 22.41\ (\text{L mol}^{-1}) \times 1000 \times 60\% \times \text{Degradation rate coefficient}\ (\%) \quad (4)$$

where a is the biomass type; TS are the total solids, specific for biomass type (% total biomass); OC is the organic carbon content, specific for biomass type (% TS); 12.01 g mol^{-1} is the molar mass of carbon; 22.41 L mol^{-1} is the molar volume of gas under standard conditions (273.15 K, 101.33 kPa); and 60% is the assumed CH_4 content of the biogas [39–41]. The percentages of the content of total solids (% TS) and organic carbon (% OC) were set, for each biomass type, according to the Phyllis2 database [42]. Then, a degradation rate coefficient of 50% was applied based on mean values reported by several authors [16,20,43].

2.6. Potential Energy Value of Biomethane from Available Agricultural Wastes and Comparison with the Piedmont Tractor Fleet Energy Requirements

The potential energy yield obtainable from estimated biomethane potential production was computed considering the energy content of biomethane equal to 33.09 MJ Nm^{-3} (net calorific value), as reported by Cignini et al. (2020) [44].

Subsequently, the annual requirement of biomethane needed to replace the diesel was obtained by comparing the thermal energy currently produced with the annual diesel fuel consumption from the agricultural machinery fleet in Piedmont. For this purpose, the density value (0.85 kg L^{-1}) and the net calorific value (42.84 MJ kg^{-1}) [45] were computed with the diesel fuel consumed yearly by the Piedmont tractor fleet (estimated as described in Section 2.2).

2.7. Emissions Comparison between Biomethane and Diesel as Fuel in the Piedmont Tractor Fleet

Carbon dioxide emissions from agricultural tractors by replacing diesel with biomethane as fuel were estimated according to equation (Equation (1)), adapted from Shin and Kim, (2018) [33]. In detail, FC is the average biomethane annual requirement to replace the diesel fuel (m^3), determined in the previous step; SG is the specific gravity for biomethane (0.729 kg m^{-3}), as reported by Cignini et al. (2020) [44]; and EF is the CO_2 emission factor (2.75 kg kg^{-1}), calculated based on stoichiometric equation (assuming an ideal combustion process where fuel is burned completely).

3. Results

3.1. Carbon Dioxide Emission from Tractors in the Piedmont Region

The database of the Piedmont region "Agricultural Machineries Users data warehouse" [32] reports an average fuel consumption of approximately 215.05×10^6 L $year^{-1}$. Therefore, applying Equation (1), an annual CO_2 emission of approximately 570.3×10^3 t was obtained.

3.2. Available Crop Residues for Biomethane Production

The main feedstock is represented by crop residues derived from annual crops (Table 1). This kind of residual biomass is mainly composed of straw and stalks of cereal crops (93.2%), particularly of maize stalks (47.7%). The remaining share of crop residues derives from industrial crops (4.3%) and horticultural crops (2.5%) (Table 1). Overall, the available biomass to produce biomethane would amount, on average, to 2.04×10^6 t year^{-1}.

Table 1. Agricultural residues available from cereals, industrial and horticultural crops in Piedmont (average values over the last seven years 2015–2021) [28]. Available crop residues have been calculated according to Equation (2).

Crop Type	Harvested Biomass ($t \times 10^3$)	Harvest Index (%)	Crop Residue ($t \times 10^3$)	Collection Factor (%)	Available Crop Residue ($t \times 10^3$)
Maize	1369.3	53.0	1214.3	80.0	971.5
Rice	786.9	56.0	618.3	80.0	494.6
Soft wheat	437.5	50.0	437.5	80.0	350.0
Barley	102.5	50.0	102.5	80.0	82.0
Soy	50.2	40.0	75.4	80.0	60.3
Sunflower	11.9	40.0	17.9	80.0	14.3
Canola	5.9	28.0	15.2	80.0	12.2
Horticultural crops	298.1	82.0	65.4	80.0	52.3

3.3. Number and Type of Animals Reared in Piedmont and Relative Effluent Production

Livestock excreta, the second feedstock category considered in the study for biomethane production, amounts on average, over the last seven years (2015–2021) [28], to 14.22×10^6 t year^{-1}. The potential production of solid and liquid excreta produced in one year, for each animal category, is shown in Table 2. The largest contribution is related to cattle slurry (41.2%) and cattle manure (32.8%), followed by pig slurry (21.9%).

Table 2. Quantity of livestock sewage by stabled livestock in Piedmont based on the mean number of reared animals from 2015 to 2021 (data aggregated by species). Livestock wastes have been calculated according to Equation (3).

Category of Animal	Number of Heads (n.)	Quantity of Produced Livestock Waste ($t \times 10^3$)		Quantity of Collectable Livestock Waste ($t \times 10^3$)	
		Slurry	Manure	Slurry	Manure
Cattle	842,550	6504.4	5178.8	5853.9	4660.9
Pigs	1,229,939	3455.8	3.1	3110.2	2.8
Sheep and goats	174,103	67.0	143.6	60.3	129.2
Poultry	43,285,724	27.1	265.0	24.4	238.5
Equines	13,517	0.0	129.0	0.0	116.1
Rabbits	606,998	20.6	0.0	18.6	0.0

3.4. Biomethane Potential Production in the Piedmont Region

Considering the available agricultural wastes in the Piedmont region, the annual potential biomethane yield was calculated to be 909.7×10^6 m^3 year^{-1} (Table 3). Different biogas specific yields were computed in relation to the chemical characteristics of each considered feedstock. As reported in Table 3, the amount of total solids (TS) and carbon content (OC) affect the expected specific biomethane yield.

Except for soya (180.6 m^3 t^{-1} TS), obtained specific yields are remarkably similar among crop residues, ranging from 207.4 to 252.1 m^3 t^{-1} TS for barley straw and wheat straw, respectively. Considering livestock excreta, a great variability characterized the specific biomethane yields, ranging from 101.3 m^3 t^{-1} TS for sheep and goat manure to 255.8–274.3 m^3 t^{-1} TS for pig manure and equine manure, respectively. In terms of total yield, maize stalk and cattle manure have guaranteed the highest potential biomethane yield, accounting together for 50.4% of the total potential biomethane yield estimated for the Piedmont region.

Table 3. Annual potential biomethane yield of agricultural waste, calculated according to Equation (4).

Biomass Type	Available Biomass	TS [1]	OC [2]	CH_4	Degradation Rate Coefficient	Expected Specific $BioCH_4$ Yield	Total Potential $BioCH_4$ Yield
	($t \times 10^3$)	(%)	(% TS)	(%)	(%)	($m^3\ t^{-1}$ TS)	($m^3 \times 10^6$)
Maize stalk	971.4	92.0	44.8	60.0	50.0	250.6	224.0
Rice straw	494.6	39.8	39.8	60.0	50.0	222.5	43.7
Wheat straw	350.0	92.7	45.1	60.0	50.0	252.2	81.8
Barley straw	82.08	93.1	37.1	60.0	50.0	207.4	15.8
Soya stalk	60.3	91.3	32.3	60.0	50.0	180.6	9.9
Sunflower stalk	14.3	90.8	42.7	60.0	50.0	239.2	3.1
Canola stalk	12.2	94.1	42.8	60.0	50.0	239.4	2.7
Horticultural residue	52.3	90.3	42.3	60.0	50.0	236.9	11.2
Cattle slurry	5854.0	12.2	38.9	60.0	50.0	217.7	155.5
Pig slurry	3110.2	7.9	35.0	60.0	50.0	195.7	48.1
Sheep/goat slurry	60.3	52.2	40.6	60.0	50.0	227.3	7.2
Poultry slurry	24.4	24.8	28.5	60.0	50.0	159.6	1.0
Rabbit slurry	18.6	27.8	37.7	60.0	50.0	210.7	1.1
Cattle manure	4660.9	30.0	30.0	60.0	50.0	167.9	234.8
Pig manure	2.8	27.0	45.7	60.0	50.0	255.8	0.2
Sheep/goat manure	129.3	61.4	18.1	60.0	50.0	101.3	8.0
Poultry manure	238.5	60.3	41.2	60.0	50.0	230.5	33.2
Equine manure	116.1	88.9	49.0	60.0	50.0	274.3	28.3
TOTAL							909.7

[1] Total Solids; [2] Organic Carbon content

3.5. Energy Value of Biomethane from Available Agricultural Wastes and Contribution to the Piedmont Tractor Fleet Energy Requirements

The estimated annual potential biomethane yield from available agricultural waste is equivalent to a thermal energy of 30.1×10^9 MJ year^{-1} (see Section 2.6). This value is 3.8 times higher than the energy requirements for the Piedmont tractor fleet estimated from the mean annual diesel fuel consumption over the last seven years (7.8×10^9 MJ year^{-1}). Thus, with respect to the total potential biomethane yield, only a share of 26.0% (7.8×10^9 MJ year^{-1}) would be enough to meet the energetic needs of the agricultural machinery in the Piedmont region.

3.6. Carbon Dioxide Emissions Comparison between Biomethane and Diesel as Fuel in the Piedmont Tractor Fleet

In the present study, the potential environmental contribution of replacing diesel fuel with biomethane was estimated as the theoretical reduction in CO_2 emissions, focusing exclusively on the "tank to wheel" path, which means that only emissions from fuel combustion were computed (see Section 2.7). The comparison highlighted that by replacing diesel (215.0×10^6 L year^{-1}, equivalent to 570.3×10^3 t of CO_2 year^{-1}), with biomethane (236.5×10^6 m^3 year^{-1}, equivalent to 474.8×10^3 t of CO_2 year^{-1}), approximately 95.5 t of CO_2 year^{-1} would be saved, corresponding to a total potential 16.8% reduction of CO_2 emissions.

4. Discussion

Due to the territorial vocation, maize and rice are the principal crops in the Piedmont region. Therefore, these two crops generate most of the residues (Table 1). On the other hand, the greatest amount of livestock manure derives from cattle and pig breeding, due to high numbers of intensive farms characterizing the Piedmont region [46].

The formulas used in the present study allow us to hypothesize a correct production of biomethane. Indeed, as shown in Table 4, the calculated biomethane production values are in line with those reported in the literature.

Table 4. Expected biomethane yield of each agricultural by-product and biomethane yield reported in the literature.

Biomass Type	Calculated Specific Biomethane Yield	Reported Biomethane Yield *	References
	(m^3 CH_4 t VS^{-1})	(m^3 CH_4 t VS^{-1})	
Maize stalk	341.3	400	[47]
Rice straw	334.0	280–453	[21]
Wheat straw	357.5	244–455	[21]
Barley straw	246.0	244–455	[21]
Soya stalk	332.4	144–418	[21]
Sunflower stalk	269.2	300–330	[48]
Canola stalk	327.9	300–330	[48]
Horticultural residue	405.7	340	[49]
Cattle slurry	262.4	110–375	[47]
Pig slurry	381.5	300	[50]
Sheep/goats slurry	348.6	36–307	[21]
Poultry slurry	275.4	320	[49]
Rabbit slurry	239.7	286	[51]
Cattle manure	184.5	120–210	[47,52]
Pig manure	293.0	317	[53]
Sheep/goats manure	184.6	36–307	[21]
Poultry manure	279.6	320	[49]
Equine manure	409.6	116–562	[21]

* The Equation (4) calculates the theoretical biomethane production on the basis of the organic carbon (OC) content (% TS) of each considered biomass; therefore, to compare our results with the biomethane yields reported in the literature, values have been converted on the basis the volatile solids (VS) content (% dry matter), according to the Phyllis2 database [42].

With regard to the actual biomethane production capacity, the presence of governmental subsidies could be decisive in determining the development of the biomethane industry as an alternative solution for biogas exploitation. Indeed, according to González-Castaño et al. (2021) [54], the lower number of biomethane production plants in comparison with biogas production plants lays on the lack of specific subsidies to support biomethane production. Incidentally, subsidies to produce biomethane are already a current political measure in some European countries, including Italy [55]. As highlighted by Selvaggi, et al. (2018) [56] until 2018, due to feed-in tariff (FiT), all the biogas produced in Italy has been used to produce electricity.

New incentive policies are recently encouraging biomethane production from biogas, safeguarding areas with high carbon stock such as forests, wetlands and peatlands (RED II) [24]. Furthermore, the use of AD practice could represent a suitable alternative for livestock manure management, fulfilling the limits imposed by the Nitrates Directive (91/676/EEC) [57]. Indeed, AD enhances N removal because of chemical changes occurring during the process, i.e., the increase of NH_4^+/TKN [58], which is readily available for crops and prevents nitrates leaching.

Although the first methane tractor prototype dates back to World War II [16], the market for methane tractors is currently still small. Indeed, the only tractor model powered by methane is New Holland T6-180, with a nominal power of 107 kW. This indicates the need for greater efforts by the institutions with incentives and the construction of infrastructures suitable for the distribution of methane and by manufacturers with the development of a greater number of engines to meet the needs of the market.

4.1. Study Limitations

The authors acknowledge some limitations of the present study. With regard to the estimation of crop residues, it is necessary to specify that all collectable residues after harvest were assumed to be available for biomethane production, but this could vary widely according to the local conditions and practices. A fraction of the remaining harvest could find alternative uses, such as in livestock forage and bedding or directly returned to farmland as organic fertilizer. Indeed, as reported by Scarlat et al. (2018) [6], the estimation of the amount of residue that must be left on the cropland is a challenge and entails a high degree of uncertainty, since it depends to a high extent on the local conditions.

The obtained theoretical biomethane production has been calculated by considering specific biomethane yield of each single biomass. However, according to Meiramkulova et al. (2018) [59], the potential biomethane production can increase when the co-digestion technique is used. In particular, co-digestion offers benefits such as: dilution of toxic compounds, increased biogas yield odors and pathogen reduction, enhanced nutrient balance, the synergistic effect of microorganisms and increased weight of biodegradable organic substances [60]. Furthermore, the authors acknowledge that a number of additional factors may affect the actual biomethane production, as well as biomethane provision and utilization. Indeed, in this study, the estimated available biomass and potential biomethane production have been calculated without considering logistics. As a matter of fact, some constraints may be related to the phase of biomass collection and conveyance to the production plant (e.g., related to feedstock supply constraints or distance limits), but also to the number of plants and their biomethane production capacity or to the presence of facilities and networks for the end-product distribution and refueling [61,62].

A further limitation of the study Is related to the calculation of the energetic value of biomethane from available agricultural wastes. This was obtained through the energy density, expressed in MJ kg^{-1}; thus, subsequent evaluations were made by comparing the energetic content of fuels. However, the authors acknowledge that the real fuel consumption of tractors depends on many factors, including the specific tractor model, engine power, speed of field operations and external conditions [63].

Finally, concerning the theoretical reduction in CO_2 emissions, this computation was focused exclusively on the "tank to wheel" path, which means that only emissions from fuel combustion were computed. Moreover, the associated emissions of CH_4 and N_2O were not considered, since, as calculated by Flammini et al. (2021) [64], they would be five to six orders of magnitude smaller compared to CO_2 on a per ton basis.

4.2. Suggestions for Further Research

There is a wide range of opportunities for future studies starting from the present analysis. Once the availability of the biomass obtainable from agricultural wastes at the regional level has been established, and it has been ascertained that it satisfies the energy requirements to replace diesel fuel for tractors, the technical-economic viability of this prospected scenario should be evaluated. In detail, the number and size of AD plants currently operating in the studied area should be assessed to evaluate the actual production capacity with respect to the amounts of available biomass and potential biomethane production estimated in this study. Then, the presence of biomethane facilities and infrastructures should be analyzed to assess if the obtainable biomethane can also be distributed to farms that are not directly involved in the production of biogas/biomethane. Regarding the economic viability, production costs and savings in replacing diesel fuel with biomethane should be estimated. Furthermore, the evaluation pursued in this study could be extended to more comprehensive areas/other countries and to other types of residual feedstock, such as municipal solid waste. With regard to CO_2 emissions, it is important to underline that they have been calculated taking into account the net calorific value of diesel and biomethane; therefore, they correspond substantially to a theoretical potential value. For this reason, as a future step, performance tests of tractor prototypes powered by biomethane should be carried out evaluating the actual consumption of diesel and biomethane, also calculating the actual CO_2 emissions.

5. Conclusions

The agricultural sector plays a well-established role in food and feed production; however, in the last decades, it progressively gained importance also for renewable energy production, in particular through the AD process. For years, most AD plants have been using energy crops—above all, maize silage—mainly due to their high specific methane yields which makes the co-digestion of low-yielding animal manure feasible [65]. However, the utilization of energy crops is debatable as they can compete for agricultural land use with food and feed supply [66,67].

The present study examined the potential production of biomethane at the regional level, resulting from the anaerobic digestion of crop residues and livestock manure without causing competition with food and feed. Based on the average values of available residual biomass over the last seven years (2015–2021) in the Piedmont region, the annual potential biomethane yield and related thermal energy were estimated to be more than sufficient to meet the energy requirements for the regional tractors' fleet. Moreover, by replacing diesel with biomethane, a potential 16.8% reduction in CO_2 emissions could be reached.

In conclusion, the study's results underline the possibility and importance of using agricultural wastes for biomethane production, satisfying both the energy requirements of the regional agricultural sector, the need to achieve carbon neutrality and land use efficiency. The present study of the production in Piedmont of biogas used the Biogasdoneright^{TM}" (BDR) model, which includes a set of practices that link biogas production with sustainable agriculture [49]. The Biogasdoneright^{TM} concept also extends to the use of digestate on the farm, bringing a series of benefits such as: (i) providing fertilizers on the soil, (ii) reducing the use of mineral fertilizers, and (iii) increasing the carbon storage in the soil. This concept also involves the use of other non-agricultural sources of biomass, such as organic fractions of municipal solid waste, wood processing residues and the recovery of landfill gas. However, in the present work, only crop residues and livestock wastes have been considered to assess the self-subsistence of the agricultural sector in biofuel production.

Author Contributions: Conceptualization, N.P. and E.C.; methodology, G.B. and D.A.; data curation, G.B. and D.A.; writing—original draft preparation, G.B. and D.A.; writing—review and editing, N.P.; supervision, E.C.; funding acquisition, E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Regional Development Fund, the Italian Government, and the Piedmont region within the programme P.O.R. FESR 2014–2020, grant number 351-44.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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