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Article

Analysis of Specific Greenhouse Gas Emissions Savings from Biogas Production Based on Agricultural Residues and Industrial By-Products

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Abstract: The aim of this study was to analyse specific greenhouse gas emissions savings for a variety of agricultural residues, industrial by-products, and municipal biowaste. One of the most viable alternatives to fossil fuels is bioenergy, particularly biogas produced by the anaerobic digestion of renewable feedstocks. The revised Renewable Energy Directive (D 2018/2001) recognizes that biogas production from agricultural residues, livestock production, and industrial by-products is an acknowledged greenhouse gas mitigation technology in cases where their use results in a certain level of specific greenhouse gas savings. This study delivered values for the maximum transport distance of agricultural residues and industrial by-products to achieve the greenhouse gas (GHG) emissions-saving requirement defined by Directive 2018/2001. It analysed the greenhouse gas emissions reduction for numerous feedstocks for which Directive 2018/2001 has not defined the default and typical values but which could be used as sustainable substitutes for currently dominantly used maize silage in biogas production. The results obtained in this work define the maximum transport and distribution distance for which biogas produced from considered feedstocks achieved required specific greenhouse gas emissions savings (80%), compared with fossil fuel comparator. The obtained results can be used as the constraints in the optimisation of the biomass supply chains for the feedstocks considered in this work.

Keywords: greenhouse gas emission saving; biogas; agricultural residues; industrial by-products

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1. Introduction

Biogas production has been on the rise in Europe in the last two decades as countries seek to reduce their dependence on fossil fuels and meet climate change targets. Biogas plants can range greatly in terms of installed capacity, from micro plants in developing countries, small-scale plants used on farms, and large-scale plants used in centralised systems in cities [1]. Although mostly used to generate electricity and heat, biogas can also be utilised to create biomethane, a fuel that can replace natural gas in transportation and industrial applications. Biofuels are the only commercially viable alternative already utilized for transport and industrial needs [2].

Up to 72% of the feedstocks used for biogas production come from the agricultural sector [3], primarily maize silage. The competitive use of biogas feedstocks with food and feed production has raised not only environmental but also socioeconomic concerns, reflected in new sustainability requirements defined by European Union (EU) legislation [4]. The revised Renewable Energy Directive, which came into effect in December 2018, has established sustainability and the greenhouse gas (GHG) emission-savings criteria with which biogas used in transport, electricity, heating, and cooling production, must comply. The new Directive enhances the sustainability requirements for biogas feedstocks and adds new requirements for specific greenhouse gas emission savings from biogas production, which biogas facilities must adhere to in order to contribute to renewable energy goals and qualify for government funding. As one of these criteria, the Directive states that the GHG savings from the use of biomass for heating, cooling, and electricity production must be at least 70% for plants that started to work in 2021 and 80% for plants starting operation in 2026 [5]. The Directive also defines typical and default values for GHG savings for the three mostly used biogas feedstocks: manure, biowaste, and maize whole plant (maize silage).

A significant amount of sustainable feedstocks and a thorough understanding of the sustainable potential of biomass supply are necessary to achieve GHG savings [6]. The utilisation of materials previously regarded as waste, such as agricultural and industrial residues and by-products, is receiving increased attention, as it not only improves the sustainability of biogas production but also improves waste management and resource efficiency.

Research Problem and Literature Review

The environmental sustainability of biomass utilisation for energy purposes has raised significant concerns. It has been reported that biomass utilisation may result in unsolved challenges and trade-offs concerning the accounting of GHG and non-GHG emissions [7]. The environmental sustainability of biomass utilisation is a complex problem which depends on various factors such as the feedstock type, feedstock preprocessing and processing technology, transportation and distribution distance, emissions from the fuel in use, etc. Because of its high complexity, the importance of this problem has increased in the last decades. Hence, a significant number of research papers have investigated various types of environmental sustainability performance of biomass utilisation for energy production. Some of them are presented in the following paragraphs.

Hamelin et al. [8] performed the life cycle assessment of biogas production based on manure and the following co-substrates: straw, garden waste, food waste, energy crops, and animal urine and faeces. The results, given in kgCO_2eq per functional unit, prioritised source-segregated solid manure as co-substrates, followed by straw and biowastes, while energy crops were identified as co-substrates whose utilisation would result in adverse environmental impacts. In their recent work, Meng et al. [9] examined the viability of total or partial replacement of peat by maize straw biogas residues and manure biogas residues. The results showed that a biogas plant that produced 10,000 m^3 biogas daily could achieve savings of 439.4 tonnes/year of CO_2 through the proposed replacement. Den Boer et al. [10] calculated that using kitchen waste for biogas production could lead to 680,000 tCO_2eq savings per year.

The transport distance of the biomass supply and biomass availability throughout the year have a significant impact on the energy conversion efficiency and GHG reductions in anaerobic digestion (AD) technology [11]. Anaerobic digestion (AD) is a collection of processes by which microorganisms break down biodegradable material in the absence of oxygen. The results of AD are biogas and digestate. Berglund et al. [12] performed the energy life cycle analysis of eight feedstocks for biogas production. The results showed that the difference between energy output and input was positive in the cases of transport distances less than 700 km for slaughterhouse waste, 580 km for municipal organic waste, 240 km for straw, 220 for pig manure, and 200 km for cow manure. In their study, Uusitalo et al. [13] concluded that using biogas to produce heat and electricity leads to greater GHG reductions than composting feedstock, yet not as high as in the case of its utilisation for transport. In the work of Balcioglu et al. [14], the authors calculated that if 60% of cattle manure and all available chicken manure in Turkey were co-digested with other waste feedstock, this could lead to annual GHG emissions reduction of up to 2.5%. Wąs et al. [15] assessed the GHG mitigation potential of biogas production that uses agricultural waste and manure as biogas feedstock in Ukraine. Results indicated that the theoretical potential of GHG savings ranged between 5% to 6.14%, while technical potential varied between 2.3% to 2.8% of total GHG emissions. Tamburni et al. [16] calculated that biogas production from agricultural waste could result in GHG emission savings of up to 3,000,000 MgCO_2eq in the Emilia Romagna region.

As can be seen from the literature review, environmental sustainability and GHG savings have been studied extensively, obtaining results in different forms using a variety of methods. However, there are still numerous feedstocks recognised as novel feedstocks for biogas production (mostly so-called waste materials), but the constraints to achieving required GHG savings still need to be defined, as there are limited data on GHG emissions from the biogas production chain that can serve as typical and defaults limits. To address this gap, the research object of this study was to define the maximal transport distance of various novel biomass feedstock that complies with the GHG savings of 80%, compared with fossil fuels, as required in Directive 2018/2001. This was calculated for agricultural residues, municipal biowaste, and industrial by-products. This work hypothesised that all considered feedstocks would achieve the requested GHG savings (80%) for transport and distribution distances up to 50 km. The method used for the calculation is presented in the section below.

2. Method

The method used in this work is based on the method developed by the Joint Research Centre and implemented in Directive 2018/2001 [5]. Directive 2018/2001 includes disaggregated typical and default GHG and GHG saving values for biogas used to produce electricity and heat for wet manure, maize whole plant (maize silage), and biowaste.

The method can be used for the determination of specific GHG emissions from different solid and gaseous pathways. In this method, the Global Warming Potential (GWP) is used as the climatic metric. Global Warming Potential is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking into account how long it remains active in the atmosphere [17]. As defined in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [18], the GWP of methane is equal to 25, and for nitrous oxides is 298 for a period of 100 years.

Biogas feedstocks analysed in this work are:

- **Agricultural residues:** straws (wheat straw, barley straw, oat straw, and triticale straw), and maize stover;
- **Industrial residues:** grape pressings, tomato pomace, brewers' spent grain, olive pomace, and sugar beet pulp;
- **Municipal biowaste:** The method is described in detail in the following subsections.

2.1. Calculation of Greenhouse Gas Emissions from the Production and Use of Biogas

The general equation used to calculate greenhouse gas emissions from the production and use of biogas is:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad (1)$$

where

E is the total emissions from the use of the fuel (gCO_2eq/MJ);

e_{ec} is emissions from the extraction or cultivation of feedstocks (gCO_2eq/MJ);

e_l is annualised emissions from carbon stock changes caused by a land-use change (gCO_2eq/MJ);

e_p is emissions from processing (gCO_2eq/MJ);

e_{td} is emissions from transport and distribution (gCO_2eq/MJ);

e_u is emissions from the fuel in use (gCO_2eq/MJ);

e_{sca} is emission reduction from soil carbon accumulation due to improved agricultural management (gCO_2eq/MJ);

e_{ccs} is emission savings from CO_2 capture and geological storage (gCO_2eq/MJ);

e_{ccr} is emission savings from CO_2 capture and replacement (gCO_2eq/MJ).

In the subsections below, each emission factor is described in greater detail.

2.1.1. Emissions from the Extraction or Cultivation of Feedstocks (e_{ec})

Emissions from collecting, drying, and storing feedstocks, waste, leaks, and the production of chemicals or goods used in extraction or culture were all included in the definition of emissions from the extraction or cultivation of feedstocks [5]. These emissions apply when agricultural feedstocks like palm, maize, sugarcane, soybean, or rapeseed are extracted or grown. The emissions from the cultivation or extraction of feedstocks were regarded as zero when residues, by-products, and waste materials were utilised as feedstocks for biogas generation [19].

2.1.2. Annualised Emissions from Carbon Stock Changes Due to Land-Use Change (e_l)

By averaging emissions from carbon stock changes over a 20-year period, we determined the annualised emissions from carbon stock changes caused by a change in land use [5]. Any alteration in the carbon stock between the classified land categories of grassland, forestland, cropland, wetland, settlements, and other lands was considered a land-use change [20]. The calculation was based on Equation (2) [5]:

$$e_l = \frac{(CS_R - CS_A)}{P * 20} * 3.664 - e_B \tag{2}$$

where

CS_R is the carbon stock per unit area corresponding to the reference land use. The reference land use is the land use as of January 2008 or 20 years prior to receiving feedstock, whichever was more recent. It is quantified as a mass of carbon per hectare (gC/ha), which includes both soil and vegetation;

CS_A is the quantity of carbon stored per area corresponding to the actual land use. It is quantified as a mass of carbon per hectare (gC/ha), which includes both soil and vegetation;

P is the crop's productivity, expressed as the amount of biofuel produced per hectare per year (MJ/ha·year);

e_B is a bonus of 29 gCO_2eq/MJ, applied when biomass is obtained from restored degraded land (gCO_2eq/MJ).

2.1.3. Emissions from Processing (e_p)

Emissions from processing refer to emissions that result from the actual processing itself—waste generation, product leakage, and the production of chemicals and other processing-related products. In addition, regardless of whether fossil fuel inputs were burned during processing, these emissions also included CO_2 emissions proportional to their carbon content. The benchmark for measuring the emissions of greenhouse gases caused by electricity not produced on a biogas site was the average emission intensity of electricity production and distribution in a given area. Regardless of whether or not they were processed into intermediate products before being converted into the end product, agricultural residues and industrial by-products were regarded as having zero life cycle greenhouse gas emissions until the collection process [5].

The agricultural residues having a bulk density of less than 0.2 tonne/m^3 required a processing step before prior transportation: baling, additional grinding, or clustering. This is represented by a single process [19] in Table 1.

Table 1. Emissions from bailing/processing agricultural residues.

Baling/Processing				
Input	**Output**	**Unit**	**Amount**	**Source**
Agri-residue	-	MJ/MJ_{bale}	1.0	[19,21]
Diesel	-	MJ/MJ_{bale}	0.010	[19,21]
-	Bales	MJ	1.0	[19,22]

Table 1. *Cont.*

Baling/Processing				
Input	**Output**	**Unit**	**Amount**	**Source**
-	CH_4	g/MJ_{bale}	1.23×10^{-5}	[19,22]
-	N_2O	g/MJ_{bale}	3.03×10^{-5}	[19,22]

2.1.4. Emissions from Transport and Distribution (e_{td})

GHG emissions from the transport and distribution (e_{td}) should include all transport and distribution steps in the value chain. e_{td} was calculated from the following equation [20]:

$$e_{td} = \frac{\left(d_{loaded} * K_{loaded} + d_{empty} * K_{empty}\right) * EF_{fuel}}{E_{bio.feedstock}} \quad (3)$$

where

d_{loaded} is the transport and distribution distance of a loaded truck (km);
K_{loaded} is fuel use of loaded truck (L/km);
d_{empty} is the transport and distribution distance of an empty truck (km);
K_{empty} is the fuel consumption of an empty truck (L/km);
EF_{fuel} is fuel's emission factor (gCO_2eq/l);
$E_{bio.feedstock}$ is the biogas potential of loaded biomass feedstocks (MJ).

Typical values for transport and distribution calculation are given in Table 2. According to the JRC report [19], it was assumed that a 40 t truck would be used to deliver the feedstock to biogas sites (27 t payload).

Table 2. Typical e_{td} values calculation [19].

	K_{empty} [L/km]	K_{loaded} [L/km]	EF_{fuel} [gCO_2eq/l]
Value	0.3	0.35	3157

The Biogas potential of loaded biomass feedstocks is calculated by Equation (4):

$$E_{bio.residues} = \rho_{residues} * V_{truck} * y_{biogas} * s_{CH_4} * LHV_{CH_4} \quad (4)$$

where

$\rho_{residues}$ is bulk density of residues (t/m^3);
V_{truck} is truck load capacity (m^3);
y_{biogas} is biogas yield from 1 tonne of fresh feedstock (m^3/t);
s_{CH_4} is methane content of biogas (%);
LHV_{CH_4} is methane lower heating value (MJ/m^3).

Typical values for calculating the biogas potential of loaded biogas feedstocks for the considered feedstocks are given in Table 3.

Table 3. Typical values for the calculation of biogas potential.

Biogas Feedstock	$\rho_{residues}$ (t/m^3)	y_{biogas} (m^3/t)	s_{CH_4} (%)
Maize stover	0.060 [23]	276 [24]	55 [24]
Wheat straw	0.043 [25]	125 [24]	52.5 [24]
Barley straw	0.037 [25]	125 [24]	52.5 [24]
Oat straw	0.049 [25]	125 [24]	52.5 [24]
Triticale straw	0.043 [25]	125 [24]	52.5 [24]

Table 3. *Cont.*

Biogas Feedstock	$\rho_{residues}$ (t/m^3)	y_{biogas} (m^3/t)	s_{CH_4} (%)
Grape pressings	0.525 [26]	150 [24]	52.5 [24]
Tomato pomace	0.73 [27]	94 [28]	53 [29]
Brewers' spent grain	0.45 [30]	89 [31]	62 [31]
Olive pomace	0.9 [32]	121 [33]	71 [33]
Sugar beet pulp	0.561	96 [34]	50 [34]

It is important to highlight that for feedstocks with a bulk density greater than 0.75 t/m^3, the feedstock load was constrained by weight, while for bulk densities less than 0.75 t/m^3, it was volume constrained. The bulk density of agricultural residues could be increased 8–12 times at different bailing/briquetting process parameters [25].

2.1.5. Emissions from the Fuel in Use (e_u)

Emissions of the fuel (biogas) in use (e_u) were considered to be zero for biofuels (biogenic CO_2 combustion emission). However, e_u factor should take into account the emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) of the fuel in use [5,35].

2.1.6. Emission Savings from Soil Carbon Accumulation via Improved Agricultural Management (e_{sca})

Emission savings from soil carbon accumulation via improved agricultural management refers to the practice that results in an increase in soil carbon. Those savings could be calculated only in cases of improved manure management, shifting to minimal or zero tillage, use of compost, or improved crop rotations [36]. To assess those savings, Equation (2) can be used, replacing the 20 years with the appropriate number of years for a given period.

2.1.7. Emission Savings from CO_2 Capture and Geological Storage (e_{ccs})

Emission savings from CO_2 capture and geological storage (e_{ccs}) include averted emissions through CO_2 capture and geological storage directly associated with fuel extraction, transportation, processing, and distribution [5]. They could only be considered if proven that the current storage ensures that the leakage does surpass the current state of technology [19].

2.1.8. Emission Savings from CO_2 Capture and Replacement (e_{ccr})

Savings on emissions from CO_2 capture and replacement (e_{ccr}) were only possible when CO_2 that comes from biomass was captured and utilised to replace CO_2 that comes from fossil fuels in the creation of goods and services for sale [5]. The savings could be included in the overall calculation only if proven that CO_2 replaces CO_2 that comes from fossil sources and is employed in the production of goods and services for commerce [19].

2.2. Calculation of Greenhouse Gas Emissions from Heat and Electricity

In this study, the assumption was that biogas produced from considered feedstocks would be used in cogeneration (CHP) plants to produce electrical and thermal energy. In order to allocate emissions to each final energy commodity, the following equations were used [5]:

$$EC_{el} = \frac{E}{\eta_{el}} \cdot \left(\frac{C_{el} \cdot \eta_{el}}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h} \right) \tag{5}$$

$$EC_h = \frac{E}{\eta_h} \cdot \left(\frac{C_h \cdot \eta_h}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h} \right) \tag{6}$$

where:

EC_{el} is total GHG emissions associated with electrical energy (gCO_2eq/MJ);

EC_h is total GHG emissions associated with thermal energy (gCO_2eq/MJ);

η_{el} is electrical efficiency, determined as the annual electrical energy output divided by the energy content of annual fuel input (%);

η_h is heat efficiency, determined as the annual useful thermal energy output divided by the energy content of the annual fuel input (%);

C_{el} is a fraction of exergy in the electricity (-). For electricity, the fraction of exergy is set to 100%;

C_h is a fraction of exergy in the useful heat, calculated as Carnot efficiency (-). It is defined as:

$$C_h = \frac{T_h - T_0}{T_h} \tag{7}$$

where:

T_h is the temperature of the useful heat at the point of delivery (K);

T_0 is environmental temperature, set at 273.15 K (K).

2.3. Calculation of Greenhouse Gas Emissions Savings from Heat and Electricity Generated from Biogas

The following equations define greenhouse gas emissions from heat and electricity for respective fossil fuel comparators in order to calculate GHG savings obtained from heat $GHG\ SAVINGS_{,heat}$ and electricity $GHG\ SAVINGS_{,electricity}$ generated from biogas:

$$GHG\ SAVINGS_{,heat} = \frac{EC_{F(h)} - EC_h}{EC_{F(h)}} \tag{8}$$

$$GHG\ SAVINGS_{,electricity} = \frac{EC_{F(el)} - EC_{el}}{EC_{F(el)}} \tag{9}$$

where

$EC_{F(h)/F(el)}$ is total emissions from the fossil fuel comparator for useful thermal energy/electrical energy (gCO_2eq/MJ);

$EC_{h/el}$ is total emissions from the useful thermal energy/electrical energy generated from biogas (gCO_2eq/MJ).

The values of fossil fuel comparators were equal to 183 gCO_2eq/MJ for electrical energy and 80 gCO_2eq/MJ for useful thermal energy.

3. Results and Discussion

As previously noted, the savings of GHG emissions from biogas used in CHP engines after being produced from various kinds of agricultural and industrial residues and by-products, as well as municipal biowaste, are computed. Here, it was presumed that a CHP engine meets the electricity and heat needs in the biogas generation process (referred to as Case 1 in Directive 2018/2001). The temperature at the delivery site was considered to be 80 °C (353.15 K), and the heat efficiency and power efficiency were presumed to be 40% and 36%, respectively. These figures were chosen in accordance with the operating values of the biogas plants in operation.

3.1. Emissions from the Extraction or Cultivation of Raw Material (e_{ec})

Since the direct use of agricultural land is the creation of an agricultural product that is not used for the generation of biogas, the utilisation of considered feedstocks did not generate emissions from extraction or cultivation.

3.2. Annualised Emissions from Carbon Stock Changes (e_l)

Because agricultural land is not required to produce the examined feedstocks, their utilisation did not result in land-use change. Hence, e_l could be neglected (taken to be zero), as those emissions were allocated to the cultivated agricultural goods.

3.3. Emissions from Processing (e_p)

Two cases of agricultural residues were considered. In the first case, the residues were baled to improve their bulk density; this was not performed in the second case. The values used for the calculation were obtained from Table 1 and from default values of processing emissions for agricultural residues with density > 0.2 t. For industrial by-products and municipal biowaste, values used for calculation were set in accordance with the default values for biowaste in both open digestate and closed digestate configurations. The values for both groups of feedstocks are presented in Tables 4 and 5.

Table 4. Emissions from processing and agricultural residues.

e_p (gCO_2eq/MJ)	Maize Stover	Wheat Straw	Barley Straw	Oat Straw	Triticale Straw
Unbaled	0	0	0	0	0
Baled	1.1	1.1	1.1	1.1	1.1

Table 5. Emissions from processing, municipal biowaste industrial by-products.

e_p (gCO_2eq/MJ)	Municipal Biowaste	Grape Pressings	Tomato Pomace	Olive Pomace	Brewers' Spent Grain	Sugar Beet Pulp
Open digestate	0	0	0	0	0	0
Close digestate	21.8	21.8	21.8	21.8	21.8	21.8

3.4. Emissions from the Fuel in Use (e_u)

As previously stated, biogenic CO_2 combustion emissions were considered to be zero for biogas. Regarding biogas, the fuel's typical non-CO_2 emissions were equal to 8.9 gCO_2/MJ, while default values were anticipated to be 40% higher than the typical values [21].

3.5. Emission Savings from Soil Carbon Accumulation via Improved Agricultural Management (e_{sca})

For the considered feedstocks, it was presumed that they do not fulfil the requirements needed to include this factor in the GHG savings, defined in the Method section.

3.6. Emission Savings from CO_2 Capture and Geological Storage (e_{ccs}) and Replacement (e_{ccr})

As most biogas plants operating nowadays do not have a CO_2 capture storage and replacement system, it was assumed that no GHG savings come from CO_2 capture storage and replacement.

3.7. Emissions from Transport and Distribution (e_{td})

As can be seen from Equation (3), GHG emissions from transport and distribution were a function of transport distance. Those values are presented in diagrams in Figure 1 for unbaled agricultural residues, Figure 2 for baled agricultural residues, and Figure 3 for municipal biowaste and industrial by-products.

Unbaled agricultural residues had a considerable increase in transport emissions per kilometre, as shown in Figure 1, because of their low bulk density. Barley straw had the highest increase in emissions per kilometre because of its lowest density. The emissions from transportation and distribution for barley straw outweighed the emissions from all other factors when the transport distribution was 33 km or greater. On the other hand, maize stover had the lowest rise in emissions per kilometre because of its higher density and higher biogas yield. In the case of distributions of 60 km or more, transportation emissions outweighed other sources of emissions in this situation.

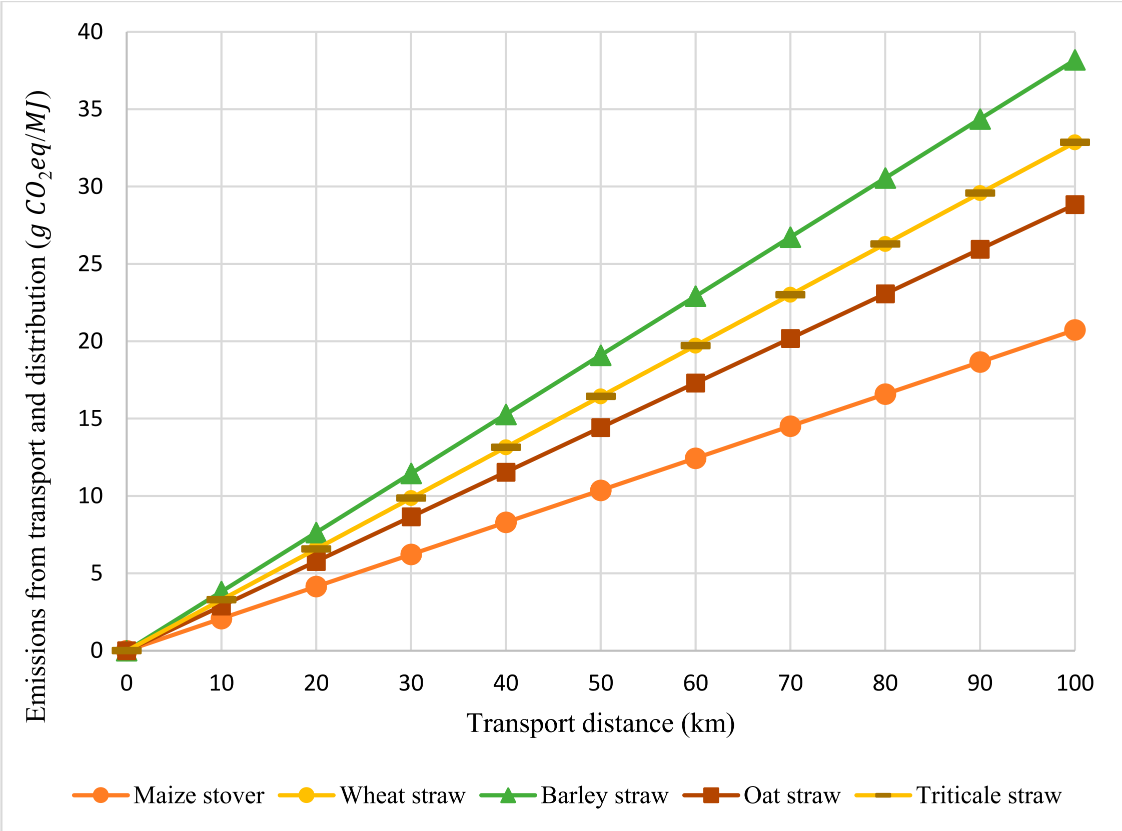

Figure 1. Emissions from transport and distribution of agricultural residues (unbaled).

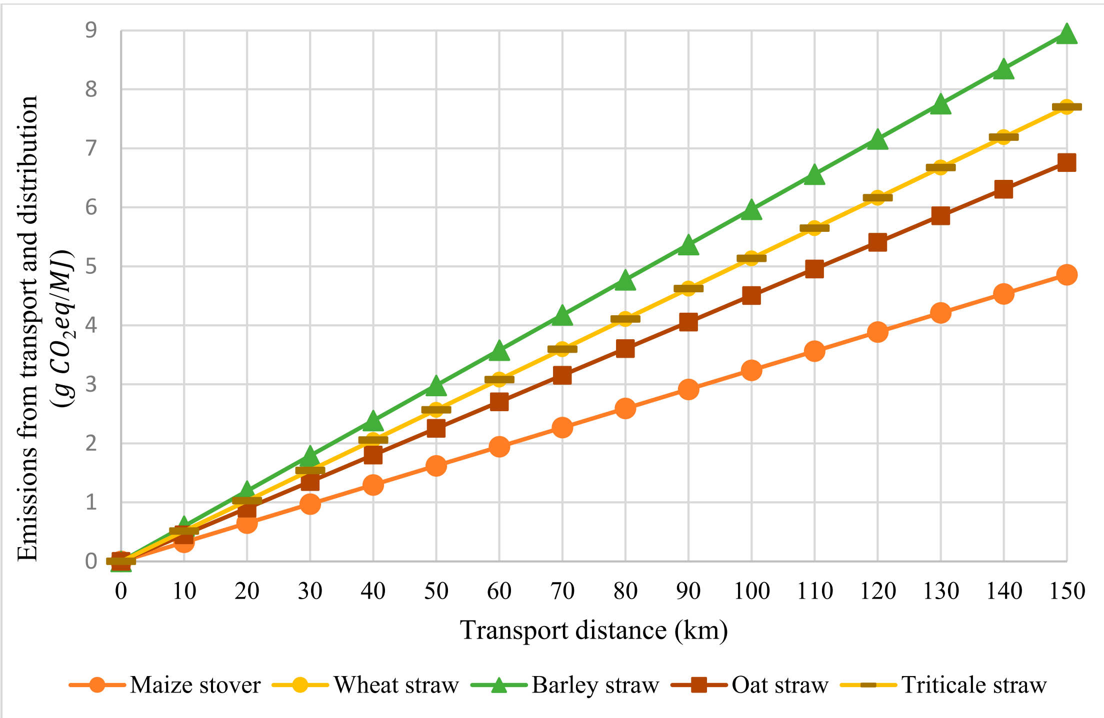

Figure 2. Emissions from transport and distribution of agricultural residues (baled).

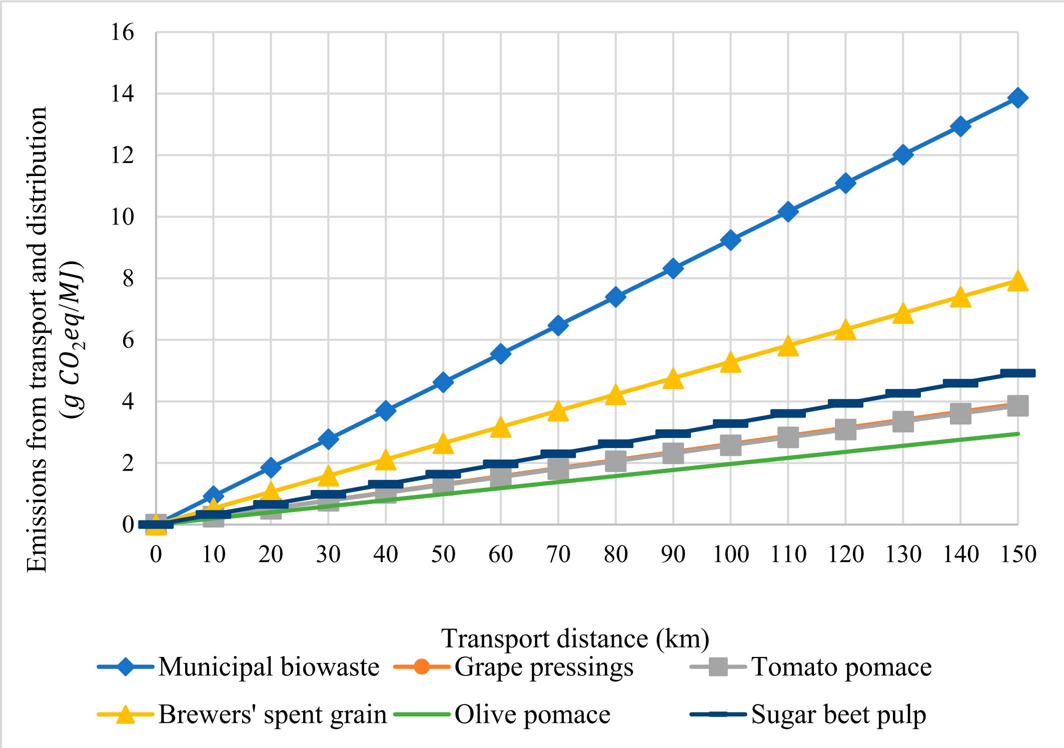

Figure 3. Emissions from transport and distribution -municipal biowaste and industrial by-products.

The baling of agricultural residues increases the bulk density eight times [25]. Because of the shape of a bale, it was assumed that bales could fill up to 80% of the truck storage space. Emissions of transport and distribution for baled agricultural residues are presented in Figure 2.

The baling of agricultural by-products increased the bulk density and, as a result, greatly slowed the increase in emissions from transit and distribution while slightly increasing the emissions of feedstock processing. Baled agricultural residues had a five-fold lower impact on distribution and transportation-related specific emissions than in the previous case.

Figure 3 shows the emissions from the distribution and transport of municipal biowaste and industrial by-products as a function of distribution and transport.

Brewers' spent grain had the most significant rise in specific transport emissions among the analysed industrial by-products, whereas olive pomace had the lowest increase, as can be seen in Figure 3. Nevertheless, compared with the agricultural residues, those numbers are still much lower (even with the second case). This is caused by the industrial by-products' greater bulk density. Municipal biowaste, on the other hand, had a significant increase in emissions per kilometre due to lower bulk density.

3.8. Greenhouse Gas Emissions Savings from Heat and Electricity Generated from Biogas as a Function of Transport Distance

Biogas plants with CHP engines must achieve both GHG savings for electricity and usable heat to comply with Directive 2018/2001. It is evident from the computed GHG reductions for heat and electricity production that the percentage of GHG savings for the generation of electricity was lower. As a result, the benchmark for calculating the maximum transport distance was 80% of GHG savings for electricity production.

GHG savings of unbaled agricultural residues are presented in Figure 4 as a function of transport distance.

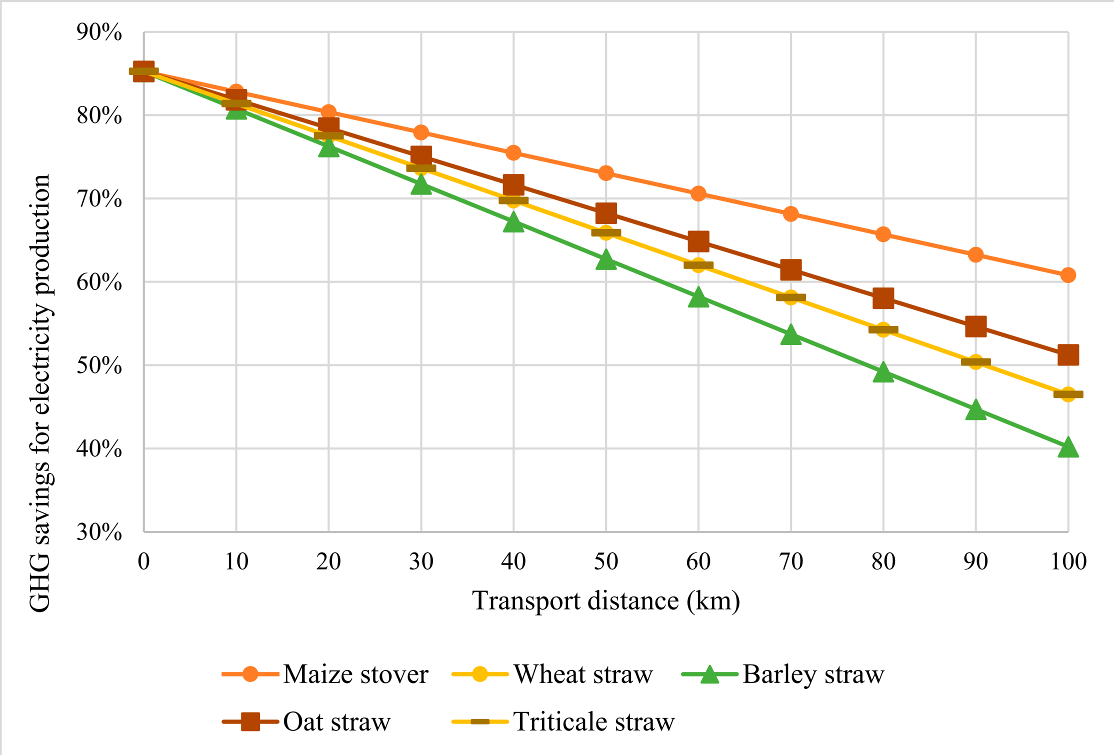

Figure 4. GHG savings for electricity production-agricultural residues (unbaled).

From the diagram presented in Figure 4, the maximum travel distance to achieve 80% of GHG savings from the utilisation of biogas, which uses unbaled agricultural residues as feedstock, can be determined. Those values are defined in Table 6. The greatest travel distance of unbaled agricultural residues was fairly low, ranging from 12 km for barley straw to 21 km for maize stover, as shown in Figure 4 and Table 6.

Table 6. Maximum travel distance for achieving 80% of GHG savings using unbaled agricultural residues.

	Maize Stover	Wheat Straw	Barley Straw	Oat Straw	Triticale Straw
D, max (km)	21	14	12	15	14

Figure 5 shows GHG savings of baled agricultural residues as a function of transport distance.

The baling of agricultural residues greatly enhanced specific GHG savings as a function of transport distance, as predicted from the data shown in Figure 2, although it increased processing emissions. Hence, for baled agricultural leftovers, the maximum travel distance ranged from 65 km for wheat and triticale straw to 104 km for maize stover. Those values can be determined from the diagram presented in Figure 5 and are defined in Table 7.

Table 7. Maximum travel distance for achieving 80% of GHG savings using baled agricultural residues.

	Maize Stover	Wheat Straw	Barley Straw	Oat Straw	Triticale Straw
D, max (km)	104	65	55.5	74	65

Figure 6 shows GHG savings of municipal biowaste and industrial residues as a function of transport distance.

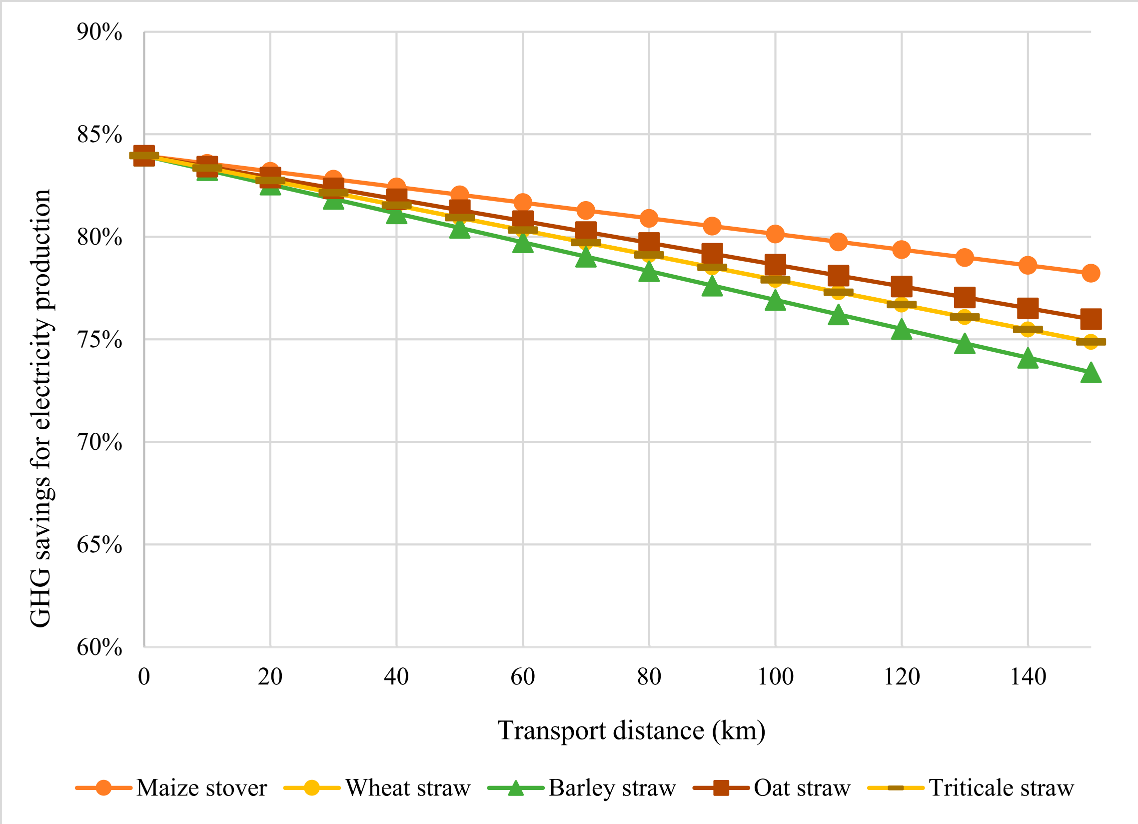

Figure 5. GHG savings for electricity production from agricultural residues (baled).

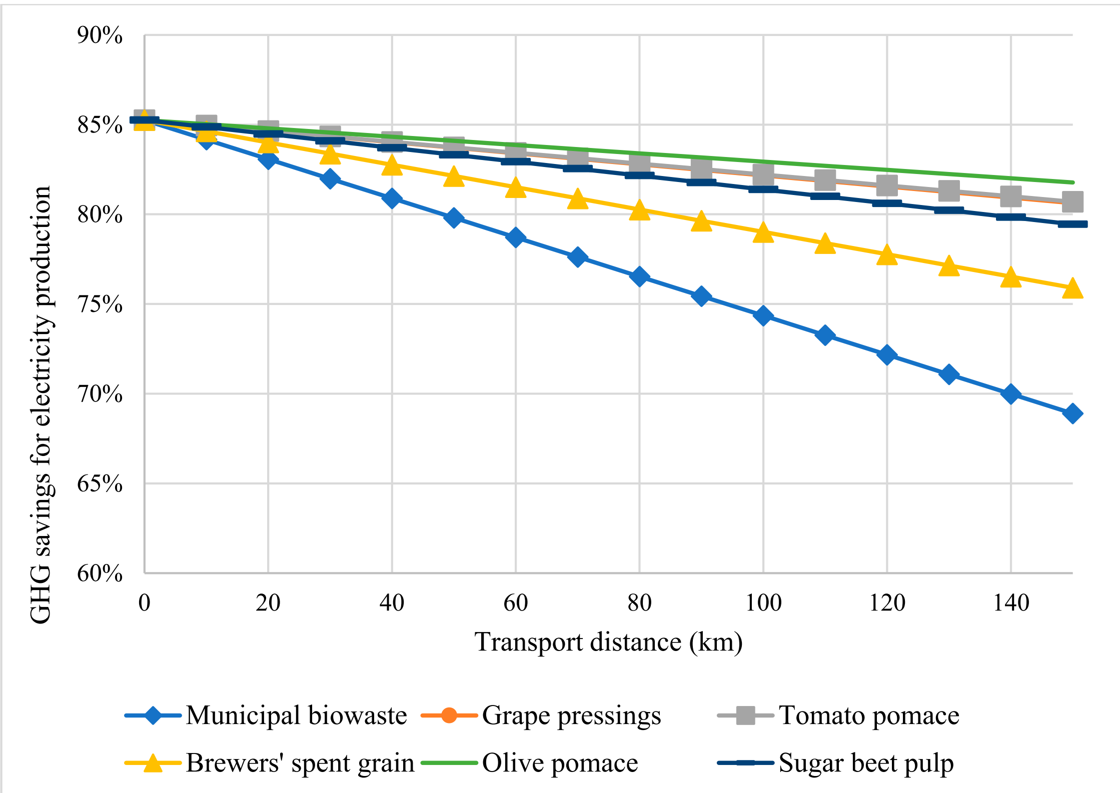

Figure 6. GHG savings for electricity production-municipal biowaste and industrial by-products.

It is important to note that Figure 6 presents only the case with closed digestate, as the considered feedstocks could not achieve 80% of GHG savings in the event of an open digestate. The maximum travel distance for municipal biowaste was 48 km, while for the industrial by-products, it ranged from 84 km for brewers' spent grain to 227 km for olive pomace. Those values can be determined from the diagram presented in Figure 6 and are defined in Table 8. Compared with agricultural residues, industrial by-products could achieve the required savings with a higher transport distance because of higher bulk density.

Table 8. Maximum travel distance for achieving 80% of GHG savings-municipal biowaste and industrial by-products.

	Municipal Biowaste	**Grape Pressings**	**Tomato Residues**	**Brewers' Spent Grain**	**Olive Pomace**	**Sugar Beet Pulp**
D, *max* (km)	48	170	173	84	227	136

The examined feedstocks were a sustainable option for producing biogas as they did not require agricultural land (unlike the already widely used maize silage) and satisfied the sustainability requirements defined in Directive 2018/2001. These requirements state that biogas feedstocks should not be produced from raw materials obtained from land with a high biodiversity value, such as primary forests, areas for the protection of rare or endangered ecosystems or species, highly biodiverse grasslands, wetlands, etc., and must adhere to the criteria for forestry, land use, and land-use change (LULUCF).

The results showed that emissions from transportation and distribution had a substantial impact on total emissions and the resulting reductions in greenhouse gas emissions for the cases and feedstock groups discussed in this study.

The maximum transport distance between the examined feedstocks greatly varied, as shown by the results. Given that waste materials were preferred as biogas feedstock, it is clear that the scope of the analysed feedstocks must be broadened, and the maximum distance for each of the examined feedstocks must be defined. The hypothesis of this work, stating that considered feedstocks can reach 80% GHG savings in the case of a travel distance of up to 50 km, was incorrect for municipal biowaste and unbaled agricultural residues.

4. Conclusions

This paper conducted an analysis based on the method outlined in Directive 2018/2001 of greenhouse gas emissions and specific greenhouse gas emissions savings from biogas production using agricultural residues (wheat straw, barley straw, oat straw, triticale straw, and maize stover), municipal biowaste, and industrial by-products (grape pressings, tomato residues, brewers' spent grain, olive pomace, sugar beet pulp) as feedstock. This method is a GHG accounting method, which includes numerous emission factors for biogas electricity and heating production. The emissions were calculated/determined for each emission factor, except for the emissions from transport and distribution, which were calculated and presented as a function of a transport distance. According to calculations, the maximum travel distance for unbaled agricultural residues to achieve 80% GHG savings when compared with fossil fuel comparators ranged from 12 km for barley straw to 21 km for maize stover. The low bulk density of agricultural residues was the primary cause of the short transport distance. In the case of baled agricultural residues, the maximum travel distance ranged from 65 km for wheat and triticale straw to 104 km for maize stover. The maximum travel distance for municipal biowaste was 48 km, while for industrial by-products, it was significantly higher: 170 km for grape pressings, 173 km for tomato residues, 84 km for brewers' spent grain, 227 km for olive pomace, and 136 km for sugar beet pulp. These results can be attributed to the higher bulk density of industrial residues.

Research findings demonstrate that transportation emissions have a significant impact on biogas production's potential to achieve the required greenhouse gas emissions savings.

A substantial difference in the results further supports the need to increase the number of feedstocks for which default and typical values are available. Finally, it can be stated that for municipal biowaste, unbaled wheat and barley straw, the hypothesis that examined feedstocks can reach 80% GHG savings in the case of a travel distance up to 50 km is incorrect. Researchers, policymakers, and operators of biogas facilities are anticipated to benefit from this research and use the results in future planning.

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Abbreviations

AD	Anaerobic digestion
CHP	Combined heat and power
EU	European Union
GHG	Greenhouse gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change, and Forestry

References

1. Parralejo, A.I.; Royano, L.; González, J.; González, J.F. Small scale biogas production with animal excrement and agricultural residues. *Ind. Crops Prod.* **2019**, *131*, 307–314. [CrossRef]
2. Stančin, H.; Mikulčić, H.; Wang, X.; Duić, N. A review on alternative fuels in future energy system. *Renew. Sustain. Energy Rev.* **2020**, *128*, 109927. [CrossRef]
3. Bioenergy Europe. *Statistical Report 2020*; Bioenergy Europe: Brussels, Belgium, 2020.
4. Lovrak, A.; Pukšec, T.; Grozdek, M.; Duić, N. An integrated Geographical Information System (GIS) approach for assessing seasonal variation and spatial distribution of biogas potential from industrial residues and by-products. *Energy* **2022**, *239*, 122016. [CrossRef]
5. EU Directive (EU). 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Off. J. Eur. Union* **2018**, *2018*, 82–209.
6. Black, M.J.; Whittaker, C.; Hosseini, S.A.; Diaz-Chavez, R.; Woods, J.; Murphy, R.J. Life Cycle Assessment and sustainability methodologies for assessing industrial crops, processes and end products. *Ind. Crops Prod.* **2011**, *34*, 1332–1339. [CrossRef]
7. Pirelli, T.; Chiumenti, A.; Morese, M.M.; Bonati, G.; Fabiani, S.; Pulighe, G. Environmental sustainability of the biogas pathway in Italy through the methodology of the Global Bioenergy Partnership. *J. Clean. Prod.* **2021**, *318*, 128483. [CrossRef]
8. Hamelin, L.; Naroznova, I.; Wenzel, H. Environmental consequences of different carbon alternatives for increased manure-based biogas. *Appl. Energy* **2014**, *114*, 774–782. [CrossRef]
9. Meng, X.; Wang, Q.; Lv, Z.; Cai, Y.; Zhu, M.; Li, J.; Ma, X.; Cui, Z.; Ren, L. Novel seedling substrate made by different types of biogas residues: Feasibility, carbon emission reduction and economic benefit potential. *Ind. Crops Prod.* **2022**, *184*, 115028. [CrossRef]
10. Boer, J.D.; Obersteiner, G.; Gollnow, S.; Boer, E.D.; Bodnárné Sándor, R. Enhancement of food waste management and its environmental consequences. *Energies* **2021**, *14*, 1790. [CrossRef]
11. Milani, M.; Montorsi, L. Energy recovery of the biomass from livestock farms in italy: The case of Modena province. *J. Sustain. Dev. Energy Water Environ. Syst.* **2018**, *6*, 464–480. [CrossRef]
12. Berglund, M.; Börjesson, P. Assessment of energy performance in the life-cycle of biogas production. *Biomass Bioenergy* **2006**, *30*, 254–266. [CrossRef]

13. Uusitalo, V.; Havukainen, J.; Manninen, K.; Höhn, J.; Lehtonen, E.; Rasi, S.; Soukka, R.; Horttanainen, M. Carbon footprint of selected biomass to biogas production chains and GHG reduction potential in transportation use. *Renew. Energy* **2014**, *66*, 90–98. [CrossRef]
14. Balcioglu, G.; Jeswani, H.K.; Azapagic, A. Evaluating the environmental and economic sustainability of energy from anaerobic digestion of different feedstocks in Turkey. *Sustain. Prod. Consum.* **2022**, *32*, 924–941. [CrossRef]
15. Wąs, A.; Sulewski, P.; Krupin, V.; Popadynets, N.; Malak-Rawlikowska, A.; Szymańska, M.; Skorokhod, I.; Wysokiński, M. The potential of agricultural biogas production in ukraine—Impact on GHG emissions and energy production. *Energies* **2020**, *13*, 5755. [CrossRef]
16. Tamburini, E.; Gaglio, M.; Castaldelli, G.; Fano, E.A. Biogas from Agri-Food and Agricultural Waste Can Appreciate Agro-Ecosystem Services: The Case Study of Emilia Romagna Region. Biogas from Agri-Food and Agricultural Waste Can Appreciate Agro-Ecosystem Services: The Case Study of Emilia Romagna Region. *Sustainability* **2020**, *12*, 8392. [CrossRef]
17. Eurostat Global-Warming Potential (GWP). Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Global-warming_potential_(GWP) (accessed on 21 March 2023).
18. Intergovernmental Panel on Climate Change. Climate Change 2007: Mitigation. In *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2007.
19. Giuntoli, J.; Agostini, A.; Edwards, R.; Marelli, L. Solid and gaseous bioenergy pathways: Input values and GHG emissions. In *JRC Science and Policy Reports*; Joint Research Centre: Brussels, Belgium, 2017.
20. International Sustainability et Carbon Certification (ISCC). *Greenhouse Gas Emissions*; International Sustainability et Carbon Certification (ISCC): Köln, Germany, 2016.
21. *GEMIS, v. 4.9*; Xtra-residue\straw bales-DE-2010; European Environment Agency: Copenhagen, Denmark, 2014.
22. EMEP/EEA. Chapter 1. A.4.c.ii-Tier 1-Table 3-1—Agricultural Machines. In *Guidebook*; EMEP/EEA: Copenhagen, Denmark, 2013.
23. Thoreson, C.P.; Darr, M.J.; Webster, K.E. Corn Stover Densification Methods and their Large-Scale Logistical Impacts—Preliminary Analysis. In *Agricultural and Biosystems Engineering Conference Proceedings and Presentations*; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2010. [CrossRef]
24. Menardo, S.; Airoldi, G.; Cacciatore, V.; Balsari, P. Potential biogas and methane yield of maize stover fractions and evaluation of some possible stover harvest chains. *Biosyst. Eng.* **2015**, *129*, 352–359. [CrossRef]
25. Tumuluru, J.S.; Tabil, L.G.; Song, Y.; Iroba, K.L.; Meda, V. Impact of process conditions on the density and durability of wheat, oat, canola, and barley straw briquettes. *Bioenergy Res.* **2015**, *8*, 388–401. [CrossRef]
26. Burg, P.; Vítěz, T.; Turan, J.; Burgová, J. Evaluation of grape pomace composting process. *Acta Univ. Agric. Silvic. Mendel. Brun.* **2014**, *62*, 875–881. [CrossRef]
27. Coelho CM, M.; de Mattos Bellato, C.; Santos JC, P.; Ortega EM, M.; Tsai, S.M. Effect of phytate and storage conditions on the development of the 'hard-to-cook'. *J. Sci. Food Agric.* **2007**, *1243*, 1237–1243. [CrossRef]
28. Ulusoy, Y.; Ulukardeşler, A.H.; Ünal, H.; Alibaş, K. Analysis of biogas production in Turkey utilising three different materials and two scenarios. *Afr. J. Agric. Res.* **2009**, *4*, 996–1003.
29. Li, Y.; Li, Y.; Zhang, D.; Li, G.; Lu, J.; Li, S. Solid state anaerobic co-digestion of tomato residues with dairy manure and corn stover for biogas production. *Bioresour. Technol.* **2016**, *217*, 50–55. [CrossRef] [PubMed]
30. Mussatto, S.I.; Dragone, G.; Roberto, I.C. Brewers' spent grain: Generation, characteristics and potential applications. *J. Cereal Sci.* **2006**, *43*, 1–14. [CrossRef]
31. Panjičko, M.; Zupančič, G.D.; Fanedl, L.; Logar, R.M.; Tišma, M.; Zelić, B. Biogas production from brewery spent grain as a mono-substrate in a two-stage process composed of solid-state anaerobic digestion and granular biomass reactors. *J. Clean. Prod.* **2017**, *166*, 519–529. [CrossRef]
32. Amel, C.L.; Rafik, B. Olive pomace based lightweight concrete, an experimental approach and contribution. *MATEC Web Conf.* **2018**, *149*, 01068. [CrossRef]
33. Al-Addous, M.; Alnaief, M.; Class, C.; Nsair, A.; Kuchta, K.; Alkasrawi, M. Technical Possibilities of Biogas Production from Olive and Date Waste in Jordan. *BioResources* **2017**, *12*, 9383–9395. [CrossRef]
34. Pilarski, K.; Pilarska, A.A.; Boniecki, P.; Niedbała, G.; Durczak, K.; Witaszek, K.; Mioduszewska, N.; Kowalik, I. The efficiency of industrial and laboratory anaerobic digesters of organic substrates: The use of the biochemical methane potential correction coefficient. *Energies* **2020**, *13*, 1280. [CrossRef]
35. European Commission. *Annex A: Methodology for Calculation of GHG Emission Avoidance*; European Commission: Brussels, Belgium, 2020.
36. European Commission. Communication from the Commission on the Practical Implementation of the EU Biofuels and Bioliquids Sustainability Scheme and on Counting Rules for Biofuels. Available online: http://ec.europa.eu/energy/renewables/transparency_platform/transparency_platform_en.htm (accessed on 21 March 2023).