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An Evaluation of the Energy Potential of Agri-Food Waste: Green Residues from Tomato (*Solanum lycopersicum* L.) and Shea Nutshells (*Vitellaria paradoxa*)

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Abstract: Addressing the agricultural challenges of agri-food waste accumulation, this study assessed the energy potential of green residues from tomato (*Solanum lycopersicum* L. cv. Kmicic) plants in different fertilizer configurations and Shea nutshell (*Vitellaria paradoxa*) waste. Two key parameters were compared: (I) *Calorific Value* (*CV*), representing thermal treatment, and (II) *Biogas* and *Biomethane production* potential, representing biochemical treatment. Potential was estimated using the Baserga method and the fermentable organic matter (*FOM*) method. Additionally, the effect of tomato fertilization on the elemental composition and energy potential of its waste was analyzed. Shea waste showed better properties for both thermal and biochemical utilization, with a *CV* of 16.29 MJ/kg. The Baserga and *FOM* methods of estimation showed that the highest *Biogas yields* from Shea waste were 504.18 and 671.39 L_N/kg *DM*, respectively. Among fertilized tomato residues, volcanic tuff fertilizer additive resulted in an optimal *C*/*N* ratio (28.41) and a high *Biogas production* potential of 457.13 L_N/kg *DM* (Baserga) and 542.85 L_N/kg *DM* (*FOM*). These findings demonstrate the feasibility of employing tomato waste and Shea waste as promising feedstock for energy production.

Keywords: biowaste and bioenergy; waste-to-energy; biogas and biomethane production; calorific value

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1. Introduction

Sustainable development in the energy sector relies on low-energy-intensive production, efficient resource and raw material management (including the integration of renewable energy sources) and effective waste management strategies. Implementing circular economy principles is essential to achieving these goals. Utilizing waste biomass for energy production presents a promising approach to addressing these challenges, offering a pathway to enhance resource efficiency while contributing to environmental protection and sustainable business practices.

Biomass, due to its widespread availability and role in the carbon cycle, is recognized as a renewable and zero-emission energy source [1]. Biomass has potential to significantly enhance energy self-sufficiency, particularly in rural and remote areas, as well as in developing regions such as African countries [2]. It was estimated that 1 billion tons of agricultural biomass waste can generate an energy equivalent of 0.55 billion tons of coal, potentially reducing CO_2 emissions by 1.5 billion tons [3]. Biomass encompasses a wide range of agricultural and food waste, including fruits, vegetables, dairy products, grains, animal by-products, and oils. Every year around the world, about 1.3 billion tons of food is

treated as waste [4]. These feedstocks can be converted into various forms of usable energy, such as fuels, heat, electricity, and, through cogeneration, the simultaneous production of heat and electricity [2]. Biomass energy can be harnessed into two primary processing methods—thermochemical and biochemical conversion [5]. In 2021, approximately 8.5 EJ of energy was supplied from biofuels and waste in Europe, with higher outputs recorded in Africa (15.5 EJ) and Asia (excluding China—15.2 EJ) [6]. Combustion remains the most common but least environmentally sustainable method for heat generation. According to the Confederation of European Waste-to-Energy Plants (CEWEP), 103 million tons of municipal solid waste were thermally processed in Europe in 2021 through 499 Waste-to-Energy Plants [7]. The efficiency of the combustion depends on several factors, including the biomass's *CV*, *moisture* content, air supply, and furnace type. Preliminary thermal treatments, such as torrefaction, pyrolysis, gasification, and hydrothermal liquefaction, can enhance biomass properties for energy conversion. These processes yield various products, including biocarbon, bio-oil, pyrolysis gas, syngas, and hydrochar, depending on the specific method employed. Biochemical biomass processing involves chemical and enzymatic treatments of lignocellulosic feedstocks to extract components that microorganisms degrade to produce biofuels or biochemicals [5]. One of the primary biofuels, biogas, is generated through anaerobic digestion (AD), a process where organic material is decomposed by microorganisms under anaerobic conditions, yielding biogas and digestate [8]. Biomethane, derived from biogas, has a higher *CV* (35.7 MJ/m^3) compared to biogas (16.7–21 MJ/m^3) [9]. Approximately 90% of *Biomethane production* is attributed to AD processes [10]. In 2022, Europe produced an estimated 16.8 billion m^3 of biogas and 4.2 billion m^3 of biomethane [11]. Both biogas and biomethane are promising renewable fuels with applications in combined heat and power generation and as transportation fuels, contributing significantly to energy sustainability [12]. A limitation of biochemical biomass treatment is the extended hydraulic retention time (HRT), which restricts further material transformation [13]. The efficiency and progression of both thermochemical and biochemical processes are highly dependent on the chemical composition of the biomass. Technical analysis and elemental composition studies are fundamental for assessing the feasibility of thermal processing methods. For biochemical methods, theoretical biogas and biomethane potential can be estimated based on biomass elemental composition or by analyzing digestible components such as *ash*, *proteins*, *fats*, *crude fiber*, and *nitrogen-free extracts* [14]. This approach provides a rapid and sufficiently accurate assessment, facilitating feasibility and profitability analyses for potential investments in biomass energy production [15].

Agri-food waste are frequently studied materials due to their high content of organic substances, which possess methane production potential. These raw materials exhibit varying degrees of degradation and potential for *Biogas production*, meaning that the AD process occurs with varying intensity [4,10]. According to Wiącek and Tys [9], municipal waste with high organic content, such as food waste and green waste, are promising methane-producing substrates. Due to the versatility of the AD process, waste from various sources, including green areas (grass), urban areas (branches), industry (meat—slaughterhouse waste), processing (pomace), agriculture (straw), household (kitchen leftovers), forestry (sawdust), and aquaculture (shells), can all be used as substrates [4,10].

The aim of this study was to investigate the energy potential of selected green post-production waste in the context of their thermal and biochemical processing. Two distinct types of biomass, difficult to utilize and discarded, were chosen for analysis: green residues from tomato plant and Shea nutshells. The selection of these waste types was influenced by their geographical availability, as each biomass type is cultivated and readily accessible in two different regions, allowing for localized energy production and contributing to the promotion of sustainable development. Tomato waste is mainly generated in regions

with intensive greenhouse farming and agricultural practices, such as Europe. In contrast, Shea nutshells come from African countries where *Vitellaria paradoxa* trees grow widely. Research on their energetic applications is relatively scarce, with existing studies primarily focusing on mono- and co-AD. Szilagyi et al. [16] studied *Biogas production* from tomato waste (stems and leaves) in mono- and co-AD (with corn stover), as well as the influence of tomatine and tomatidine on bacterial cultures. Tomato plant waste proved to be a promising monosubstrate, ensuring a *Biogas production* of 290 mL CH_4/g *VS*, and in co-AD, even 570 mL CH_4/g VS. The authors demonstrated that tomatine can significantly influence the AD process, indicating that tomato waste should be used as a co-substrate. Tomatine and tomatidine are glycoalkaloids in the tomato plant that have antibacterial and antifungal properties. Conducting studies on the content of these potential inhibitors may be crucial for ensuring the proper course of AD. In the study by Saghouri et al. [17], *Biogas production* was examined from tomato processing wastes, resulting in a total of 142 L of biogas with a CH_4 content of 60.50%. Almeida et al. [18] studied *Biogas production* from different tomato waste (rotten tomato, unripe tomato, and tomato branches). The highest production value (324 mL CH_4/g *VS*) was obtained for the mixture in a 3.7:1.2:1 ratio. Tomato waste is a substrate that is often studied with animal-origin substrates in co-AD, as seen in works by Saev et al. [19], Li et al. [20], Alharbi et al. [21], and Wang et al. [22]. However, research on green tomato plant residues remains relatively rare. The utilization and management of Shea waste is not a popular area of research due to the origin of the raw material (African countries). Limited access to the raw material has resulted in few studies, with only local researchers contributing to the field. Ofosu and Aklaku [23] studied the optimal ratio of Shea waste (pulp after the production of Shea butter) in co-AD (with cattle manure) at 50:50, 75:25, and 90:10. They concluded that the highest *Biogas production* occurred at the 50:50 ratio, with over 0.20 L CH_4/g *DOM*/day, and a CH_4 content of around 60%. Ofosu et al. [24] examined changes in pH and process stability during co-AD of Shea waste (pulp) and cattle dung at different ratios—50:50, 75:25, and 90:10. They concluded that Shea waste is not recommended for mono-AD, as pH significantly decreases. However, the process was stable for the 50:50 ratio, with maximum *Biogas production* reaching 37 L/day, and CH_4 content above 60%. These studies focused on post-processing waste from Shea butter production and did not include the Shea nutshells.

The study evaluated the energy potential of two types of agricultural production waste: green residues from tomato plant (*Solanum lycopersicum* L. cv. Kmicic), remaining after harvesting ripe fruit, and Shea nutshells (*Vitellaria paradoxa*). The investigation included technical and proximate analyses to assess their suitability for thermal energy generation and their potential for *Biogas* and *Biomethane production* through biochemical treatment. An estimation of potential was carried out using the Baserga method and the fermentable organic matter method. Additionally, for tomato residues, the impact of fertilization on energy potential was analyzed. Elemental composition (*C*, carbon; *N*, nitrogen; *S*, sulfur) was determined for all samples, and its influence on the energy conversion processes was discussed.

2. Materials and Methods

2.1. Materials

The biomass materials analyzed in this study included green residues (peduncles, stalks, and leaves) from tomato plants (*Solanum lycopersicum* L. cv. Kmicic). These residues were collected after the harvest of ripe fruit in collaboration with the Department of Horticulture at the West Pomeranian University of Technology in Szczecin, Poland. The tomato plants were grown in various configurations of original fertilizer mixtures, in

2 L containers, using a commercial seedlings substrate from Kronen as the control (*T0*). Fertilizer additives included basalt flour (*T1*), gabbro flour (*T2*), and volcanic tuff (*T3*).

Shea nutshell waste (*Vitellaria paradoxa*) (*SN*) was sourced from Sanwill in Szczecin, Poland.

The following reagents were used to perform the experiments: nitric(V) acid (Chempur); sulfuric(VI) acid (Chempur); hydrochloric acid (Chempur); perchloric acid (Chempur); boric acid (Chempur); sodium hydroxide (Chempur); potassium hydroxide (Chempur); acetone (Chempur); n-hexane (Avantor Performance Materials Poland S.A., Gliwice, Poland); n-octanol (Chempur); ammonium metavanadate (Chempur); ammonium heptamolybdate tetrahydrate (Merck), potassium dihydrogen phosphate (PolAura); chloroethane (WarChem), anhydrous sodium sulfate (Chempur), bromophenol blue (Chempur).

2.2. Methods

Both biomass types were air-dried, crushed, and sieved to a maximum particle size of 0.2 mm. The material fractions were stored in tight containers. The analytical *moisture* content in all samples of biomass was measured by a drying method on a moisture analyzer (WPS 110S, RADWAG) [25]. All determinations were performed in triplicate (n = 3) to ensure accuracy.

2.2.1. Technical and Elemental Analysis of Biomass

Volatile Solids Content

The volatile solids (*VS*) content in all samples of biomass was determined by roasting in a muffle furnace (LSM01, SNOL) [26].

Ash Content

The ash (*A*) content in all samples of biomass was determined by roasting in the muffle furnace (LSM01, SNOL) [27].

Calorific Value

The *Calorific Value* (*CV*) in all samples of biomass was measured using the dynamic method in the calorimeter (C 2000, IKA) [28].

C, N, S Content

The *C*, *N*, and *S* content in all samples of biomass were determined according to the apparatus manufacturer's procedure using elemental analyzer CNS (Costech).

Total Phosphorus Content

The total phosphorus (*P*) content in *SN* was carried out using the vanadium–molybdenum method on a UV–Vis spectrophotometer (Thermo Scientific Evolution 201, Thermo Fisher Scientific). Absorbance was measured at the wavelength λ = 390 nm, and the optical path length was 1 cm.

Selected Metals Content

The selected metals (potassium, *K*; magnesium, *Mg*; calcium, *Ca*; sodium, *Na*; copper, *Cu*; zinc, *Zn*; nickel, *Ni*; manganese, *Mn*; iron, *Fe*; lead, *Pb*; and ca*dm*ium, *Cd*) contents in *SN* were determined by Atomic Absorption Spectrometry method with acetylene–air flame atomization (Solar S4, Thermo Fisher Scientific).

2.2.2. Determination of Digestible Components

Protein Content

The protein (*Pr*) content in all samples of biomass was determined by the Kjeldahl method. Mineralization with concentrated sulfuric acid was performed on a manual mineralizer (KI 11/26, Gerhardt). Steam distillation was performed in a steam distillation system (Vapodest, Gerhardt). Titration with hydrochloric acid was performed using a digital burette (Continuous RS, VITLAB).

Fat Content

The fat (*F*) content in all samples of biomass was determined according to the Soxhlet analysis. Samples were extracted with hexane. The solvent was evaporated using a vacuum evaporator (Rotavapor R-215, Buchi).

Crude Fiber Content

The crude fiber (*CF*) content in all samples of biomass was determined by the Weende method. Acid-base extraction was performed in a fiber analyzer (FIWE 3, Velp).

To complement the analytical results, additional calculations were performed to determine the content of dry matter (*DM*), dry organic matter (*DOM*), and carbohydrate fraction (nitrogen-free extracts, *NFE*), for which direct chemical analyses were not conducted. These calculations were based on Equations (1)—(4).

$$DM\ [\%] = 100\% - M \quad (1)$$

where *DM*—dry matter [%]; *M*—moisture [%].

$$DOM\ [\%] = (DM - A) \cdot 100\% \quad (2)$$

where *DOM*—dry organic matter [%]; *DM*—dry matter [g/kg]; *A*—ash [g/kg].

$$NFE\ [\%] = (DM - A - CF - F - \mathrm{Pr}) \cdot 100\% \quad (3)$$

where *NFE*—nitrogen-free extracts [%]; *CF*—crude fiber [g/kg]; *F*—fat [g/kg]; *Pr*—protein [g/kg].

$$CH\ [\%] = NFE + CF \quad (4)$$

where *CH*—carbohydrates [%].

2.2.3. Estimating Biogas and Biomethane Production Capacity

Estimation methods rely on calculations derived from the physicochemical parameters of substrates. These methods universally assume the complete decomposition of organic matter in the substrate, which in reality is impossible to achieve [29]. The methodologies are based on the assumption that the biochemical reactions occurring during methane fermentation in digesters are analogous to those in the digestive system of ruminants (e.g., cows) during food digestion [30]. To complement these methods, physicochemical analyses—such as the Weende analysis and proximate analysis, which include determinations of *A*, *Pr*, *F* and *CF*—are recommended [31].

The results of these methods should be interpreted as approximate values for *Biogas yield*. This is due to the unique kinetics of biochemical reactions in digesters, particularly during co-AD, where various synergistic effects may occur. Analyses based on the digestibility of organic compounds will not replicate the actual conditions in digesters, where parameters such as pH, temperature, and organic loading rate, as well as feedstock decomposition, significantly influence outcomes, especially at shorter retention times [24]. Despite

these limitations, the methods remain valuable for preliminary assessments, including estimating raw material requirements and evaluating investment viability [30].

The Baserga Method

The *Biogas* and *Biomethane production* potential was estimated using the table-based methodology proposed by Urs Baserga. The Baserga method is based on the analogy of the chemical composition of feedstock and their nutritional value, and the chemical composition of the substrate and *Biogas production* [31]. This approach involves evaluating the digestible components (*Pr*, *F* and *CH*) based on their content in *DM* and *DOM*. The method utilizes reference digestibility data and *Biogas*/*Biomethane yield* values for each component [32].

The *Biogas* and *Biomethane production* results are presented in normalized liters per kilogram of dry organic matter (L_N/kg *DOM*) of the substrate and normalized liters per kilogram of dry matter (L_N/kg *DM*). Equations (5)–(9) were applied in the preparation of the analysis table:

$$\textit{Digestible component}\ [\text{kg/kg DM}] = \textit{component} \cdot \textit{digestibility factor} \quad (5)$$

where *digestible component*—content of digestible component [kg/kg *DM*]; *component*—*Pr*, *F* or *CH* [kg/kg *DM*]; and *digestibility factor*—factor for individual component [%].

$$DOM_{comp}\ [\text{kg/kg DOM}] = \textit{digestible component/DOM} \quad (6)$$

where DOM_{comp}—recalculated dry organic matter for the component [kg/kg *DOM*]; and *DOM*—dry organic matter [kg/kg *DOM*].

$$Yield_{biogas}\ [\text{LN/kg DOM}] = DOM_{comp} \cdot biogas\ factor_{comp} \quad (7)$$

where $Yield_{biogas}$—*biogas yield* [L_N/kg *DOM*]; and $biogas\ factor_{comp}$—biogas conversion factor for the component [–].

$$Yield_{biomethane}\ [\text{LN/kg DOM}] = DOM_{comp} \cdot biomethane\ factor_{comp} \quad (8)$$

where $Yield_{biomethane}$—*biomethane yield* [L_N/kg *DOM*]; and $biomethane\ factor_{comp}$—biomethane conversion factor for the component [−].

$$CH_4\ [\%] = Yield_{biomethane}/Yield_{biogas} \cdot 100\% \quad (9)$$

where CH_4—methane content in biogas [%].

Fermentable Organic Matter

The *Biogas* and *Biomethane production* potential was assessed based on the content of easily and hardly fermentable carbohydrates in the substrates. Calculations were conducted using an equation empirically determined by Friedrich Weissbach (Equation 10) [33]. For the tested substrates, the average formula specific to plant-based materials was applied to calculate the fermentable organic matter (*FOM*).

$$FOM\ [\text{g/kg } DM] = 984 - A - 0.47 \cdot CF - 0.00104 \cdot CF^2 \quad (10)$$

where *FOM*—fermentable organic matter [g/kg *DM*]; *A*—ash [g/kg *DM*]; *CF*—crude fiber [g/kg *DM*].

The *FOM* represents the fraction of organic matter that can be decomposed by microorganisms under anaerobic conditions. To estimate *Biogas* and *Biomethane production* potential based on *FOM* content, Weissbach proposed specific conversion formulas (Equations (11) and (12)) [34]:

$$Yield_{biogas}\ [\mathrm{LN/kg}\ DM] = 0.80 \cdot FOM \quad (11)$$

where $Yield_{biogas}$—biogas yield [L_N/kg *DM*].

$$Yield_{biomethane}\ [\mathrm{LN/kg}\ DM] = 0.42 \cdot FOM \quad (12)$$

where $Yield_{biomethane}$—biomethane yield [L_N/kg *DM*].

2.2.4. Statistical Analysis

Statistical analyses were performed using Statistica 13.3. The results are presented as mean ± standard deviation (*SD*). To evaluate the normality of the data distribution, the Shapiro–Wilk test was used, as it is preferred for smaller sample sizes due to its high statistical power. To verify equality of variances among groups, the robust Levene's test was applied, which is critical assumption for conducting one-way analysis of variance (ANOVA). ANOVA was chosen to assess comparison of means among multiple groups (more than three), ensuring reliable conclusions about group differences. Post hoc analysis was performed using the Tukey test to identify specific group pairs exhibiting significant differences. A significance level of $p \leq 0.05$ was assumed for all analyses.

3. Results

3.1. Characterization of Waste for Energy Purposes

The technical analysis results (Table 1) revealed that *SN* contained significantly higher levels of *DOM* and *VS*, and nearly half the amount of *A* compared to *T0*. Additionally, *SN* demonstrated a higher *CV* of 16.29 MJ/kg, compared to 13.53 MJ/kg for *T0*.

Table 1. Results for technical analysis of tomato residues (*T0*) and Shea waste (*SN*).

Material	Parameter				
	***DM* [%]**	***DOM* [%]**	***VS* [%]**	***A* [%]**	***CV* [MJ/kg]**
T0	90.44 ^{*a} ± 0.18	75.16 ^{a} ± 4.96	33.41 ^{a} ± 1.15	15.28 ^{a} ± 0.03	13.53 ^{a} ± 0.08
SN	90.75 ^{a} ± 0.27	82.99 ^{b} ± 4.96	37.89 ^{b} ± 0.38	7.76 ^{b} ± 0.19	16.29 ^{b} ± 0.02

T0—tomato residues from commercial substrate; *SN*—Shea nutshells. *DM*—dry matter [%]; *DOM*—dry organic matter [%]; *VS*—volatile solids [%]; *A*—ash [%]; *CV*—Calorific Value [MJ/kg]. * Values marked with the same letter for a given parameter do not differ significantly, according to Tukey's test at the significance level of $p \leq 0.05$.

The elemental composition of the studied waste materials showed comparable levels of *C* and *N* (Table 2). However, the *S* content differed significantly, with *SN* containing only 0.28%, representing over a threefold decrease compared to *T0*. This finding was reflected in the calculated *C*/*S* ratio which was 39.95 for *T0* and 148.21 for *SN*.

Table 2. Results for elemental analysis (*C*, *N*, *S*) and their ratios (*C*/*N*, *C*/*S*) of tomato residues (*T0*) and Shea waste (*SN*).

Material	Parameter				
	***C* [%]**	***N* [%]**	***S* [%]**	***C/N***	***C/S***
T0	39.95 ^{a} ± 5.05	2.10 ^{a} ± 0.22	1.00 ^{a} ± 0.05	19.02	39.95
SN	41.50 ^{a} ± 0.64	2.44 ^{a} ± 0.06	0.28 ^{b} ± 0.04	17.01	148.21

T0—tomato residues from commercial substrate; *SN*—Shea nutshells. *C*—carbon [%]; *N*—nitrogen [%]; *S*—sulfur [%]. Values marked with the same letter for a given parameter do not differ significantly according to Tukey's test at a significance level of $p \leq 0.05$.

The *SN* waste exhibited the highest concentrations of *K* (23.57 mg/g) and *Mg* (2.26 mg/g) (Table 3) among the macronutrients analyzed, and *Fe* (0.5043 mg/g) among the micronutrients analyzed.

Table 3. The results for the content of macro-, microelements and toxic metals of Shea waste (*SN*).

Element	*SN*
P [mg/g]	1.69 ± 0.03
K [mg/g]	23.57 ± 0.04
Mg [mg/g]	2.26 ± 0.06
Ca [mg/g]	0.49 ± 0.03
Na [mg/g]	0.141 ± 0.003
Cu [mg/g]	0.0015 ± 0.0002
Zn [mg/g]	0.0287 ± 0.0014
Ni [mg/g]	n.d.
Mn [mg/g]	0.0213 ± 0.0004
Fe [mg/g]	0.5043 ± 0.0252
Pb [mg/g]	0.0023 ± 0.0002
Cd [mg/g]	0.00050 ± 0.00004

SN—Shea nutshells. n.d.—no data (below detection limit).

3.2. Estimating Biogas and Biomethane Production Capacity

An analysis of digestible components revealed that, for most fractions, *SN* contained higher amounts compared to *T0* residues (Table 4). The only exception was *CF*, which was present in greater quantities in *T0* residues.

Table 4. The results of the content of digestible compounds of tomato residues (*T0*) and Shea waste (*SN*).

Material	Parameter				
	***Pr* [%]**	***F* [%]**	***CF* [%]**	***NFE* [%]**	***CH* [%]**
T0	0.39 ± 0.02	0.74 ± 0.02	21.02 ± 0.89	53.01	74.03
SN	0.59 ± 0.02	0.88 ± 0.03	11.41 ± 0.23	70.11	81.52

T0—tomato residues from commercial substrate; *SN*—Shea nutshells. *Pr*—protein [%]; *F*—fat [%]; *CF*—crude fiber [%]; *NFE*—nitrogen-free extracts [%]; *CH*—carbohydrates [%].

An estimation of *Biogas* and *Biomethane production* using the Baserga method (Table 5) yielded comparable gas outputs for both substrates, with *SN* demonstrating a higher potential for gas production compared to *T0* residues. *Biogas yield*s were 504.18 for *SN* and 454.47 L_N/kg *DM* for *T0*, while *Biomethane yield*s were 254.22 and 228.94 L_N/kg *DM*, respectively.

Table 5. The results for the Baserga method of estimating the *Biogas* and *Biomethane yield* of tomato residues (*T0*) and Shea waste (*SN*).

Material	***Biogas Yield* [L_N/kg *DOM*] (*CH_4* content)**	***Biogas Yield* [L_N/kg *DM*]**	***Biomethane Yield* [L_N/kg *DOM*]**	***Biomethane Yield* [L_N/kg *DM*]**
T0	546.87 (50.37%)	454.47	275.48	228.94
SN	551.32 (50.42%)	504.18	277.99	254.22

T0—tomato residues from commercial substrate; *SN*—Shea nutshells. *DOM*—dry organic matter; *DM*—dry matter.

The energy potential of the wastes, as assessed by the *FOM* method, showed a much wider degree of variability (Table 6).

Table 6. The results for the fermentable organic matter method of estimating the *Biogas* and *Biomethane yield* of tomato residues (*T0*) and Shea waste (*SN*).

Material	*FOM* Content [g/kg *DM*]	*Biogas Yield* [L_N/kg *DM*]	*Biomethane Yield* [L_N/kg *DM*]
T0	686.45	549.16	288.31
SN	839.23	671.39	352.48

T0—tomato residues from commercial substrate; *SN*—Shea nutshells. *FOM*—fermentable organic matter; *DM*—dry matter.

The *FOM* content of *SN* was determined to be 839.23 g/kg *DM*, representing a significant increase compared to the 686.45 g/kg *DM* observed in *T0*. Consistent with this finding, *SN* yielded higher volumes of biogas (671.39 L_N/kg *DM*) and biomethane (352.48 L_N/kg *DM*).

3.3. The Effect of Fertilization of Tomato Waste on Energy Potential

The results of the technical analysis (Table 7) demonstrated that the fertilization significantly affected *DM* content in tomato residues ($p \leq 0.05$). The highest *DM* content was observed in *T2* (91.94%). For the *DM* index, variance homogeneity was demonstrated, and the distribution was normal. Statistically significant differences were also observed in the *DOM* parameter, with *T0* exhibiting the highest *DOM* content (75.16%), which was significantly greater compared to residues fertilized with *T1* and *T2*. The *VS* content was significantly higher in residues fertilized with *T2*, reaching 35.43%, while the *VS* content in other residues was comparable, ranging from 32.28% for *T3* to 33.69% (*T0*). For this parameter, variance was homogeneous, and the distribution was normal. The *A* content was significantly higher in residues fertilized with *T1* and *T2* compared to *T0* and *T3*. These results exhibited significant differences, with variance homogeneity confirmed, though the distribution deviated from the Gaussian curve. The type of fertilizer applied also significantly influenced the *CV* of tomato residues ($p \leq 0.05$). The highest *CV* was noted for *T2*—14.12 MJ/kg, whereas the lowest was recorded for *T1*—12.37 MJ/kg. These results were characterized by variance heterogeneity and a normal distribution.

Table 7. Results for technical analysis of differently fertilized tomato residues (*T0*, *T1*, *T2*, *T3*).

Material	Parameter				
	***DM* [%]**	***DOM* [%]**	***VS* [%]**	***A* [%]**	***CV* [MJ/kg]**
T0	90.44 ± 0.18	75.16 ± 4.96	33.41 ± 1.15	15.28 ± 0.03	13.53 ± 0.08
T1	91.26 ± 0.06	70.41 ± 4.96	33.69 ± 0.65	20.85 ± 0.26	12.37 ± 0.06
T2	91.94 ± 0.13	71.33 ± 4.96	35.43 ± 0.50	20.61 ± 0.02	14.12 ± 0.04
T3	90.96 ± 0.05	74.80 ± 4.96	32.28 ± 0.69	16.16 ± 0.20	13.22 ± 0.06

T0—tomato residues from commercial substrate; *T1*—fertilized with basalt flour; *T2*—fertilized with gabbro flour; *T3*—fertilized with volcanic tuff. *DM*—dry matter [%]; *DOM*—dry organic matter [%]; *VS*—volatile solids [%]; *A*—ash [%]; *CV*—Calorific Value [MJ/kg].

The fertilizer additives applied had a significant impact on the content of *C*, *N*, and *S* in the tomato residues ($p \leq 0.05$). The highest *C* content was observed in *T0* (39.95%), while the lowest was found in *T1*—31.34% (Table 8). For *C* content, heterogeneity of variance was demonstrated, and the distribution deviated from the Gaussian curve. The highest *N* content was recorded in *T2* (2.68%), whereas the lowest was in *T3* (1.16%), indicating a difference of nearly 57%. The *N* results exhibited heterogeneous variance, but the distribution was normal. The *S* content ranged between 1.00% (*T0*) and 1.50% (*T1*). Variance was heterogeneous, and the distribution was normal. Specific trends were noted in the calculated *C*/*N* and *C*/*S* ratios. The highest *C*/*N* ratios were observed in *T3* (28.41) and *T1* (24.48), whereas the lowest values were recorded for *T0* (19.02) and *T2*

(12.77). Conversely, for the *C*/*S* ratio, the highest values were calculated for *T0* (39.95) and *T2* (32.90), while the lowest were found in *T3* (27.47) and *T1* (20.89).

Table 8. Results for elemental analysis (*C*, *N*, *S*) of differently fertilized tomato residues (*T0*, *T1*, *T2*, *T3*).

Material	Parameter				
	C **[%]**	***N*** **[%]**	***S*** **[%]**	***C/N***	***C/S***
T0	39.95 ± 5.05	2.10 ± 0.22	1.00 ± 0.05	19.02	39.95
T1	31.34 ± 0.66	1.28 ± 0.06	1.50 ± 0.24	24.48	20.89
T2	34.22 ± 0.04	2.68 ± 0.01	1.04 ± 0.10	12.77	32.90
T3	32.96 ± 0.12	1.16 ± 0.06	1.20 ± 0.41	28.41	27.47

T0—tomato residues from commercial substrate; *T1*—fertilized with basalt flour; *T2*—fertilized with gabbro flour; *T3*—fertilized with volcanic tuff. *C*—carbon [%]; *N*—nitrogen [%]; *S*—sulfur [%].

The analysis of digestible components revealed significant differences in the content of *Pr*, *F*, and *CF* ($p \leq 0.05$) (Table 9). The highest *Pr* content was observed in *T2*. For the *Pr* index, variance homogeneity was demonstrated, and the distribution was statistically significant. The highest *F* content was recorded in *T3* (2.58%). For the *F* index, the variance was heterogeneous, and the distribution was normal. The *CF* content across the tested residues was comparable, ranging from 19.43% in *T1* to 21.16% in *T2*. For *CF* results, the variance was homogeneous, but the distribution deviated from the Gaussian curve. The *SN* exhibited the highest *NFE* content at 70.11%. For the tomato residues, the highest *NFE* and *CH* contents were found in *T0*. Significantly lower proportions of these digestible components were observed in residues fertilized with *T1* and *T2*.

Table 9. Results of digestible compounds of differently fertilized tomato residues (*T0*, *T1*, *T2*, *T3*).

Material	Parameter				
	Pr **[%]**	***F*** **[%]**	***CF*** **[%]**	***NFE*** **[%]**	***CH*** **[%]**
T0	0.39 ± 0.02	0.74 ± 0.02	21.02 ± 0.89	53.01	74.03
T1	0.29 ± 0.01	1.82 ± 0.03	19.43 ± 0.77	48.87	68.30
T2	0.59 ± 0.01	1.54 ± 0.03	21.16 ± 0.54	48.04	69.20
T3	0.31 ± 0.03	2.58 ± 0.01	20.92 ± 0.88	50.99	71.91

T0—tomato residues from commercial substrate; *T1*—fertilized with basalt flour; *T2*—fertilized with gabbro flour; *T3*—fertilized with volcanic tuff. *Pr*—protein [%]; *F*—fat [%]; *CF*—crude fiber [%]; *NFE*—nitrogen-free extracts [%]; *CH*—carbohydrates [%].

The highest potential *Biogas yield* (457.13 L_N/kg *DM*) and *Biomethane yield* (233.50 L_N/kg *DM*) were estimated for *T3* (Table 10), which also corresponded to the highest CH_4 content in biogas at 51.08%. The lowest *Biogas production* (426.59 L_N/kg *DM*) was calculated for *T1*. The lowest *Biomethane production* (216.65 L_N/kg *DM*) was calculated for *T2*.

Table 10. The results for the Baserga method of estimating the *Biogas* and *Biomethane yield* of differently fertilized tomato residues (*T0*, *T1*, *T2*, *T3*).

Material	***Biogas Yield*** **[L_N/kg *DOM*] (CH_4 Content)**	***Biogas Yield*** **[L_N/kg *DM*]**	***Biomethane Yield*** **[L_N/kg *DOM*]**	***Biomethane Yield*** **[L_N/kg *DM*]**
T0	546.87 (50.37%)	454.47	275.48	228.94
T1	552.91 (50.83%)	426.59	281.04	216.83
T2	550.06 (50.77%)	426.75	279.25	216.65
T3	555.89 (51.08%)	457.13	283.95	233.50

T0—tomato residues from commercial substrate; *T1*—fertilized with basalt flour; *T2*—fertilized with gabbro flour; *T3*—fertilized with volcanic tuff. *DOM*—dry organic matter; *DM*—dry matter.

The maximum *FOM* content, *Biogas yield*, and *Biomethane yield* were obtained for waste *T0*, with values of 686.45 g/kg *DM*, 549.16 L_N/kg *DM*, and 288.31 L_N/kg *DM*, respectively (Table 11). In contrast, *T2* exhibited the minimum *FOM* content and the lowest *Biogas* and *Biomethane production*, with corresponding values of 631.88 g/kg *DM*, 505.50 L_N/kg *DM*, and 265.39 L_N/kg *DM*.

Table 11. The results for the fermentable organic matter method of estimating the *Biogas* and *Biomethane yield* of differently fertilized tomato residues (*T0*, *T1*, *T2*, *T3*).

Material	*FOM Content* [g/kg *DM*]	*Biogas Yield* [L_N/kg *DM*]	*Biomethane Yield* [L_N/kg *DM*]
T0	686.45	549.16	288.31
T1	644.92	515.93	270.86
T2	631.88	505.50	265.39
T3	678.56	542.85	285.00

T0—tomato residues from commercial substrate; *T1*—fertilized with basalt flour; *T2*—fertilized with gabbro flour; *T3*—fertilized with volcanic tuff. *FOM*—fermentable organic matter; *DM*—dry matter.

4. Discussion

4.1. Characterization of Waste for Energy Purposes

4.1.1. Thermal Treatment

The *CV* of tomato plant residues and Shea nutshells was comparable to typical values for energy crops, which range between 15 and 17 MJ/kg (at a *moisture* content of 10–20%) [35]. The relatively high *CV* of the tested residues may be attributed to their low *moisture* content, which in biomass generally ranges from 5% to 52% [35]. *Moisture* content is a critical parameter influencing combustion efficiency, as lower *moisture* levels result in higher energy release and shorter combustion times [36]. The *moisture* content in the analyzed residues was comparable, averaging 9.4%, and did not explain the differences in *CV* between *T0* and *SN*. Both *moisture* and *A* are considered ballast components that reduce the energy potential of fuels. *Moisture* lowers the *CV* by absorbing heat during combustion, while *A* represents non-combustible material, reducing the proportion of organic matter available for energy conversion. A negative correlation, albeit with a low coefficient of determination ($R^2 < 0.50$), was observed between *A* content and *CV* [36]. The results indicated that the *CV* of the studied residues was inversely proportional to *A* content. *SN*, which exhibited the lowest *A* content, had the highest *CV* among the tested residues, whereas *T1*, with the highest *A* content, had the lowest *CV*.

Another key factor influencing the *CV* of biomass is the chemical composition of the material, particularly its *C* content and extractable components, especially those with phenolic structures [37]. A significant correlation ($R^2 = 0.58$) has been observed between the *CV* and lignin content in the feedstock [38]. High *C* content in the fuel is a critical determinant of fuel quality and positively impacts the *CV* ($R^2 = 0.93$) [39]. Ismaila et al. [39] investigated biomass briquettes derived from herbaceous plants, grasses, and agricultural residues as energy sources based on their *CV* and elemental composition, including *C*. They demonstrated that the *CV* of briquettes depends on elemental composition, particularly the proportions of *C*, H, and O. Biomass briquettes with the highest *C* content (maize husks—75.98% and switchgrass—75.13%) exhibited the highest *CV* (calculated using Boie's equation as 28.34 MJ/kg and 28.92 MJ/kg, respectively). This is consistent with our findings, where *SN* exhibited the highest *CV* due to its high *C* content. For tomato residues, the highest *CV* were observed in *T0* and *T2*, which also had the highest *C* content.

Another important technical parameter characterizing solid fuels is the *VS* content which is correlated with fuel mass loss. Low *VS* content enhances combustion efficiency and improves fuel quality [40]. High *VS* content can create challenges in controlling combustion

by altering ignition and burning conditions and requiring additional air supply to ensure complete, smokeless combustion. In this regard, tomato residues exhibited more favorable characteristics, with *VS* content approximately 10% lower than *SN*. Among the tomato residues, *T3* had the lowest *VS* content.

The impact of the components on the *CV* of the analyzed waste materials is illustrated by the calculated significant correlations between their *CV* and the contents of *VS*, *A*, and *C* (Figure 1).

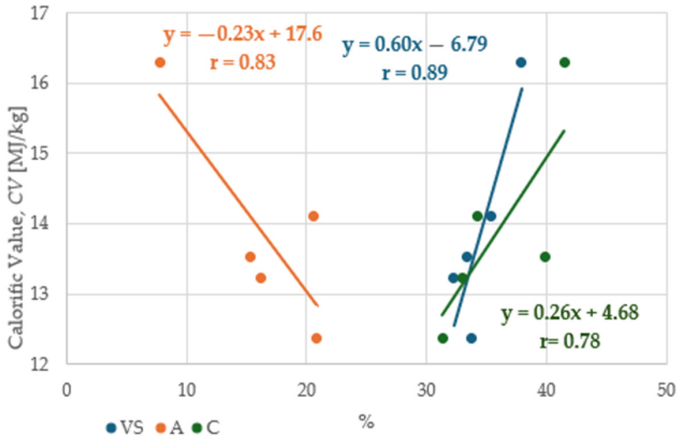


Figure 1. Correlations between Calorific Value (*CV*) and content: Volatile Solids (*VS*), Ash (*A*), and Carbon (*C*).

The quality of fuel intended for energy purposes is also significantly influenced by the content of other mineral components. The presence of *N* and *S* in the fuel impacts the release of harmful gases (e.g., nitrogen oxides and sulfur oxides) into the atmosphere, which negatively affects the environment [39]. The *S* content in *SN* was three times lower than in *T0*. Among the variously fertilized tomato residues, *T1* and *T3* were characterized by the lowest *N* and *S* contents.

4.1.2. Biochemical Treatment

The physicochemical properties of feedstock substrates significantly influence the efficiency of *Biogas* and *Biomethane production* [41]. High *DM* content in the raw material can impede its use as a monosubstrate in AD and may result in low *Biogas yield*s [32]. However, dry fermentation has certain advantages, including reduced water requirements and higher volumetric methane production [42]. Among the studied substrates, *SN* exhibited the highest *DM* content, followed by *T2* among the tomato residues. The potential of a substrate for biogas productivity is determined by its content of *DOM*—fresh mass minus ballast [11]. Mezes et al. [41] investigated the impact of the physicochemical composition of plant- and animal-derived substrates on *Biogas production*, demonstrating that feedstocks with the highest organic matter content are the most efficient for *Biogas production*. In this study, *SN* exhibited the highest *DOM* content. Orhorhoro et al. [43] examined the effect of *VS* content in co-AD (using water hyacinth, wastewater, pig dung, cow dung, and leftovers as co-substrates) on *Biogas production*. The highest *Biogas yield* (91.1% *VS* content—2.88 kg cumulative *Biogas yield*) was achieved with substrates containing the highest *VS* content. This is consistent with the present study, where *SN* had the highest *VS* content and yielded high theoretical *Biogas production* values in both methods. Steffen et al. [44] studied the impact of *A* content on the *Biogas production* potential, finding that high *A* content (up to approximately 50%) did not negatively affect the AD process. In this study, tomato residues had the highest *A* content, which can be attributed to the chemical composition of the applied fertilizers, specifically igneous rocks (basalt and gabbro).

The optimal *C*/*N* ratio for efficient *Biogas production* is generally considered to be between 20 and 30 [45]. While *T3* and *T1* met this criterion, *T0*, *T2*, and *SN* exhibited lower *C*/*N* ratios. Low *C*/*N* ratios are associated with increased ammonia concentrations, which can inhibit methanogenesis [46]. The *C*/*S* ratio, a key indicator of hydrogen sulfide content, was also investigated. Lower *C*/*S* ratios correlate with higher hydrogen sulfide production and a greater proportion in the biogas. The most favorable *C*/*S* ratio was observed for *SN*.

An elemental analysis of *CNS* revealed that fertilized waste did not significantly differ in terms of *N* content, a crucial nutrient. *SN* exhibited a relatively high *N* content. The content of macronutrients and micronutrients is crucial during AD due to their varied impact, e.g., on the activity of microbial cultures (microelements supporting bacterial growth include *Fe*, *Ni*, cobalt—Co, and molybdenum—Mo) [47]. The literature indicates that low concentrations of elements (*Fe*, *Ni*, Co) can enhance AD efficiency [48]. The content of elements can have a stimulatory, inhibitory, or toxic effect, depending on the element's concentration and pH in the digester [46]. The optimal ratio of the most important elements in the fermentation mixture is *C*:*N*:*P*:*S*—600:15:5:1 [15]. A deficiency of elements can lead to reduced *Biogas production* [46]. Economou et al. [49] monitored three full-scale biogas plants for 120 days, adding supplements during the AD process: zeolite and citric acid for the first and third plants, and trace elements (*Mn*, *Ni*, Co, *Zn*, selenium—Se, *Cu*, and boron—B) for the second. They concluded that zeolite adsorbed ammonia, while citric acid regulated the pH of the system. For other microelements, a reduction in system toxicity was observed, resulting in process stability.

The application of fertilizer additives resulted in a significantly higher nutrient content (particularly *P*, *Ca*, and *Cu*) in tomato waste, as demonstrated by the analysis of macro- and microelements as well as toxic metals (Table 12) [50]. This contrasts with tomato waste grown in commercial substrate, which showed lower levels of these elements. Basalt is a silicate-rich igneous rock containing various elements, including *Mg*, *Fe*, *P*, *K*, and *Ca* [51]. The use of basalt in horticulture and agriculture improves soil fertility, enriches the soil with necessary nutrients as a slow-release fertilizer, and influences soil pH [52]. Gabbro, in terms of chemical composition, is equivalent to basalt, with the only difference being the grain size. Basalt has fine-grained crystals, whereas gabbro has coarse-grained crystals [53]. Silicate rocks have been recognized as fertilizers that improve soil properties and contribute to increased crop yields [54]. Volcanic tuff is a porous sedimentary rock rich in *Ca*, *Mg*, and *K* [55]. The use of tuff as a fertilizer positively impacts crop yield, improves both crop quality and soil, while also neutralizing acidic pH [56]. Owczarek et al. [50] investigated the elemental composition of tomato waste under various fertilization configurations, focusing on the ecological management of tomato plant residues. Based on a literature review and the content of key nutrients, the authors concluded that tomato waste is a promising feedstock for local biofuel production, including biogas. The highest fertilization indicators were achieved with tomato waste fertilized with gabbro flour due to its high *K*, *Mg*, and *Ca* content. The fertilizing properties of the mentioned additives (basalt flour, gabbro flour, and volcanic tuff) may balance nutrient requirements and compensate for the need for additional supplementation.

Biowaste can be contaminated with various elements, including *Cd*, Cr (chromium), *Cu*, *Ni*, *Pb*, and *Zn*, which directly affect the AD process [57]. Certain trace elements, such as *Zn* and *Cu*, may contribute to enzyme deactivation, thereby slowing down the overall AD process [48]. Borowski et al. [58] investigated the impact of the addition of mineral fertilizers (Substral and Agrecol) on *Biogas production* from vegetable waste in a processing plant. The use of Substral resulted in higher *Biogas yield*s (420 L/kg *VS*) due to its higher content of *Mg*, *Fe*, and Mo. According to the authors, Agrecol, which contained more *Zn* and *Cu*, may have had a toxic effect on methanogens. Alrawashdeh et al. [48] studied the

effects of heavy metals (including *Fe*, *Ni*, *Zn*, and *Cu*) on the AD process using olive-mill waste. They concluded that the toxicity effect followed this order: *Cu* > *Ni* > *Pb* > Cr > *Zn* > *Fe*, and depending on the dose, a stimulatory effect could occur. The authors calculated the maximum concentrations of heavy metals that contribute to increased *Biogas production* as follows: *Fe*—2.9 mg/L, *Zn*—0.335 mg/L, Cr—1.211 mg/L, *Pb*—0.297 mg/L, *Ni*—0.082 mg/L, and *Cu*—1406.25 mg/L. Among the studied materials, the content of *Zn* and *Cu* in *SN* was the lowest when compared to other substrates.

Table 12. Content of selected macro- and microelements, as well as toxic metals, in tomato waste samples [50].

Element	*T0*	*T1*	*T2*	*T3*
P [mg/g]	1.31 ± 0.03	2.00 ± 0.04	2.08 ± 0.03	1.48 ± 0.01
K [mg/g]	11.24 ± 0.38	14.00 ± 0.35	24.33 ± 0.36	9.87 ± 0.20
Mg [mg/g]	6.41 ± 0.21	5.95 ± 0.13	6.70 ± 0.08	7.23 ± 0.07
Ca [mg/g]	19.01 ± 0.25	22.84 ± 0.22	22.11 ± 1.89	22.49 ± 0.20
Na [mg/g]	1.40 ± 0.03	2.41 ± 0.01	1.01 ± 0.004	1.07 ± 0.08
Cu [mg/g]	0.0032 ± 0.0001	0.0052 ± 0.0001	0.0073 ± 0.0003	0.0060 ± 0.0002
Zn [mg/g]	0.0600 ± 0.0034	0.04 ± 0.0011	0.03 ± 0.0005	0.03 ± 0.0011
Ni [mg/g]	0.0021 ± 0.0025	n.d.	n.d.	0.0011 ± 0.0012
Mn [mg/g]	0.2300 ± 0.0028	0.03 ± 0.0004	0.15 ± 0.0013	0.19 ± 0.0018
Fe [mg/g]	0.370 ± 0.017	0.30 ± 0.001	0.37 ± 0.007	0.51 ± 0.014
Pb [mg/g]	0.0014 ± 0.0002	0.0005 ± 0.0002	0.0013 ± 0.0009	n.d.
Cd [mg/g]	0.0014 ± 0.0001	0.0008 ± 0.000008	0.0016 ± 0.0002	0.0013 ± 0.0001

T0—tomato waste from commercial substrate; *T1*—tomato waste fertilized with basalt flour; *T2*—tomato waste fertilized with gabbro flour; *T3*—tomato waste fertilized with volcanic tuff. n.d.—no data (below detection limit).

This study determined the content of the following toxic metals—*Cd* and *Pb*. *Cd* is highly toxic to methanogenic bacteria, which are responsible for methane production [59]. The lowest *Cd* content was found in *SN* waste. *Pb* negatively affects the activity of microorganisms, contributing to the damage of bacterial cells [48]. Compared to the other materials, the *SN* contained the highest amount of *Pb* in their composition. Abdel-Shafy and Mansour [60] studied the impact of the toxicity of mercury, Hg (0.025–0.125 mg/kg), *Cd* (3.4–17.0 mg/kg), and Cr(III) (15.5–77.5 mg/kg) on the AD process, where the substrate was sewage sludge. They demonstrated that the presence of toxic metals in the fermentation chamber caused a significant reduction in *Biogas production*. The extent of biogas reduction due to the introduction of inhibitors followed this order: Cr(III) (70.5%), *Cd* (84.8%), Hg (the largest toxic effect—92%). Łagocka et al. [61] determined the maximum concentrations of toxic metals in organic fertilizers, such as: *Cd* 5 mg/kg, Cr 100 mg/kg, *Ni* 60 mg/kg, *Pb* 140 mg/kg, and Hg 2 mg/kg. It is recommended to avoid substrates and media containing significant amounts of toxic metals. However, some heavy metals, such as *Fe*, *Ni*, *Cu*, and *Zn* (in appropriate doses), play a role as essential trace elements necessary for proper functioning.

4.2. Estimating of Biogas and Biomethane Production

The components that affect the AD process include *Pr*, *F*, and *CH* [62]. The degree of substrate degradation is linked to the rate at which organic components ferment. *CH* ferments the fastest, as it consists of easily fermentable fractions—*NFE* (such as sugars and starch), and more resistant fractions like *CF*, which are complex structures (such as cellulose, hemicellulose, and lignin). *Pr* ferments next, while *F*, which has the highest methane potential, is the most difficult to digest and ferments last [63]. According to Kovacs et al. [64], substrates rich in *Pr* may lead to increased *Biogas production*. The *Pr* content in the studied materials (tomato waste and *SN*) was low enough that the theoretical *Biogas production* from *Pr* was approximately 2.26 L_N/kg *DOM*. High *F* content contributes to increased *Biogas production*, but long-chain fatty acids may form, which inhibit the AD

process. *F* content influenced the theoretical *Biogas yield* (ranging from 8.98 to 31.47 L_N/kg *DOM*), though no material had *F* content exceeding 3% due to the nature of the substrates. The *T3* waste exhibited the highest *F* content among the fertilized tomato residues, which also demonstrated the highest *Biogas yield* (according to Baserga) and CH_4 content in the produced biogas. The CH_4 content in the biogas was influenced by a combination of favorable factors: high *F* content, an optimal *C*/*N* ratio (recommended range of 20–30), and *DOM* content. Klimiuk et al. [65] studied the theoretical and experimental *Biogas production* from fermented plant materials (maize, sugar sorghum, *Miscanthus* x giganteus, and *Miscanthus sacchariflorus*) with varying fiber content. Authors found that the efficiency of cellulose and hemicellulose degradation depended on the ratio of polysaccharides to lignin in the plant material. Based on these studies, it can be concluded that a low content of *CF* is beneficial for *Biogas production*. However, for higher *CF* values, it is necessary to determine the proportions of cellulose, hemicellulose, and lignin. Nakhate et al. [66] studied the impact of lignin content on *Biogas production* and found that high lignin content significantly reduces *Biogas production* due to low biodegradability and the need to adapt microbial metabolic pathways to lignin breakdown, which disrupts the dynamics of the entire process. In this paper, tomato waste showed a significant proportion of *CF* compared to *SN*. *CH*-rich substrates are the best for potential *Biogas* and *Biomethane production*, but their rapid degradation can lead to process instability [67]. Xue et al. [67] examined the effect of the proportions of *CH*, *F*, and *Pr* on *Biogas production* in co-AD. The highest theoretical methane production (595 mL CH_4/g *VS*) was achieved for the *F*:*CH*:*Pr* ratio of 63.25:22.62:14.13, suggesting an interaction that promotes *Biogas production*.

There is a relative dearth of scientific literature dedicated to methods for estimating the theoretical *yield* of *Biogas* and *Biomethane*. This paucity is primarily due to the widespread reliance on the biochemical methane potential (BMP) test, an experimental method employed to assess the methanogenic potential of a substrate. While several studies have comparatively evaluated experimental and calculated values for various computational methods, providing a foundation for the assertion that such methods are reliable and do not significantly diverge from empirically derived values, the overall body of literature remains limited (Table 13). This indicates that the evaluated methods for calculating the theoretical *Biogas production* potential are effective as estimation tools.

Table 13. A modified comparison of the biogas value of feedstock, both experimentally and computationally.

Feedstock	Experimental *Biogas Yield* [L_N/kg *DM*] (*CH_4* Content)	Computational *Biogas Yield* [L_N/kg *DM*] (*CH_4* Content)	Error * [%]	Estimation Method	References
Beetroots	557.79 (51.80%)	585.89 (51.00%)	−5.04	Weende analysis and digestibility of organic constituents	[68]
Maize	541.71 (53.97%)	595.45 (52.10%)	−9.92		
White cabbage waste	705.20 (54.17%)	669.60 (55.20%)	5.05		
Maize silage	591.09 (53.65%)	569.05 (52.02%)	3.73	Weende analysis and digestibility of organic constituents	[69]
Grass silage	445.59 (53.85%)	491.59 (53.39%)	−10.32		
Rape seed oil	1052.47 (70.75%)	1199.40 (68.00%)	−13.96		
Feedstock	**Experimental Methane Yield [L_N/kg *DM*]**	**Computational Methane Yield [L_N/kg *DM*]**	**Error [%]**	**Estimation Method**	**References**
Kitchen waste	122.81	157.76	−28.46	Equation based on organic composition	[70]
Fruit and vegetable waste	11.29	15.05	−33.30		
Yard waste	110.53	280.26	−153.56		
Fruit waste	165.58	238.52	-44.05	Buswell equation	[71]
Vegetable waste	105.02	201.47	−91.84		
Garden waste	255.67	313.05	−22.44		
Food waste	352.12	457.27	−29.86	Buswell equation	[72]
Dairy industry waste	303.19	387.70	−27.87		
Brewery waste	439.89	462.82	−5.21		

DM—dry matter. * The error values were calculated using the following equation: (experimental yield—computational yield)/experimental yield · 100.

It is noteworthy that for the studies conducted by Gruber [68] and Speckmaier et al. [69], certain theoretical *Biogas yield*s were lower than those obtained experimentally. Such discrepancies can be attributed to synergistic effects or biochemical and metabolic changes occurring within the digester [69]. Comparing the literature values for *Biogas production* with results obtained from computational methods, namely Baserga and *FOM*, it can be concluded that the studied feedstocks exhibit robust theoretical predictions. The smallest deviations between theoretical and experimental production potentials were observed for methods based on the Weende analysis, which formed the basis for the results presented in this study. For the Baserga method, the average theoretical *Biogas yield* is approximately 453.82 L_N/kg *DM*. The theoretical production capacities are similar (except for *SN*, where *Biogas production* exceeded 500 L_N/kg *DM*), as the content of each fraction is accounted for. According to the Baserga method, the average theoretical *Biomethane yield* is approximately 230.03 L_N/kg *DM*, which aligns with the characteristic values reported in the literature for fruit (238.62 L_N/kg *DM*) and vegetable (201.47 L_N/kg *DM*) waste. For the *FOM* method, there is a greater variation in *Biogas yield* results—from 505.50 L_N/kg *DM* (*T2*) to 671.39 L_N/kg *DM* (*SN*)—as the results are based on the content of *A* and *CF* in the feedstock. In the *FOM* method, fewer components are considered significant: Weissbach posits that the higher the *A* (ballast) and *CF* (hard-to-degrade fraction) content, the lower the *FOM* content, i.e., the fraction useful for *Biogas production*. There are few reports in the literature regarding the *FOM* method, apart from the previously mentioned studies by Weissbach (Section 2.2.3). Fischer et al. [73] investigated the average fuel efficiency of agricultural biogas plants. They concluded that the *CV* allows for the determination of the energy potential of agricultural biogas plants. According to the authors, the *CV* should be converted to *DOM* and *FOM* content (according to Weissbach), as this enables the comparison of different plant feedstocks in various concepts (in terms of energy efficiency). The conducted research demonstrated that the studied waste can be processed for energy purposes, both for combustion and *Biogas production*. In both cases, *SN* waste exhibited a slightly higher energy potential. The technical analysis of biomass is a useful tool in assessing the energy potential of biomass used in both thermal and biochemical processing.

5. Conclusions

The study investigated the energy potential of two distinct, unconventional, and challenging-to-manage agricultural by-products. This study distinguishes itself from previous research by adopting employing a novel approach to capacity assessment tools and by utilizing unconventional waste materials. The valorization of fertilized crop residues through AD offers presents a significant advantages, as it can meet the demand for macro- and micronutrients within the system and reduce operational costs. The findings demonstrate the feasibility of employing tomato waste and Shea nutshells for *Biogas* and *Biomethane production*, establishing them as promising feedstock. Shea nutshell waste demonstrated superior properties for both thermal and biochemical utilization. Their *CV* was 16.29 MJ/kg and, which was 20.4% higher compared to tomato waste. Using the Baserga and *FOM* estimation methods showed that the *Biogas yields* from Shea nutshells were 504.18 and 671.39 LN/kg *DM*, respectively, which represented an increase of 11.0% and 22.3% higher compared to tomato waste. The study also highlighted the significant impact of fertilization on the *Biogas production* potential of green residues from tomato plants. Determining the energy potential of these waste materials introduces new possibilities for *Biogas* and *Biomethane production* from agri-food waste. The delineation of their potential energetic potential capabilities of tested waste introduces new avenues for *Biogas* and *Biomethane production* from agri-food waste. However, challenges associated with their large-scale

application must be considered, including the seasonal variability of the feedstock, selective harvesting, and the necessity for localized processing.

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References

1. Bracmort, K. *Biomass: Comparison of Definitions in Legislation*; Congressional Research Service: Washington, DC, USA, 2013.
2. Bakari, R.; Asha, R.; Hossein, M.; Huang, X.; Islam, N.F.; Liew, R.K.; Narayan, M.; Lam, S.S.; Sarma, H. Converting food waste to biofuel: A sustainable energy solution for Sub-Saharan Africa. *Sustain. Chem. Environ.* **2024**, *7*, 100126. [CrossRef]
3. Mao, G.; Huang, N.; Chen, L.; Wang, H. Research on biomass energy and environment from the past to the future: A bibliometric analysis. *Sci. Total Environ.* **2018**, *635*, 1081–1090. [CrossRef]
4. Sher, F.; Smječanin, N.; Hrnjić, H.; Karadža, A.; Omanović, R.; Šehović, E.; Sulejmanović, J. Emerging technologies for biogas production: A critical review on recent progress, challenges and future perspectives. *Process Saf. Environ. Prot.* **2024**, *188*, 834–859. [CrossRef]
5. Jha, S.; Nanda, S.; Acharya, B.; Dalai, A.K. A Review of Thermochemical Conversion of Waste Biomass to Biofuels. *Energies* **2022**, *15*, 6352. [CrossRef]
6. Department of Economic and Social Affairs. *Energy Statistics Pocketbook 2024*, 1st ed.; Energy Statistics Pocketbook Series; United Nations Research Institute for Social Development: Geneva, Switzerland, 2024.
7. CEWEP—The Confederation of European Waste-to-Energy Plants. Available online: https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2021/ (accessed on 5 December 2024).
8. Curkowski, A.; Mroczkowski, P.; Oniszk-Popławska, A.; Wiśniewski, G. *Biogaz Rolniczy—Produkcja i Wykorzystanie*; Mazowiecka Agencja Energetyczna: Warszawa, Poland, 2009.
9. Wiącek, D.; Tys, J. Biogaz—Wytwarzanie i możliwości jego wykorzystania. *Acta Agrophysica* **2015**, *1*, 1–92.
10. Pavičić, J.; Novak Mavar, K.; Brkić, V.; Simon, K. Biogas and Biomethane Production and Usage: Technology Development, Advantages and Challenges in Europe. *Energies* **2022**, *15*, 2940. [CrossRef]
11. Teraz Środowisko. Biogaz i biometan w Polsce 2024. Available online: https://www.teraz-srodowisko.pl/publikacje/biogaz-biometan-insight-Polska-2024/teraz-srodowisko-publikacja-biogaz-biometan-insight-Polska-2024.pdf (accessed on 8 October 2024).
12. Kuboń, M.; Skibko, Z.; Borusiewicz, A.; Romaniuk, W.; Gajda, J.S.; Kłosowska, O.; Wasąg, Z. Influence of the Parameters of an Agricultural Biogas Plant on the Amount of Power Generated. *Appl. Sci.* **2024**, *14*, 4200. [CrossRef]
13. Awasthi, M.K.; Sar, T.; Gowd, S.C.; Rajendran, K.; Kumar, V.; Sarsaiya, S.; Li, Y.; Sindhu, R.; Binod, P.; Zhang, Z.; et al. A comprehensive review on thermochemical, and biochemical conversion methods of lignocellulosic biomass into valuable end product. *Fuel* **2023**, *342*, 127790. [CrossRef]
14. Fachagentur Nachwachsende Rohstoffe; Deutsches Biomasseforschungszentrum; Kuratorium für Technik und Bauwesen in der Landwirtschaft; Institut für Agrartechnologie und Biosystemtechnik. Leitfaden Biogas: Von der Gewinnung zur Nutzung. *Bioenergie*. 2016. Available online: https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf (accessed on 7 October 2024).
15. Myczko, A.; Myczko, R.; Kołodziejczyk, T.; Golimowska, R.; Lenarczyk, J.; Janas, Z.; Kliber, A.; Karłowski, J.; Dolska, M. *Budowa i eksploatacja biogazowni rolniczych: Poradnik dla inwestorów zainteresowanych budową biogazowni rolniczych*; Publishing of the Institute of Technology and Life Sciences: Warszawa, Poland; Poznań, Poland, 2011.
16. Szilágyi, Á.; Bodor, A.; Tolvai, N.; Kovacs, K.L.; Bodai, L.; Wirth, R.; Bagi, Z.; Szepesi, A.; Marko, V.; Kakuk, B.; et al. A comparative analysis of biogas production from tomato bio-waste in mesophilic batch and continuous anaerobic digestion systems. *PLoS ONE* **2021**, *16*, e0248654. [CrossRef]

17. Saghouri, M.; Mansoori, Y.; Rohani, A.; Hossein, M.; Khodaparast, H.; Sheikhdavoodi, M.J. Modelling and evaluation of anaerobic digestion process of tomato processing wastes for biogas generation. *J. Mater. Cycles Waste Manag.* **2017**, *20*, 561–567. [CrossRef]
18. Almeida, P.V.; Rodrigues, R.P.; Teixeira, L.M.; Santos, A.F.; Martins, R.C.; Quina, M.J. Bioenergy Production through Mono and Co-Digestion of Tomato Residues. *Energies* **2021**, *14*, 5563. [CrossRef]
19. Saev, M.; Koumanova, B.; Simeonov, I. Anaerobic co-digestion of wasted tomatoes and cattle dung for biogas production. *J. Univ. Chem. Technol. Metall.* **2009**, *44*, 55–60.
20. Li, Y.; Li, Y.; Zhang, D.; Li, G.; Lu, J.; Li, S. Solid state anaerobic co-digestion of tomato residues with dairy manure and corn stover for biogas production. *Bioresour. Technol.* **2016**, *217*, 50–55. [CrossRef]
21. Alharbi, M.; Alseroury, F.; Alkthami, B. Biogas Production from Manure of Camel and Sheep Using Tomato and Rumen as Co-Substrate. *J. Ecol. Eng.* **2023**, *24*, 54–61. [CrossRef]
22. Wang, Y.; Li, Y.; Yao, L.; Fu, L.; Liu, Z. The Biogas Production Potential and Community Structure Characteristics of the Co-Digestion of Dairy Manure and Tomato Residues. *Agronomy* **2024**, *14*, 881. [CrossRef]
23. Ofosu, M.A.; Aklaku, E.D. Determining the optimum proportion of Shea waste in anaerobic co-fermentation process. *J. Sci. Technol.* **2010**, *20*, 119–128. [CrossRef]
24. Ofosu, M.A.; Adonadaga, M.-G.; Sackey, I.; Ampadu, B. Substrate-induced pH changes and process stability of anaerobic digestion of shea waste. *J. Appl. Sci. Environ. Manag.* **2021**, *24*, 2035–2042. [CrossRef]
25. *PN-EN ISO 18134-3:2023-12*; Solid Biofuels—Determination of Moisture Content—Part 3: Moisture in General Analysis Sample, 2023. Available online: https://www.pkn.pl/ (accessed on 5 October 2024).
26. *PN-EN ISO 18123:2023-10*; Solid Biofuels—Determination of Volatile Matter, 2023. Available online: https://www.pkn.pl/ (accessed on 5 October 2024).
27. *PN-EN ISO 18122:2023-05*; Solid Biofuels—Determination of Ash Content, 2023. Available online: https://www.pkn.pl/ (accessed on 5 October 2024).
28. *PN-81/G-04513*; Paliwa stałe—Oznaczanie ciepła spalania i obliczanie wartości opałowej. 1981. Available online: https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/metody-badania-jakosci-paliw-stalych-18761768 (accessed on 5 October 2024).
29. Institut für Energetik und Umwelt gGmbH; Bundesforschungsanstalt für Landwirtschaft; Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. *Biogaz produkcja i wykorzystywanie*; Institut für Energetik und Umwelt gGmbH: Leipzig, Germany, 2005.
30. Podkówka, W. *Biogaz rolniczy—Odnawialne źródło energii. Teoria, praktyczne zastosowanie*; Powszechne Wydawnictwo Rolnicze i Leśne: Warszawa, Poland, 2012.
31. Podkówka, Z.; Podkówka, W. Zasady obliczania wartości "biogazowej" substratu na podstawie składu chemicznego. *Przegląd Hod.* **2008**, *7*, 28–29.
32. Baserga, U. Landwirtschaftliche Co-Vergarungs Biogasanlagen. Biogas aus organischen Reststoffen und Energiegras. *FAT-Berichte* **1998**, *512*, 1–11.
33. Weißbach, F. Zur Bewertung des Gasbildungspotenzials von nachwachsenden Rohstoffen. *Agric. Eng.* **2008**, *63*, 356–358. [CrossRef]
34. Weißbach, F. Das Gasbildungspotenzial von Halm- und Körnerfrüchten bei der Biogasgewinnung. *Agric. Eng.* **2009**, *64*, 317–321. [CrossRef]
35. Piskier, T. A method of estimation of the caloric value of the biomass. Part I—Biomass energy potential. *J. Mech. Energy Eng.* **2017**, *1*, 189–194.
36. Lunguleasa, A.; Spirchez, C.; Zeleniuc, O. Evaluation of the calorific values of wastes from some tropical wood species. *Maderas Cienc. Tecnol.* **2020**, *22*, 269–280. [CrossRef]
37. Esteves, B.; Sen, U.; Pereira, H. Influence of Chemical Composition on Heating Value of Biomass: A Review and Bibliometric Analysis. *Energies* **2023**, *16*, 4226. [CrossRef]
38. Ruiz-Aquino, F.; Ruiz-Angel, S.; Feria-Reyes, R.; Santiago-Garcia, W.; Suarez-Mota, M.E.; Rutiaga-Quinones, J.G. Wood Chemical Composition of Five Tree Species from Oaxaca, Mexico. *Bioresources* **2019**, *14*, 9826–9839. [CrossRef]
39. Ismaila, A.; Zakari, I.Y.; Nasiru, R.; Tijjani, B.I.; Abdullahi, I.; Garba, N.N. Investigation on biomass briquettes as energy source in relation to their calorific values and measurement of their total carbon and elemental contents for efficient biofuel utilization. *Adv. Appl. Sci. Res.* **2013**, *4*, 303–309.
40. Aliah, H.; Winarti, I.; Iman, R.N.; Setiawan, A.; Safarina, R.; Sawitri, A. Influence of Sieve Size on Calorific Value and Proximate Properties of Bio-Briquette Composites. *J. Ecol. Eng.* **2023**, *24*, 25–34. [CrossRef]
41. Mézes, L.; Bai, A.; Nagy, D.; Cinka, I.; Gabnai, Z. Optimization of Raw Material Composition in an Agricultural Biogas Plant. *Trends Renew. Energy* **2017**, *3*, 61–75. [CrossRef]
42. Ingabire, H.; Ntambara, B.; Mazimpaka, E. Characterization and analysis of fish waste as feedstock for biogas production. *Int. J. Low-Carbon Technol.* **2023**, *18*, 212–217. [CrossRef]
43. Orhorhoro, E.K.; Ebunilo, P.O.; Sadjere, G.E. Experimental Determination of Effect of Total Solid (TS) and Volatile Solid (VS) on Biogas Yield. *Am. J. Mod. Energy* **2017**, *3*, 131–135. [CrossRef]

44. Steffen, F.; Requejo, A.; Ewald, C.; Janzon, R.; Saake, B. Anaerobic digestion of fines from recovered paper processing—Influence of fiber source, lignin and ash content on biogas potential. *Bioresour. Technol.* **2016**, *200*, 506–513. [CrossRef]
45. Dioha, I.J.; Ikeme, C.H.; Nafi'u, T.; Soba, N.I.; Yusuf, M.B.S. Effect of carbon to nitrogen ratio on biogas production. *Int. Res. J. Nat. Sci.* **2013**, *1*, 1–10.
46. Manyi-Loh, C.E.; Lues, R. Anaerobic Digestion of Lignocellulosic Biomass: Substrate Characteristics (Challenge) and Innovation. *Fermentation* **2023**, *9*, 755. [CrossRef]
47. Zieliński, M.; Kisielewska, M.; Dębowski, M.; Elbruda, K. Effects of Nutrients Supplementation on Enhanced Biogas Production from Maize Silage and Cattle Slurry Mixture. *Water. Air. Soil Pollut.* **2019**, *230*, 117. [CrossRef]
48. Alrawashdeh, K.A.b.; Gul, E.; Yang, Q.; Yang, H.; Bartocci, P.; Fantozzi, F. Effect of Heavy Metals in the Performance of Anaerobic Digestion of Olive Mill Waste. *Processes* **2020**, *8*, 1146. [CrossRef]
49. Economou, E.A.; Dimitropoulou, G.; Prokopidou, N.; Dalla, I.; Sfetsas, T. Anaerobic Digestion Remediation in Three Full-Scale Biogas Plants through Supplement Additions. *Methane* **2023**, *2*, 265–278. [CrossRef]
50. Owczarek, M.; Siwek, H.; Buchwał, A.; Bojko, K. Zawartość wybranych makro- i mikroelementów odpadów pomidora zwyczajnego (*Solanum lycopersicum*) w aspekcie ich zagospodarowania. In *Postępy w Technologii i Inżynierii Chemicznej 2024*; Wydawnictwo Uczelniane Zachodniopomorskiego Uniwersytetu Technologicznego w Szczecinie: Szczecin, Poland, 2024; pp. 84–98.
51. Rodrigues, M.; da Silva Junges, L.F.; Mozorovicz, C.; Seidel Ziemmer, G.; Kosera Neto, C.; Américo de Andrade, E.; Izabel dos Passos, A.; Palczewski Pacheco, F.; Cezar, E.; de Melo Teixeira, L. Paraná basin basalt powder: A multinutrient soil amendment for enhancing soil chemistry and microbiology. *J. South Am. Earth Sci.* **2024**, *141*, 104957. [CrossRef]
52. Conceição, L.T.; Silva, G.N.; Holsback, H.M.S.; Oliveira, C.d.F.; Marcante, N.C.; Martins, É.d.S.; Santos, F.L.d.S.; Santos, E.F. Potential of basalt dust to improve soil fertility and crop nutrition. *J. Agric. Food Res.* **2022**, *10*, 100443. [CrossRef]
53. Hassan, M.S.; Mohamed, E.T. The Effect of Gabbroic Rock on Vegetative Growth, and Nutrient Status of Sesame. *Asian J. Agric. Food Sci.* **2017**, *5*, 113–125.
54. Silva, F.J.P.; Carvalho, A.M.X.; Borges, P.H.C. The gabbro dacite blend as soil remineralizer. *Rev. Bras. Ciênc. Agrár.—Braz. J. Agric. Sci.* **2022**, *17*, 1–9. [CrossRef]
55. Al-Ajlouni, M.G.; Othman, Y.A.; Abu-Shanab, N.S.; Alzyoud, L.F. Evaluating the Performance of Cocopeat and Volcanic Tuff in Soilless Cultivation of Roses. *Plants* **2024**, *13*, 2293. [CrossRef]
56. Al-Zboon, K.K.; Al-Tabbal, J.A.; Al-Kharabsheh, N.M.; Al-Mefleh, N.K. Natural volcanic tuff as a soil mulching: Effect on plant growth and soil chemistry under water stress. *Appl. Water Sci.* **2019**, *9*, 123. [CrossRef]
57. Roß, C.-L.; Nielsen, K.; Krieger, J.; Hoffmann, M.; Sensel-Gunke, K.; Ellmer, F.; Kautz, T. Monitoring N:P Ratio and Cd, Cu, Pb, and Zn Contents in Different Types of Anaerobic Digestates: A Six-Year Study Case. *Int. J. Agron.* **2020**, *2020*, 8816088. [CrossRef]
58. 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]
59. Guo, Q.; Majeed, S.; Xu, R.; Zhang, K.; Kakade, A.; Khan, A.; Hafeez, F.Y.; Mao, C.; Liu, P.; Li, X. Heavy metals interact with the microbial community and affect biogas production in anaerobic digestion: A review. *J. Environ. Manag.* **2019**, *240*, 266–272. [CrossRef]
60. Abdel-Shafy, H.I.; Mansour, M.S.M. Biogas production as affected by heavy metals in the anaerobic digestion of sludge. *Egypt. J. Pet.* **2014**, *23*, 409–417. [CrossRef]
61. Łagocka, A.; Kamiński, M.; Cholewiński, M.; Pospolita, W. Korzyści ekologiczne ze stosowania pofermentu z biogazowni rolniczych jako nawozu organicznego. *Kosm. Ser. Biol. Pol. Tow. Przyr. Kopernika* **2016**, *65*, 601–607.
62. Gołaszewski, J. Wykorzystanie substratów pochodzenia rolniczego w biogazowniach w Polsce. *Postępy Nauk Rol.* **2011**, *2*, 69–94.
63. Abubakar, A.M. Biodigester and Feedstock Type: Characteristic, Selection, and Global Biogas Production. *J. Eng. Res. Sci.* **2022**, *1*, 170–187. [CrossRef]
64. Kovács, E.; Wirth, R.; Maróti, G.; Bagi, Z.; Nagy, K.; Minárovits, J.; Rákhely, G.; Kovács, K.L. Augmented biogas production from protein-rich substrates and associated metagenomic changes. *Bioresour. Technol.* **2015**, *178*, 254–261. [CrossRef] [PubMed]
65. Klimiuk, E.; Pokój, T.; Budzyński, W.; Dubis, B. Theoretical and observed biogas production from plant biomass of different fibre contents. *Bioresour. Technol.* **2010**, *101*, 9527–9535. [CrossRef] [PubMed]
66. Nakhate, S.P.; Gupta, R.K.; Poddar, B.J.; Singh, A.K.; Tikariha, H.; Pandit, P.D.; Khardenavis, A.A.; Purohit, H.J. Influence of lignin level of raw material on anaerobic digestion process in reorganization and performance of microbial community. *Int. J. Environ. Sci. Technol.* **2021**, *19*, 1819–1836. [CrossRef]
67. Xue, S.; Wang, Y.; Lyu, X.; Zhao, N.; Song, J.; Wang, X.; Yang, G. Interactive effects of carbohydrate, lipid, protein composition and carbon/nitrogen ratio on biogas production of different food wastes. *Bioresour. Technol.* **2020**, *312*, 123566. [CrossRef]
68. Gruber, W.L. Biogasanlagen—Lohnt der Einsatz von Kofermenten? *Mais* **2003**, *3*, 4–7.
69. Speckmaier, M.; Schlattmann, M.; Metzner, T.; Gronauer, A. Bestimmung des Biogasertrags aus Co-Substraten im diskontinuierlichen Durchflussverfahren. *Agric. Eng.* **2005**, *60*, 340–341. [CrossRef]

70. Li, Y.; Zhang, R.; Liu, G.; Chen, C.; He, Y.; Liu, X. Comparison of methane production potential, biodegradability, and kinetics of different organic substrates. *Bioresour. Technol.* **2013**, *149*, 565–569. [CrossRef] [PubMed]
71. Yasim, N.S.E.M.; Buyong, F. Comparative of experimental and theoretical biochemical methane potential generated by municipal solid waste. *Environ. Adv.* **2023**, *11*, 100345. [CrossRef]
72. Llanos-Lizcano, R.; Senila, L.; Modoi, O.C. Evaluation of Biochemical Methane Potential and Kinetics of Organic Waste Streams for Enhanced Biogas Production. *Agronomy* **2024**, *14*, 2546. [CrossRef]
73. Fischer, E.; Postel, J.; Ehrendreich, F.; Nelles, M. Using the mean fuel efficiency to energetically assess agricultural biogas plants. *Landtechnik* **2016**, *71*, 139–154. [CrossRef]

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