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Anaerobic Co-Digestion of Common Reed and Plant-Based Biowaste from Households

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Abstract: Organic wastes from households, private gardens, the maintenance of urban greenery, and active nature conservation measures are often difficult to manage. This lignocellulosic biomass may be suitable for anaerobic digestion (AD). However, the mono-digestion of plant material, such as waste from active conservation measures for wetlands, results in a low methane (CH_4) yield. The aim of this study was to assess the feasibility of using common reed silage for co-digestion with plant-based biowaste from households. The specific methane yield (SMY) was determined in biochemical methane potential (BMP) tests performed on biowaste, reed silage, and combinations of reed silage with 10%, 30%, 50%, 70%, and 90% of biowaste on a fresh weight basis. The lowest SMY was observed for the mono-digestion of reed silage (160.40 ± 4.09 NL $kg_{VS}{}^{-1}$), while biowaste had the highest CH_4 yield (284.03 ± 7.03 NL $kg_{VS}{}^{-1}$). The subsequent addition of biowaste enhanced CH_4 production from 158.57 ± 7.88 NL $kg_{VS}{}^{-1}$ (10% of biowaste) to 233.28 ± 11.91 NL $kg_{VS}{}^{-1}$ (90% of biowaste). A key advantage of biogas production is its role in reducing CO_2 emissions into the atmosphere, which result from the use of conventional fuels for energy generation. The avoided CO_2 emissions generated in electricity and heat production range between 378.62 $kgCO_2$ $t_{TS}{}^{-1}$ and 676.36 $kgCO_2$ $t_{TS}{}^{-1}$ depending on the reed silage-to-biowaste ratio used for biogas production. This study reveals that reed silage is not an optimal feedstock for biogas production, and its share in co-digestion with biowaste should not exceed 10% of the total input to the biogas plant.

Keywords: clean energy; specific methane yield; greenhouse gas

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1. Introduction

Growing populations and an increase in resource consumption and energy demand have led to a serious climate crisis and many other environmental, social, and economic problems. Current efforts to reduce greenhouse gas (GHG) emissions affect many sectors of the economy, as well as consumer attitudes and even people's behaviour and habits. GHG reduction also applies to waste management. In 2022, 230 million tonnes of municipal waste was generated in the European Union (EU), which corresponds to 522 kg of waste per capita [1]. In the same year, the recycling of municipal waste reached 49% [2]. In the EU, in 2022, more than 59 million tonnes of food was wasted, which means the generation of 132 kg of food waste per inhabitant. The highest share (54%) of total food waste was from households [3].

In Poland, in 2023, 13.4 million tonnes of municipal waste was generated, of which 48% was recovered through recycling (16%), thermal processing with energy recovery (20%), and biological processing, namely, composting and fermentation (12%) [4]. Food waste in Poland amounted to 4.5 million tonnes, 55% of which came from households [5].

The circular economy approach to waste management increases the role of anaerobic digestion (AD) in organic waste treatment. AD is an anaerobic process in which microorganisms break down organic matter and convert it into biogas, which contains 50–70% CH_4, and a nutrient-rich byproduct, i.e., digestate [6–9]. This solution reduces waste and, unlike solar or wind power, generates stable energy, provides valuable fertilizer, and contributes to the reduction in GHG emissions [9,10]. AD is more environmentally friendly than composting due to less odour and GHG emissions and can be more economic viable at a large scale [11].

The CH_4 yield depends on the feedstock characteristics and operational parameters [6]. Food waste is characterized by a low C:N ratio and pH but contains high amounts of easily biodegradable organic matter with a high biogas potential, as it predominantly consists of carbohydrates, fat, and proteins [11,12]. Biodegradable waste from parks and gardens is a lignocellulosic biomass, and its biodegradability depends highly on the composition of its organic components, namely, cellulose, hemicellulose, and lignin [13]; the content differs not only between various species but also between communities [14], biotopes [15], and geographical locations [16]. A new and additional source of lignocellulosic feedstock, which is considered as waste which is difficult to manage, could be biomass from biotope management and paludiculture [17]. The problem of managing this biomass will increase, as one of the specific targets of the Nature Restoration Law is restoring drained peatlands under agricultural use [18]. Conversely, natural wetland habitats are threatened by the common reed, a highly competitive invasive species. The management strategy for the invasive reed includes the practice of mowing the grass, which results in the generation of a large amount of waste [19].

The utilization of reed biomass for the purpose of biogas production is a plausible application. Preliminary studies have demonstrated that the CH_4 yield from the reed ranges between 102 ± 5 NL $kg_{VS}{}^{-1}$ and 188 NL $kg_{VS}{}^{-1}$ [20,21] and is much lower than the specific methane yield (SMY) of maize silage. In contrast to the aforementioned findings, Ohlsson et al. [22] demonstrated that the SMY of the common reed from the Baltic Sea area was 400 NL $kg_{VS}{}^{-1}$. The studies of Baute et al. [23] and Roj-Rojewski et al. [21] revealed that the AD process of reed biomass harvested in the spring or early summer resulted in a higher SMY compared to the CH_4 yield from biomass harvested in the autumn. The low SMY prompts the search for ways to increase biogas production and its CH_4 content, either through pretreatment or co-digestion. Mechanical pretreatment, such as cutting [24], grinding [25], and steam explosion [20], has been shown to significantly increase biogas and CH_4 production from the reed, potentially improving its economic feasibility. The co-digestion of 2% NaOH-pretreated reed and cow dung increased biogas production by 49% [26]. The addition of nickel, copper, or chromium to the anaerobic co-digestion of the reed and cow dung resulted in the better stability of the process, the enhanced degradation of lignin and hemicellulose, the transformation of intermediates into volatile fatty acids (VFAs), and thus an increase in biogas yield [27–29]. The anaerobic co-digestion of the common reed with faeces and kitchen waste with the addition of zeolite resulted in an enhancement in the CH_4 content from 44.10% to 65.30% [30]. However, the substitution of maize silage with reed silage reduced the CH_4 yield by 13–35%, depending on the percentage of added reed [31].

The aim of this study was to evaluate the potential of common reed silage for co-digestion with biowaste in biogas production, addressing a knowledge gap in the search for sustainable and efficient bioenergy sources. The results will provide valuable insights into the feasibility of utilizing the common reed—harvested from natural wetlands as part of active conservation practices—together with plant-based household waste as a renewable feedstock for biogas generation. Given the anticipated expansion of paludiculture across

Europe, identifying practical and scalable pathways for reed waste utilization is becoming increasingly urgent. At the same time, fruit and vegetable waste remains one of the largest contributors to food waste in the EU, with substantial amounts produced both during primary production and at the consumption stage [32]. This research offers an important contribution to the development of integrated waste-to-energy systems by exploring the synergy between two underutilized lignocellulosic waste streams, advancing circular bioeconomy goals and climate mitigation strategies.

2. Materials and Methods

2.1. Substrates and Inoculum

Two substrates were used in the experiment: the common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) and biowaste from households. The reed was harvested in the late autumn in 2020 from a natural wetland. After delivery to the laboratory, the plant material (2 kg of fresh matter) was cut into 2–4 cm pieces, compressed, and wrapped in 5 layers of silage wrap foil and ensiled without additives. The ensilage process took 5–6 weeks. The biowaste consisted of potato (40%), apple (20%), carrot (15%), beet (15%), and a mixture of various plant wastes (15%) (on a fresh weight basis). In the experiment, the digestate from an agricultural biogas plant treating maize silage with 10–20% of food and agricultural waste under mesophilic conditions was used as inoculum. Prior to the experiment, the inoculum was degassed at a temperature of 38 °C. The chemical properties of the inoculum and substrates used in the experiment are presented in Table 1.

Table 1. Chemical composition of feedstock and inoculum (mean ± SD, n = 3).

Parameter	Biowaste	Reed Silage	Inoculum
Total solids (TSs), %	16.71 ± 0.05 a *	62.85 ± 0.99 b	6.03 ± 0.19 c
Volatile solids (VSs), %TSs	91.95 ± 0.41 a	91.16 ± 0.27 a	76.54 ± 0.19 b
Total Kjeldahl nitrogen (TKN), g kg_{DM}^{-1}	14.23 ± 0.20 a	14.60 ± 0.53 a	82.16 ± 2.07 b
Total organic carbon (TOC), g kg_{DM}^{-1}	405.80 ± 7.11 a	379.11 ± 7.81 b	412.80 ± 2.19 a
C:N	29:1	26:1	5:1

* Lowercase letters—statistical differences at $p < 0.05$ among substrates and inoculum.

2.2. Experimental Setup

The SMY was measured in the batch test. The batch test included biowaste, reed silage, and combinations of reed silage with 10%, 30%, 50%, 70%, and 90% of biowaste on a fresh weight basis. The biochemical methane potential (BMP) test was conducted using eudiometers, with bottles of a total volume of 1 L and a working volume of approximately 340 mL being incubated in a water bath at 38 ± 1 °C. In order to achieve an inoculum-to-substrate ratio (ISR) of 2:1 based on volatile solids (VSs), 200 g of inoculum and an adequate quantity of both substrates were added. Distilled water was added to the reactors to obtain a total solid (TS) content of 5%. Three bottles containing only 200 mL of inoculum and water were used as controls. The bottles were purged with nitrogen for 2 min to eliminate oxygen. The CH_4 yield of each biowaste, reed silage, and each combination of biowaste and reed silage was measured in triplicate with three eudiometers. The volume of biogas was measured by means of confined liquid displacement, and the chemical composition of the biogas was determined using a portable biogas analyser, DP-28BIO (Nanosens, Wysogotowo, Poland). The batch test was carried out until the daily CH_4 production in the longest-running trial decreased to below 1% of the total cumulative volume of CH_4 observed over three consecutive days. As a result, the experiment was terminated after

45 days. The total cumulative CH_4 yield was calculated at the end of the BMP test. The modified Gompertz model [33] was used to determine the kinetics of CH_4 production:

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

where the following variables are used:

$G(t)$—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).

All gas volumes are reported under standard conditions (0 °C and 1.013 bar) per kg VSs added (NL CH_4 kg_{VS}^{-1}).

2.3. Chemical Analyses

The following parameters of the inoculum, biowaste, and reed silage were measured: total solids (TSs), volatile solids (VSs), total Kjeldahl nitrogen (TKN) content, total phosphorus (TP) content, and total organic carbon (TOC) content. According to standard methods, the TSs were determined by drying the sample at 105 °C until constant weight; the VS content was determined after the incineration of dried material at 550 °C for 5 h in a muffle furnace [34]. The TKN was determined in fresh samples by the Kjeldahl method in a Vapodest 50s analyzer (Gerhardt, Königswinter, Germany). The TOC content was measured in the TOC-L analyzer with an SSM-5000A Solid Sample Combustion Unit (Shimadzu, Kyoto, Japan). The analyses were performed in triplicate, and the results are given on a dry weight basis.

2.4. Calculations and Statistical Analyses

Calculations of potential energy generated from biogas in biogas plants fed with the studied feedstock used the SMY determined during laboratory tests. The calculations assumed that 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. The thermal energy consumption in the biogas plant was assumed to be 30%, and the electric use was considered to be 9% of the produced energy [35].

The reduction in CO_2 emissions was calculated based on the electricity and heat production in a biogas plant fed with biowaste, reed silage, and their combinations. We assumed that the electricity and heat generated from conventional fuels would be replaced with energy produced in the biogas plant. The emission factors for electricity (597 kg CO_2 MWh^{-1}) and heat (94.84 kg CO_2 GJ^{-1}) were adopted from the National Centre for Emissions Management (NCEM) [36,37]. The calculations did not consider the direct and indirect emissions related to the reed harvest, ensiling, and transportation as well as biowaste collection and transportation.

The VS reduction was estimated based on the BMP test and VS content measured at the beginning and end of the experiment. The percentage of VS reduction was calculated using the following equation:

$$\%VS\ reduction = \frac{VS_{initial} - VS_{final}}{VS_{initial}} \times 100 \quad (2)$$

One-way analysis of variance (ANOVA; single factor) and Tukey's Honest Significant Difference (HSD) post hoc test at $p < 0.05$ were used to determine the significance of differences in the chemical composition of the inoculum and both studied substrates. ANOVA and Tukey's HSD post hoc test ($p < 0.05$) were also applied to examine the effect of the substitution of reed silage with biowaste. Before the analysis, the normal distribution of the data was checked with the Shapiro–Wilk test, and the homogeneity of variance was assessed with the Levene test. When data failed the tests, they were log-transformed to achieve normality and the homogeneity of variance. All statistical tests were performed using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Feedstock and Inoculum Characteristics

The highest TSs were found for reed silage, while much lower TSs were obtained for the biowaste and inoculum. A statistically significant difference ($p < 0.05$) was observed for both the substrates and inoculum. Both substrates were characterized by a similar VS content and TKN content, which were significantly higher ($p < 0.05$) than those of the inoculum. On the contrary, the TOC content was similar for the biowaste and inoculum and was significantly ($p < 0.05$) higher than the value obtained for the reed silage. The C:N ratio in both substrates was similar (Table 1).

The initial TSs were comparable in all reactors, as the experiment was designed to start the BMP test with a TS content of 5%. As determined at the end of the experiment, the TS and VS contents exhibited discrepancies in the rate of decomposition of reed silage and biowaste. At the end of the experiment, the lowest TSs were observed in the reactor with biowaste, which indicates its best digestibility. The overall differences between the initial and final TSs were around 1%. There were more pronounced differences in the VS content. For reed silage and biowaste, the changes in the TSs were 19.53% and 31.19%, respectively, while for VSs, they ranged from 12.97% to 35.71%. The initial VS content in all reactors was very similar according to the experimental setup. Biowaste was characterized by the lowest final VSs, while the highest final VS content was found in the reactor with reed silage. The decreased amount of reed in co-digested reed and biowaste combinations slightly lowered the content of the final VSs. The first clear change in VS reduction was evident in the presence of a 10% addition of biowaste to the reed silage. In the case of the TSs, the alterations were most significant in the substrate combination with 70% of biowaste, while in case of the VSs, the alterations were most significant in the presence of 90% of biowaste.

3.2. Methane Yield from Mono- and Co-Digestion of Reed Silage and Biowaste

The lowest SMY was observed for reed silage mono-digestion (Table 2). The partial substitution of reed silage with biowaste impacted CH_4 production in co-digestion. The substitution of 10% to 30% on a fresh matter basis had almost no effect on the CH_4 production. The incorporation of biowaste in quantities ranging from 50% to 70% on a fresh matter basis significantly ($p < 0.05$) increased the CH_4 yield by ~15%. A pronounced enhancement in CH_4 production occurred after the addition of 70% biowaste. The SMY of biowaste mono-digestion was found to be 77% higher than the CH_4 yield from reed silage.

Table 2. Methane production of mono- and co-digestion of reed silage and biowaste.

Feedstock	Specific Methane Production	Maximum Daily Methane Production	Methane Content
	NL kg_{VS}^{-1}	NL kg_{VS}^{-1}	%
PHR	160.40 ± 4.09 ab *	5.94 ± 0.09 a	57.0 ± 1.7 a
BIO-10	158.57 ± 7.88 a	6.18 ± 0.23 a	58.0 ± 1.0 ab
BIO-30	171.06 ± 5.09 abc	6.31 ± 0.09 a	56.3 ± 1.2 a
BIO-50	185.58 ± 11.17 c	8.30 ± 0.34 a	58.0 ± 1.7 ab
BIO-70	183.41 ± 7.77 bc	9.69 ± 1.12 a	61.3 ± 0.6 b
BIO-90	233.28 ± 11.91 d	17.18 ± 1.66 b	67.7 ± 1.2 c
BIO	284.03 ± 7.03 e	27.81 ± 3.58 c	74.0 ± 1.0 d

* Lowercase letters—statistical differences at $p < 0.05$ among co-digested combinations and mono-digested reed silage and biowaste. PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste.

Assuming that reed silage is an additive in the AD of biowaste, even a small addition of reed silage equivalent to 10% reduces the CH_4 yield by almost 18%. The further addition of reed silage to the substrate combination results in a substantial decline in CH_4, reaching approximately 35%. Furthermore, when the amount of reed silage exceeds the amount of biowaste on a fresh matter basis (reed silage addition of 70% and 90%), CH_4 production falls by 40–44% (Table 3).

Table 3. Changes in methane production of mono- and co-digestion of reed silage and biowaste.

PHR	BIO-10	BIO-30	BIO-50	BIO-70	BIO-90	BIO
Increase in the amount of methane in relation to reed [%]						
	−1.14	6.65	15.70	14.35	45.44	77.08
43.53	44.17	39.77	34.66	35.43	17.87	
Decrease in the amount of methane in relation to biowaste [%]						
PHR	**BIO-10**	**BIO-30**	**BIO-50**	**BIO-70**	**BIO-90**	**BIO**

PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste.

3.3. Daily Methane Production from Mono- and Co-Digestion of Reed Silage and Biowaste

The co-digestion of reed silage with biowaste exhibited rapid CH_4 production during the initial phase of the AD process. Even though there were some variations, the course of the AD process was similar for every combination of substrates (Figure 1). For reed silage and its combinations with biowaste up to 30%, only one peak of maximum CH_4 production was detected on day 4. In contrast, other combinations exhibited two peaks of maximum daily CH_4 production occurring on day 2 and day 4. The mono-digestion of biowaste also followed this pattern, with the first peak corresponding to the daily maximum CH_4 production.

Increasing the amount of biowaste in all combinations led to an improvement in the daily CH_4 production, which was very pronounced for days of maximum daily production. Furthermore, the studied combinations of substrates differed with respect to the duration of the period when the daily CH_4 production persisted at a high rate. This is particularly

evident for the addition of 90% biowaste and the mono-digestion of biowaste, where CH_4 production exceeded 20 NL kg_{VS}^{-1} even on days 7–8, while the daily CH_4 production of other combinations did not exceed 7 NL kg_{VS}^{-1}.

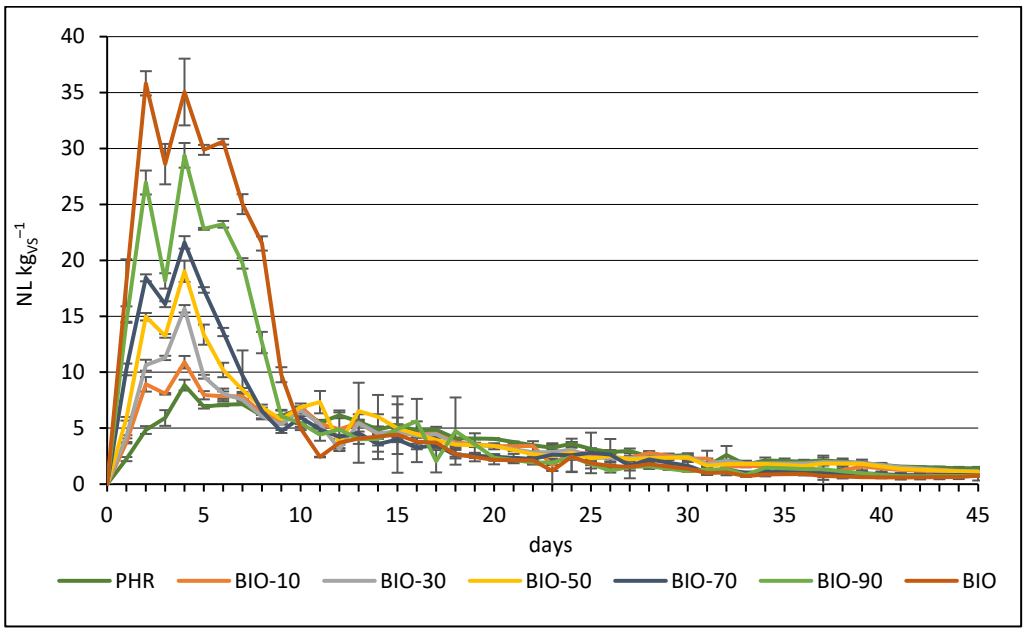

Figure 1. Daily methane production from mono- and co-digestion of reed silage and biowaste. PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste. Standard deviations are shown as vertical bars.

3.4. Cumulative Methane Production from Mono- and Co-Digestion of Reed Silage and Biowaste

As expected, the higher SMY of biowaste enhanced the cumulative CH_4 production with the increasing substitution of reed silage with biowaste. The CH_4 production on a daily basis affected the curves displaying the cumulative CH_4 values over the experiment's 45 days (Figure 2). The quantity of biowaste added to the reed silage had a very significant impact on the reduction in the CH_4 production process. The mono-digestion of reed silage and the co-digestion of its combinations with a low quantity of biowaste up to 30% resulted in a long hydraulic retention time (HRT) of up to 40 days. High amounts of biowaste (90%) in the co-digestion and the mono-digestion of biowaste were characterized by a short HRT equal to 23 and 20 days, respectively.

3.5. Energy Balance and GHG Emissions

The analysis of the total energy that can be produced from biogas obtained from the mono-digestion of reed silage and biowaste and the co-digestion of these two substrates revealed that between ~3000 MJ and ~5500 MJ of energy can be produced from 1 tonne of volatile solids added (t_{VS}). The largest quantities of total energy (over 4500 MJ) can be generated from the co-digestion of reed silage in combination with 90% biowaste and from the mono-digestion of biowaste (Figure 3a). The remaining combinations are capable of generating from 3000 MJ to 3600 MJ of energy. We can observe a similar pattern when expressing the energy in MJ per tonne of total solids added (t_{TS}). However, if the energy is expressed in MJ per tonne of fresh matter added, the highest value is observed for biogas produced from reed mono-digestion (Figure 3b,c).

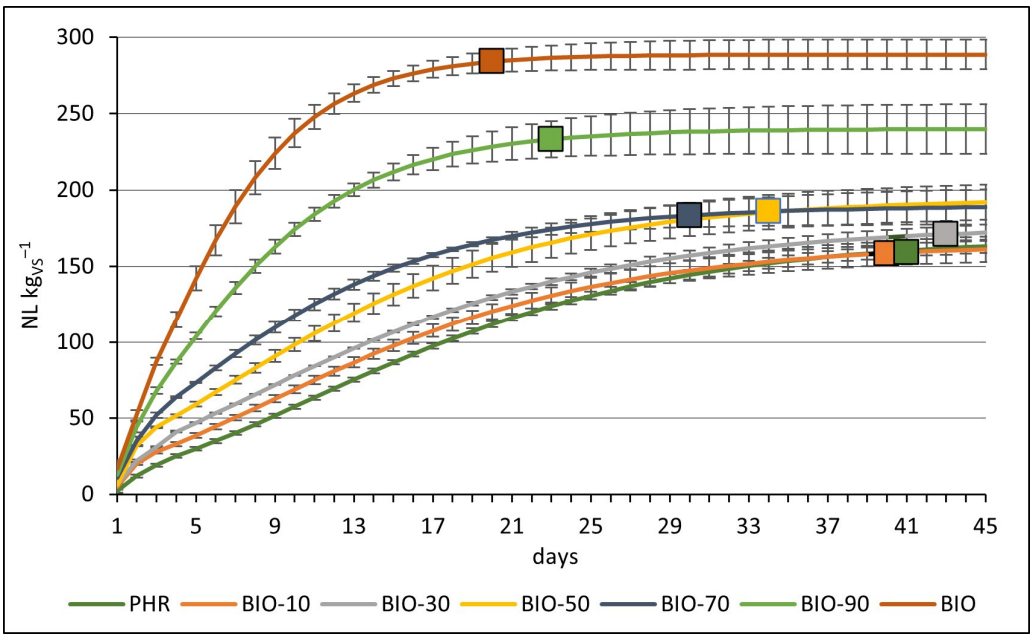

Figure 2. Cumulative methane production from mono- and co-digestion of reed silage and biowaste. PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste. Squares mean the day when the daily CH_4 production fell below 1% of the total cumulative volume of CH_4 observed over three consecutive days. Standard deviations are shown as vertical bars.

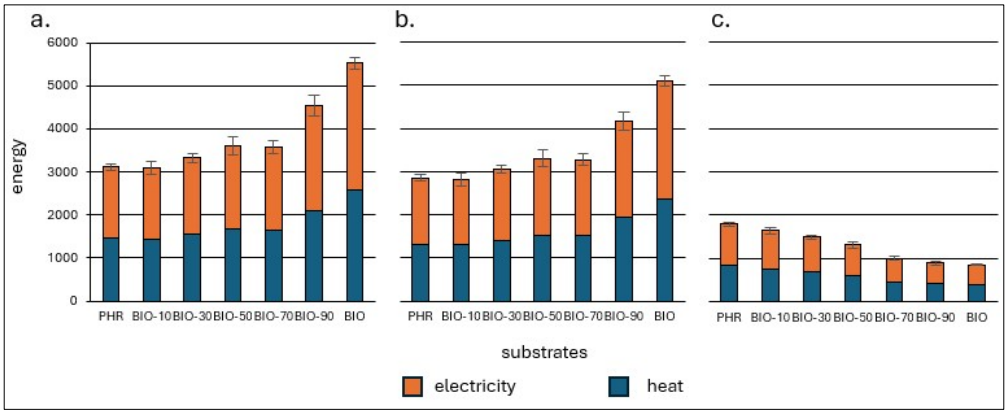

Figure 3. Total energy generation from biogas produced by mono- and co-digestion of reed silage and biowaste (**a**) in MJ per tonne of volatile solids added, MJ t_{VS}^{-1}; (**b**) in MJ per tonne of total solids added, MJ t_{TS}^{-1}; and (**c**) in MJ of tonne of fresh matter added, MJ t_{FM}^{-1}. PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste. Standard deviations are shown as vertical bars.

When the same energy is expressed in t_{FM}, there is a steady decrease in the amount of energy produced, from ~1800 MJ for reed silage to ~850 MJ for biowaste (Figure 3c). When considering the type of energy, thermal energy and electricity each account for approximately 50% of the total possible energy production.

The analysis of electricity generation from biogas produced from reed silage and biowaste showed that ~500 kWh t_{VS}^{-1} to ~800 kWh t_{VS}^{-1} of electricity can be obtained (Figure 4). Low amounts of electricity are generated from reed silage and its combinations with up to 70% biowaste, while a significant increase in electricity can be obtained from

reed silage with 90% biowaste and from biogas produced through the mono-digestion of biowaste.

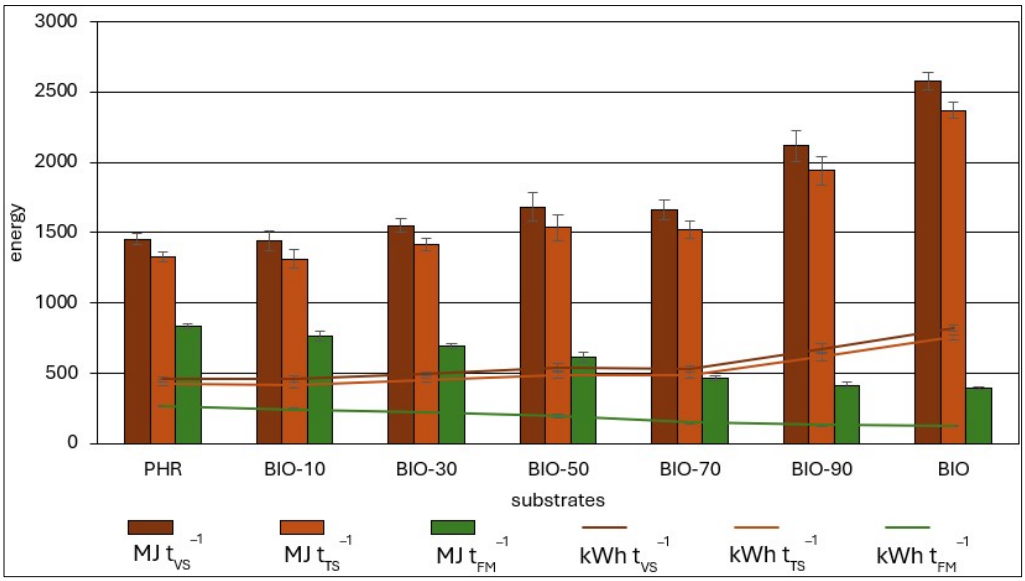

Figure 4. Electricity and heat generation from biogas produced by mono- and co-digestion of reed silage and biowaste. PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste; BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste. Standard deviations are shown as vertical bars.

In contrast, the conversion of electricity production into the fresh matter of feedstock reveals that the maximum electrical energy output is produced by reed silage in an amount equal to 260 kWh t_{FM}^{-1}, while the minimum is obtained from biowaste (120 kWh t_{FM}^{-1}).

A major benefit of biofuel production, including biogas, is its role in reducing CO_2 emissions into the atmosphere, which result from the use of conventional fuels for energy generation. A comparative analysis of biogas produced from the mono- and co-digestion of biomass examined in this study reveals that the level of avoided CO_2 emissions is approximately twofold higher in the case of biowaste compared to reed silage (Table 4).

Table 4. CO_2 emissions avoided by using reed silage and biowaste as co-substrates in a biogas plant.

Feedstock	CO_2 Emissions Avoided		
	$kgCO_2\ t_{TS}^{-1}$		
	Electricity	**Heat**	**Total**
PHR	252.79	125.84	378.62
BIO-10	249.97	124.44	374.41
BIO-30	269.84	134.33	404.17
BIO-50	293.02	145.87	438.89
BIO-70	290.02	144.37	434.39
BIO-90	369.93	184.15	554.08
BIO	451.57	224.79	676.36

PHR—reed silage; BIO-10—reed silage with 10% content of biowaste; BIO-30—reed silage with 30% content of biowaste BIO-50—reed silage with 50% content of biowaste; BIO-70—reed silage with 70% content of biowaste; BIO-90—reed silage with 90% content of biowaste; BIO—biowaste.

4. Discussion

4.1. Feedstock Characteristics

The chemical composition of the reed depends on several factors, such as biotope [15,38], geographical location [16], climatic and weather conditions, flooding [39], and time of harvest [21,40]. Seasonal changes and growth stages are important factors impacting the chemical composition of the reed [41]. The TS content of the reed silage used in this study was 62.85%, which is higher than the value obtained for reed silage prepared from plants harvested from the same wetland in 2019 [42] but within the range of TSs reported for plants harvested in July, August, and October in 2015 [21]. The TS content of the reed ranges from 30.8% to 93.8% [23,43]. Several authors have reported high TS values ranging from 81.7% to 93% [24,30,44,45]. A higher TS content is often associated with late harvest. Dubrovskis and Kazulis [24] reported much lower TSs (41.49–56.25%) for reed biomass harvested in June compared to TS values (90.73–93.00%) for reed plants harvested in the cold season. Similar findings were reported by Temel et al. [46], who analysed the TS content of both silage and fresh plants harvested at the end of the vegetative stage, beginning of panicle formation, and full panicle stage. The lowest TS values of 43.53% (fresh plants) and 44.84% (silage) were observed at the end of vegetative stage. In fresh plants, the TS value (55.16%) was the highest at the full panicle stage. Similarly, low TS values (48.8–54.6%) were reported by Tran et al. [26] and Pelegrin and Holzem [25].

The VS content obtained in this study was 91.16%TSs, similar to the results obtained for reed silage from plants harvested in 2019 from the same wetland [42]. Roj-Rojewski et al. [21] reported the VS content of reed silage from plants harvested in June 2015 as 92.2%TSs. However, biomass harvested in the late summer and early fall had a lower VS content, equal to 85.8%TSs and 97.4%TSs, respectively. In general, the VS content was within the range reported in the literature (83.80–97.80%TSs) [24,30,43].

The TKN content in this study was 14.60 g kg_{DM}^{-1}, which is consistent with values reported in the literature [22,26,30,47]. In contrast, Wöhler-Geske et al. [41] reported a very low TKN content, between 0.53 g kg_{DM}^{-1} and 0.68 g kg_{DM}^{-1}. Much lower results compared to this study were also reported by López-González et al. [48], who found a TKN content of 6.27 g kg_{DM}^{-1}, and by Obolewski et al. [49], who reported a TKN content in the reed of 7.82 g kg_{DM}^{-1}. However, the result obtained in this study was lower than that in our previous study [42] and values reported by Roj-Rojewski et al. [21]. The TOC content of the reed reported in the literature ranges from 392 g kg_{DM}^{-1} to 526.3 g kg_{DM}^{-1} [21,22,26,30,41,47–49]. In contrast, Baran et al. [43] reported a significantly higher TOC content, equal to 870.5 g kg_{DM}^{-1}. The result obtained in this study (379.11 g kg_{DM}^{-1}) was lower than the lowest value reported by López-González et al. [48].

The physicochemical properties of biowaste are difficult to compare since the composition of this waste can vary significantly. According to Jiménez-Rosado et al. [50], biowaste can be defined as any biodegradable organic waste of vegetable and/or animal origin that is susceptible to biological degradation. The majority of studies on biogas production from biowaste consider kitchen waste, which consists of food scraps comprising fruit and vegetable wastes, waste oils and greases, cooking waste from food processing, and cooked leftovers [51]. The chemical composition of kitchen waste depends on the source and can include a range of organic and inorganic components such as lipids, proteins, carbohydrates, and starch [52]. The heterogeneity of kitchen waste also depends on geographical location [53]. Moreover, the composition of green biowaste from gardens varies seasonally more than that of kitchen waste from households [54]. According to Škorjanc et al. [55], food waste includes edible and inedible parts, which consist of lipids, hemicellulose, cellulose, starch, lignin, and proteins. These compounds make up 82–96% of the total volatile matter. Consequently, the chemical composition of kitchen or food waste may differ significantly

from the biowaste used in this study. Moreover, a comparison of biowaste from the present study with composted waste may be subject to a substantial margin of error, as grasses, leaves, and weeds are typically composted, rather than vegetable kitchen waste.

The TS content of kitchen waste or food waste differs significantly and ranges from 10.57% up to 82.30% [56]. However, in the majority of studies, the TS content is between 10 and 30% [57–62]. The TS content of biowaste in this study was 16.71%, which is within the range given in the literature. The VS content of kitchen waste is high and ranges from 77%TSs to 98.6%TSs [56–58,60,62]. The VS content (91.95%TSs) of the biowaste in this study was higher than values obtained for fruit waste and vegetable waste [62] and most studied kitchen waste [57,60]. The TKN content of the studied biowaste was 14.23 g kg_{DM}^{-1} and was within the range of values reported for biowaste and kitchen waste (2.5–59.36 g kg_{DM}^{-1}) [57–59,61]. The TOC content of biowaste in this study was 405.8 g kg_{DM}^{-1}, which was similar to values reported by Hu et al. [59] and Montoneri et al. [57]. On the contrary, Wo et al. [58] and Sathya et al. [61] observed a higher TOC equal to 471 g kg_{DM}^{-1} and 528 g kg_{DM}^{-1}, respectively.

The similar VS, TKN, and TOC contents of reed and biowaste are primarily due to the fact that the biowaste used in this study was composed of plant parts that were discarded during meal preparation. The biowaste did not contain any animal waste, which is mainly a source of fats and protein, while plant-based waste is a source of carbohydrates [63]. The significantly higher TS content in the reed (62.8%) is due to the late time of its harvest in the late autumn when lignification increases with the maturity of the plants [13]. On the contrary, the biowaste consists of fresh parts of vegetables and fruits which are harvested when their moisture content is high. The TS content in potato varies between 11.9 and 22.6% [63–65], while apple waste typically contains 19% to 27% of TSs [63,66].

4.2. Methane Production

The common reed can be up to 4 m high [67], and in natural habitats, it can produce biomass from 3 t_{DM} ha^{-1} to 10 t_{DM} ha^{-1} [68–70], while in paludiculture, the reed yield can be up to 16 t_{DM} ha^{-1} [71]. The species dominates fresh and brackish marshes and is widely present all over the world. However, in many habitats, the reed is an invasive species which should be harvested to preserve natural ecosystems. The common reed has significant intraspecific variability; however, according to the study of Eller et al. [72], the genotype has no impact on the CH_4 yield. The SMY of the reed is, however, affected by the time of harvest [21,23]. The CH_4 yield obtained in this study (160.4 NL kg_{VS}^{-1}) from plants harvested in the autumn was similar to the results shown by Dubrovskis and Kazulis [24] who reported an SMY of 110–215 NL kg_{VS}^{-1} from reed harvested in the winter and was lower than the SMY of reed cut in June (180–290 NL kg_{VS}^{-1}). Higher CH_4 yields of 214–232 NL kg_{VS}^{-1} and 188 NL kg_{VS}^{-1} were also reported by Eller et al. [72] and Lizasoain et al. [20], respectively. The SMY obtained in the current study is within the range given by Baute et al. [23] who reported a CH_4 yield range from 107.6 NL kg_{VS}^{-1} for reed harvested in mid-October to 172.4 NL kg_{VS}^{-1} for reed cut in early July. Furthermore, Eller et al. [72] obtained a much higher SMY of 200–229.6 NL kg_{VS}^{-1} from plants of different genotypes. The CH_4 production from common reed harvested in 2015 in natural wetlands of the Narew River in Poland depended on the time of cutting and was 277 NL kg_{VS}^{-1} from plants harvested in mid-summer, 235 NL kg_{VS}^{-1} from biomass cut in late summer, and 181 NL kg_{VS}^{-1} from reed harvested in early fall [21]. Contrary to these findings, the SMY of common reed harvested from the same wetland in September 2019 was 160 NL kg_{VS}^{-1} [42], while the CH_4 yield from biomass obtained in late autumn in 2020 was only 135.2 NL kg_{VS}^{-1} [31]. The differences can be attributed to the harvest time, weather conditions, water level, and time of flooding. The discrepancies in the SMY obtained from the same

material could result from the different inoculum used in both experiments and other conditions such as freezing the plant material.

The continuous process in biogas plants requires a constant supply of feedstock. Therefore, plant biomass which is harvested only once a year should be preserved. Ensiling is one of the most common methods of preservation of plant biomass like maize, grass, etc. This method is often used for reed preservation. In this study, the reed biomass was cut into small 2–4 cm pieces and ensiled without additives. The results of studies on the effect of ensiling on biogas production from different substrates are inconclusive. According to Herrmann and Rath [73], ensiling increases the CH_4 production; however, the results reported by Kreuger et al. [74] were contradictory since ensiling had no significant effect on the SMY of maize, while Brown et al. [75] observed a slightly positive effect of ensiling the feedstock on biogas production. On the contrary, Czubaszek et al. [76] reported that ensiling both with and without additives did not affect the biogas production in wet fermentation technology. In the present study, the ensiled material had a high TS content (~62%) and a pH of 6.68, indicating poor ensiling performance. The high TS content and probably high lignin content together with the lack of additives could negatively influence the process of ensiling [31].

Nevertheless, the low SMY of the common reed reduces its suitability for biogas production in mono-digestion. Various pretreatment methods have been studied to enhance the CH_4 yield, e.g., grinding, shredding, or treating with an alkali or acid. Shredding the dry, winter-harvested material to 1 mm increased the CH_4 production from 110 NL $kg_{VS}{}^{-1}$ to 215 NL $kg_{VS}{}^{-1}$, and shredding the fresh material harvested in the summer to 2 mm led to an increase in the CH_4 production, from 180 NL $kg_{VS}{}^{-1}$ to 290 NL $kg_{VS}{}^{-1}$ [24]. A similar increase in CH_4 production was observed by Eller et al. [72] when ground reed was used instead of chopped reed. Al-Iraqi et al. [77] also revealed that small particles (<1 mm) increased the CH_4 yield. Pelegrin and Holzem [25] evaluated several pretreatment methods, including cutting/shredding, grinding, thermal, ultrasound, alkali, acid, aerobic, and anaerobic. All methods enhanced the CH_4 yield; however, the highest increase was observed after shredding, grinding, and thermal pretreatment. According to Al-Iraqi et al. [77], pretreatment with 2% sodium hydroxide (NaOH) concentration for 72 h is optimal for the anaerobic digestion of the reed in continuous anaerobic digesters at a pilot or full scale.

Another possible method of increasing the CH_4 yield is the co-digestion of the reed with other feedstock. The study of Czubaszek et al. [31] revealed that the co-digestion of maize silage with a 10%, 30%, and 50% content of reed silage reduced the CH_4 yield by 13%, 28%, and 35%, respectively. Another disadvantage of reed silage addition was increased ammonia (NH_3) and hydrogen sulphide (H_2S) concentrations in biogas. However, the substitution of maize silage with reed silage decreases the GHG emissions from maize cultivation. The co-digestion of the reed with biowaste from households showed that only the addition of 10% of reed results in a high CH_4 yield of between 300 and 350 NL $kg_{VS}{}^{-1}$, while the co-digestion of these two substrates at ratio of 50:50 decreases the CH_4 production to 200–250 NL $kg_{VS}{}^{-1}$. The same study revealed that the SMY of biowaste, ranging between 351 NL $kg_{VS}{}^{-1}$ and 399 NL $kg_{VS}{}^{-1}$, was much higher than the SMY of the reed, which ranged between 72 NL $kg_{VS}{}^{-1}$ and 221 NL $kg_{VS}{}^{-1}$ [78]. Our study revealed that the addition of 30% biowaste decreases the CH_4 yield significantly and that 10% is the threshold value for reed silage addition to other feedstock which does not significantly disturb the performance of AD.

Other studies showed that pretreatment methods may be the solution and may increase the CH_4 yield from reed co-digestion. The co-digestion of common reed pretreated with 2% NaOH and cow dung at a 2:1 ratio showed a significant increase in the CH_4 yield compared

to the untreated mono-digestion of reed and cow dung [26]. The addition of clinoptilolite (type of zeolite) increased the CH_4 yield, inhibited acidification, and enhanced volatile fatty acid (VFA) destruction [30]. Furthermore, the addition of chromium (IV) as $K_2Cr_2O_7$ to the co-digestion of reed straw and cow dung enhanced the biogas yield. The best performance was obtained for 30 mg/L Cr^{6+}, which increased the biogas yield by up to 19% and the CH_4 content by up to 39.21% [29]. The co-digestion of the ground reed pretreated with 2% NaOH and food waste (such as bread, vegetables, fruit, meat, fish, eggs, juice, desserts) at different ratios revealed that the highest and most stable biogas production was obtained at a (food waste-to-reed) ratio of 25:75 with an ISR of 1:2. In contrast, at an ISR of 1:1, at all substrate mixing ratios, the highest biogas production was obtained at a food waste-to-reed ratio of 75:25 with the mono-digestion of food waste [79]. In the present study, the increasing addition of biowaste to reed silage significantly increased the CH_4 yield. However, in this study, the ISR was 2:1. This is in contrast to the ISR in the study of Al-Iraqi et al. [79]. The ISR may have a significant impact on the AD process in co-digestion systems. Several studies have revealed that the ISR influences the acidification, the VFA concentration, and consequently the production of CH_4 [79–81].

The differences in the SMY of the reed are mainly due to the time of harvest [21,23,24,77,78]. Late mowing results in material rich in lignin with a low content of cellulose and hemicellulose. In the AD process, hemicellulose is hydrolysed and acidified faster than cellulose, which has higher CH_4 potential. The co-digestion of both components has a synergistic effect on the CH_4 yield [82]. In contrast, lignin is a complex and high-molecular-weight structure that provides support and resistance against microbial attacks [83] and therefore is more resistant to the AD process. The high lignin content results from the maturity of the reed harvested in the late autumn. Lignification, which increases with the maturity of plants, is a physiological process influenced by genetic and environmental factors and reflects the extent of lignin deposition in the plant cell wall [13]. According to the literature, the lignin content in the reed ranges between 7.3%TSs and 23.6%TSs [41,47,84–89]. The lignin content in the reed collected in September 2019 from the natural wetland of the Narew River was equal to 21.90%TSs [42] and was higher than the content of this component in sedges. As indicated by Jung et al. [83], the reed is less valuable as a feedstock for biofuels in comparison to miscanthus, switchgrass, and sorghum owing to its higher lignin content.

In contrast, the vegetables and fruits which constitute biowaste have a low lignin content. According to the literature, vegetables and fruits have a lignin content of between 0.40%TSs and 10.8%TSs [90–92]. This low lignin content together with a low TS content and high VS content may enhance the AD process through rapid hydrolysis [93] and results in higher CH_4 production. Another explanation for the much higher SMY obtained from biowaste is the high content of potato in this substrate. The high anaerobic degradability of starch, which is the main component of potato waste, may enhance biogas production [64]. The AD of vegetable market wastes (consisting of a mixture of waste vegetables, fruits, and flowers obtained from a vegetable market) in a two-phase semi-continuous anaerobic reactor resulted in a CH_4 production of between 157 NL kg_{VS}^{-1} and 469 NL kg_{VS}^{-1} depending on the organic loading rate (OLR) [94]. Fruit and vegetable waste (apple, banana, carrot, potato, and lettuce in equal quantities) digested in a single-phase anaerobic reactor produced a CH_4 yield of 450 NL kg_{VS}^{-1} [95]. A similarly high CH_4 production from fruit and vegetable waste was reported by Masebinu et al. [96], who reported a CH_4 production of 500 NL kg_{VS}^{-1} with an optimal OLR of 2.68 and 2.97 kg_{VS} m^{-3} per day. The AD of fruit and vegetable waste composed of ensiled corn waste (68%), ensiled green peas (12%), ensiled green bean waste (12%), cauliflower and broccoli wastes (1%), and waste carrot with peelings (7%) demonstrated a moderate CH_4 production of

258–301 NL kg_{VS}^{-1}. The experiment was performed in semi-continuous reactors with a low OLR of 1 g_{VS} L^{-1} per day [97]. Furthermore, Pavi et al. [98] reported an SMY of fruit and vegetable waste equal to 275.9 NL kg_{VS}^{-1}. In the present study, the SMY of biowaste composed of vegetable waste was similar to the values reported by Pavi et al. [98] and Borowski et al. [97]. The differences in the CH_4 yield resulted from the variety of fruit and vegetable waste used in the experiments as well as from different methods of experiments and different temperatures and OLRs. Higher results were mainly obtained in semi-continuous reactors [94–96] in comparison to the SMY studied in closed reactors with biogas measured by the water displacement method [98].

The positive synergy effects often observed in co-digestion, due to the balance of several parameters in the co-substrate mixture, offer potential for higher methane yields [99]. However, in this study, the synergistic effect of co-digestion has not been observed due to the similar chemical composition of both feedstocks. Even though the SMY of biowaste was significantly higher than the SMY of reed silage, the addition of the biowaste did not enhance the methane yield. The addition of 10% biowaste to reed silage accelerated the AD of readily degradable components; however, it also caused the faster depletion of these components, resulting in the premature cessation of CH_4 production when compared with the slowly hydrolysing reed. Consequently, the cumulative CH_4 value in the mixture of the reed with 10% biowaste is marginally lower than that of the reed alone. However, it is crucial to note that there is no statistically significant difference between the results. A similar mechanism was observed in the combinations of the reed with the addition of 50% biowaste and the addition of 70% biowaste. The studies on the co-digestion of reed silage with maize silage also revealed that the addition of 10% reed silage to maize silage significantly decreased the methane production. The addition of reed silage increased the hydrogen sulphide (H_2S) and ammonia (NH_3) concentrations in biogas. High H_2S and NH_3 concentrations were also observed in the biogas produced from reed silage monodigestion [31]. These results are also consistent with studies by Hartung et al. [71] on the co-digestion of *Typha latifolia* with maize. The addition of 10% *Typha latifolia* significantly reduced the SMY of the maize silage. However, the substitution of maize with *Phalaris arundinacea* up to 30% did not significantly reduce the biogas yield, as the specific biogas yield of this species was comparable to that of maize [71].

4.3. Energy Balance and GHG Emissions

The total energy that can be produced from biogas obtained from the AD of the reed, biowaste, and their co-digestion ranges from 3000 MJ t_{VS}^{-1} to 5500 MJ t_{VS}^{-1}. The energy generated from biogas produced from waste can significantly contribute to reducing GHG emissions. Balcioglu et al. [100] revealed that using organic waste and chicken manure as a feedstock for biogas production leads to lower environmental impacts than those of a typical energy system based on fossil fuel. The generation of energy from biogas derived from urban, agricultural, and forestry byproducts has been demonstrated to result in substantial GHG emissions reductions compared to conventional fossil sources of energy production [101]. In the present study, the level of GHG emission avoidance by the replacement of fossil fuels with biogas depends on the methane yield from different feedstock combinations. The lowest reduction in GHG emissions was calculated for reed silage. However, if the reed originated from paludiculture, the GHG savings would be higher since rewetting the drained peatlands for reed cultivation may result in GHG emission savings of up to over 20 t CO_2 eq. per hectare per year [102]. The AD of biowaste instead of the more common composting contributes to a reduction in GHG emissions not only by replacing fossil fuels with biogas but also by avoiding the emissions from composting.

5. Conclusions

The findings of this study indicate that reed silage is not an optimal feedstock for biogas production. Its lignocellulosic fibres, particularly the high content of recalcitrant lignin, significantly hinder the AD process. A comparative analysis of CH_4 yields from the mono-digestion of reed silage and plant-based biowaste from households revealed that the biowaste produced nearly twice as much CH_4 as the reed. Furthermore, the time required for the almost complete decomposition of ensiled reed was twice as long as that required for biowaste. Biowaste is characterized by a lower TS content, and typically, vegetable and fruit waste contains less lignin. Therefore, this type of waste produces high amounts of CH_4.

The incorporation of biowaste as a co-substrate, constituting up to 70% of the total input, did not lead to a substantial improvement in CH_4 production. A significant increase in the CH_4 yield was observed only when biowaste accounted for 90% of the substrate combination. Conversely, when biomass obtained from the protective management of wetlands is considered as a co-substrate in the AD of biowaste, its share should not exceed 10% of the total input to the biogas plant. An increased proportion of reed silage has been found to result in a substantial decline in CH_4 production, exceeding 30%. The reduction in CH_4 production may be attributed to the maturity of the harvested reed, which consequently increases lignification. Other reasons may include the inhibitory effect of high concentrations of H_2S and NH_3 in the biogas from the reed and an imbalanced C:N ratio during the AD process.

Future studies should focus on the determination of which components might be responsible for the observed effects and what pretreatment method may enhance biogas production from the reed and in co-digestion with other substrates.

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References

1. Eurostat. Municipal Waste by Waste Management Operations. Available online: https://ec.europa.eu/eurostat/databrowser/view/env_wasmun__custom_15352477/default/table?lang=en (accessed on 21 February 2025).
2. Eurostat. Municipal Waste by Waste Management Operations. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/ENV_WASMUN (accessed on 21 February 2025).
3. Eurostat. Statistics Explained. Food Waste and Food Waste Prevention-Estimates. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates (accessed on 21 February 2025).
4. Statistics Poland. Statistical Analyses. In *Environment 2024*, 1st ed.; Statistics Poland: Warsaw, Poland, 2024.
5. Eurostat. Food Waste and Food Waste Prevention by NACE Rev. 2 Activity-Tonnes of Fresh Mass. Available online: https://ec.europa.eu/eurostat/databrowser/view/env_wasfw/default/table?lang=en (accessed on 21 February 2025).
6. Al Seadi, T.; Rutz, D.; Prassl, H.; Köttner, M.; Finsterwalder, T.; Volk, S.; Janssen, R. *Biogas Handbook*, 1st ed.; University of Southern Denmark Esbjerg: Esbjerg, Denmark, 2008.

7. Linville, J.L.; Shen, Y.; Wu, M.M.; Urgun-Demirtas, M. Current State of Anaerobic Digestion of Organic Wastes in North America. *Curr. Sustain. Renew. Energy Rep.* **2015**, *2*, 136–144. [CrossRef]
8. Meegoda, J.N.; Li, B.; Patel, K.; Wang, L.B. A Review of the Processes, Parameters, and Optimization of Anaerobic Digestion. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2224. [CrossRef]
9. Jameel, M.K.; Mustafa, M.A.; Ahmed, H.S.; Mohammed, A.J.; Ghazy, H.; Shakir, M.N.; Lawas, A.M.; khudhur Mohammed, S.; Idan, A.H.; Mahmoud, Z.H.; et al. Biogas: Production, Properties, Applications, Economic and Challenges: A Review. *Results Chem.* **2024**, *7*, 101549. [CrossRef]
10. Costa, A.; Ely, C.; Pennington, M.; Rock, S.; Staniec, C.; Turgeon, J. *Anaerobic Digestion and Its Applications*, 1st ed.; U.S. Environmental Protection Agency: Washington, DC, USA, 2015.
11. Lin, L.; Xu, F.; Ge, X.; Li, Y. Improving the Sustainability of Organic Waste Management Practices in the Food-Energy-Water Nexus: A Comparative Review of Anaerobic Digestion and Composting. *Renew. Sustain. Energy Rev.* **2018**, *89*, 151–167. [CrossRef]
12. Angelidaki, I.; Sanders, W. Assessment of the Anaerobic Biodegradability of Macropollutants. *Rev. Environ. Sci. Biotechnol.* **2004**, *3*, 117–129. [CrossRef]
13. 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]
14. Melts, I.; Ivask, M.; Geetha, M.; Takeuchi, K.; Heinsoo, K. Combining Bioenergy and Nature Conservation: An Example in Wetlands. *Renew. Sustain. Energy Rev.* **2019**, *111*, 293–302. [CrossRef]
15. Herrmann, C.; Prochnow, A.; Heiermann, M.; Idler, C. Biomass from Landscape Management of Grassland Used for Biogas Production: Effects of Harvest Date and Silage Additives on Feedstock Quality and Methane Yield. *Grass Forage Sci.* **2014**, *69*, 549–566. [CrossRef]
16. Mosier, N. Features of Promising Technologies for Pretreatment of Lignocellulosic Biomass. *Bioresour. Technol.* **2005**, *96*, 673–686. [CrossRef]
17. Beer, F.; Wichtmann, W.; Villegas, L.; Agus, F. Paludiculture. In *Recarbonizing Global Soils: A Technical Manual of Best Management Practices*; FAO: Rome, Italy, 2021; Volume 5, ISBN 978-92-5-134900-7.
18. Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on Nature Restoration and Amending Regulation (EU) 2022/869 (Text with EEA Relevance). 2024. Available online: https://climate-laws.org/document/regulation-eu-2024-1991-of-the-european-parliament-and-of-the-council-of-24-june-2024-on-nature-restoration-and-amending-regulation-eu-2022-869_93bc (accessed on 21 February 2025).
19. Banaszuk, P.; Kamocki, A.K.; Wysocka-Czubaszek, A.; Czubaszek, R.; Roj-Rojewski, S. Closing the Loop-Recovery of Nutrients and Energy from Wetland Biomass. *Ecol. Eng.* **2020**, *143*, 105643. [CrossRef]
20. Lizasoain, J.; Rincón, M.; Theuretzbacher, F.; Enguídanos, R.; Nielsen, P.J.; Potthast, A.; Zweckmair, T.; Gronauer, A.; Bauer, A. Biogas Production from Reed Biomass: Effect of Pretreatment Using Different Steam Explosion Conditions. *Biomass Bioenerg.* **2016**, *95*, 84–91. [CrossRef]
21. 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]
22. Ohlsson, L.-O.; Karlsson, S.; Rupar-Gadd, K.; Albers, E.; Welander, U. Evaluation of Laminaria Digitata and *Phragmites Australis* for Biogas Production and Nutrient Recycling. *Biomass Bioenerg.* **2020**, *140*, 105670. [CrossRef]
23. Baute, K.; Van Eerd, L.; Robinson, D.; Sikkema, P.; Mushtaq, M.; Gilroyed, B. Comparing the Biomass Yield and Biogas Potential of *Phragmites australis* with *Miscanthus x giganteus* and *Panicum virgatum* Grown in Canada. *Energies* **2018**, *11*, 2198. [CrossRef]
24. Dubrovskis, V.; Kazulis, V. Biogas Production Potential from Reeds. *RE&PQJ* **2012**, *10*, 886–889. [CrossRef]
25. Pelegrin, J.; Holzem, R.M. Evaluating the Impacts of Phragmites Australis Pretreatment Methods on Biogas and Methane. *MJUR* **2017**, *7*, 244–259.
26. Tran, G.V.; Unpaprom, Y.; Ramaraj, R. Effects of Co-Substrate Concentrations on the Anaerobic Co-Digestion of Common Reed and Cow Dung. *AJARCDE* **2019**, *3*, 28–32. [CrossRef]
27. Tian, Y.; Zhang, H.; Chai, Y.; Wang, L.; Mi, X.; Zhang, L.; Ware, M.A. Biogas Properties and Enzymatic Analysis during Anaerobic Fermentation of Phragmites Australis Straw and Cow Dung: Influence of Nickel Chloride Supplement. *Biodegradation* **2017**, *28*, 15–25. [CrossRef]
28. Hao, H.; Tian, Y.; Zhang, H.; Chai, Y. Copper Stressed Anaerobic Fermentation: Biogas Properties, Process Stability, Biodegradation and Enzyme Responses. *Biodegradation* **2017**, *28*, 369–381. [CrossRef]
29. Zhang, H.; Han, X.; Tian, Y.; Li, Y.; Yang, K.; Hao, H.; Chai, Y.; Xu, X. Process Analysis of Anaerobic Fermentation of *Phragmites Australis* Straw and Cow Dung Exposing to Elevated Chromium (VI) Concentrations. *J. Environ. Manag.* **2018**, *224*, 414–424. [CrossRef]

30. Wang, X.; Zhang, L.; Xi, B.; Sun, W.; Xia, X.; Zhu, C.; He, X.; Li, M.; Yang, T.; Wang, P.; et al. Biogas Production Improvement and C/N Control by Natural Clinoptilolite Addition into Anaerobic Co-Digestion of Phragmites Australis, Feces and Kitchen Waste. *Bioresour. Technol.* **2015**, *180*, 192–199. [CrossRef] [PubMed]
31. Czubaszek, R.; Wysocka-Czubaszek, A.; Wichtmann, W.; Zając, G.; Banaszuk, P. Common Reed and Maize Silage Co-Digestion as a Pathway towards Sustainable Biogas Production. *Energies* **2023**, *16*, 695. [CrossRef]
32. Caldeira, C.; De Laurentiis, V.; Corrado, S.; van Holsteijn, F.; Sala, S. Quantification of Food Waste per Product Group along the Food Supply Chain in the European Union: A Mass Flow Analysis. *Resour. Conserv. Recycl.* **2019**, *149*, 479–488. [CrossRef]
33. 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] [PubMed]
34. APHA. *Standard Methods: For the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, DC, USA; American Water Works Association: Denver, CO, USA; Water Pollution Control Federation: Alexandria, VA, USA, 1998; ISBN 978-0-87553-235-6.
35. Curkowski, A.; Mroczkowski, P.; Oniszk-Popławska, A.; Wśniewski, G. *Agricultural Biogas-Production and Usage*, 1st ed.; Mazowiecka Agencja Energetyczna Sp. z o.o.: Warsaw, Poland, 2009. (In Polish)
36. The National Centre for Emissions Management. *Emission Factors for CO_2, SO_2, NO_x CO and Total Particulate Matter for Electrical Energy on the Basis of Information in National Database on Emissions of Greenhouse Gases and Other Substances for 2023*; The National Centre for Emissions Management: Warsaw, Poland, 2024. (In Polish)
37. The National Centre for Emissions Management. *Calorific Values (CO) and CO_2 Emission Factors (EC) in 2022 to Be Reported under the Emission Trading Scheme for 2025*; The National Centre for Emissions Management: Warsaw, Poland, 2024. (In Polish)
38. Cao, Y.; Natuhara, Y. Composition and Distribution of Common Reed (*Phragmites australis*) Along an Urbanized River: A Case from Central Japan. *Appl. Ecol. Environ. Res.* **2020**, *18*, 3935–3950. [CrossRef]
39. Engloner, A.I.; Németh, K.; Gere, D.; Stefán, D.; Óvári, M. Effects of Water Depth and Water Level Fluctuation on the Total and Bio-Available Element Concentrations in Riverine Reed Stands. *Ecol. Indic.* **2020**, *114*, 106328. [CrossRef]
40. Wenzel, M.; Kabengele, G.; Dahms, T.; Barz, M.; Wichtmann, W. *Bioenergie aus Nassen Mooren. Thermische Verwertung von Halmgutartiger Biomasse aus Paludikultur*, 1st ed.; Institut für Botanik und Landschaftsökologie, Universität Greifswald, Greifswald Moor Centrum: Greifswald, Germany, 2022. (In German)
41. Wöhler-Geske, A.; Moschner, C.R.; Gellerich, A. Provenances and Properties of Thatching Reed (*Phragmites australis*). *Appl. Agric. Forestry Res.* **2016**, *66*, 1–10. [CrossRef]
42. Czubaszek, R.; Wysocka-Czubaszek, A.; Wichtmann, W.; Banaszuk, P. Specific Methane Yield of Wetland Biomass in Dry and Wet Fermentation Technologies. *Energies* **2021**, *14*, 8373. [CrossRef]
43. Baran, M.; Váradyová, Z.; Kráčmár, S.; Hedvábný, J. The Common Reed (*Phragmites australis*) as a Source of Roughage in Ruminant Nutrition. *Acta Vet. Brno* **2002**, *71*, 445–449. [CrossRef]
44. Asano, K.; Ishikawa, T.; Araie, A.; Ishida, M. Improving Quality of Common Reed (*Phragmites communis* Trin.) Silage with Additives. *Asian-Australas. J. Anim. Sci.* **2018**, *31*, 1747–1755. [CrossRef]
45. Albrecht, K.; Neudecker, F.; Veigel, S.; Bodner, S.; Keckes, J.; Gindl-Altmutter, W. The Suitability of Common Reed (*Phragmites australis*) for Load-Bearing Structural Materials. *J. Mater. Sci.* **2023**, *58*, 15411–15420. [CrossRef]
46. Temel, S.; Keskin, B.; Güner, Z.; Atalay, A.İ. Determination of Yield and Quality Characteristics of Common Reed (*Phragmites australis* (Cav.) Trin. Ex Steud) Harvested at Different Growth Stages. *Turk. J. Field Crops* **2023**, *28*, 70–78. [CrossRef]
47. Borin, M.; Florio, G.; Barbera, A.; Cirelli, G.L.; Albergo, R.; Palazzo, S. Preliminary Evaluation of Macrophyte Wetland Biomasses to Obtain Second Generation Ethanol. In Proceedings of the 19th European Biomass Conference and Exhibition, Berlin, Germany, 6–10 June 2011.
48. López-González, D.; Avalos-Ramirez, A.; Giroir-Fendler, A.; Godbout, S.; Fernandez-Lopez, M.; Sanchez-Silva, L.; Valverde, J.L. Combustion Kinetic Study of Woody and Herbaceous Crops by Thermal Analysis Coupled to Mass Spectrometry. *Energy* **2015**, *90*, 1626–1635. [CrossRef]
49. Obolewski, K.; Strzelczak, A.; Kiepas-Kokot, A. Chemical Composition of Reed *Phragmites australis* (Cav.) Trin. Ex Steud. Versus Density and Structure of Periphyton In Various Aquatic Ecosystems. *J. Elementol.* **2007**, *12*, 63–79.
50. Jiménez-Rosado, M.; Perez-Puyana, V.; Romero, A. The Use of Biowaste for the Production of Biodegradable Superabsorbent Materials. *Curr. Opin. Food Sci.* **2023**, *49*, 100975. [CrossRef]
51. Sharma, A.; Kuthiala, T.; Thakur, K.; Thatai, K.S.; Singh, G.; Kumar, P.; Arya, S.K. Kitchen Waste: Sustainable Bioconversion to Value-Added Product and Economic Challenges. *Biomass Conv. Bioref.* **2025**, *15*, 1749–1770. [CrossRef]

52. Rex, P.; Meenakshisundaram, N.; Barmavatu, P. Sustainable Valorisation of Kitchen Waste through Greenhouse Solar Drying and Microwave Pyrolysis—Technology Readiness Level for the Production of Biochar. *J. Environ. Health Sci. Eng.* **2024**, *22*, 381–395. [CrossRef]
53. de Abreu, Í.B.S.; de Sousa, M.H.; da Silva, A.P.; de Araújo Padilha, C.E.; Sales, A.T.; da Silva, A.S.A.; Dutra, E.D.; Menezes, R.S.C. Global Variability of Food Waste Chemical Composition and Its Consequences on the Production of Biofuels and Chemical Compounds. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 1309–1324. [CrossRef]
54. Hanc, A.; Novak, P.; Dvorak, M.; Habart, J.; Svehla, P. Composition and Parameters of Household Bio-Waste in Four Seasons. *Waste Manag.* **2011**, *31*, 1450–1460. [CrossRef]
55. Škorjanc, A.; Goričanec, D.; Urbancl, D. Assessing Energy Potential and Chemical Composition of Food Waste Thermodynamic Conversion Products: A Literature Review. *Energies* **2024**, *17*, 1897. [CrossRef]
56. Meng, Q.; Liu, H.; Zhang, H.; Xu, S.; Lichtfouse, E.; Yun, Y. Anaerobic Digestion and Recycling of Kitchen Waste: A Review. *Environ. Chem. Lett.* **2022**, *20*, 1745–1762. [CrossRef]
57. Montoneri, E.; Boffa, V.; Savarino, P.; Perrone, D.; Ghezzo, M.; Montoneri, C.; Mendichi, R. Acid Soluble Bio-Organic Substances Isolated from Urban Bio-Waste. Chemical Composition and Properties of Products. *Waste Manag.* **2011**, *31*, 10–17. [CrossRef]
58. Wo, D.; Bi, G.; Li, L.; Kong, X.; Jiang, E.; Xie, J. Iron-Fortified Anaerobic Co-Digestion Performance of Kitchen Waste and Pennisetum Hybrid. *Bioenerg. Res.* **2023**, *16*, 651–659. [CrossRef]
59. Hu, N.; Tong, Z.; Li, F.; Zhang, X.; Gao, H.; Zhou, J.A. Two-Stage Strategy Combining Vermicomposting and Membrane-Covered Aerobic Composting to Achieve Value-Added Recycling of Kitchen Waste Solid Residues. *Waste Dispos. Sustain. Energy* **2024**, *6*, 501–510. [CrossRef]
60. Hu, F.; Fu, N.; Wei, Q.; Liu, S.; Hu, Y.; Zhang, S.; Wang, X.; Peng, X.; Dai, H.; Wei, Y. Effect of Alkali Pretreatment Time on Kitchen Waste Anaerobic Digestion Performance Enhanced by Alkali Pretreatment Combined with Bentonite: Performance Enhancement, Microbial Community Structure, and Functional Gene Analysis. *Environ. Sci. Pollut. Res.* **2024**, *31*, 7167–7178. [CrossRef] [PubMed]
61. Sathya, T.A.; Alarjani, K.M.; Elshikh, M.S.; Flanetraj, S.R.; Ponnuswamy, V. Co-Composting of Green Leaves and Kitchen Waste: Characterization of Organic Amendments, Microbial Activity and Analysis of Defence Enzymes in Plants. *Biomass Conv. Bioref.* **2024**, 1–12. [CrossRef]
62. Gautam, B.; Tiwari, S.; Pokhrel, M.R.; Tomberlin, J.K.; Khanal, P. Expanding Black Soldier Fly (BSF; *Hermetia illucens*; Diptera: Stratiomyidae) in the Developing World: Use of BSF Larvae as a Biological Tool to Recycle Various Organic Biowastes for Alternative Protein Production in Nepal. *Biotechnol. Rep.* **2025**, *45*, e00879. [CrossRef]
63. Slopiecka, K.; Liberti, F.; Massoli, S.; Bartocci, P.; Fantozzi, F. Chemical and Physical Characterization of Food Waste to Improve Its Use in Anaerobic Digestion Plants. *Energy Nexus* **2022**, *5*, 100049. [CrossRef]
64. Kaparaju, P.; Rintala, J. Anaerobic Co-Digestion of Potato Tuber and Its Industrial by-Products with Pig Manure. *Resour. Conserv. Recycl.* **2005**, *43*, 175–188. [CrossRef]
65. Dias, R.D.C.; Melo, C.A.D.; Faria, A.T.; Silva, D.V.; Ferreira, M.K.; dos Reis, M.R. Effects of Tembotrione on Potato Crop in a Tropical Soil. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1652–1661. [CrossRef]
66. Czubaszek, R.; Wysocka-Czubaszek, A.; Tyborowski, R. Methane Production Potential from Apple Pomace, Cabbage Leaves, Pumpkin Residue and Walnut Husks. *Appl. Sci.* **2022**, *12*, 6128. [CrossRef]
67. Nagy, G. The Application and Treatment of Freshwater Macrophytes as Potential Biogas Base Materials: A Review. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114513. [CrossRef]
68. Granéli, W. Reed Phragmites Australis (Cav.) Trin. Ex Steudel as an Energy Source in Sweden. *Biomass* **1984**, *4*, 183–208. [CrossRef]
69. Brix, H.; Sorrell, B.K.; Lorenzen, B. Are Phragmites-Dominated Wetlands a Net Source or Net Sink of Greenhouse Gases? *Aquat. Bot.* **2001**, *69*, 313–324. [CrossRef]
70. Köbbing, J.F.; Thevs, N.; Zerbe, S. The Utilisation of Reed (*Phragmites australis*): A Review. *Mires Peat* **2013**, *13*, 1–14.
71. Hartung, C.; Andrade, D.; Dandikas, V.; Eickenscheidt, T.; Drösler, M.; Zollfrank, C.; Heuwinkel, H. Suitability of Paludiculture Biomass as Biogas Substrate—Biogas Yield and Long-Term Effects on Anaerobic Digestion. *Renew. Energy* **2020**, *159*, 64–71. [CrossRef]
72. Eller, F.; Ehde, P.M.; Oehmke, C.; Ren, L.; Brix, H.; Sorrell, B.K.; Weisner, S.E.B. Biomethane Yield from Different European *Phragmites australis* Genotypes, Compared with Other Herbaceous Wetland Species Grown at Different Fertilization Regimes. *Resources* **2020**, *9*, 57. [CrossRef]
73. Herrmann, A.; Rath, J. Biogas Production from Maize: Current State, Challenges, and Prospects. 1. Methane Yield Potential. *Bioenergy Res.* **2012**, *5*, 1027–1042. [CrossRef]

74. Kreuger, E.; Nges, I.; Björnsson, L. Ensiling of Crops for Biogas Production: Effects on Methane Yield and Total Solids Determination. *Biotechnol. Biofuels.* **2011**, *4*, 44. [CrossRef]
75. 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]
76. Czubaszek, R.; Wysocka-Czubaszek, A.; Banaszuk, P.; Zając, G.; Wassen, M.J. Grass from Road Verges as a Substrate for Biogas Production. *Energies* **2023**, *16*, 4488. [CrossRef]
77. Al-Iraqi, A.R.; Gandhi, B.P.; Folkard, A.M.; Barker, P.A.; Semple, K.T. Determine the Optimal Parameters for Biogas Production from Common Reed (*Phragmites australis*). *Bioenerg. Res.* **2024**, *17*, 1302–1314. [CrossRef]
78. Willfors, A. Exploring Biogas from Common Reed. Available online: https://research.fi/en/results/publication/0694257524 (accessed on 29 March 2025).
79. Al-Iraqi, A.R.; Gandhi, B.P.; Folkard, A.M.; Barker, P.A.; Semple, K.T. Influence of Inoculum to Substrate Ratio and Substrates Mixing Ratio on Biogas Production from the Anaerobic Co-Digestion of *Phragmites australis* and Food Waste. *Bioenerg. Res.* **2024**, *17*, 1277–1287. [CrossRef]
80. Xu, F.; Li, Y. Solid-State Co-Digestion of Expired Dog Food and Corn Stover for Methane Production. *Bioresour. Technol.* **2012**, *118*, 219–226. [CrossRef]
81. Brown, D.; Li, Y. Solid State Anaerobic Co-Digestion of Yard Waste and Food Waste for Biogas Production. *Bioresour. Technol.* **2013**, *127*, 275–280. [CrossRef]
82. 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]
83. Jung, S.-J.; Kim, S.-H.; Chung, I.-M. Comparison of Lignin, Cellulose, and Hemicellulose Contents for Biofuels Utilization among 4 Types of Lignocellulosic Crops. *Biomass Bioenerg.* **2015**, *83*, 322–327. [CrossRef]
84. Cotana, F.; Cavalaglio, G.; Pisello, A.; Gelosia, M.; Ingles, D.; Pompili, E. Sustainable Ethanol Production from Common Reed (*Phragmites australis*) through Simultaneuos Saccharification and Fermentation. *Sustainability* **2015**, *7*, 12149–12163. [CrossRef]
85. Elhaak, M.A.; Mohsen, A.A.; Hamada, E.-S.A.M.; El-Gebaly, F.E. Biofuel Production from *Phragmites australis* (Cav.) and *Typha domingensis* (Pers.) Plants of Burullus Lake. *Egypt. J. Exp. Biol. (Bot.)* **2015**, *11*, 237.
86. Murawski, M.; Grzelak, M.; Waliszewska, M.; Knioła, A.; Czekała, W. Energy Value and Yielding from Extensively Used Meadows. *Fragm. Agron.* **2015**, *32*, 71–78. (In Polish)
87. Honoré, M.; Pimbert, S.; Lecompte, T. Characterisation of Plant Flours for Biocomposite Applications Focussing on *Phragmites australis* Properties. *Biosyst. Eng.* **2020**, *197*, 367–377. [CrossRef]
88. Van Tran, G.; Unpaprom, Y.; Ramaraj, R. Methane Productivity Evaluation of an Invasive Wetland Plant, Common Reed. *Biomass Conv. Bioref.* **2020**, *10*, 689–695. [CrossRef]
89. Waliszewska, B.; Grzelak, M.; Gaweł, E.; Spek-Dźwigała, A.; Sieradzka, A.; Czekała, W. Chemical Characteristics of Selected Grass Species from Polish Meadows and Their Potential Utilization for Energy Generation Purposes. *Energies* **2021**, *14*, 1669. [CrossRef]
90. Holloway, W.D.; Tasman-Jones, C.; Maher, K. Towards an Accurate Measurement of Dietary Fibre. *N. Z. Med. J.* **1977**, *85*, 420–423. [PubMed]
91. Hartley, R.D. The Lignin Fraction of Plant Cell Walls. *Am. J. Clin. Nutr.* **1978**, *31*, S90–S93. [CrossRef]
92. Szymańska-Chargot, M.; Chylińska, M.; Gdula, K.; Kozioł, A.; Zdunek, A. Isolation and Characterization of Cellulose from Different Fruit and Vegetable Pomaces. *Polymers* **2017**, *9*, 495. [CrossRef] [PubMed]
93. Ji, C.; Kong, C.-X.; Mei, Z.-L.; Li, J. A Review of the Anaerobic Digestion of Fruit and Vegetable Waste. *Appl. Biochem. Biotechnol.* **2017**, *183*, 906–922. [CrossRef]
94. Dhanalakshmi Sridevi, V.; Rema, T.; Srinivasan, S.V. Studies on Biogas Production from Vegetable Market Wastes in a Two-Phase Anaerobic Reactor. *Clean Technol. Environ. Policy* **2015**, *17*, 1689–1697. [CrossRef]
95. Ganesh, R.; Torrijos, M.; Sousbie, P.; Lugardon, A.; Steyer, J.P.; Delgenes, J.P. Single-Phase and Two-Phase Anaerobic Digestion of Fruit and Vegetable Waste: Comparison of Start-up, Reactor Stability and Process Performance. *Waste Manag.* **2014**, *34*, 875–885. [CrossRef]
96. Masebinu, S.O.; Akinlabi, E.T.; Muzenda, E.; Aboyade, A.O.; Mbohwa, C. Experimental and Feasibility Assessment of Biogas Production by Anaerobic Digestion of Fruit and Vegetable Waste from Joburg Market. *Waste Manag.* **2018**, *75*, 236–250. [CrossRef]
97. Borowski, S.; Cieciura-Włoch, W.; Liczbiński, P. Enhancement of Biogas Production from Vegetable Waste by Application of Mineral Fertilizers. *Bioenergy Res.* **2024**, *17*, 972–982. [CrossRef]
98. Pavi, S.; Kramer, L.E.; Gomes, L.P.; Miranda, L.A.S. Biogas Production from Co-Digestion of Organic Fraction of Municipal Solid Waste and Fruit and Vegetable Waste. *Bioresour. Technol.* **2017**, *228*, 362–367. [CrossRef] [PubMed]
99. Mata-Alvarez, J.; Macé, S.; Llabrés, P. Anaerobic Digestion of Organic Solid Wastes. An Overview of Research Achievements and Perspectives. *Bioresour. Technol.* **2000**, *74*, 3–16. [CrossRef]

100. 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]
101. Tonini, D.; Hamelin, L.; Alvarado-Morales, M.; Astrup, T.F. GHG Emission Factors for Bioelectricity, Biomethane, and Bioethanol Quantified for 24 Biomass Substrates with Consequential Life-Cycle Assessment. *Bioresour. Technol.* **2016**, *208*, 123–133. [CrossRef]
102. Tanneberger, F.; Birr, F.; Couwenberg, J.; Kaiser, M.; Luthardt, V.; Nerger, M.; Pfister, S.; Oppermann, R.; Zeitz, J.; Beyer, C.; et al. Saving Soil Carbon, Greenhouse Gas Emissions, Biodiversity and the Economy: Paludiculture as Sustainable Land Use Option in German Fen Peatlands. *Reg. Environ. Change* **2022**, *22*, 69. [CrossRef]

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