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Grass from Road Verges as a Substrate for Biogas Production

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Abstract: Maintenance of urban green infrastructure generates a large amount of biomass that can be considered a valuable feedstock for biogas production. This study aims to determine the effect of the cutting time and method of substrate preservation on the specific methane yield (SMY) of urban grass collected from road verges and median strips between roadways in wet (WF) and dry fermentation (DF) technology. The grass was collected three times in a growing season, including in spring, summer, and autumn. The biochemical methane potential (BMP) test was performed on fresh grass, grass ensiled without additives, and grass ensiled with microbiological additives. In addition, the energy potentially produced from biogas and the avoided CO_2 emissions were calculated. The highest SMY (274.18 ± 22.59 NL kg_{VS}^{-1}) was observed for the fresh grass collected in spring and subjected to WF. At the same time, the lowest CH_4 production (182.63 ± 0.48 NL kg_{VS}^{-1}) was found in the grass ensiled without additives, collected in summer, and digested in DF technology. A comparison of the SMY obtained from the same grass samples in the WF and DF technologies revealed that higher CH_4 yields were produced in WF. The electricity and heat production were affected by the time of grass cutting, ensilage method, and AD technology. Generally, less electricity but more heat was produced in DF technology. The least electricity (469–548 kWh t_{DM}^{-1}) was produced from the grass cut in spring and subjected to DF, while the most electricity (621–698 kWh t_{DM}^{-1}) was obtained from the grass collected in autumn and subjected to WF. In the case of heat production, the situation was reversed. The least heat (1.4–1.9 GJ t_{DM}^{-1}) was produced by the grass collected in spring and subjected to WF, while the most heat (2.2–2.7 GJ t_{DM}^{-1}) was produced by the grass collected in autumn and subjected to DF. Ensilage decreased the electricity and heat production in almost all the cuttings. The total reduction in CO_2 emissions may amount to 2400 kg CO_2 per 1 hectare of road verges. This significant reduction demonstrates that the use of grass from roadside verges in biogas plants should be considered a feasible option. Even though urban grass should be considered a co-substrate only, it can be a valuable feedstock that may partially substitute energy crops and reduce the area needed for energy purposes. Our results reveal that biogas production from the grass waste in WF technology is a stable process. The cutting time and preservation method do not affect the AD process. In DF technology, fresh grass, especially from the late growing season used as feedstock, extends the time of biomass decomposition and, therefore, should be avoided in a real-life biogas plant.

Keywords: road verges; median strips; methane production; wet fermentation; dry fermentation; grass silage; urban areas

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1. Introduction

Climate change negatively affects biodiversity by increasing forest fires, decreasing crop yields, and affecting people's health. The European Union (UE), as the world's third most significant greenhouse gas (GHG) emitter after China and the United States, set new targets in 2015 in a transition to climate neutrality in 2050. The Green Deal, a roadmap for the EU to become climate neutral in 2050, sets not only the targets for the reduction in GHG emissions, but also underlines the potential for CO_2 absorption by forests, improving energy efficiency and increasing the share of renewable energy consumed to 32% by 2030 [1]. Biomass is an important energy source and is vital in transitioning from fossil fuel-based energy to sustainable energy production [2]. Lignocellulosic wastes may be a sustainable alternative for energy crops as a feedstock for bio-energy production.

Climate change affects not only nature and rural areas, but also towns and cities; however, the impact is not uniform. Urban areas across Europe may suffer from increased heat extremes, a higher risk of floods and winter storms, multiple other climatic hazards, and a decrease in summer precipitation and low river flows [3]. In the EU, ~70% of the population lives in urban areas [4]; therefore, urban adaptation and climate change mitigation are now essential issues. At the same time, cities are the key source of GHG and are responsible for 75% of global CO_2 emissions [5]; therefore, the reduction in GHG emissions in urban areas is one of the critical factors in the EU transition to climate neutrality.

Nowadays, cities face the following two significant challenges: the reduction in GHG emissions and the adaptation to global climate change. Green infrastructure is one of the solutions for excess heat events and flooding, and may also support biodiversity, pollinators, and carbon sequestration in urban areas. The urban green infrastructure consists of vegetated green surfaces such as parks, trees, small forests, grasslands, private gardens, and cemeteries [6]. The grassed areas of verges and median strips between roadways can also contribute to the green infrastructure. Increasing green spaces in cities improves the quality of human life. Still, at the same time, the amount of grass cuttings is continuously growing, and profitable or at least helpful utilization of this waste becomes a problem. The most common utilization pathway of green waste is composting. Although composting and compost have undisputable advantages such as waste reduction, a decrease in methane (CH_4) emissions from landfills, carbon sequestration, soil improvement, prevention of soil erosion, improvement of plant nutrition, and reduction in chemical fertilizer application, the composting process has several disadvantages such as GHG emissions from transporting the material for composting and from composting itself, energy use during composting, and related with this, indirect and direct GHG emissions and fugitive emissions from composting operation and storage [7].

The grass is a lignocellulosic biomass that promises to be a sustainable energy source that can be converted to electricity and heat through anaerobic digestion (AD). AD of green waste benefits from GHG reduction and decreases the amount of waste. The residue from the AD process (digestate) can be used as fertilizer and, therefore, may contribute to a circular economy in urban areas. However, the AD process must be feasible and economically sound. An unavoidable limitation in the use of grasses for the biogas production is the lower biogas potential and much lower yield than maize. This means that more grass biomass must be used in a biogas plant to produce the same amount of energy [8]. The co-digestion of grass can be an option to keep biogas yields high [9]. According to Poulsen and Adelard [10], the co-digestion of grass residues with agricultural waste is also more prominent than their mono-digestion. In turn, Vogel et al. [11] reported that dry fermentation with a percolation system led to a high biogas yield from the grass harvested as a part of landscape management measures. Lignocellulose biodegradability in the grass is relatively low because of a high amount of lignin. Therefore, disintegration techniques or other pre-treatment methods, which often require additional energy, are needed. However, processing the material via intensive anaerobic fermentation followed by mechanical and heat dewatering and subsequent pyrolysis of digestate seems to be a promising option for the profitable utilization of urban green cuttings [12].

Biogas can be produced by wet (WF) or dry fermentation (DF) technology. DF technology is simpler to operate, more energy-efficient [13], and avoids several problems that often occur in WF [14,15]. Despite various process parameters and the feedstock, the core communities of microorganisms in digesters operating under dry and wet conditions are similar [16], and the CH_4 yield of both technologies is comparable to laboratory experiments [17] and the industrial scale [18]. Additionally, dry AD plants offer several important benefits, including greater flexibility over the type of feedstock accepted, shorter retention times, reduced water use, and more flexible management and opportunities for marketing the end product [19].

The biogas production rate from lignocellulosic material is affected by the cell wall structure of plants. The main polymers in plant cell walls are cellulose, hemicellulose, and lignin. Cellulose and lignin are relatively resistant to hydrolysis, and the crystalline structure of cellulose is a barrier for microbial and enzymatic degradation during AD [20], while hemicellulose is easily hydrolyzed by hemicellulose enzymes [21]. Therefore, the biodegradability of grass in AD is limited mainly by the concentration of cellulose and lignin [20]. However, the specific methane yield (SMY) of cellulose is higher than that of hemicellulose, even though hemicellulose is hydrolyzed more quickly than cellulose. The most difficult polymer to digest is lignin [22]. High SMY can be achieved from biomass with low lignin concentration [23], and since lignification increases with the plant's maturity [24], the harvest time is of significant importance for the biogas yield. The CH_4 yield decreases due to the increased lignin content in mature plants [21,24]. Numerous studies on the AD of wild and cultivated grasses showed that the highest SMY was obtained from plants harvested in a juvenile development stage [25–28]. The SMY of grasses is reduced with maturity, not only through lignification, but also due to the leaf-to-stem ratio, since a higher SMY is typical for leaves [27].

Grass preservation as silage is preferable in a biogas plant since ensilage guarantees a high quality and constant supply of feedstock for the entire year [29]. Several studies investigated the impact of ensilage on the biogas production from grass. Grass silage usually has a higher CH_4 yield than fresh biomass and can be stored for a long time and, therefore, can be used for the entire year [30–33]. The increased SMY from silage results from the degradation of resistive polysaccharides and the production of intermediates such as volatile fatty acid (VFA) for methanogens during ensilage [34]. The critical factors, such as low moisture content, high accessible carbohydrate content, and low buffering capacity, together with reduced particle size and high packing density, minimize the CH_4 loss during storage [35] and enhance biogas production [30]. Controlling the ensilage process often requires addition of additives which can be divided into the following groups: fermentation stimulants, aerobic deterioration inhibitors, nutrients, and absorbents. A wide range of commercial biological or chemical additives is available; however, they are mainly oriented toward the high-quality animal feed [35]. According to Korres et al. [21], the effect of additives on biogas production is relatively moderate, and several other studies on the relationships between the ensiling additives and SMY reported contradictory results [36,37].

Most studies on biogas or CH_4 production from grass focus on WF [8,24,25,27,38–44], so less is known about grass digestion in dry technology. The research primarily focuses on one technology and compares the grass harvested in different seasons [26,28,44,45]. The influence of grass ensilage on biogas production was also studied [30,32]. However, these studies focused only on WF technology. Contradictory results from the studies on the effect of additives in the ensilage process on biogas potential revealed another knowledge gap. However, the comparison of WF and DF technology together with the AD of grass from different harvests and preservation methods have not been studied.

The current study aims to determine the effect of the cutting time and method of substrate preservation on the specific methane yield (SMY) of urban grass collected from road verges and median strips between roadways in WF and DF technology. The results of this study reveal the significance of the time of cutting, preservation method, and fermentation technology in the anaerobic digestion of grass. This work may provide a basis for practical environmentally friendly utilization of urban grass waste.

2. Materials and Methods

2.1. Substrates and Inocula

Methane potential tests were performed on grass harvested from grassed verges between the roadway and sidewalk and from median grassed strips in Białystok (53°07′ N, 23°09′ E, 136 m a.s.l.). Białystok is located in the northeastern part of Poland and is the capital city of the Podlaskie Voivodeship. The city covers an area of 102 km^2 and is inhabited by 297,000 citizens [46]. The area is characterized by a temperate climate with continental influences, with an average annual temperature of 7.6 °C (1995–2019) and an average annual precipitation of 608 mm (1995–2019), with peaks occurring between May and August [47]. In 2019, the mean temperature (9.2 °C) and the precipitation (617.6 mm) were higher than the long-term averages. The species composition of the grassed verges and median strips was dominated by perennial ryegrass (*Lolium perenne* L.). Kentucky bluegrass (*Poa pratensis* L.) and red fescue (*Festuca rubra* L.) were apart from this species but with much less coverage. According to Jankowski et al. [48], these species are most suitable for lawns in Poland. Plant material was collected three times in the year 2019, in spring (25 April 2019), in summer (31 July 2019), and in autumn (7 October 2019), during the green area maintenance performed by the external company employed by the City Hall of Białystok. Every time, grass cut in tillering phase was collected from the heap of plant material harvested along the street. After collection, plant material was brought to the laboratory immediately and was left for 24 h to dry at room temperature to reduce the water content. Then, the material was cut into 2–4 cm pieces. One part was ensiled without additives, and the other was ensiled with a microbiological additive containing the lactobacilli *Lactobacillus plantarum*, *Pediococcus acidilactici*, and *Lactobacillus paracasei*. The ensilage process took 5–6 weeks while fresh material was stored at −20 °C until the biochemical methane potential tests (BMP).

The digestate from a mesophilic agricultural biogas plant fed with maize silage with the addition of 10–20% of food and farming wastes was used as inoculum in the study. The digestate delivered to the laboratory was degassed at 38 °C and was used for WF experiments without further treatment. After degassing, the inoculum for the DF experiment was centrifuged at 3500 rpm for 30 min. The liquid fraction was discarded, and the solid part was used in the experiment.

2.2. Biochemical Methane Potential Tests

BMP was performed in wet and dry technologies. The BMP in WF technology was conducted in OxiTop® bottles (WTW, Weilheim, Germany) with a volume of 1 L and a working volume of ca. 300 mL. The reactors were incubated in a thermostatic incubator at 38 ± 1 °C. The bottles were filled with 200 mL of inoculum and the plant material (fresh, ensiled without additives, and ensiled with an additive) was added in a ratio of 2:1 $VS_{inoculum}$ to $VS_{substrate}$. A TS of 5% in the reactors was achieved by adding distilled water. Bottles with 200 mL of inoculum and distilled water were used as control. The reactors were flushed with nitrogen for 2 min to maintain anaerobic conditions. Batch trials were conducted in triplicate for each substrate and control. The BMP trials were performed with plant material collected in spring, summer, and autumn.

BMP tests in DF technology were conducted in a set of eudiometers. The bottles with a volume of 1 L were filled with 100 g of solid inoculum and substrates in a ratio of 1:1 $VS_{inoculum}$ to $VS_{substrate}$. TS of substrate and inoculum mixture in the reactors was 16–21%. The reactors were incubated in a water bath at 38 ± 1 °C. Three bottles with 100 g of inoculum were used as control. The bottles were purged with nitrogen gas for 5 min to ensure an anaerobic environment. Batch trials were conducted in triplicates; however, due to some technical problems, the batch trials of fresh material from spring cutting and ensiled material from summer cutting were performed in duplicate, while the CH_4 potential of the fresh material from summer cutting was measured only in one reactor.

2.3. Chemical Analyses

The TS content was determined by drying the material to a constant weight at 105 ± 2 °C. The volatile solids (VS) content was determined after incineration at 550 °C for 6 h in a muffle furnace according to the standard method [49]. Substrate pH was measured in 1:10 substrate/water suspension using HQ40D meter (Hach, Loveland, CO, USA). Total Kjeldahl nitrogen (TKN) content was measured by the Kjeldahl method in Vapodest 50 s analyzer (Gerhardt, Königswinter, Germany). After nitric acid/hydrogen peroxide microwave digestion in ETHOS One (Milestone s.r.l., Milan, Italy), the phosphorus (P) content was determined with an ammonium metavanadate method using UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan), and the potassium (K) and sodium (Na) contents were measured using flame photometry (BWB Technology, Newbury, UK). Total organic carbon (TOC) content was measured in a TOC-L analyzer with a SSM-5000A Solid Sample Combustion Unit (Shimadzu, Kyoto, Japan). The contents of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) were obtained using a LECO CHNS 628 elemental analyzer (St. Joseph, MI, USA). The concentration of metals in fresh grass samples from 3 cuttings was performed using ICP/MS Agilent 8800 (Agilent, Santa Clara, CA, USA). All analyses were run in triplicate, and all results were given on a dry weight basis.

The crude fibers (CF), neutral detergent fibers (NDF), acid detergent fibers (ADF), and acid detergent lignin (ADL) of plant material were determined using the FibreBag system (Gerhardt, Königswinter, Germany). The samples were first treated with 0.13 mol L^{-1} sulfuric acid solution followed by a 0.23 mol L^{-1} potassium hydroxide solution, and then the CF content was analyzed. The NDF content was determined with heat-stable α-amylase and corrected for ash content. The ADF and ADL contents were analyzed using AOAC official method 973.18 [50]. Cellulose was calculated as the difference between ADF and ADL, and hemicellulose was calculated as the difference between NDF and ADF. The ADL was considered as lignin, assuming the fraction of lignin-bound nitrogen is negligible. All the analyses were run in triplicate. All the results are given on a dry weight basis. The degree of lignification was calculated as the concentration of lignin in lignocelluloses [24].

2.4. Biogas Calculations

In the OxiTop® system, the biogas production was measured every 240 min based on pressure changes in the reactor using the OxiTop® measuring head. In eudiometers, the volume of biogas was measured by confining liquid displacement. In both cases, the biogas was sampled with 20 mL gas-tight glass syringes, and the portable biogas analyzer DP-28BIO (Nanosens, Wysogotowo, Poland) was used to measure the biogas composition. The measurements were performed every day, and after running the experiment for 10 days, measurements were carried out only twice a week. The batch test was conducted until the daily CH_4 production was less than 1% of the total cumulative volume of CH_4 observed over three consecutive days. SMY was calculated as NL kg_{VS}^{-1} (NL = normal liter, i.e., gas volume corrected to 0 °C and 1.013 bar).

The kinetics of CH_4 production was determined using the modified Gompertz model, which is commonly used to determine the relationship between cumulative gas production and fermentation time as follows [51]:

$$G(t) = G_0 \times exp\left\{-exp\left[\frac{R_{max} \times e}{G_0}(\lambda - t) + 1\right]\right\} \quad (1)$$

where:

$G(t)$—cumulative CH_4 production at a specific time t (mL);
G_0—CH_4 production potential (mL);
R_{max}—maximum daily CH_4 production rate (mL day^{-1});
λ—duration of lag phase (minimum time to produce CH_4) (days);
t—cumulative time for CH_4 production (days);
e—mathematical constant (2.71828).

In addition, based on the plotted curves, the time (days) when 50% (T50) and 95% (T95) of the possible CH_4 production were reached was determined.

2.5. Calculations of Energy and GHG Emissions

The calculations of potential energy produced in the biogas plant fed with the studied grass material used SMY that was determined via the laboratory tests. Thermal energy consumption in the biogas plant was assumed to be 30%, and electric use was considered to be 9% of the energy produced. The biogas is converted to electricity and heat in the combined heat and power (CHP) unit. The CHP unit's electrical and thermal conversion efficiency was assumed to be 38% and 43%, respectively.

Energy production per 1 hectare for urban grass was calculated based on the BMP results and assumed crop yields. Energy generation per 1 ha was compared to maize; the maize's yield was taken from Statistics Poland [52]. Energy production from biogas generated from maize was taken from [53].

The reduction in GHG emissions was calculated based on electricity and heat production in the biogas plant fed with urban grass, and emission factors for coal were adopted from The National Centre for Emissions [54].

2.6. Statistical Analyses

Differences in chemical properties and lignocellulosic composition among substrates used in the BMP batch trials, and the statistical differences among SMY were assessed with a simple one-way ANOVA. The normality and the homogeneity of variance were checked before ANOVA using Shapiro–Wilk and Levene tests, respectively. Differences among means were determined using Tukey's test. The Welch test was used if the assumption of the homogeneity of variance was not met. The SMY results from different fermentation technologies were compared using Student's *t*-test. If the results were not normally distributed, the non-parametrical U Mann–Whitney test was performed. The level of accepted statistical significance was $p < 0.05$. All statistical analyses were performed using STATISTICA 12 software (Tibco Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Chemical Properties of Grass

3.1.1. The Effect of Cutting Time on Chemical Properties of Grass

The influence of the cutting time on the chemical composition was analyzed for the fresh and ensiled grasses. In the fresh grass, the highest TS with the lowest VS content constituted only ~68% of the TS that was found in the FG-Sp. The fresh grass from the subsequent cuttings had lower TS and higher VS concentrations. The pH value was higher in the FG-Sp than in the fresh grasses from summer and autumn cuttings (Table 1). The TOC concentrations in the fresh material did not change with time, while the TKN and TP concentrations were lower in the FG-Sp than in the grasses cut later in the growing season. The K content was also the lowest in spring, then increased to 23.48 ± 1.36 g $kg_{DM}{}^{-1}$ in summer and decreased in autumn (Table 2). The Na concentration was highest in spring, and substantially reduced in summer and autumn to non-detectable values.

Based on the proximate and ultimate analyses, the fresh grass had the lowest ash content in autumn with the highest volatile matter (VM) content and C content. However, at the same time, the S content was also much higher than in the FG-Sp (Table 3).

Table 1. Total solids, volatile solids, and pH (averages ± SD) of studied materials from three cutting times.

Substrates	Total Solids (TS)	Volatile Solids (VS)	pH
	%	%TS	
FG-Sp	38.00 ± 1.35	68.22 ± 7.98	6.17 ± 0.01
GS-Sp	37.37 ± 0.58	67.93 ± 7.58	5.44 ± 0.03
GSA-Sp	38.48 ± 0.77	60.60 ± 2.46	5.45 ± 0.01
FG-Su	25.83 ± 0.97	84.70 ± 1.32	5.96 ± 0.04
GS-Su	29.11 ± 0.37	83.34 ± 2.08	4.54 ± 0.03
GSA-Su	27.85 ± 0.55	86.05 ± 0.63	4.55 ± 0.01
FG-Au	29.34 ± 0.97	88.83 ± 0.10	5.97 ± 0.04
GS-Au	30.33 ± 0.30	87.69 ± 0.08	4.15 ± 0.02
GSA-Au	29.74 ± 0.04	87.20 ± 0.15	4.14 ± 0.01

FG-Sp—spring fresh grass, GS-Sp—spring grass ensiled without additives, GSA-Sp—spring grass ensiled with additive, FG-Su—summer fresh grass, GS-Su—summer grass ensiled without additives, GSA-Su—summer grass ensiled with additive, FG-Au—autumn fresh grass, GS-Au—autumn grass ensiled without additives, GSA-Au—autumn grass ensiled with additive.

Table 2. Chemical composition (averages ± SD) of studied materials from three cutting times.

Substrates	Total Kjeldahl Nitrogen (TKN)	Total Phosphorus (TP)	Total Potassium (K)	Total Sodium (Na)	Total Organic Carbon (TOC)	C:N	N:P
	$g\ kg_{DM}^{-1}$						
FG-Sp	20.76 ± 0.23	1.99 ± 0.19	10.96 ± 1.43	3.12 ± 0.48	373.8 ± 18.29	18	10
GS-Sp	22.12 ± 0.63	2.32 ± 0.06	12.97 ± 1.12	4.58 ± 0.41	323.49 ± 63.45	15	10
GSA-Sp	22.48 ± 1.16	2.36 ± 0.08	11.89 ± 0.80	3.99 ± 0.15	297.74 ± 12.78	13	9
FG-Su	25.89 ± 0.84	3.42 ± 0.26	23.48 ± 1.36	0.85 ± 0.44	371.63 ± 22.42	7	8
GS-Su	28.39 ± 0.67	3.72 ± 0.04	24.94 ± 0.35	0.85 ± 0.10	368.04 ± 8.66	14	8
GSA-Su	28.63 ± 0.87	3.97 ± 0.13	26.55 ± 1.17	0.88 ± 0.04	365.48 ± 10.15	13	7
FG-Au	27.67 ± 1.12	3.06 ± 0.05	15.00 ± 0.08	n.d.	381.87 ± 3.17	13	9
GS-Au	25.87 ± 0.34	3.55 ± 0.12	18.72 ± 0.46	n.d.	421.68 ± 14.38	16	7
GSA-Au	27.44 ± 0.92	3.43 ± 0.13	18.13 ± 0.53	n.d.	429.66 ± 24.69	16	8

FG-Sp—spring fresh grass, GS-Sp—spring grass ensiled without additives, GSA-Sp—spring grass ensiled with additive, FG-Su—summer fresh grass, GS-Su—summer grass ensiled without additives, GSA-Su—summer grass ensiled with additive, FG-Au—autumn fresh grass, GS-Au—autumn grass ensiled without additives, GSA-Au—autumn grass ensiled with additive. n.d.—not detected.

Table 3. Proximate and ultimate analysis (averages ± SD) of fresh grasses from three cutting times.

Substrates	Ash	VM	FC	C	H	N	S
	%						
FG-Sp	16.92 ± 0.07 a	62.15 ± 0.18 a	15.01 ± 0.08 a	38.31 ± 0.28 a	7.23 ± 0.04 a	2.10 ± 0.00 a	0.25 ± 0.01 a
FG-Su	12.54 ± 0.14 b	66.27 ± 0.52 b	14.89 ± 0.48 a	40.60 ± 0.23 b	7.61 ± 0.04 b	2.49 ± 0.00 b	0.36 ± 0.00 b
FG-Au	10.96 ± 0.05 c	67.84 ± 0.10 c	14.98 ± 0.07 a	41.91 ± 0.03 c	7.73 ± 0.02 c	2.62 ± 0.01 c	0.33 ± 0.00 c

VM—volatile matter, FC—fixed carbon, C—carbon, H—hydrogen, N—nitrogen, S—sulfur. FG-Sp—spring fresh grass, FG-Su—summer fresh grass, FG-Au—autumn fresh grass. Lowercase letters indicate statistical differences at $p < 0.05$ between FG-Sp, FG-Su, and FG-Au.

All studied metals were detected in the fresh grass; however, no Hg was found in the FG-Sp, and Cu was not detected in the FG-Sp and FG-Su, but it was detected in the FG-Au. The time of cutting affected the heavy metal concentration in the studied grass. The highest content of all studied elements, except Cu and Hg, was observed in the FG-Sp (Table 4). In the following months, the heavy metal concentration dropped significantly ($p < 0.05$) and was the lowest in the FG-Au; however, the difference between the summer and autumn values was not significant, except for Cd and Hg.

Table 4. Metal concentrations (averages ± SD) in fresh grasses from three cutting times.

Heavy Metals / Substrates	Spring Fresh Grass (FG-Sp)	Summer Fresh Grass (FG-Su)	Autumn Fresh Grass (FG-Au)
	mg kg_{DM}^{-1}		
Chromium (Cr)	14.43 ± 2.94 a	7.54 ± 3.49 ab	2.67 ± 0.20 b
Manganese (Mn)	175.24 ± 11.92 a	116.98 ± 3.17 ab	34.87 ± 3.85 b
Iron (Fe)	3970.23 ± 635.23 a	977.88 ± 416.44 ab	295.52 ± 6.00 b
Nickel (Ni)	3.37 ± 0.77 a	0.78 ± 0.59 b	1.45 ± 0.01 ab
Copper (Cu)	n.d.	n.d.	19.53 ± 2.75
Zinc (Zn)	80.16 ± 34.09 a	31.04 ± 8.37 ab	1.73 ± 0.68 b
Cadmium (Cd)	0.26 ± 0.09 a	0.27 ± 0.03 a	0.07 ± 0.02 b
Mercury (Hg)	n.d.	1.93 ± 0.11 a	1.41 ± 0.31 b
Lead (Pb)	8.79 ± 2.58 a	2.45 ± 1.52 b	1.61 ± 0.16 b

Lowercase letters indicate statistical differences at $p < 0.05$ between FG-Sp, FG-Su, and FG-Au; n.d.—not detected.

The cellulose and lignin contents increased significantly ($p < 0.05$) in summer and was similar in autumn. The lignification was the lowest (although not significantly) in spring and did not change from summer to autumn (Table 5). The cutting time did not affect the fresh grasses' crude fiber or hemicellulose contents.

Table 5. Lignocellulose characteristics (averages ± SD) of fresh grass from three cutting times.

Substrates	Spring Fresh Grass (FG-Sp)	Summer Fresh Grass (FG-Su)	Autumn Fresh Grass (FG-Au)
	%TS		
Crude fiber	23.93 ± 3.39 a	22.15 ± 0.83 a	24.78 ± 1.61 a
Lignin	15.11 ± 2.48 a	20.15 ± 1.01 b	20.32 ± 0.66 b
Hemicellulose	21.28 ± 10.30 a	15.94 ± 1.59 a	18.15 ± 1.05 a
Cellulose	10.81 ± 2.06 a	15.88 ± 1.13 b	17.94 ± 1.61 b
Lignification	32.6 ± 6.6 a	38.8 ± 2.4 a	38.0 ± 0.9 a

Lowercase letters indicate statistical differences at $p < 0.05$ between FG-Sp, FG-Su, and FG-Au.

In the ensiled grasses, a pattern similar to that of the fresh material was observed during the growing season for the values of TS, VS, TP, K, and Na (Figure 1). Differences in the TKN concentration in the grass silages were found for the different cutting periods. The lowest values were observed in spring, while the TKN concentration increased in summer and decreased again in autumn. The TOC in the ensiled material increased significantly with the grass maturity. The pH of the grass silages was equal to ~4.5 in summer and equal to ~4.1 in the material cut in autumn.

3.1.2. The Effect of the Preservation Method on Chemical Properties of Grass

The ensilage method's influence on the grass's chemical composition was analyzed separately for every cutting. In the spring material, the TKN, P, and Na contents differed between the fresh grass and ensiled material; however, the ensilage method did not affect the mineral composition of the grass. The ensilage decreased the pH of the material significantly, but the application of a microbiological additive did not differentiate the silages. The TS, VS, K, and TOC contents were similar in the fresh and ensiled material (Figure 2). In summer, the ensilage did not affect the TS, VS, Na, and TOC contents. The TKN in the FG-Su was lower than the values observed in the silages. The contents of P and K were different between the FG-Su and GSA-Su. The pH in both silages was equal to ~4.5 and was lower than in the fresh material. The material cut in autumn had similar TS, VS, and TKN contents in the fresh grass and in the silages. The ensilage influenced the P, K, and TOC contents, which were higher in the silages than in the fresh material. The pH of both silages was similar and lower than in the fresh grass (Figure 2).

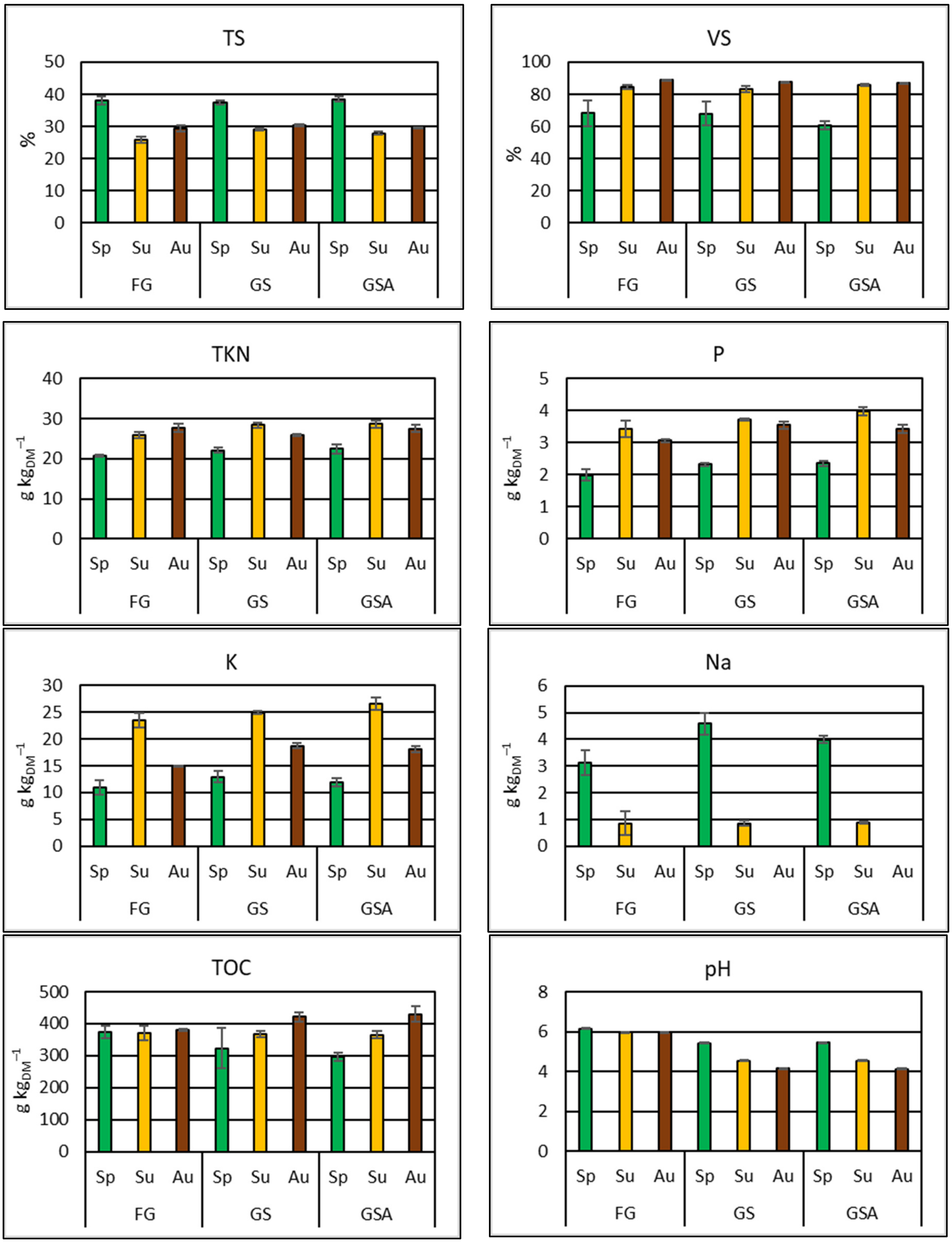

Figure 1. The effect of cutting time on chemical properties of fresh grass, ensiled grass without additives, and ensiled grass with additive. Standard deviations are shown as the vertical bars. FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive, Sp—spring, Su—summer, Au—autumn.

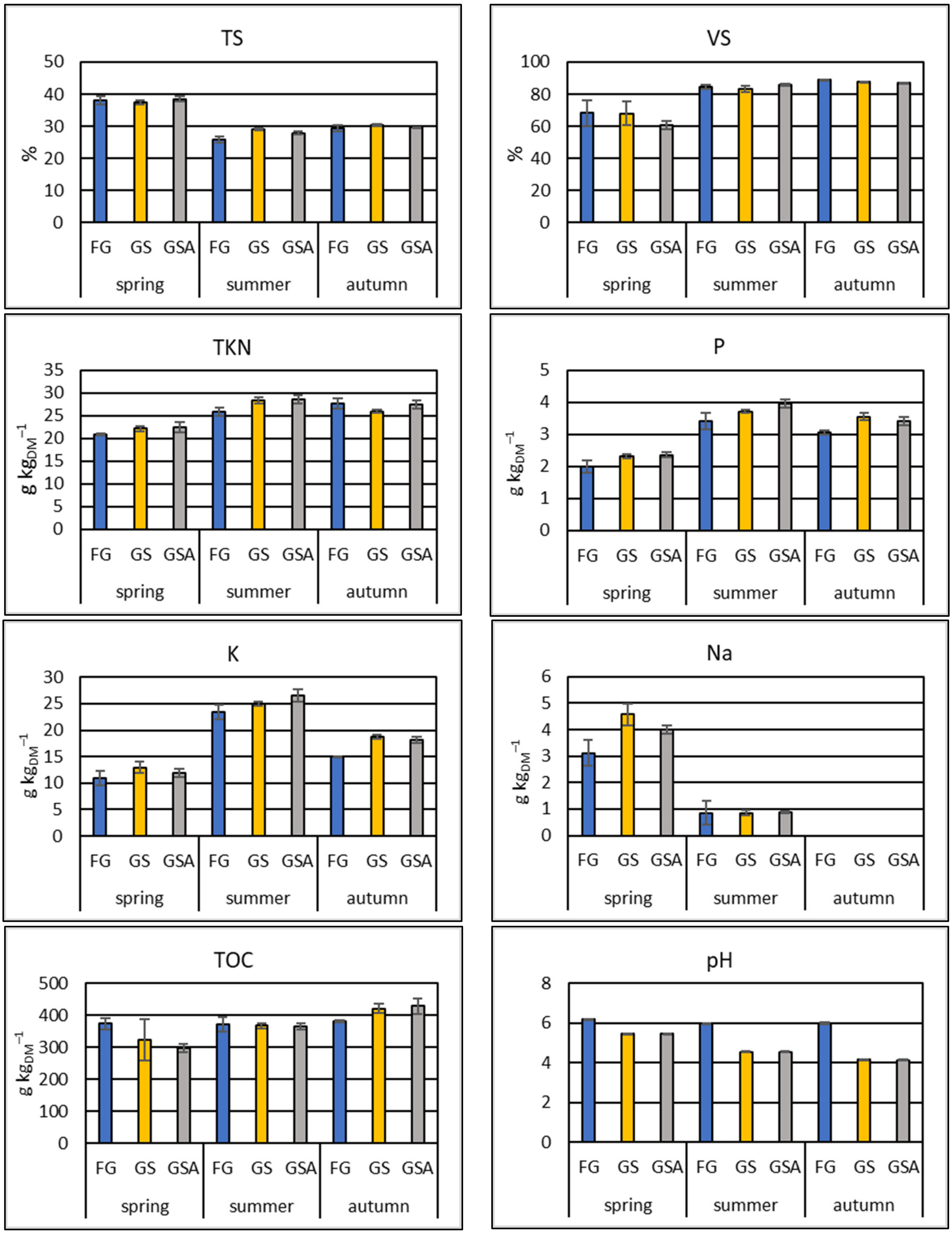

Figure 2. The effect of the preservation method on chemical properties of grass cut in spring, summer, and autumn. Standard deviations are shown as the vertical bars. FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive.

3.2. The SMY of Grass

The cutting time quite clearly influenced the CH_4 production from the analyzed grasses (Table 6). The material collected in spring produced the highest amount of CH_4, while the SMY of the summer grasses was the lowest. A comparison of all the analyzed systems revealed that the highest SMY was observed for the FG-Sp subjected to WF, while the lowest CH_4 production was found in the GS-Su digested in the DF technology.

Table 6. The CH_4 yield (averages ± SD) from fresh grass and grass silages in dry and wet fermentation.

Substrates	Fresh Grass (FG)		Grass Ensiled without Additives (GS)		Grass Ensiled with Additive (GSA)	
	NL kg_{VS}^{-1}					
	WF	DF	WF	DF	WF	DF
Spring	274.18 ± 22.59	232.79 ± 1.19	243.76 ± 5.27	213.54 ± 8.48	268.53 ± 5.07	234.34 ± 9.11
Summer	234.84 ± 18.63	217.70	226.21 ± 16.62	182.63 ± 0.48	223.50 ± 15.50	188.81 ± 2.72
Autumn	239.21 ± 7.70	224.47 ± 2.96	238.14 ± 11.35	223.71 ± 3.66	252.41 ± 3.17	223.90 ± 4.93

WF—wet fermentation, DF—dry fermentation.

The comparison of the SMY obtained from the same grass samples in the WF and DF technologies revealed that higher CH_4 yields were produced in WF. The substrate preparation also influenced the rate of the CH_4 production. The ensilage process in most cases lowered the CH_4 yield (Figure 3); however, these differences in most cases were not statistically significant.

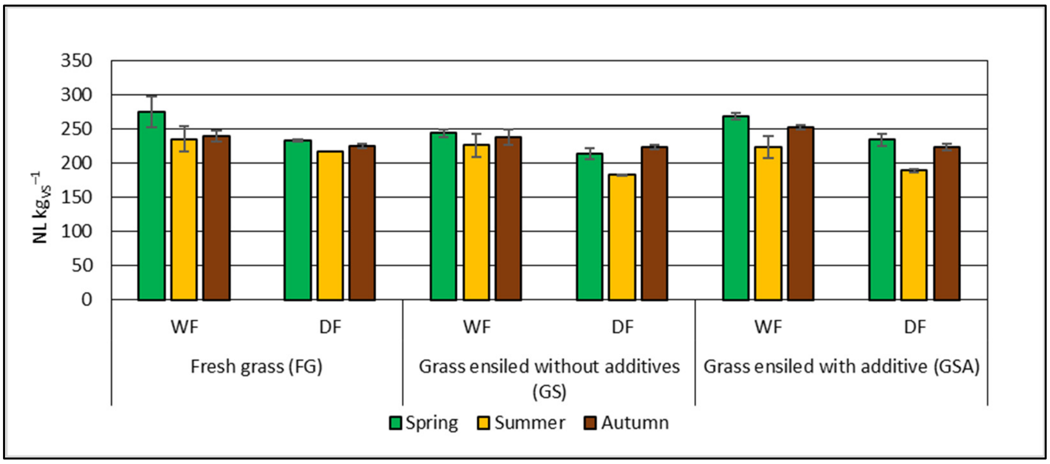

Figure 3. Specific CH_4 yield depending on the biogas production technology, cutting time, and the method of grass preservation. WF—wet fermentation, DF—dry fermentation. Standard deviations are shown as the vertical bars.

The duration of WF was similar regardless of the cutting time or the grass preservation method and lasted from 23 to 30 days. The daily production rate was also similar for all the substrates irrespective of the time of cutting (Figure 4). The maximum daily CH_4 production occurred on days 4–7, ranging between 25 NL kg_{VS}^{-1} and 33 NL kg_{VS}^{-1}. The grass collected in autumn showed the lowest CH_4 production but rapidly reached the daily maximum. In turn, the grass collected in spring achieved the highest SMY.

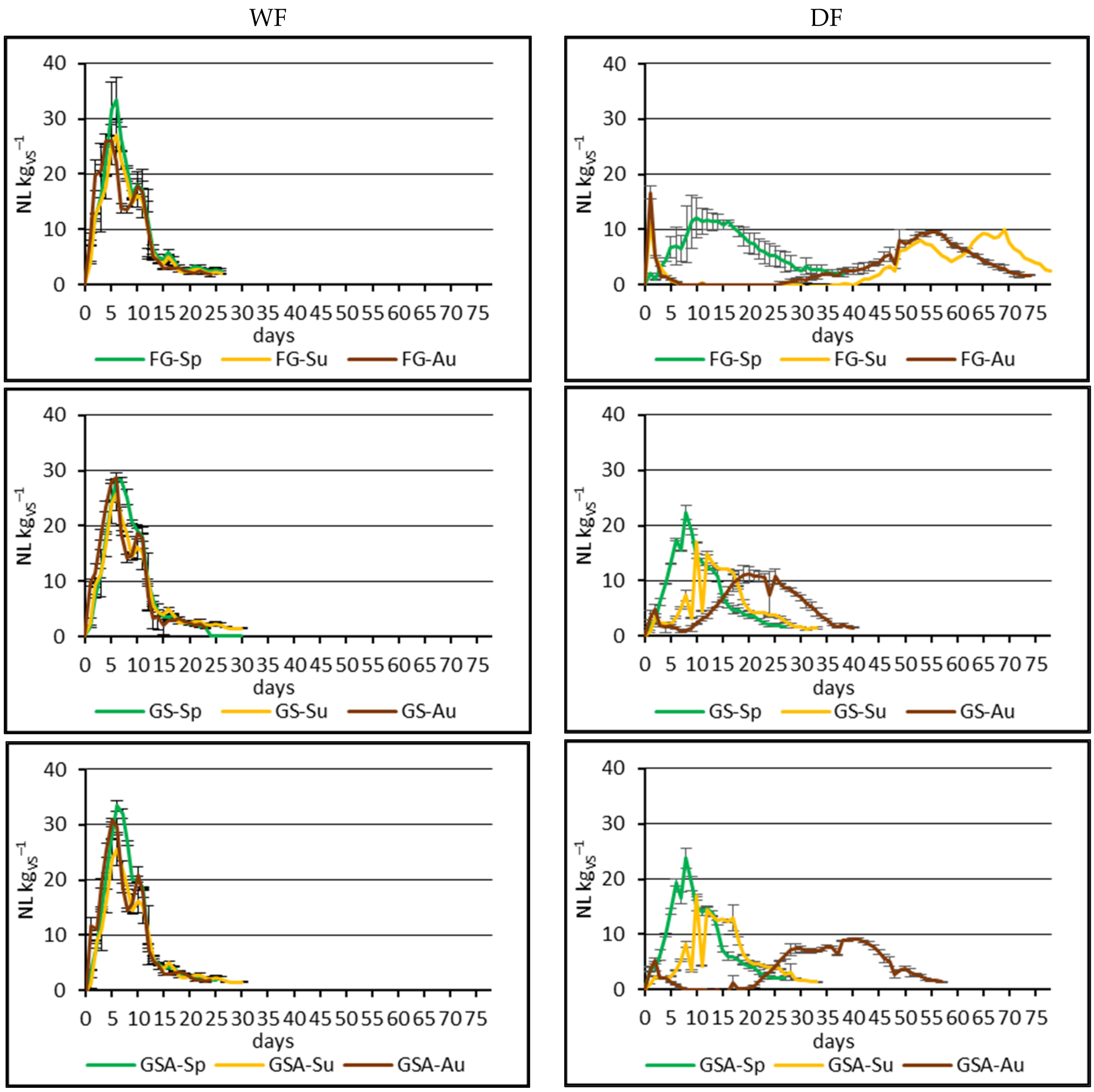

Figure 4. Daily CH_4 production depending on the biogas production technology and sampling date. Standard deviations are shown as the vertical bars. WF—wet fermentation, DF—dry fermentation, FG-Sp—spring fresh grass, GS-Sp—spring grass ensiled without additives, GSA-Sp—spring grass ensiled with additive, FG-Su—summer fresh grass, GS-Su—summer grass ensiled without additives, GSA-Su—summer grass ensiled with additive, FG-Au—autumn fresh grass, GS-Au—autumn grass ensiled without additives, GSA-Au—autumn grass ensiled with additive.

The CH_4 production was more variable regarding the process duration and maximum daily rate in the DF technology. In this type of AD, the cutting time and the preservation method had a more significant impact on the CH_4 production than in WF. The BMP trials ran from 27 days for the grass silages from spring to 78 days for the fresh grass from summer (Figure 4). The CH_4 production in the AD of the fresh grasses collected in different seasons started after a lag phase. The CH_4 production from the FG-Sp began immediately, while the time lag for the FG-Au was 26 days, and the time lag for the FG-Su was 41 days. The grass collected in spring also obtained the highest maximum CH_4 daily production. The ensilage process significantly accelerated the process of DF, especially in the case of the grass collected in summer, which resulted in a significant reduction in the lag phase and, consequently, in the fermentation time. Additionally, the grass silages from spring and summer showed a higher daily CH_4 rate. The influence of the ensilage process on this parameter was much less marked in the case of the grass collected in autumn.

In the AD of the grasses collected in summer and autumn, the ensilage shortened the lag phase significantly (Figure 5). In the WF technology, in all cases, a sharp and linear increase in the CH_4 production was observed at the beginning of the AD. In the DF technology, a similar course of CH_4 production was found, but only for the grass cut in spring, regardless of the preservation method.

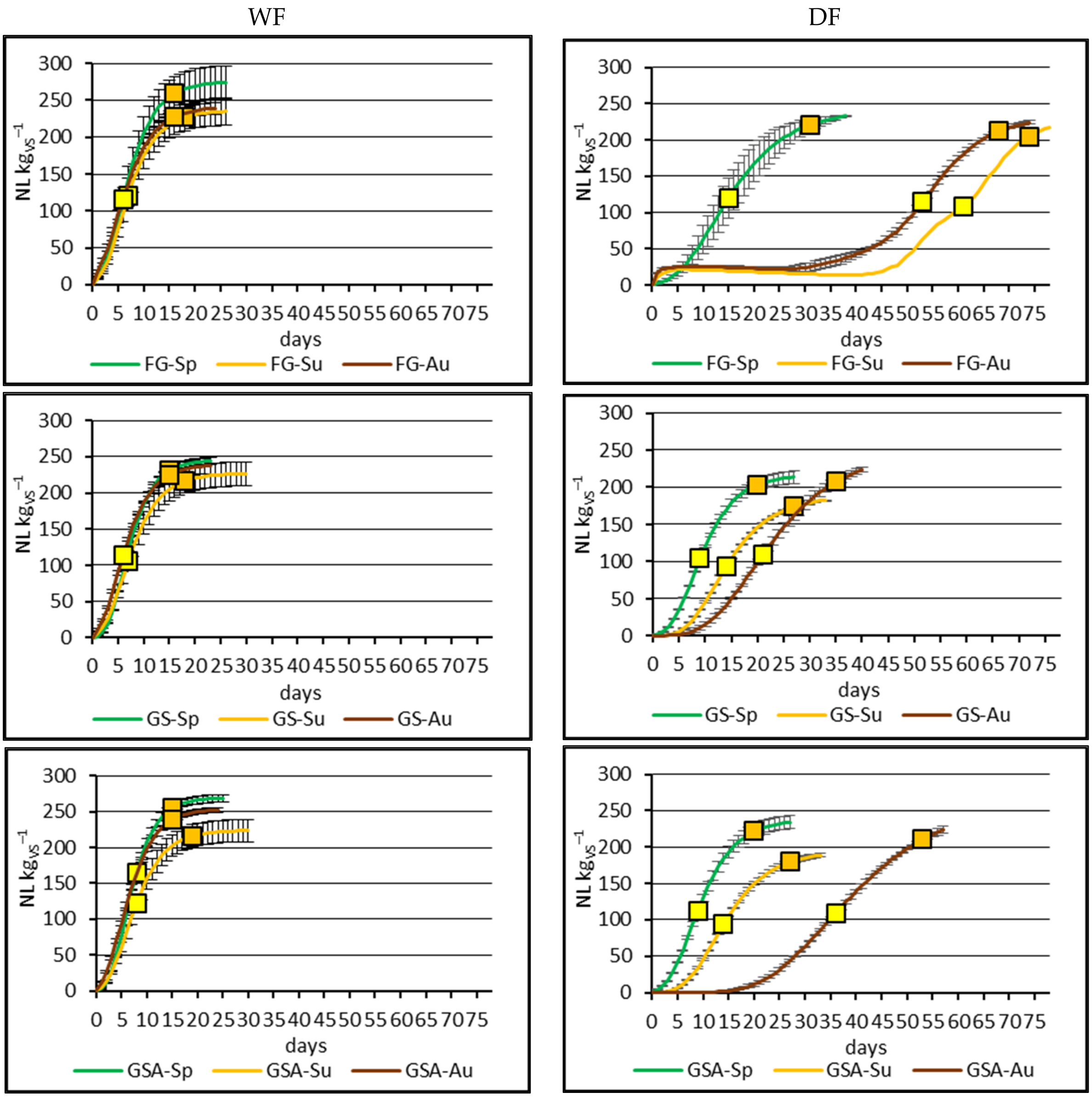

Figure 5. Cumulative CH_4 production. Standard deviations are shown as the vertical bars. The yellow squares and orange squares mean T50 and T95, respectively. WF—wet fermentation, DF—dry fermentation, FG-Sp—spring fresh grass, GS-Sp—spring grass ensiled without additives, GSA-Sp—spring grass ensiled with additive, FG-Su—summer fresh grass, GS-Su—summer grass ensiled without additives, GSA-Su—summer grass ensiled with additive, FG-Au—autumn fresh grass, GS-Au—autumn grass ensiled without additives, GSA-Au—autumn grass ensiled with additive.

In the WF technology, irrespective of the grass preservation method and time of material collection, the time after which the analyzed material produced 50% of the potential CH_4 (T50) amounted to 6–7 days (Figure 5). The time after the studied material produced 95% of the potential CH_4 ranged from 15 to 18 days. In the DF technology, the variability in

T50 and T95 was the highest for the fresh grasses, ranging from 15 to 61 days (T50) and between 31 and 74 days (T95). In all seasons, regardless of the preservation method, the grass collected in spring achieved 50% and 95% of the potential CH_4 in the shortest time, while the grass collected in autumn needed the longest time.

The CH_4 content in biogas is one of the most important parameters, apart from the biogas yield, determining the profitability of biogas production. The average CH_4 content in the biogas produced from the grass cut in different seasons and preserved with other methods did not differ. The average CH_4 content was also similar in both technologies, and in the WF technology, it was ~63%, while in the DF technology, it was ~65% (Figure 6).

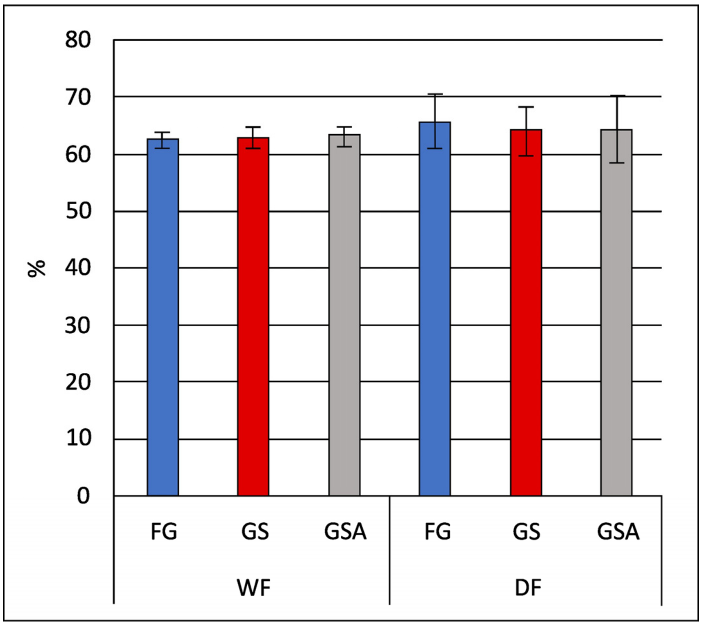

Figure 6. The percentage of CH_4 in the produced biogas (averaged values for the entire year) depending on method of grass preparation and biogas production technology. Standard deviations are shown in the vertical bars. WF—wet fermentation, DF—dry fermentation, FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive.

In the WF technology, the CH_4 concentration of ~60% was reached after 5–6 days and stayed at this level until the experiment ended regardless of the cutting time and substrate preservation method. In the DF technology, the CH_4 concentration throughout the batch assay showed differences among the studied grasses. The fresh grass from consecutive cuttings during the growing season needed more time to achieve the CH_4 concentration of ~60% than in the WF technology. The shortest time was observed for the FG-Sp (17 days), while the FG-Su needed 58 days, and the FG-Au needed 47 days to achieve 60% of CH_4 in the biogas. The ensilage affected the CH_4 production, especially in the grasses cut in summer and in autumn. The same level of CH_4 (~60%) in the AD of the grass silages from summer and autumn, irrespective of the preservation method, was reached after 11 to 18 days. The only exception was the GSA-Au, which needed 29 days.

3.3. Energy Balance and CO_2 Emissions

Differences in the moisture of the analyzed grasses resulted in differences in the energy production expressed per t_{DM} of feedstock. The electricity and heat production were affected by the time of grass cutting, ensilage method, and AD technology. Generally, less electricity but more heat was produced in the DF technology (Table 7). The least electricity was produced from the grass cut in spring. The ensilage decreased the electricity production in almost all the cuttings. The heat generation was also affected by the ensilage. The highest production was achieved from the fresh material, but a similar output was obtained from the grass silages with microbiological additive, except for the grass cut in spring (Table 7).

Table 7. The amounts of energy that can be produced during AD of urban grass.

Substrates	Electricity Production kWh $t_{DM}{}^{-1}$		Heat Production GJ $t_{DM}{}^{-1}$	
	WF	**DF**	**WF**	**DF**
FG-Sp	593	548	1.9	2.1
GS-Sp	506	510	1.6	1.9
GSA-Sp	460	469	1.4	1.8
FG-Su	655	595	2.1	2.3
GS-Su	598	525	1.9	2.0
GSA-Su	650	664	2.0	2.5
FG-Au	756	718	2.4	2.7
GS-Au	621	571	1.9	2.2
GSA-Au	698	674	2.2	2.6

WF—wet fermentation, DF—dry fermentation, FG-Sp—spring fresh grass, GS-Sp—spring grass ensiled without additives; GSA-Sp—spring grass ensiled with additive, FG-Su—summer fresh grass, GS-Su—summer grass ensiled without additives, GSA-Su—summer grass ensiled with additive, FG-Au—autumn fresh grass, GS-Au—autumn grass ensiled without additives, GSA-Au—autumn grass ensiled with additive.

The electricity produced per year per 1 ha was similar regardless of the AD technology and preservation method, and mainly depended on the yield (Figure 7). Slight differences occurred only in the DF technology, where the lowest electricity was produced from the grass ensiled with an additive. Therefore, the electricity produced per 1 ha of grass, irrespective of the assumed yield, was much lower than what would be produced from maize.

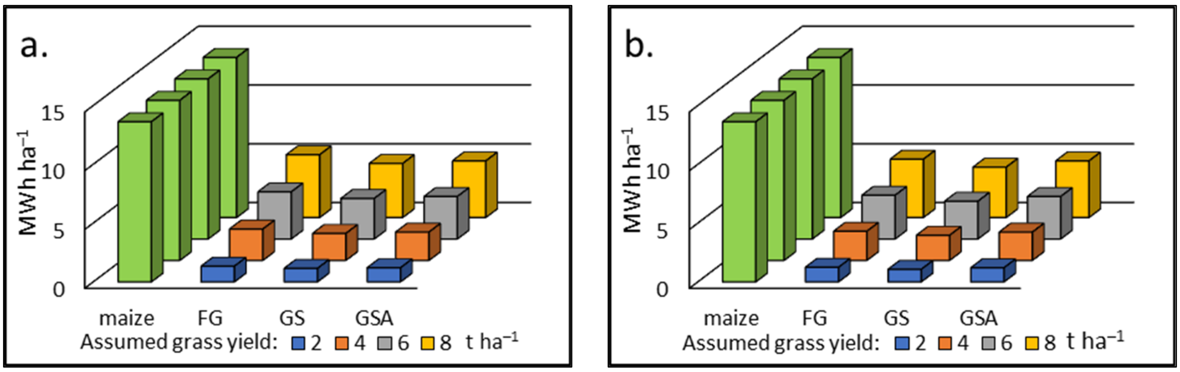

Figure 7. Electricity production in wet (**a**) and dry (**b**) technology depending on the grass yield. Maize—maize silage, FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive.

Due to a lower heat demand of the biogas plants operating in the DF technology, the heat production from this system was higher than in the WF technology (Figure 8). Other parameters, such as the preservation method and yield, affected the heat production per ha in a comparable way as in the case of electricity. The heat production per 1 ha from the biogas produced from the grass was also much lower than the heat obtained from a biogas plant fed with maize due to the much higher yield of the latter crop.

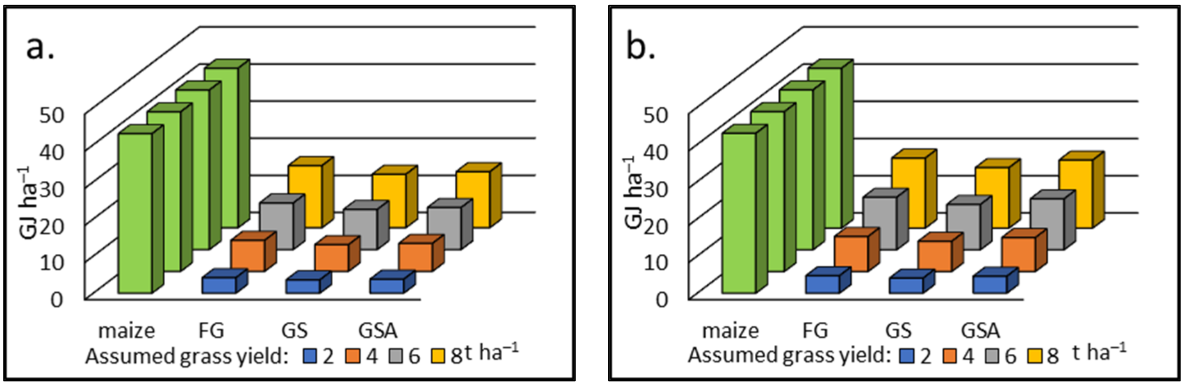

Figure 8. Heat production in wet (**a**) and dry (**b**) technology depending on the grass yield. Maize—maize silage, FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive.

The electricity and heat generated from the biogas produced in a biogas plant fed with urban grass reduces the CO_2 emissions from coal burning. Higher emissions from electricity generation are avoided if biogas is produced in the WF technology, while emission avoidance from heat generation is more pronounced. If feedstock preparation was considered in CO_2 emissions, a higher avoidance rate occurred in the AD of the fresh grass (Table 8).

Table 8. Avoided CO_2 emissions due to biogas production from urban grass for electricity and heat generation.

Substrates	Emissions Avoided through Electricity Production		Emissions Avoided through Heat Production	
	kg CO_2 $t_{DM}{}^{-1}$			
	WF	DF	WF	DF
FG	466.31	433.09	195.72	220.14
GS	401.39	373.75	168.47	189.97
GSA	420.52	420.40	176.50	213.68

WF—wet fermentation, DF—dry fermentation, FG—fresh grass, GS—grass ensiled without additives, GSA—grass ensiled with additive.

Assuming an average grass yield of 4 t_{DM} ha^{-1} and avoided emissions of 400 kg CO_2 $t_{DM}{}^{-1}$ for electricity and 200 kg CO_2 $t_{DM}{}^{-1}$ for heat, the total reduction in CO_2 emissions may amount to 2400 kg CO_2 per 1 hectare of road verges.

4. Discussion

4.1. Chemical Properties of Grass

Grass maintenance on verges and median grassed strips assumes frequent cutting. Even though in many cities, a novel approach is applied to grassed areas with less frequent cuttings in verges but also gardens and meadows, these areas still produce biomass from cutting, which needs to be utilized. Instead of popular composting, which results only in one product, the AD process offers electricity and heat from a renewable source and fertilizer, which is only a by-product of energy production. However, the profitability of such a project depends on the quality, SMY, amount, and availability of feedstock. Grass cuttings in urban areas depend on the climate conditions, weather, and other environmental and social aspects. In Poland, the grass verges along streets are typically cut three to seven times a year, and the number of cuttings depends on the grass growth and weather conditions.

In our study, the grasses cut in three seasons (spring, summer, and autumn) differed. The TS and VS contents were similar to those reported by De Moor et al. [9], Lehtomäki and Björnsson [20], Lehtomäki et al. [30], and Seppälä et al. [25], who studied *Poinae* and *Loliinae* grasses. The decrease in the TS throughout the growing season agreed with the results of Seppälä et al. [25], who reported a lower TS content in the grass from the second cut. The TKN concentration in the grass cut in spring was in good agreement with Piepenschneider [55] and Nizami and Murphy [38], who studied grasses from plant communities similar to those analyzed in this study. In contrast, the TKN content in the grasses from the summer and autumn cuttings was higher than that reported by Piepenschneider [55]. However, the TKN values reported in the literature are wide, ranging from 9.8 g kg_{DM}^{-1} [9] to 37 g kg_{DM}^{-1} [20]. The TKN concentration in the grass from the autumn cutting in the present study was higher than the values reported for roadsides by De Moore et al. [9] and Lehtomäki et al. [30]. The differences in the TKN concentrations may be due to different cutting regimes and fertilization. The TOC content in our study was lower than the values given by Nizami and Murphy [38] and by Lehtomäki and Björnsson [20]. Regardless of the preservation method, the TP content in the summer and autumn grasses was similar to the values shown by Piepenschneider [55] for two-cut grass from an urban area, and lower than that reported by Mattioli et al. [43]. The TP content of our spring grass was lower than the TP concentration given by Piepenschneider [55], but still higher than the values reported by Mattioli et al. [43]. All the grass cuttings had a higher TP content than the agricultural grasses and grasses from nature conservation areas but were much lower than the *Poinae* and *Loliinae* grasses from roadside verges, as reported by Herrmann et al. [56]. In our study, the K content differed among the cutting time but was unaffected by the preservation method. The K content in the spring and autumn grasses was similar to the values given by Hermann et al. [56] and Nizami et al. [29], while the K content in the summer grass was more similar to the results provided by Piepenschneider [55] for two-cut and four-cut grass from urban areas. The cutting period also influenced the Na content in the grass. The highest values were found in the spring grass, and these were higher than those reported in the literature [57], whereas the results from summer were in the range of the values reported in the literature [29,55,57].

The ensilage affected the pH of the grass in all the cutting periods. The pH of the grass silages depends on the TS content. In the case of a higher TS content, good preservation can be achieved at a higher pH. Therefore, the necessary acidity for efficient ensilage can be a quantifying parameter. Critical pH, as a function of TS content, can be a good quantifying parameter of the silage quality [35]. The highest pH in the silages was observed in the grass with the highest TS content cut in spring. The quality of the silage from the spring grass was good according to the Gross scale [58]. A lower TS content resulted in a pH ~4.5 for the summer grass and ~4.1 for the autumn grass, respectively. All the silages from the summer and autumn cuttings were very good according to the Gross scale [58]. Our results also agree with those of Ambye-Jensen et al. [31], who studied *Festulolium* Hykor and Radkowski and Radkowska [59], who analyzed grass from meadows. The results from the literature show the pH of grass silage from 4.1 to 5.0 [30,38–40,59]. In our study, adding an additive did not influence the pH of the silage. The studies by Zhao et al. [32] revealed that the switchgrass ensiled without additives performed the worst after 30 days, with a pH equaling 5.3 with a low TS content of ~24.7%. The addition of bacteria *L. brevis* and bacteria *L. brevis* with xylanase lowered the pH to 4.5 and 4.2, respectively.

A frequently raised issue related to the biomass used as an energy source but obtained from urban areas and road verges is the potential contamination with heavy metals. Their presence in feedstock may disrupt biogas production since a high concentration of heavy metals inhibits AD due to changing the enzyme structure and reducing the methanogen growth [60,61]. An accumulation of heavy metals in digestate limits the possibility of using this by-product as fertilizer [61]. However, it should be realized that metals are often introduced into the digester to stimulate the AD process [61]. In England, the heavy metal content in the grass from road verges and digestate from this feedstock was similar to the values in agricultural biomass [61]. However, it is recommended to consider the specific situation and analyze the content of heavy metals both in the feedstock and in the soils that would be fertilized with digestate.

In our study and in other studies, the grass cutting time appears to be of primary importance for the SMY of the grasses. The maturity of the plants changes the proportions of the cell wall components along with progressive lignification. The higher lignin content in plant material decreases the digestibility and biogas production [24,37]. In addition, late harvesting causes a decrease in the crude protein and crude fat contents, both of which increase the CH_4 content of the biogas [62]. Additionally, the stem-to-leaves ratio increases with the advancing stage of vegetation [21], and since leaves produce higher CH_4 amounts [27], the SMY of matured grass decreases.

The lignin content in the fresh plant material cut in summer and autumn was higher in our experiment than those reported in the literature for the *Poinae* and *Loliinae* grasses [30,31,41,42,44,63], while the lignin in the fresh grass from spring was similar to the values given by Antonopoulou et al. [63], Yu et al. [41], Cadavid-Rodríguez and Bolaños-Valencia [42], and Lehtomäki et al. [30]. The cellulose content in the grass from all cutting periods was lower than the values shown in the literature for the *Poinae* and *Loliinae* grasses [31,63,64]. However, its content in the grass from autumn was similar to the results obtained by Antonopoulou et al. [63]. The hemicellulose content was in good agreement with the values reported by Ambye-Jensen et al. [31], Juneja et al. [64], and Chiumenti et al. [44] for the spring grass. The summer grass had a lower hemicellulose content compared to the values by Chumenti et al. [44], who studied grass composed mainly by *Poaceae*, with a prevalence of *Poa* spp. and *Festuca* spp., *Sorghum* spp., and *Phragmites* spp. The variation in the content of the cell wall components may be affected by the species composition, geographical location, time of cutting, and grass management. Keady [65] reported that N fertilization increases the cellulose and hemicellulose contents in perennial ryegrass. Malinowska and Wiśniewska-Kadżajan [66] also reported an increase in the cellulose content under the fertilization of the Felopa variety of *Festulolium brauni* (K. Richt.) A. Camus, while the hemicellulose content and lignification degree decreased at the same time.

4.2. The SMY of Grass

Most studies show that the SMY of grass harvested later in the season is lower [24–28]. However, this applies somewhat to grasses collected from road verges as part of their maintenance. According to Triolo et al. [24], frequent mowing shortens the physiological vegetation age, which reduces the degree of lignification. A high frequency (3–4 times a year) of cutting results in collecting the biomass at an early stage of maturity, which favors the AD process [45]. In the two-cut management system analyzed by Piepenschneider et al. [45], the lignin content between the first and the second mowing increased markedly. At the same time, it remained at a similar level in the four-cut system, which was reflected in the greater amount of CH_4 obtained. Additionally, in our study, the lignocellulose content had a negligible impact on the SMY.

The SMY of the studied grass ranged between 223.50–274.18 NL kg_{VS}^{-1} (144.96–206.46 NL kg_{TS}^{-1}) and 182.63–232.79 NL kg_{VS}^{-1} (152.20–208.15 NL kg_{TS}^{-1}) in the case of WF and DF, respectively. The values from WF are slightly higher than those reported by Piepenschneider et al. [45] for the two-cut management system of urban green areas, while they are similar to those given by Delafield [67], who reported an SMY equal to 277 NL kg_{VS}^{-1} for grass from the road verges in Wales. Similar values were also obtained by Brown et al. [68] for the grasses composed by *Poa* spp., *Festuca* spp., and *Lolium* spp. from the road verges of Lincolnshire in England. The biogas potential of grass from road verges is lower than the values for grass residues from urban areas reported by Bedoić et al. [8]. However, the SMY of grass from a roadside or from grass residues reported in the literature is significantly lower than that of the maize silage. Delafield [67] emphasizes that most studies showed a similar SMY of various grasses, and therefore, the grass yield seems to be a much more crucial factor influencing the biogas production than the species, management, or origin of the material.

The feedstock supply with constant parameters allows a stable operation and biogas production. Introducing new feedstock requires a start-up phase when new material is added slowly to enable the microorganisms to adapt to new conditions. Our results reveal that the biogas production from the grass in the WF technology was stable regardless of the time of grass cutting or preservation method. Therefore, the risk of AD failure resulting from feeding digester with ensiled or fresh grass cut in different seasons is low. In DF, a significant delay in the decomposition of fresh grass, mainly harvested in summer and autumn, indicates a need to ensile the plant material. The ensiling of grass plays a key role in preserving the energy content, maintaining the optimal methane yield for several months. The fermentation process in ensiling can lead to a breakdown of some complex carbohydrates, such as hemicellulose, which contributes to the decrease in the NDF and ADF content. The lactic acid bacteria also have the ability to degrade lignin to some extent, further reducing the ADF content [69]. The ensiling additives and maturity of the material may influence the methane yield of grass silage [37]. Ensilage changes the properties of feedstock, while parameters such as particle size, use of additives, and duration affect the ensilage process and the silage quality, and thus, the formation of CH_4 [37]. Brown et al. [68] found a slight but positive effect of ensiling the feedstock on biogas production. The direct effect of ensiling on SMY gives contradictory results. In our study, the grass ensiling did not affect the biogas production in the WF technology, while in the DF technology, ensiling significantly accelerated the process and shortened the lag phase.

4.3. Energy Balance and CO_2 Emissions

Biogas production from grass cut as a part of urban greenery maintenance has several advantages, such as waste utilization, energy and fertilizer production, and reduced GHG emissions. The grass used as feedstock in a biogas plant may partially replace maize silage and, at the same time, reduce the area of maize cultivation as an energy crop, and decrease a pressure on agricultural land. AD performance is a more energy-efficient process than grass composting since the latter requires high energy for the formation and mixing of the material [44]. According to Pergola et al. [70], producing 1 ton of compost requires between 1500 and 2000 MJ of energy.

Grass used as feedstock in the biogas production also reduces GHG emissions. According to Salter et al. [71], producing biomethane for transport in England and Wales would reduce CO_2 emissions by 24,000 tons per year. Biogas production also reduces the fossil fuels required to produce an equivalent amount of electricity and heat, and therefore reduces GHG emissions. The replacement or at least addition of AD to composting also contributes to the reduction in GHG emissions, since during composting, gases such as CO_2, CH_4, N_2O, and NH_3 are released. CO_2 is the main product of the decomposition of composted material, while other gases are released in methanogenic and denitrification processes under anaerobic conditions occurring in parts of composting material which is not well aerated. The emission factors related to composting may range from 199 to 250 kg of CO_2 eq. t^{-1} [70]. However, Boldrin et al. [72] estimated an even higher emission factor that equaled 300 kg of CO_2 eq. t^{-1}. The replacement of maize silage with grass from urban greenery maintenance reduces the area cultivated with energy crops and the GHG emissions, since maize cultivation, harvest, and transportation to the biogas plant release extra GHGs. Direct emissions come from fuel combustion, while indirect emissions are related to the production of machinery necessary for cultivation and the production of fertilizers and plant protection products [7]. Grass cutting also requires machinery; however, grass cutting as a part of greenery maintenance is carried out anyhow, regardless of the use of grass waste for biogas production.

4.4. The Advantages and Disadvantages of Grass Fermentation in Wet and Dry Technology

The energy produced per unit of feedstock mass is much lower in the case of grass in comparison to maize silage; therefore, the grass from road verges and urban areas should not be used as mono-substrate in biogas production. Moreover, mono-substrate grass often causes technical problems in biogas plants such as blocking and floating [73]. However, the grass is a promising feedstock for co-digestion in WF technology with the material of high biogas potential. According to De Moore et al. [9], adding up to 20% of grass to manure does not cause technical problems. Additionally, using grasses as feedstock may cause abrasion, while the contamination of grasses with soil requires frequent sediment removal from the digester [37]. Therefore, DF may be a better solution in case of a large amount of grass. DF technology has several advantages including lower reactor volume, lower transportation costs, lower digestate volume, less odor nuisance, fewer energy needs, and thus, greater efficiency of energy production. Solid digestate from this process can be composted and then used as fertilizer in urban green areas [74]. However, this technology also has some drawbacks and limitations, such as a considerably longer time compared to WF for the complete decomposition of biomass, which was especially pronounced in the AD of the fresh grass harvested in summer and autumn. Even though the ensilage shortened the lag phase, a longer HRT in DF technology compared to WF technology should still be assumed.

5. Conclusions

Both dry (DF) and wet fermentation (WF) can be used for the utilization of urban grass waste. The parameters of the fermentation process significantly influence the efficiency of a biogas plant. In our study, the hydraulic retention time differed depending on the fermentation technology. Although the CH_4 yield and energy production in both the WF and DF technologies were similar, the time in which the CH_4 content reached the level acceptable for the CHP unit was noticeably short in the wet technology, while it took a much longer time in the dry technology. This was especially evident for the fresh grass cut in summer and autumn.

Our results reveal that the time of cutting and preservation method affects the hydraulic retention time in dry technology. The fermentation of fresh material from summer and autumn cuttings started after a long lag phase, and was significantly shortened by material ensiling. In WF technology, neither the cutting time nor the preservation method impacted the hydraulic retention time and daily CH_4 production.

The low CH_4 yield from urban grasses obtained in both technologies shows that the grass waste from green area maintenance should be considered only as a co-substrate in biogas production. This is indicated by the relatively low amounts of potential energy from biogas from the studied grass. Our results show that the production of electricity and heat calculated per 1 t_{DM} was affected by the technology, cutting time, and preservation method, favoring fresh material. However, the electricity and heat production calculated per 1 hectare of the grassed area is not significantly affected by the cutting time and preservation method but depends mainly on the yield. Even though urban grass should be considered a co-substrate, it can be a valuable feedstock which may partially substitute energy crops such as maize silage. Such substitution would decrease the area of maize cultivated for energy purposes and would reduce the GHG emissions related to its cultivation. Our results reveal that biogas production from the grass waste in WF technology is a stable process. This feedstock's cutting time and preservation method do not affect the AD process. In DF technology, fresh grass, especially from late growing season, used as feedstock, extends the time of biomass decomposition and should therefore be avoided in real-life biogas plants.

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References

1. News European Parliament. EU Responses to Climate Change. Available online: https://www.europarl.europa.eu/news/en/headlines/society/20180703STO07129/eu-responses-to-climate-change (accessed on 20 September 2022).
2. Adelard, L.; Poulsen, T.G.; Rakotoniaina, V. Biogas and Methane Yield in Response to Co- and Separate Digestion of Biomass Wastes. *Waste Manag. Res.* **2015**, *33*, 55–62. [CrossRef]
3. European Environment Agency. Climate Change, Impacts and Vulnerability in Europe 2016. Available online: https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016 (accessed on 17 April 2023).
4. Eurostat. Urban and Rural Living in the EU. Available online: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20200207-1 (accessed on 20 September 2022).
5. UNEP. Cities and Climate Change. Available online: http://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/cities-and-climate-change (accessed on 15 April 2023).
6. European Environment Agency. Urban Green Infrastructure. 2018. Available online: https://www.eea.europa.eu/data-and-maps/dashboards/urban-green-infrastructure-2018 (accessed on 27 September 2022).
7. Brown, S.; Kruger, C.; Subler, S. Greenhouse Gas Balance for Composting Operations. *J. Environ. Qual.* **2008**, *37*, 1396–1410. [CrossRef]
8. Bedoić, R.; Čuček, L.; Ćosić, B.; Krajnc, D.; Smoljanić, G.; Kravanja, Z.; Ljubas, D.; Pukšec, T.; Duić, N. Green Biomass to Biogas—A Study on Anaerobic Digestion of Residue Grass. *J. Clean. Prod.* **2019**, *213*, 700–709. [CrossRef]
9. De Moor, S.; Velghe, F.; Wierinck, I.; Michels, E.; Ryckaert, B.; De Vocht, A.; Verbeke, W.; Meers, E. Feasibility of Grass Co-Digestion in an Agricultural Digester, Influence on Process Parameters and Residue Composition. *Bioresour. Technol.* **2013**, *150*, 187–194. [CrossRef]
10. Poulsen, T.G.; Adelard, L. Improving Biogas Quality and Methane Yield via Co-Digestion of Agricultural and Urban Biomass Wastes. *Waste Manag.* **2016**, *54*, 118–125. [CrossRef]
11. Vogel, T.; Ahlhaus, M.; Barz, M. Optimisation of Biogas Production from Grass by Dry-Wet Fermentation. In Proceedings of the Engineering for Rural Development, Jelgava, Latvia, 28–29 May 2009.
12. Maroušek, J.; Zeman, R.; Vaníčková, R.; Hašková, S. New Concept of Urban Green Management. *Clean Technol. Environ. Policy* **2014**, *16*, 1835–1838. [CrossRef]
13. Czubaszek, R.; Wysocka-Czubaszek, A.; Banaszuk, P. GHG Emissions and Efficiency of Energy Generation through Anaerobic Fermentation of Wetland Biomass. *Energies* **2020**, *13*, 6497. [CrossRef]
14. Abdelsalam, E.M.; Samer, M.; Amer, M.A.; Amer, B.M.A. Biogas Production Using Dry Fermentation Technology through Co-Digestion of Manure and Agricultural Wastes. *Environ. Dev. Sustain.* **2021**, *23*, 8746–8757. [CrossRef]
15. Fu, Y.; Luo, T.; Mei, Z.; Li, J.; Qiu, K.; Ge, Y. Dry Anaerobic Digestion Technologies for Agricultural Straw and Acceptability in China. *Sustainability* **2018**, *10*, 4588. [CrossRef]
16. Stolze, Y.; Zakrzewski, M.; Maus, I.; Eikmeyer, F.; Jaenicke, S.; Rottmann, N.; Siebner, C.; Pühler, A.; Schlüter, A. Comparative Metagenomics of Biogas-Producing Microbial Communities from Production-Scale Biogas Plants Operating under Wet or Dry Fermentation Conditions. *Biotechnol. Biofuels* **2015**, *8*, 14. [CrossRef]
17. Jha, A.K.; Li, J.; Zhang, L.; Ban, Q.; Jin, Y. Comparison between Wet and Dry Anaerobic Digestions of Cow Dung under Mesophilic and Thermophilic Conditions. *Adv. Water Resour. Prot.* **2013**, *1*, 28–38.
18. Luning, L.; van Zundert, E.H.M.; Brinkmann, A.J.F. Comparison of Dry and Wet Digestion for Solid Waste. *Water Sci. Technol.* **2003**, *48*, 15–20. [CrossRef] [PubMed]
19. Angelonidi, E.; Smith, S.R. A Comparison of Wet and Dry Anaerobic Digestion Processes for the Treatment of Municipal Solid Waste and Food Waste: Comparison of Wet and Dry Anaerobic Digestion Processes. *Water Environ. J.* **2015**, *29*, 549–557. [CrossRef]
20. Lehtomäki, A.; Björnsson, L. Two-Stage Anaerobic Digestion of Energy Crops: Methane Production, Nitrogen Mineralisation and Heavy Metal Mobilisation. *Environ. Technol.* **2006**, *27*, 209–218. [CrossRef]
21. Korres, N.E.; Thamsiriroj, T.; Smyth, B.M.; Nizami, A.S.; Singh, A.; Murphy, J.D. Grass Biomethane for Agriculture and Energy. In *Genetics, Biofuels and Local Farming Systems*; Lichtfouse, E., Ed.; Sustainable Agriculture Reviews; Springer: Dordrecht, The Netherlands, 2011; pp. 5–49. ISBN 978-94-007-1521-9.
22. Li, W.; Khalid, H.; Zhu, Z.; Zhang, R.; Liu, G.; Chen, C.; Thorin, E. Methane Production through Anaerobic Digestion: Participation and Digestion Characteristics of Cellulose, Hemicellulose and Lignin. *Appl. Energy* **2018**, *226*, 1219–1228. [CrossRef]
23. Amon, T.; Amon, B.; Kryvoruchko, V.; Zollitsch, W.; Mayer, K.; Gruber, L. Biogas Production from Maize and Dairy Cattle Manure—Influence of Biomass Composition on the Methane Yield. *Agric. Ecosyst. Environ.* **2007**, *118*, 173–182. [CrossRef]
24. Triolo, J.M.; Pedersen, L.; Qu, H.; Sommer, S.G. Biochemical Methane Potential and Anaerobic Biodegradability of Non-Herbaceous and Herbaceous Phytomass in Biogas Production. *Bioresour. Technol.* **2012**, *125*, 226–232. [CrossRef] [PubMed]
25. Seppälä, M.; Paavola, T.; Lehtomäki, A.; Rintala, J. Biogas Production from Boreal Herbaceous Grasses—Specific Methane Yield and Methane Yield per Hectare. *Bioresour. Technol.* **2009**, *100*, 2952–2958. [CrossRef]

26. McEniry, J.; O'Kiely, P. Anaerobic Methane Production from Five Common Grassland Species at Sequential Stages of Maturity. *Bioresour. Technol.* **2013**, *127*, 143–150. [CrossRef]
27. Dragoni, F.; Giannini, V.; Ragaglini, G.; Bonari, E.; Silvestri, N. Effect of Harvest Time and Frequency on Biomass Quality and Biomethane Potential of Common Reed (*Phragmites Australis*) Under Paludiculture Conditions. *Bioenerg. Res.* **2017**, *10*, 1066–1078. [CrossRef]
28. Roj-Rojewski, S.; Wysocka-Czubaszek, A.; Czubaszek, R.; Kamocki, A.; Banaszuk, P. Anaerobic Digestion of Wetland Biomass from Conservation Management for Biogas Production. *Biomass Bioenerg.* **2019**, *122*, 126–132. [CrossRef]
29. Nizami, A.-S.; Korres, N.E.; Murphy, J.D. Review of the Integrated Process for the Production of Grass Biomethane. *Environ. Sci. Technol.* **2009**, *43*, 8496–8508. [CrossRef] [PubMed]
30. Lehtomäki, A.; Huttunen, S.; Lehtinen, T.M.; Rintala, J.A. Anaerobic Digestion of Grass Silage in Batch Leach Bed Processes for Methane Production. *Bioresour. Technol.* **2008**, *99*, 3267–3278. [CrossRef]
31. Ambye-Jensen, M.; Johansen, K.S.; Didion, T.; Kádár, Z.; Schmidt, J.E.; Meyer, A.S. Ensiling as Biological Pretreatment of Grass (*Festulolium Hykor*): The Effect of Composition, Dry Matter, and Inocula on Cellulose Convertibility. *Biomass Bioenerg.* **2013**, *58*, 303–312. [CrossRef]
32. Zhao, Y.; Yuan, X.; Wen, B.; Wang, X.; Zhu, W.; Cui, Z. Methane Potential and Microbial Community Dynamics in Anaerobic Digestion of Silage and Dry Cornstalks: A Substrate Exchange Study. *Appl. Biochem. Biotechnol.* **2017**, *181*, 91–111. [CrossRef] [PubMed]
33. Gallegos, D.; Wedwitschka, H.; Moeller, L.; Zehnsdorf, A.; Stinner, W. Effect of Particle Size Reduction and Ensiling Fermentation on Biogas Formation and Silage Quality of Wheat Straw. *Bioresour. Technol.* **2017**, *245*, 216–224. [CrossRef]
34. Madhukara, K.; Nand, K.; Raju, N.R.; Srilatha, H.R. Ensilage of Mangopeel for Methane Generation. *Process Biochem.* **1993**, *28*, 119–123. [CrossRef]
35. Teixeira Franco, R.; Buffière, P.; Bayard, R. Ensiling for Biogas Production: Critical Parameters. A Review. *Biomass Bioenerg.* **2016**, *94*, 94–104. [CrossRef]
36. Rani, D.S.; Nand, K. Ensilage of Pineapple Processing Waste for Methane Generation. *Waste Manag.* **2004**, *24*, 523–528. [CrossRef]
37. Prochnow, A.; Heiermann, M.; Plöchl, M.; Linke, B.; Idler, C.; Amon, T.; Hobbs, P.J. Bioenergy from Permanent Grassland—A Review: 1. Biogas. *Bioresour. Technol.* **2009**, *100*, 4931–4944. [CrossRef]
38. Nizami, A.-S.; Murphy, J.D. Optimizing the Operation of a Two-Phase Anaerobic Digestion System Digesting Grass Silage. *Environ. Sci. Technol.* **2011**, *45*, 7561–7569. [CrossRef]
39. Thamsiriroj, T.; Nizami, A.S.; Murphy, J.D. Why Does Mono-Digestion of Grass Silage Fail in Long Term Operation? *Appl. Energy* **2012**, *95*, 64–76. [CrossRef]
40. Wall, D.M.; Allen, E.; Straccialini, B.; O'Kiely, P.; Murphy, J.D. Optimisation of Digester Performance with Increasing Organic Loading Rate for Mono- and Co-Digestion of Grass Silage and Dairy Slurry. *Bioresour. Technol.* **2014**, *173*, 422–428. [CrossRef] [PubMed]
41. Yu, L.; Bule, M.; Ma, J.; Zhao, Q.; Frear, C.; Chen, S. Enhancing Volatile Fatty Acid (VFA) and Bio-Methane Production from Lawn Grass with Pretreatment. *Bioresour. Technol.* **2014**, *162*, 243–249. [CrossRef]
42. Cadavid-Rodríguez, L.S.; Bolaños-Valencia, I.V. Grass from Public Green Spaces an Alternative Source of Renewable Energy in Tropical Countries. *Rev. ION* **2016**, *29*, 109–116. [CrossRef]
43. Mattioli, A.; Boscaro, D.; Dalla Venezia, F.; Correale Santacroce, F.; Pezzuolo, A.; Sartori, L.; Bolzonella, D. Biogas from Residual Grass: A Territorial Approach for Sustainable Bioenergy Production. *Waste Biomass Valor.* **2017**, *8*, 2747–2756. [CrossRef]
44. Chiumenti, A.; Boscaro, D.; Da Borso, F.; Sartori, L.; Pezzuolo, A. Biogas from Fresh Spring and Summer Grass: Effect of the Harvesting Period. *Energies* **2018**, *11*, 1466. [CrossRef]
45. Piepenschneider, M.; Bühle, L.; Hensgen, F.; Wachendorf, M. Energy Recovery from Grass of Urban Roadside Verges by Anaerobic Digestion and Combustion after Pre-Processing. *Biomass Bioenerg.* **2016**, *85*, 278–287. [CrossRef]
46. Statistics Poland. Area and Population in the Territorial Profile in 2021. Available online: https://stat.gov.pl/obszary-tematyczne/ludnosc/ludnosc/powierzchnia-i-ludnosc-w-przekroju-terytorialnym-w-2021-roku,7,18.html (accessed on 28 September 2022).
47. Górniak, A. *Climate of the Podlaskie Voivodeship in the Time of Global Warming*, 1st ed.; Wydawnictwo Uniwersytetu w Białymstoku: Białystok, Poland, 2021. (In Polish)
48. Jankowski, K.; Sosnowski, J.; Kowalczyk, R. Impact of Hydrogel and Kind of Soil Cover on the Compactness of Turf Lawns. *Inż. Ekol.* **2012**, *30*, 249–256. (In Polish)
49. APHA. *Standard Methods: For the Examination of Water and Wastewater*, 20th ed.; American Public Health Association; American Water Works Association; Water Pollution Control Federation: Washington, DC, USA, 1998; ISBN 978-0-87553-235-6.
50. AOAC. *Official Method 973.18–1977. Fiber (Acid Detergent) and Lignin (H2SO4) in Animal Feed*; AOAC: Rockville, MD, USA, 1977.
51. Wang, K.; Yun, S.; Xing, T.; Li, B.; Abbas, Y.; Liu, X. Binary and Ternary Trace Elements to Enhance Anaerobic Digestion of Cattle Manure: Focusing on Kinetic Models for Biogas Production and Digestate Utilization. *Bioresour. Technol.* **2021**, *323*, 124571. [CrossRef]
52. Statistics Poland. *Production of Agricultural and Horticultural Crops in 2021*, 1st ed.; Zakład Wydawnictw Statystycznych: Warsaw, Poland, 2022.
53. Czubaszek, R.; Wysocka-Czubaszek, A.; Wichtmann, W.; Banaszuk, W. Specific Methane Yield of Wetland Biomass in Dry and Wet Fermentation Technologies. *Energies* **2021**, *14*, 8373. [CrossRef]

54. The National Centre for Emissions Management. *Calorific Values (CO) and CO2 Emission Factors (EC) in 2019 to Be Reported under the Emission Trading Scheme for 2022*; The National Centre for Emissions Management: Warsaw, Poland, 2021. (In Polish)
55. Piepenschneider, M. Urban Grass and Grass-Leaf Litter Mixtures as Source for Bioenergy Recovery. Ph.D. Thesis, University of Kassel, Kassel, Germany, 2015.
56. Heiermann, M.; Ploechl, M.; Linke, B.; Schelle, H.; Herrmann, C. Biogas Crops—Part I: Specifications and Suitability of Field Crops for Anaerobic Digestion. *Agric. Eng. Int. CIGR J.* **2009**, *XI*, 1–17.
57. Bryson, G.M.; Barker, A.V. Sodium Accumulation in Soils and Plants along Massachusetts Roadsides. *Commun. Soil Sci. Plant Anal.* **2002**, *33*, 67–78. [CrossRef]
58. Gross, F.; Riebe, K. *Silage: Business Management, Production, Feeding*, 1st ed.; UlmeVerlag Eugen: Stuttgart, Germany, 1974; ISBN 978-3-8001-4321-4. (In German)
59. Radkowski, A.; Radkowska, I. Evaluation of the Quality and Nutritional Value of Silage from the Meadow Sward of Selected Farms in South-Eastern Poland. *Wiad. Zootech.* **2014**, *52*, 32–37. (In Polish)
60. Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of Anaerobic Digestion Process: A Review. *Bioresour. Technol.* **2008**, *99*, 4044–4064. [CrossRef] [PubMed]
61. Mason, P.E.; Higgins, L.; Climent Barba, F.; Cunliffe, A.; Cheffins, N.; Robinson, D.; Jones, J.M. An Assessment of Contaminants in UK Road-Verge Biomass and the Implications for Use as Anaerobic Digestion Feedstock. *Waste Biomass Valor.* **2020**, *11*, 1971–1981. [CrossRef]
62. Weiland, P. Biomass Digestion in Agriculture: A Successful Pathway for the Energy Production and Waste Treatment in Germany. *Eng. Life Sci.* **2006**, *6*, 302–309. [CrossRef]
63. Antonopoulou, G.; Vayenas, D.; Lyberatos, G. Biogas Production from Physicochemically Pretreated Grass Lawn Waste: Comparison of Different Process Schemes. *Molecules* **2020**, *25*, 296. [CrossRef] [PubMed]
64. Juneja, A.; Kumar, D.; Williams, J.D.; Wysocki, D.J.; Murthy, G.S. Potential for Ethanol Production from Conservation Reserve Program Lands in Oregon. *J. Renew. Sustain. Energy* **2011**, *3*, 063102. [CrossRef]
65. Keady, T.W.J.; Mayne, C.; Fitzpatrick, D.A. Prediction of Silage Feeding Value from the Analysis of the Herbage at Ensiling and Effects of Nitrogen Fertilizer, Date of Harvest and Additive Treatment on Grass Silage Composition. *J. Agric. Sci.* **2000**, *134*, 353–368. [CrossRef]
66. Malinowska, E.; Wiśniewska-Kadżajan, B. Effects of Tytanit and Nitrogen on Cellulose and Hemicellulose Content of Festulolium Braunii and on Its Digestibility. *Agronomy* **2022**, *12*, 1547. [CrossRef]
67. Delafield, M. *A Practical Trial to Investigate the Feasibility of Wide-Scale Collection of Cuttings from Roadside Verges in Powys, for Use in Biogas and Compost Production*, 1st ed.; Montgomeryshire Wildlife Trust: Welshpool, UK, 2006.
68. Brown, A.E.; Ford, J.S.; Bale, C.S.E.; Camargo-Valero, M.A.; Cheffins, N.J.; Mason, P.E.; Price-Allison, A.M.; Ross, A.B.; Taylor, P.G. An Assessment of Road-verge Grass as a Feedstock for Farm-fed Anaerobic Digestion Plants. *Biomass Bioenerg.* **2020**, *138*, 105570. [CrossRef]
69. Desta, S.T.; Yuan, X.; Li, J.; Shao, T. Ensiling characteristics, structural and nonstructural carbohydrate composition and enzymatic digestibility of Napier grass ensiled with additives. *Bioresour. Technol.* **2016**, *221*, 447–454. [CrossRef] [PubMed]
70. Pergola, M.; Persiani, A.; Pastore, V.; Palese, A.M.; D'Adamo, C.; De Falco, E.; Celano, G. Sustainability Assessment of the Green Compost Production Chain from Agricultural Waste: A Case Study in Southern Italy. *Agronomy* **2020**, *10*, 230. [CrossRef]
71. Salter, A.; Delafield, M.; Heaven, S.; Gunton, Z. Anaerobic Digestion of Verge Cuttings for Transport Fuel. *Proc. Inst. Civ. Eng.-Waste Resour. Manag.* **2007**, *160*, 105–112. [CrossRef]
72. Boldrin, A.; Andersen, J.K.; Møller, J.; Christensen, T.H.; Favoino, E. Composting and Compost Utilization: Accounting of Greenhouse Gases and Global Warming Contributions. *Waste Manag. Res.* **2009**, *27*, 800–812. [CrossRef]
73. Thamsiriroj, T.; Murphy, J.D. Difficulties Associated with Monodigestion of Grass as Exemplified by Commissioning a Pilot-Scale Digester. *Energy Fuels* **2010**, *24*, 4459–4469. [CrossRef]
74. Schäfer, W.; Lehto, M.; Teye, F. *Dry Anaerobic Digestion of Organic Residues On-Farm—A Feasibility Study. Agriffod Research Reports 77*, 1st ed.; MTT Agrifood Research Finland: Vihti, Finland, 2006.

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