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Influence of the Heating Method on the Efficiency of Biomethane Production from Expired Food Products

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Abstract: The aim of the study was to determine the effect of heating with microwave electromagnetic radiation (EMR) on the efficiency of the methane fermentation (MF) of expired food products (EFP). The research was inspired by the positive effect of EMR on the production of biogas and methane from different organic substrates. The experiment was carried out on a laboratory scale in fully mixed, semi-continuous anaerobic reactors. The technological conditions were as follows: temperature, 35 ± 1 °C; organic load rate (OLR), 2.0 $kg_{VS} \cdot m^{-3} \cdot d^{-1}$; and hydraulic retention time (HRT), 40 days. The source of the EMR was a magnetron (electric power, 300 W). There was no statistically significant influence of the use of EMR on the achieved technological effects of MF. The efficiency of biogas production was 710 ± 35 $dm^3 \cdot kg_{VS}{}^{-1}$ in the variant with EMR and 679 ± 26 $dm^3 \cdot kg_{VS}{}^{-1}$ in the variant with convection heating (CH). The methane contents were 63.5 ± 2.4% (EMR) and 62.4 ± 4.0% (CH), and the cumulative methane production after 40 days was 271.2 and 288.6 $dm^3{}_{CH4}$, respectively.

Keywords: expired food products (EFP); methane fermentation (MF); biogas; electromagnetic microwave radiation (EMR); convection heating (CH)

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1. Introduction

Food waste has been defined by the UN Food and Agriculture Organization (FAO) and includes any healthy or edible substance that is wasted, lost, or degraded at any stage of the food supply chain (Raak et al., 2017). Food waste is one of the most critical problems in the world (Muhammad and Rosentrater 2020). In the European Union, nearly 90 million t of food are wasted annually, which translates to an average of 173 kg of food waste per capita [1]. Other sources estimate the annual food loss at around 95–115 kg per capita in Europe and North America, and at 6–11 kg per capita in Sub-Saharan Africa and South and Southeast Asia [2]. Food loss increases the use of energy, water, fertilizers, and plant protection agents consumed in the course of food production, transportation, and storage. After construction and transport, these processes are the third-largest source of atmospheric greenhouse gas emissions [3]. As such, it is necessary to identify and implement ways of limiting food loss and/or utilizing expired food products (EFP). However, any such method must be economically and environmentally viable. This is in line with the principles of the circular economy (CE), a concept aimed at reducing the negative impacts of production outputs on the natural environment [4].

Food loss and waste are serious threats to the sustainability of our food systems. Innovative and multi-faced solutions are continuously being proposed, tested, and implemented by researchers, government authorities, non-government bodies, and food industries to tackle this problem of food waste [5]. Insect-based bioconversions have been reported as a marketable solution for reducing food waste [6]. This rather novel approach can efficiently convert several tonnes of food waste into valuable products including human food, animal feed, fertilizers, and other secondary industrial compounds [7]. European Union (EU) guidelines state that food waste should preferentially be used as animal feed, though for most food waste, this practice is currently illegal, because of disease control concerns [8,9].

Methane fermentation (MF) can be used to neutralize EFP, process them into fertilizers, and produce high-energy biogas, resulting in energy, environmental, and agricultural benefits [10,11]. Moreover, such processes are in line with the principles of the circular economy and can improve economic and environmental metrics [12,13]. Biogas produced in the methane fermentation process can be transformed into heat or electricity or supply the existing gas network [14]. This technology is profitable; reduces the emission of CO_2 to the atmosphere from fossil fuels; neutralizes the negative impact of EFP on the environment, including odor emissions; reduces susceptibility to crushing; and reduces sanitary risks [15]. The end product is a fertilizer with high nutritional value [16]. A number of studies have produced results that demonstrate the efficiency of biogas production from traditional organic feedstock, such as energy crop biomass, liquid manure, wastewater, and sewage sludge [17,18]. On the other hand, there is a pressing need to further examine the production of biogas from the organic fraction of municipal and industrial waste, including discarded food products. The research focuses on developing empirical models, which is very important from practical and operational points of view because they allow for a reliable estimation of the methane fermentation efficiency. This is particularly important when using mixtures of substrates with various and variable characteristics for EFP [19]. Therefore, the aim of many studies is to optimize the biogas and methane production from EFP depending on various feedstock compositions and different operating parameters for anaerobic digestion [20,21]. Methods for the pre-pretreatment and disintegration of organic substrates before the MF process and innovative bioreactor solutions are also investigated [22–26].

The rate of the biochemical degradation of organic substances is a function of microbial activity, specifically, the rate at which enzymatic reactions proceed [27]. Enzyme activity varies depending on environmental factors, including the process temperature. Thus, ensuring an optimal temperature is one of the ways to improve the efficiency of methane fermentation [28,29]. The thermal conditions inside anaerobic reactors may be precisely controlled via electromagnetic microwave radiation (EMR). The use of EMR enables energy to be directed to a mixture of anaerobic sludge and processed biomass (as the radiation absorber) [30]. This reduces energy losses caused by its absorption by structural components of the reactor [31].

Research to date has demonstrated a significant increase in the effectiveness of organic matter degradation and methanogenesis in EMR-modified systems [32,33]. Positive technological effects have been obtained with MF organic substrates, including wastewater [34], plant biomass [35], and microalgae [36], and the efficiency of organic substance biodegradation and nutrient removal under aerobic conditions has been improved [37,38]. Genetic studies comparing systems with conventional heating (CH) and microwave heating (EMR) have shown a clear differentiation in the species structure of microorganisms affected by microwave radiation [39,40]. The results achieved to date seem to confirm theories ascribing non-thermal effects to microwaves, as changes have been observed not only in the activity of individual enzymes but in entire bacterial populations as well [41,42]. A new approach, not analyzed in the research to date, is the use of EMR as a factor modeling thermal conditions and stimulating biochemical changes in EFP methane fermentation. The conducted research was aimed at verifying the hypothesis that the use of EMR is an economically and technologically justifiable way of heating fermentation chambers and that the athermal effects can lead to increases in the metabolic activity of MF microorganisms.

The aim of the present study was to determine how electromagnetic microwave radiation used as a thermal stimulant impacts the qualitative composition and yields of biogas produced by the methane fermentation of expired food products.

2. Materials and Methods

2.1. Study Design

The study was divided into two experimental variants with different methods of obtaining the target thermal conditions in the reaction tanks. In Variant 1, the reactors were placed in a thermostating cabinet in which the thermal conditions were controlled via conventional heating. In the second variant, microwaves were used as the method of heating. Other process factors (the fermentation sludge inoculum, composition and amount of EFP, and fermenter design) and technological parameters (the temperature, organic load rate, and hydraulic retention time) were comparable in both experimental variants. The research was conducted to determine the significance of the differences in biogas production efficiency and methane content.

2.2. Materials

EFP sourced from the distribution outlets of large retail chains served as the material for the study. The selected organic feedstock consisted of food products wasted most often and in the largest quantities as expired ones. The percentages by fresh matter weight of the individual EFP groups were as follows: bread (12%), meat waste (35%), fish (9%), vegetables (10%), fruit (16%), and dairy products (18%). These values were in line with the data provided by the food product distributor.

The EFP sourced from the distributor was transported to the laboratory at 4 ± 1 °C and used for the experiment directly after delivery. Due to the presence of animal-derived products in the mix, the products were sanitized at 70 °C for 60 min. The feedstock was then mixed in the given proportions and ground in a Robot Coupe Blixer at 1500 rpm for 15 s. The resultant particles averaged 2 ± 1.6 mm in size.

The anaerobic sludge, used as the inoculum for the fermentation reactors, was sourced from an enclosed digester of a municipal sewage treatment plant operating at 35 °C, with an organic load rate (OLR) of 2.3 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$ and a hydraulic retention time (HRT) of 21 days. Prior to the exact experiment, the anaerobic sludge was introduced to the examined feedstock and adapted for 40 days (one full hydraulic reactor volume exchange). The OLR was 1.0 $kg_{VS}\cdot m^{-3}\cdot d^{-1}$. The properties of the EFP and anaerobic sludge used in the experiment are presented in Table 1.

Table 1. Properties of the food products and anaerobic sludge.

Indicator	Unit	Value	
		Food Waste	Anaerobic Sludge
pH	-	7.8 ± 0.14	7.5 ± 0.1
Total solids (TS)	$g\cdot dm^{-3}$	251 ± 8.7	41.5 ± 1.7
Volatile solids (VS)	$g\cdot dm^{-3}$	229 ± 4.2	32.1 ± 2.3
Mineral solids (MS)	$g\cdot dm^{-3}$	22 ± 4.2	9.4 ± 2.3
Total carbon (TC)	$g\ TC\cdot dm^{-3}$	81.2 ± 7.9	23.3 ± 2.9
Inorganic carbon (IC)	$g\ IC\cdot dm^{-3}$	9.3 ± 1.4	4.7 ± 0.9
Total organic carbon (TOC)	$g\ TOC\cdot dm^{-3}$	74 ± 6.2	14.2 ± 1.7
N_{tot}	$g\ N_{tot}\cdot dm^{-3}$	7.1 ± 1.3	1.9 ± 0.7
C/N	-	11.4 ± 1.2	12.3 ± 0.8
P_{tot}	$g\ P_{tot}\cdot dm^{-3}$	1.7 ± 0.5	0.8 ± 0.1
Protein	$g\cdot dm^{-3}$	44.4 ± 8.1	11.9 ± 4.3
Sugars	$g\cdot dm^{-3}$	16.1 ± 2.3	1.8 ± 0.6
Lipids	$g\cdot dm^{-3}$	69.5 ± 4.9	4.9 ± 0.8
Total alkalinity	$g\ CaCO_3\cdot dm^{-3}$	8.1 ± 0.9	7.2 ± 0.4
Volatile fatty acid (VFA)	$g\ CH_3COOH\cdot dm^{-3}$	0.34 ± 0.06	0.29 ± 0.1
VFA/total alkalinity	-	0.04 ± 0.04	0.06 ± 0.03

2.3. Experimental Station

The experiment was conducted using anaerobic reactors with full mixing and an active volume of 4.0 dm^3 (total volume, 5.0 dm^3). The reactors were constructed with polypropylene, a microwave-transparent material that microwave radiation can pass through. The initial concentration of anaerobic sludge in the tanks was kept at approx. 4.0 $g_{TS} \cdot dm^{-3}$. A 400 W CH system with a 12 W fan was used in Variant 1, whereas electromagnetic microwave radiation was used in Variant 2. The microwaves were generated by a magnetron and transmitted via a wave-guide to a cabinet with fermentation tanks. The Plazmatronika® microwave generator applied in the study has fluent power control within the range of 0 to 600 W. The experiments used a power level of 300 W. The frequency of the radiation was 2.45 GHz. The heating systems were activated by thermal controllers, which reacted directly to the readings from the temperature sensors within the reactors. Methane fermentation was conducted at 35 ± 1 °C with a load of 2.0 $g_{VS} \cdot dm^{-3} \cdot d^{-1}$ in the model tanks and a hydraulic retention time (HRT) of 40 days. A 100 cm^3 sample of the digestate was collected every 24 h for analysis, with another 100 cm^3 of raw organic feedstock fed back. A diagram of the experimental station is presented in Figure 1.

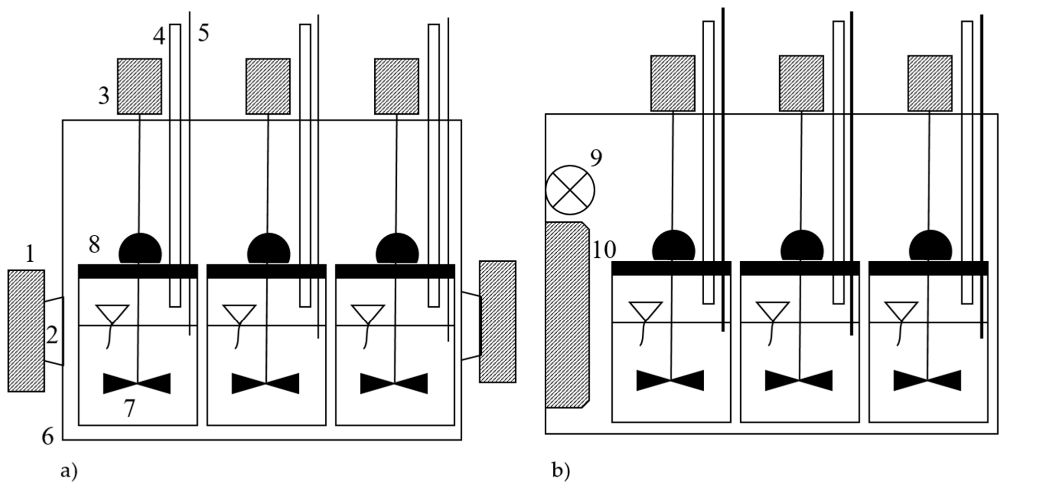


Figure 1. Design of experimental stations: (**a**) microwave heating system (electromagnetic microwave radiation (EMR)); (**b**) convection heating system (CH) (1—magnetron; 2—wave-guide; 3—agitator drive; 4—pressure measurement and biogas collection; 5—temperature sensor; 6—steel cabinet; 7—agitator; 8—model fermentation tanks; 9—fan; 10—convector).

2.4. Analytical Methods

Quantitative analyses of the EFP mixtures and inoculum sludge were conducted for all the experimental variants. The levels of total solids (TS), volatile solids (VS), and mineral solids (MS) were determined gravimetrically. The contents of total carbon (TC), inorganic carbon (IC), and total organic carbon (TOC) were determined via high-temperature combustion with infrared detection, using an Analytik Jena TOC multi NC 3100 analyzer. The contents of total nitrogen (N_{tot}) and total phosphorus (P_{tot}) were assayed with the spectrophotometric method after prior mineralization, using a Hach DR6000 spectrometer. The protein content was estimated using a conversion factor of 6.25·N_{tot}. The content of sugars was measured with gas chromatography using a GC/MS/MS Agilent Technologies 7890B unit, whereas that of lipids (ether extract) was determined gravimetrically using a solvent in accordance with the Polish Standard PN-86/C-04573/01. The total alkalinity was determined with the titration method, whereas pH was determined using the potentiometric method. The VFA concentration was determined using Macherey-Nagel Nanocolor LKT 3000 test tubes (method no. 0–50).

The biogas levels were measured with a mass flow-meter manufactured by Aalborg. The flow-meter allowed detecting the instantaneous rate of flow and included a totalizer that could calculate the total biogas yield from the start of detection. The post-fermentation gas was sampled from the reactors for quantitative analysts using a needle and a gas-tight syringe. Samples of biogas of 20 cm^3 were analyzed for composition using a GC Agillent 7890 gas chromatograph fitted with a thermal conductivity detector (TCD). The resultant biogas was further subjected to quantitative analysis using a GMF 430 analyzer from Gas Data. The percentage contents of the main biogas constituents were determined, i.e., methane (CH_4) and carbon dioxide (CO_2).

2.5. Calculation Methods

The total energy demand (E_D) was calculated using the formula:

$$E_D = P_{FH} \cdot t \left(Wh \cdot d^{-1} \right) \tag{1}$$

where:

P_{FH} = the fan and heater power (CH) in Variant 1 or magnetron power (EMR) in Variant 2 [W];
t = operation time [$h \cdot d^{-1}$].

The total energy production (E_P) generated from methane production was calculated using the following equation:

$$E_P = Y_{Methane} \cdot EV_{Methane} \left(Wh \cdot d^{-1} \right) \tag{2}$$

where:

$Y_{Methane}$ = daily CH_4 production ($dm^3 \cdot d^{-1}$);
$EV_{Methane}$ = energetic value of CH_4 ($Wh \cdot dm^{-3}$).

The energy balance (E_B) was calculated as follows:

$$E_B = E_P - E_D \left(Wh \cdot d^{-1} \right) \tag{3}$$

where:

E_D = total energy demand ($Wh \cdot d^{-1}$);
E_P = total energy production ($Wh \cdot d^{-1}$).

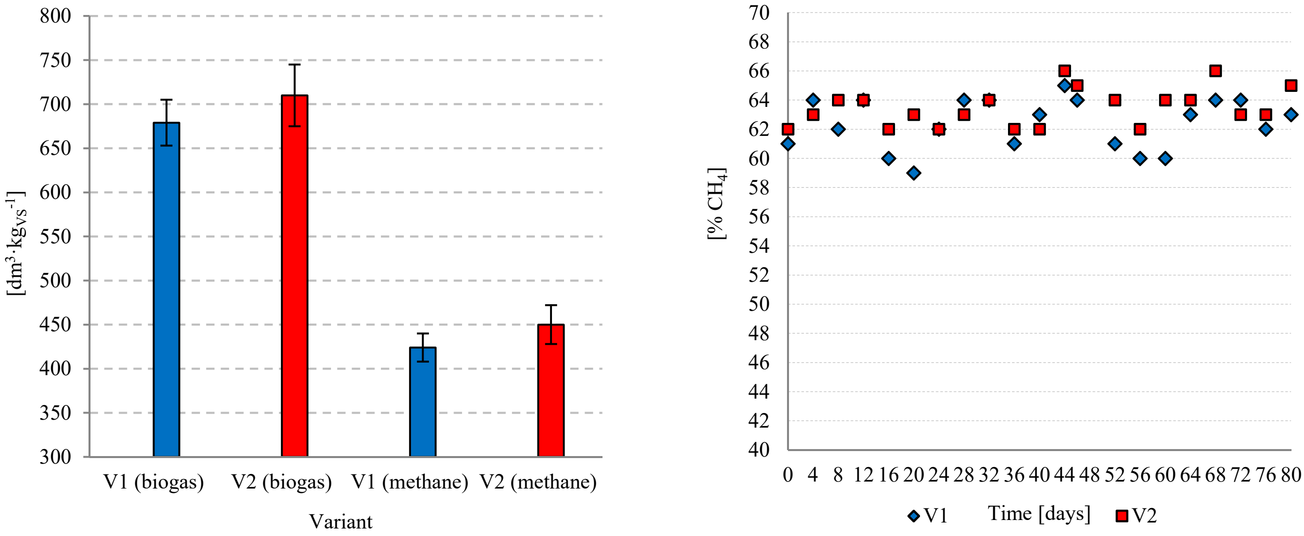
2.6. Statistical Analysis

Each experimental variant was conducted in triplicate. The statistical analysis of the experimental results was conducted using a STATISTICA 13.1 PL package (StatSoft, Cracow, Poland). The hypothesis of the normality of distribution of each analyzed variable was verified using the W Shapiro–Wilk test. One-way analysis of variance (ANOVA) was conducted in order to determine differences between variables. The homogeneity of the variance in groups was determined using a Levene test. The Tukey (HSD) test was applied to determine the statistical significance of differences between the analyzed variables. In all the tests, the results were considered significant at $p = 0.05$.

3. Results and Discussion

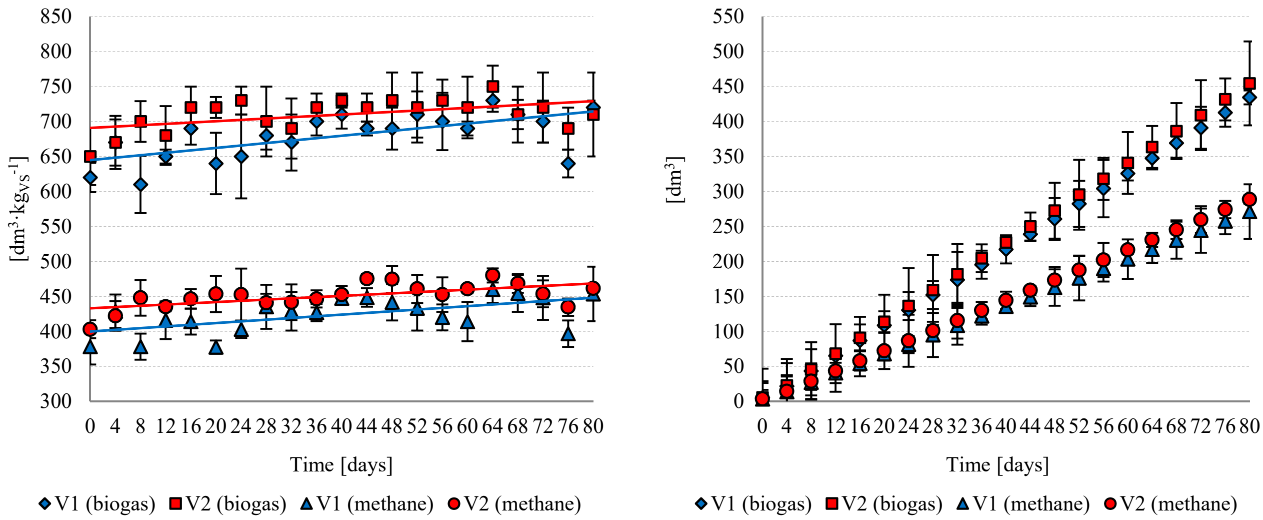
3.1. Variant 1—Conventional Heating (CH)

The biogas yield in Variant 1 averaged 679 $\pm$ 26 $dm^3 \cdot kg_{VS}{}^{-1}$ (Figure 2a). The observed levels ranged from 610 to 730 $dm^3 \cdot kg_{VS}{}^{-1}$ (Figure 3a). The methane content in the biogas approximated 62.4 $\pm$ 4.0% (Figure 2b), meaning that the average was 424 $\pm$ 16 $dm^3{}_{CH4} \cdot kg_{VS}{}^{-1}$ (Figure 2a). The daily average biogas production was 5.43 $\pm$ 0.21 $dm^3 \cdot d^{-1}$, with the daily methane production at 3.92 $\pm$ 0.14 $dm^3 \cdot d^{-1}$. The cumulative biogas produced after 80 days of bioreactor operation averaged 434.4 dm^3 and 271.2 $dm^3{}_{CH4}$ (Figure 3b). Similar results were obtained by Song et al. (2020) through the methane fermentation of food waste [43]. Laboratory-scale continuous stirred tank reactor (CSTR) digesters were used, each with a total volume of 5 dm^3 and a working volume of 4 dm^3. The yield was approx. 456 $dm^3{}_{CH4} \cdot kg_{VS}{}^{-1}$. Other researchers report that stable methane fermentation can produce methane yields ranging from 417 to 529 $dm^3_{CH4}·kg_{VS}^{-1}$ [44–48]. By contrast, Yirong (2014) showed that the typical biochemical methane potential (BMP) of mixed food waste, similar to that used in the present study, fitted within a narrower range of 440 to 480 $dm^3_{CH4}·kg_{VS}^{-1}$ [49]. Other authors obtained lower methane production efficiencies, ranging from 100 to 250 $dm^3_{CH4}·kg_{VS}^{-1}$ [50–52]. An even lower methane yield—70.72 $dm^3_{CH4}·kg_{VS}^{-1}$—was found by Zhang et al. (2016) after 35 days of an experiment [53]. This is probably due to the accumulation of volatile fatty acids and acidification of the environment occurring during the methane fermentation of food waste [54].



(**a**) (**b**)

Figure 2. Average daily production of gaseous methane fermentation (MF) products (**a**) and the methane fraction in the biogas (**b**).



(**a**) (**b**)

Figure 3. Daily (**a**) and cumulative (**b**) biogas and methane production.

3.2. Variant 2—Electromagnetic Microwave Radiation (EMR)

The use of microwaves (EMR) as a means of heating the fermentation bioreactors did not produce statistically significant improvements in methane fermentation efficiency ($p > 0.05$). In this variant, the biogas production reached 710 ± 35 $dm^3·kg_{VS}^{-1}$ (Figure 2a), with an average daily yield of 5.68 ± 0.24 $dm^3·d^{-1}$. The methane content in the biogas was 63.5 ± 2.4% (Figure 2b), which produced a methane yield of 450 ± 22 $dm^3_{CH4} \cdot kg_{VS}{}^{-1}$ (Figure 2a). The cumulative biogas production after 80 days of bioreactor operation averaged 454.4 dm^3 and 288.6 dm^3_{CH4} (Figure 3b). To date, EMR has primarily been used in thermal depolymerization processes to pre-treat organic feedstock prior to methane fermentation (Table 2). This technology has also found application in the anaerobic biodegradation of food waste. Shahriari et al. (2012) noted an 8% increase in biogas production when using microwave radiation [55]. By using EMR for food waste pre-conditioning, Zhang et al. (2016) increased methane production by 4.89% [53]. In a study by Deepanraj et al. (2017), the cumulative biogas production increased from 0.71 to 0.75 dm^3/day when microwave radiation was employed, though the methane content decreased from 62.03 to 61.55% [24].

Table 2. Possibility of using EMR in anaerobic digestion.

Application	Substrate	Optimal Conditions		Effects	Ref.
		Pretreatment Conditions	Batch Test Conditions		
Heating	Alga biomass	800 W, 2.45 GHz	35 ± 1 °C	Increase of 2.88% in biogas production *	[36]
	Dairy wastewaters	800 W, 2.45 GHz	35 °C	Increase of 14.0 to 24.0% in biogas production *, respectively	[34]
	Sida hermaphrodita silage	1600 W, 2.45 GHz	45 d	Increase of 8% in biogas production *	[35]
	Virginia mallow	1600 W, 2.45 GHz	36 °C	Increase of 8% in biogas production *	[56]
Disintegration	Silage of *Sida hermaphrodita* mixed with cattle manure	150 °C, 15 min	35 °C; 30 d	Increase of 35.6% in methane production *	[23]
	Green microalgae (Enteromorpha)	600 W, 6 min	37 °C, 150 rpm	Increase of 29.8% in biogas production *	[32]
	Microalgae from highly populated algal ponds	65.4 $MJ \cdot kg\ TS^{-1}$, 900 W, 98 °C	35 °C	Increase of 78% in biogas production *	[57]
	Activated sludge	5 min, 800 W, 13,000 $kJ \cdot kg\ SS^{-1}$ (suspended solids)	55 °C, 32 d	Increase of 311% in the VS_s/VS ratio and no difference in biogas production and production rate *	[58]
		5 min, 96 °C, 5.5% TS	33 °C, 23 d	Increase of 143% in the CODs/COD ratio and 211% in the cumulative biogas production *	[59]
		Progressive heating 1.2–1.4 $C \cdot min^{-1}$, 175 °C	33 °C, 18 d	Increase of 74.3% in COD solubilisation and 34% in biogas production *	[60]
		0.83 $kJ \cdot cm^{-3}$, 1000 W, 7–8% TS	35 °C, 20–25 d	Decreased solubilisation (CODs/COD) and increase of 15.4% in methane production *	[61]
		1168 W, 90 °C, 4% TS	35 °C, 22 d	Increase of 2.5% in the CODs/COD ratio, and 37% in the digestion rate, and no impact on methane production	[62]
	Food waste	2450 MHz, 175 °C	33 ± 1 °C, 120 rpm	Increase of 8% in biogas production *	[55]
		2450 MHz, 1000 W, 100 °C	37 ± 0.5 °C, 35 d	Increase of 4.89% in methane production *	[53]
		1460 W, 2450 MHz	30 d	Increase of 6.43% in biogas production *	[24]

* Compared to control.

EMR was analyzed as a determinant of thermal conditions in digesters by Zieliński et al. (Table 2). Research has shown that microwave radiation could affect the species composition and counts of methane-producing microorganisms [63,64]. It has also been shown that non-thermal effects of microwaves can influence the enzymatic activity of bacteria by modifying their DNA, RNA, and cellular protein synthesis [65]. The exact effects vary depending on the power, the frequency, and the microwave exposure time [66]. Studies by Zieliński (2013) showed that microwave radiation improved the production yield and composition of the resultant biogas while also promoting the growth of the fermenting microflora biomass. An OLR of 2.0 $kgCOD \cdot m^{-3} \cdot d^{-1}$ allowed producing 42.9 ± 1.1 $dm^3 \cdot d^{-1}$, with an average methane content of 64.4 ± 1.0%, when CH was used. In turn, when microwaves were employed, the biogas yield was 46.1 ± 1.1 $dm^3 \cdot d^{-1}$, with a methane fraction of 66.4 ± 1.0% [37]. Zieliński et al. (2017) determined the effect of using EMR on the efficiency of microalgal biomass methane fermentation and the qualitative composition of the resultant biogas. In both of the experimental variants (convection and microwaves), the biogas yields averaged 450 $cm^3 \cdot g_{VS}{}^{-1}$. EMR was determined to have a positive impact on the qualitative composition of the biogas. When the thermal conditions were stimulated with convection heating, the methane content was 65%. This value statistically significantly increased to almost 69% when microwaves were used ($p < 0.05$). Furthermore, the use of EMR was strongly linked to the faster adaptation of the technological system and stable effects of methane fermentation [36]. Similarly, Zielińska et al. (2013) demonstrated a positive effect of microwaves on the efficiency of the methane fermentation of milk-industry effluent. The highest biogas production was achieved when microwaves were used at a load of 1 $kgCOD·m^{-3}·d^{-1}$ under mesophilic conditions (35 °C), i.e., 0.360 + 0.006 $m^3·kgCOD_{rem}{}^{-1}$, resulting in a methane content of 67.7 ± 1.9% [67].

3.3. Energy Balance

Braguglia et al. (2018) argue that microwave radiation may serve as an attractive alternative to convection heating due to its lower energy demand (no heat loss from convection or conduction) and the breakage of hydrogen bonds through the polarization of microparticle chains [68]. The calculation of the energy balance is an important means of demonstrating the economic viability of a given method [24]. Although there were no significant differences in biogas and methane production levels, a comparative energetic analysis showed microwaves to be the more efficient solution (Table 3). The magnetron power was 300 W. The energy needed to produce the target temperature conditions in this variant equaled 90 $Wh·d^{-1}$. Using the values of methane production and its energetic value, the total potential energy produced reached 99.2 $Wh·d^{-1}$. This means that Variant 2 produced a positive net energy balance of 9.2 $Wh·d^{-1}$. In Variant 1, the power of the heating system was 412, with a daily energy demand of 206 $Wh·d^{-1}$. The energy potential of the biogas was 95.5 $Wh·d^{-1}$. Thus, the energy balance amounted to 112.5 $Wh·d^{-1}$.

Table 3. Energy balance.

Variant	Power (W)	Operation Time ($h·d^{-1}$)	Number of Reactors (-)	Total Energy Demand ($Wh·d^{-1}$)	Biogas Yield ($dm^3·kg_{VS}{}^{-1}$)	OLR ($kg_{VS}·m^{-3}·d^{-1}$)	Active Volume (dm^3)	L ($kg·d^{-1}$)	Daily Biogas Production ($dm^3·d^{-1}$)	CH_4 Concentration (%)	Daily CH_4 Production ($dm^3·d^{-1}$)	Energetic Value of CH_4 ($Wh·dm^{-3}$)	Total Energy Production ($Wh·d^{-1}$)	Energy Balance ($Wh·d^{-1}$)
V1	412	0.5	3	206	680	2	12	0.024	16.32	0.625	10.20	9.17	93.5	−112.5
V2	300	0.3		90	710				17.04	0.635	10.82		99.2	9.2

The non-thermal effects of EMR, i.e., effects that occur in systems exposed to microwaves and cannot be explained by its thermal effects, are considered to be a significant determinant of microwave radiation's influence on microflora of anaerobic bacteria [66,69]. Banik et al. (2006) demonstrated that *Methanosarcina barkeri* DS-804 exposed to microwave radiation had higher colony counts and cell sizes. In their study, a pure culture was exposed to microwave radiation at frequencies between 13.5 and 36.5 GHz for 2.0 h, and then grown for 20 days. The composition of the biogas produced by a pure *Methanosarcina barkeri* DS-804 culture changed depending on the microwave frequency. The maximum methane content in the examined biogas reached values as high as 76.5% at frequencies of 31.5 GHz, whereas the control cultures, not exposed to microwave radiation, produced methane at 52.3%. The growth stage was also significantly faster in the irradiated culture. According to the authors, the results indicate that microwaves induce specific metabolic activity that correlates with faster growth rates [70].

3.4. Practical Implications

The research work undertaken in this regard has been inspired by the effects of using microwaves in biogas and methane production through the anaerobic decomposition of organic feedstock with different characteristics, as described in the literature to date. The presented research was carried out under laboratory conditions. In order to assess the possibility of using EMR on a large scale, it is necessary to increase the technical readiness level (TRL) of this solution and to conduct research on a pilot and semi-technical scale. The applicability of the EMR in practice was confirmed in a comparative study conducted on a pilot scale, in which a hybrid bioreactor heated by microwaves or conventionally by a hot water jacket was presented [71]. The study was conducted in mesophilic (35 °C) and thermophilic (55 °C) conditions. Depending on the method of heating, the homogeneity of the temperature field in both functional parts of the reactor was determined. In mesophilic conditions, only at measurement points located directly under the wave-guide were the temperatures significantly higher than in the other zones inside the reactor. Research has proved that it is possible to homogeneously heat a bioreactor at a semi-technical scale by microwave irradiation [71].

In other semi-technical studies, a multi-section horizontal flow anaerobic reactor (HFAR) was tested [22]. The reactor was heated using microwave generators with magnetrons. There was a possibility of smooth regulation from 0 to 800 W. This type of magnetron is commonly used in microwave heating techniques due to its high performance, low price, and small dimensions. Electricity was converted into microwave energy with a conversion efficiency of 52% at 2.45 GHz. A microprocessor integrated with temperature detectors controlled the temperature inside each section of the HFAR. The temperature was maintained at 38 °C, and when it dropped below, the microwave generators automatically started. Their work was finished when the defined temperature inside the reactor was achieved. The use of the HFAR allowed obtaining high technological effects in the methane fermentation of dairy wastewater [22]

The design solution developed by the authors on a technical scale is presented below (Figure 4). Microwave generators were placed on the periphery of the reactor, and their activation was synchronized with the operation of the stirrer.

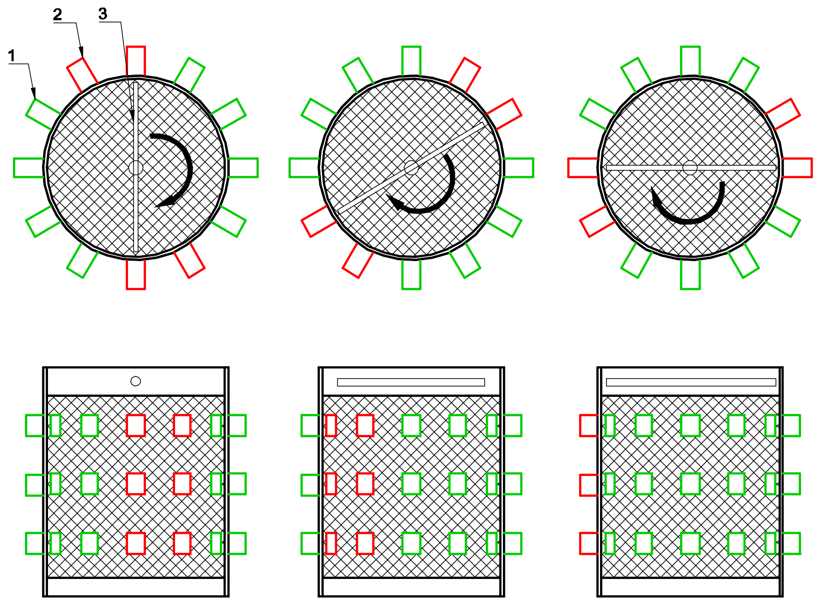


Figure 4. Scheme of operation of microwave generators heating the fermentation reactor. 1—green EMR, ON; 2—red EMR, OFF; 3—stirrer.

In another solution of the authors, the fermentation sludge was subjected to long-term exposure to small doses of microwave radiation. The research system consisted of a fermentation reactor with a cage mixing system [72], an intermediate tank, a Borger HCL 50 milling mill (Germany), and a Borger AL 50 displacement pump (Germany) (Figure 5). The raw material used in the experiment was Virginia mallow silage, hydrated to about 98% with water and bovine slurry, in a weight ratio of 2:1:1, respectively.

The active volume of the fermentation reactor was 300 dm^3. A slow-speed stirrer (20 rpm) and EMR with a frequency of 2.45 GHz were used. The temperature of fermentation was 36 ± 1.5 °C. The amount of electricity consumed by the microwave generator was monitored. In order to determine the occurrence of athermal effects of exposure to microwave radiation, in the control variant, the fermentation sludge in the intermediate tank was heated conventionally by means of an electric heating mat. The use of EMR to maintain the set temperature required electrical energy expenditure of 0.512 ± 0.016 kWh·d^{-1}.

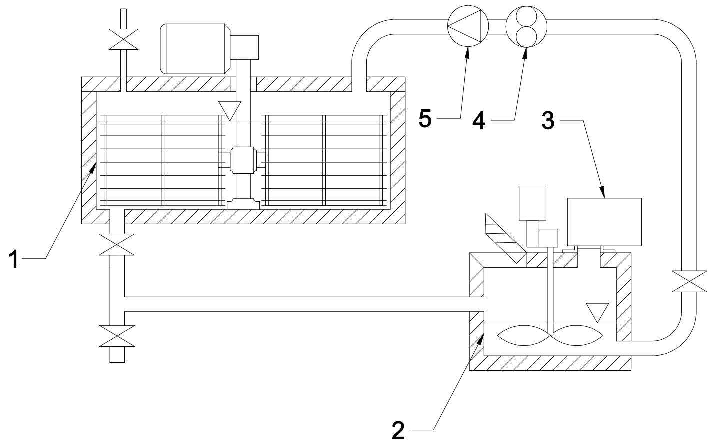


Figure 5. Scheme of the research stand. (1) Reactor with a cage mixing system; (2) intermediate tank; (3) microwave generator; (4) mill grinder; (5) displacement pump.

4. Conclusions

Methane fermentation is a well-known and widely used method of using biodegradable organic waste, including EFP, to produce energy. There are many processing systems that are applied on a fully industrial scale and produce satisfactory results in terms of the quantity and quality of biogas, as well as the stability of the digested feedstock. However, optimization strategies are still being implemented, and alternative solutions are being sought to improve the technological efficiency and economic viability of the process. One of the directions that seems promising in the long-term is the use of microwave radiation to control thermal conditions and the biochemical activity of anaerobic bacteria biocenoses. The research work undertaken in this regard has been inspired by the effects of using microwaves in biogas and methane production through the anaerobic decomposition of organic feedstock with different characteristics, as described in the literature to date.

The present study aimed to determine how the use of microwaves affects the process and products of the methane fermentation of expired food products. No statistically significant influence of EMR use on technological effects was observed. The biogas production and methane content were similar regardless of the method of heating the fermentation reactors. Microwave heating produced a positive energy balance.

The conducted research has shown that the use of EMR is an economically viable method for heating fermentation bioreactors, but it did not increase the efficiency of biogas production. In order to assess the possibility of using EMR on a large scale, it is necessary to increase the technical readiness level (TRL) of this technology and perform tests on a semi-technical scale.

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