Application of Electromagnetic Field in Anaerobic Biodigestion in Batch Reactors

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Anaerobic digestion processes with biogas production are widely used for organic waste treatment with an emphasis on energy recovery. Some recent studies have demonstrated the influence of magnetism on microbiological activity. These indicate a possible influence on the efficiency of anaerobic digestion. Thus, technologies that act in anaerobic digestion enhancement can contribute to the improvement of treatment of organic compounds. The present study aimed to verify the influence of a constant electromagnetic field on the anaerobic digestion in anaerobic reactors fed with glucose (2 g/L) at 37 ± 2 °C. In each experiment, reactors were operated with a constant electromagnetic field of 5, 7.5, and 10 mT. The inoculum was granular sludge from an anaerobic treatment plant in a non-selective media culture. Biogas production, chemical oxygen demand (COD), and solids removal were measured during the experiment. Results showed differences in methane production of 21.5% and in COD removal of 15% in the tests with an electromagnetic field of 7.5 mT. These results signs for the viability of the application of a constant magnetic field as a biostimulation agent.

Keywords: Fermentation; Electromagnetic force; Biogas; Methane; Biostimulation

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INTRODUCTION

The methane gas present in biogas resulting from the anaerobic biodigestion of organic compounds appears as a promising energy alternative (Hájek *et al*. 2019; Rozenský *et al*. 2019). It is easily stored, transported, has a high calorific value and can be obtained from several types of organic matter. Plants to manufacture biogas have been built throughout several countries. However, they have a restriction capacity due to deficiencies of biodigester technology.

Anaerobic digestion is a biochemical process that transforms complex organic matter, in the absence of oxygen, into a gas mixture, mainly methane and carbon dioxide through the syntropic action of various types of anaerobic microorganisms. This process is used for the treatment of waste and, as a renewable source of energy, through anaerobic biodigesters (Lyberatos and Sciadas 1999; Börjesson and Ahlgren 2012; Zhang *et al*. 2014; Adekunle and Okolie 2015). However, such a process is not economically effective enough (Strachotová *et al.* 2019). Recently, research has shown an increase in the biological activity by the application of a constant magnetic field and an increase in the production of methane through anaerobic digestion. Zieliński *et al.* (2014) used neodymium magnets, with a field intensity in the range of 0.16 to 0.39 T in the treatment of dairy waste. Dębowski *et al.* (2016) applied 0.6 T *via* a magnetic ceramic ring in the anaerobic digestion of algal biomass. Haritwal *et al.* (2015) studied the anaerobic digestion of cattle manure under the influence of 0.42 T using a secondary transformer core.

In addition, studies on the application of a constant magnetic field on the activated sludge digestion demonstrated modifications in the monitored parameters and identified the influence of magnetism on the activity of microbial consortium. The range of positive influence of the constant magnetic field presented in the research for aerobic treatment was between 7 and 490 mT (Jung *et al.* 1993; Zoung *et al.* 1993; Jung and Sofer 1997; Yavuz and Çelebi 2000). Electromagnetic fields can influence biological systems both *in vitro* and *in vivo* (Herbert *et al.* 1971). Electromagnetic fields can also influence biological reductive dechlorination for decontamination (Dyntar *et al.* 2018). However, research is needed in order to explain the influence of electromagnetism and, consequently, to allow for the improvement of organic waste treatment technology with energy recovery.

In this sense, the aim of this work was to analyze the influence of a constant electromagnetic field application on methane generation with no selective culture media in anaerobic batch reactors.

EXPERIMENTAL

Materials

The inoculum used was a granular sludge obtained from a full-scale up-flow anaerobic sludge blanket (UASB) reactor treating poultry slaughterhouse waste (Dacar Poultry, Tietê, São Paulo, Brazil). The culture medium for microbial growth was (g/L): glucose (10.0), meat extract (5.0), yeast extract (5.0), peptone (5.0), sodium bicarbonate (10.0), monobasic potassium phosphate (0.4), and dipotassium phosphate (0.4).

Methods

Experimental procedure

This study was performed with duplicate (1-L) anaerobic batch reactors filled with a culture medium (0.5 L), at 37 ± 2 °C, during 144 h of operation. The headspace (0.6 L) of the reactors was filled with N_2 (99.9%). The reactors were inoculated with granular sludge (100 g/L). The electromagnetic field was generated by the coil-source power supply that was constructed with copper wire and was 1.1 mm in diameter with 1.5 kg of copper. The reagent was made inside the coil. The power supply used was a model D.C. power supply TR-9158 (Guangzhou Yihua Electronic Equipment Co., Ltd., Guangzhou, China). The tests were performed for electromagnetic field strengths of 5, 7.5, and 10 mT. The chosen magnetic field range sought to be among the lowest range found in the literature for better application in real scales, since the application of the magnetic field could require expenditure of electrical energy.

The magnetic field inside the reactor was measured with a digital Teslameter (Model Phyve; PHYWE Systeme GmbH & Co. KG Robert-Bosch-Breite, Göttingen, Germany).

Analytical methods

The variables studied were the sequence of solids chosen to ascertain the efficiency of the removal of solids by the microbial consortium, and the production of biogas and methane to ascertain the conversion of the organic substrate into gases.

Total volatile solids (TVS), total solids (TS), total fixed solids (TFS), chemical oxygen demand (COD), and pH tests were performed according to APHA, AWWA, and WEF standards (2005). The sugar conversion analyses were performed according to Dobois *et al*. (1954) and adapted by Herbert *et al*. (1971).

The internal pressure of the reactors was measured with a Labitrix differential pressure gauge (model XL28.1; Driesen + Kern GmbH, Hamburg, Germany).

The percentage of methane from the biogas was measured with LANDTEC GEM-2000 gas analyzer equipment (LANDTEC North America Inc., Colton, CA, USA), with an accuracy of 3%. The volume of biogas produced inside the reagent bottles was estimated using the Clapeyron equation (Eq. 1),

$$n = P \times V / \mathrm{R} \times T \qquad (1)$$

where n is the number of biogas molecules produced, P is the pressure inside of the reactor, V is the gas volume or headspace volume (600 mL), R is the gas constant (0.0820574587 $L \cdot atm \cdot K^{-1} \cdot mol^{-1}$), and T is the operation temperature (310.15 K).

The mean values of biogas and methane obtained from the duplicate of the anaerobic batch reactors were adjusted using Statistica® software (Statsoft, Trial Version, Aliso Viejo, CA, USA). The maximum value of methane production was obtained by nonlinear sigmoidal adjustment of the modified Gompertz equation according to Eq. 2,

$$H = Px \exp\left\{-\exp\left[\frac{Rm.e}{P}(\lambda - t) + 1\right]\right\} \qquad (2)$$

where H is the accumulated value of biogas or methane (mmol/gTVS), P is the production of biogas or potential methane (mmol/gTVS), λ is the time interval of the phase Lag (h), and T is 2,718 incubation time (h).

RESULTS AND DISCUSSION

It was possible to notice that the reactors submitted to a magnetic field with an intensity of 5 mT presented similar dynamics in relation to the removal of the solids, indicating that the procedures were developed satisfactorily. Nevertheless, the applied intensity did not influence anything in terms of modifying the obtained values (Table 1).

Table 1. Initial and Final Solids

Average (5 mT)	TS (g/L)	TVS (g/L)	TFS (g/L)
Initial	39.40 39.40 25.87	27.17 27,17 16.06	12.21 12.21 19.73
Control reactor	27.77	15.92	11.85
Average (7.5 mT)			
Initial 144 h of operation	41.04 21.97	27.27 10.36	13.77 11.61
Control reactor	27.35	16.18	11.16
Average (10 mT)	ST (g/L)	STV (g/L)	STF (g/L)
Initial 144 h of operation	40.13 24.94	27.73 15.50	12.40 9.44
Control reactor	27.66	17.73	9.92

The results of the tests under an electromagnetic field of 7.5 mT showed a reduction in the volatile solids that was higher in the magnetized reactor than in the control reactor. There was a verified increase of volatile solids removal of 21% for the average of the magnetized reactors in relation to the average of the control reactors.

The values of the electromagnetic field tests of 10 mT also indicated a higher percentage of solid removal in the magnetized reactors with 8% more compared to the control reactor.

The results of pH (Fig. 1) indicated the effectiveness of H+ by methanogenic activity and reaction with sodium bicarbonate, maintaining the pH of the reactors within the optimal range, as described by Zhang *et al.* (2014).

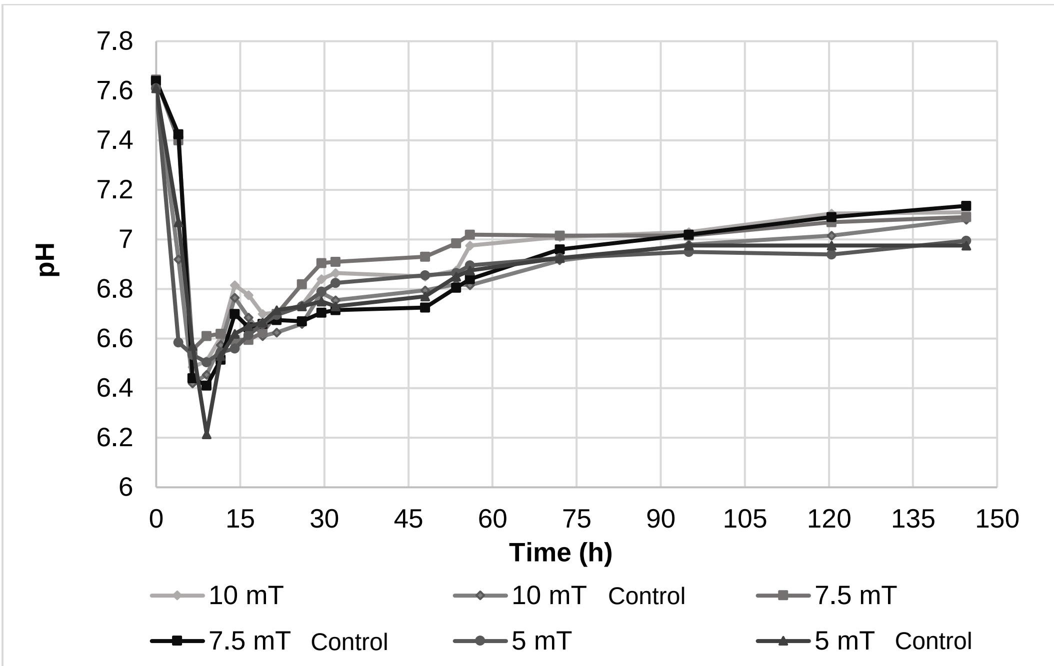

Fig. 1. pH behaviour during the tests

Effects of pH change *via* application of a magnetic field in the water, on the order of + 0.62 units, were confirmed by Joshi and Kamat (1966). However, Quickenden *et al.* (1997) and Gehr *et al.* (1995) did not observe any change of pH with magnetic treatment of water. Many studies present changes in the solution pH under magnetic fields. However, in no study were the authors able to control the pH of the solution (Parsons *et al.* 1997).

The COD removal results of the tests with a 5 m electromagnetic field showed positive values for both reactors (Table 3). However, the magnetized reactors had lower values of 0.58% removal when compared to the control reactors.

Table 3. COD Concentration in Reactors

Test	5 mT	7.5 mT	10 mT
COD initial (g/L)	27.38	28.50	28.26
Final magnet (g/L)	20.97	18.80	20.48
Removal (%)	23.41	34.03	27.53
Final (g/L)	20.81	20.08	21.04
Removal (%)	23.99	29.54	25.55

The values obtained for the COD consumption of the tests under an electromagnetic field of 7.5 mT showed a 15% increase in the average removal for the reactors when compared to the mean of the control reactors.

Furthermore, the results obtained for the COD consumption during the tests with reactors under the influence of a 10 mT electromagnetic field presented values that were 7.7% higher for COD consumption when compared to the average of the control reactors.

Haritwal *et al.* (2015) found a similar result, a 14% increase in COD removal in an anaerobic reactor with a magnetic field of 0.42 T, compared to the non-magnetized reactor. Zieliński *et al.* (2014) also found a 14% decrease in COD with a magnetized reactor (380 mT). Tomska and Wolny (2008), in a study with a constant magnetic field induction of 40 mT, found no statistically significant difference in the reduction of COD by the aerobic microbial consortium through magnetic biostimulation.

The analysis of sugar consumption revealed that all glucose present in the medium was converted into new compounds by the microbial consortium, metabolized during the first 6.5 h of operation (Table 4).

Table 4. Glucose Concentration

		Initial (g/L)	4h (g/L)	6.5 h (g/L)
5 mT	Magnetized	9.63	1.69	0.34
	Control	9.63	1.25	0.29
7.5 mT	Magnetized	9.55	2.23	0.34
	Control	9.55	2.16	0.16
10 mT	Magnetized	9.51	1.58	0.07
	Control	9.51	2.33	0.26

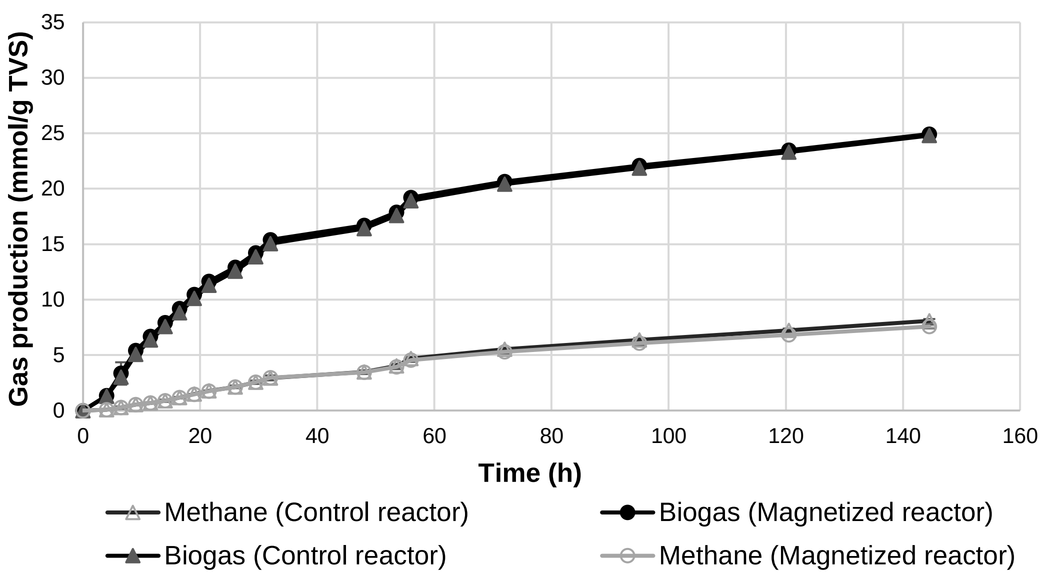

Fig. 2. Estimated accumulated biogas and methane production and average of the two tests in 144 h of operation under an electromagnetic field of 5 mT

Anaerobic biodegradation of simple substrates, such as glucose, are metabolized in acetate, carbon dioxide, and gas-hydrogen or methane gas. In the early stages of anaerobic digestion, a degradation of glucose is completed within the first 50 h of the reaction (Gajaraj *et al*. 2017). The tests performed with the application of a constant-magnetic field of 5 mT were also not favoured under afield strength with 5 mT (Fig. 2).

The experiments with 7.5 mT showed similar biogas production. However, there was an increase in the methane gas production inside the magnetized reactors compared to that of the control reactors (Fig. 3).

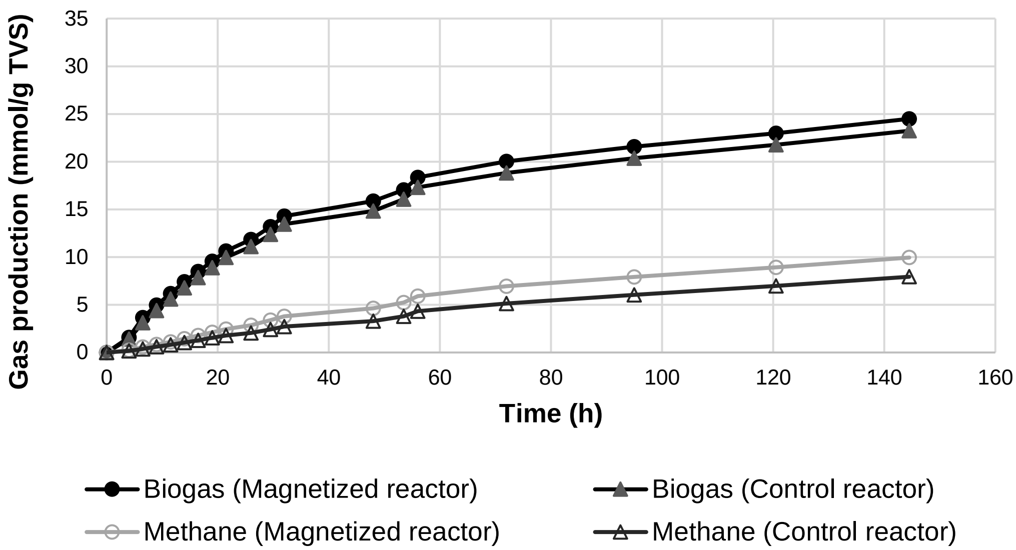

Fig. 3. Estimated accumulated production of biogas and methane and average of the two tests with crude granular mud in 144 h of operation under an electromagnetic field of 7.5 mT

During the experiments with a 10 mT electromagnetic field, the production of biogas was similar in the results. The difference occurred in the production of accumulated methane (Fig. 4).

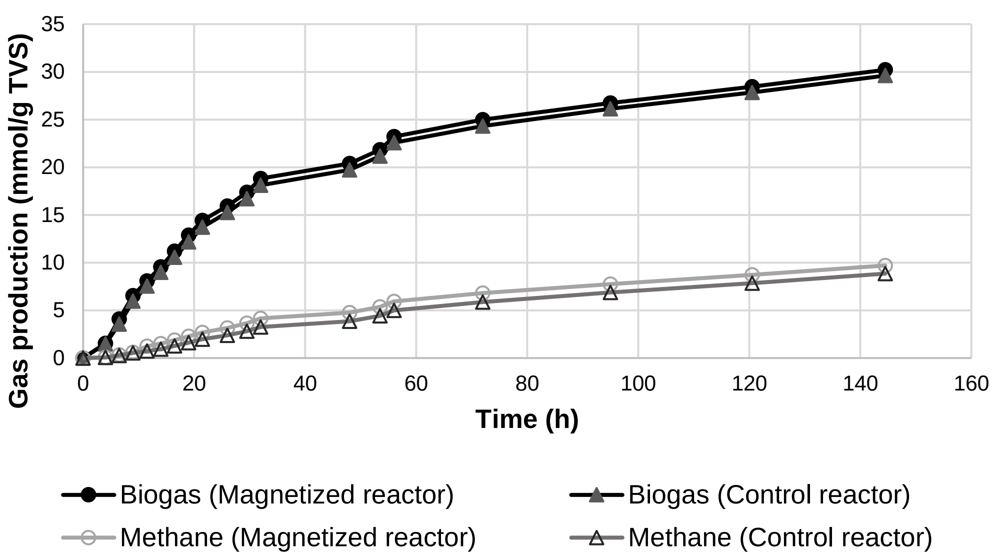

Fig. 4. Estimated accumulated biogas and methane production and average of the two tests with gross granulate in 144 operating h and a 10 mT electromagnetic field

The final values obtained from the reference production of methane gas and biogas with the application of the Gompertz model are presented in Tables 5 and 6.

Table 5. Results Obtained Through the Gompertz Model for Biogas Production

Biogas	**5 mT Magnetized**	**5 mT Control**	**7.5 mT Magnetized**	**7.5 mT Control**	**10 mT Magnetized**	**10 mT Control**
P (mmol/gTVS)	22.64	22.53	22.61	21.41	27.27	26.79
Rm (mmol/g.TVS)/h	0.44	0.43	0.38	0.36	0.55	0.53
λ (h)	----	-----	----	----	----	----
R	0.98	0.99	0.99	0.99	0.98	0.99

P = Cumulative maximum production; *Rm* = Production rate; *λ* = Time to start production; *R* = confidence interval

Biogas production began at the beginning of the experiment; accumulated final values and biogas production rates were similar for the three applied magnetic fields.

Table 6. Results Obtained Through the Gompertz Model for Methane Gas Production

Methanol	**5mT Magnetized**	**5 mT Control**	**7.5 mT Magnetized**	**7.5 mT Control**	**10 mT Magnetized**	**10 mT Control**
P (mmol/gTVS)	7.39	7.99	9.77	8.04	9.24	8.69
Rm (mmol/g.TVS)/h	0.09	0.09	0.11	0.08	0.11	0.09
λ (h)	4.38	5.00	2.21	2.90	1.75	4.60
R	0.99	0.99	0.99	0.99	0.99	0.99

P = Cumulative maximum production; *Rm* = Production rate; *λ* = Time to start production; *R* = confidence interval

The methanogenic activity obtained the greatest difference when a magnetic field of 7.5 mT was applied to the reactor; the results presented a 21.5% increase in the accumulated production in relation to the control. In this test, the magnetized reactor started methane production 41.4 min before the control reactor.

The experiment with a 10 mT field showed an accumulated difference that was 6.32% greater than the magnetized reactors in comparison to the control reactors. In addition, the start of methane production in the magnetized reactors occurred 171 min before the control reactors.

Studies indicate parameter variations in tests with the magnetic field intensity in the range of 7 to 490 mT (Tomska and Wolny 2008).

Furthermore, differences in methane production rates occurred in up to 72 h of operation. Zieliński *et al.* (2014) found an increase in the fermentation process through applying a constant magnetic field for the treatment of dairy residue. These authors found changes in COD and sludge sedimentation, but they did not find statistically significant differences in the composition of the biogas with a 4% increase in production compared to the control while using a constant magnetic field (with an intensity of 431 mT at 0.7 mm away from the magnet).

However, Haritwal *et al.* (2015) found a 40% increase in the methanogenic activity of the reactor submitted to constant magnetic field exposure when compared to the control reactor after six days of reaction. Additionally, they found that the reduction of ammoniacal nitrogen was 20% higher. In another study, promoted by Dębowski *et al.* (2014), the authors introduced artifacts with neodymium magnets in the zone of hydrolysis and acidogenesis in reactor tanks. In the cited study, powdered milk was used as a substrate, which allowed for a higher biofilm formation and a lower reduction of bacterial biomass losses. The authors of the cited study concluded that there was no statistically significant impact on the increase of investment costs of the entire facility.

The authors' study also showed an increase in biogas production and an increase in methane concentration related to the number of magnetized artifacts used.

CONCLUSIONS

1. The results of the methane analysis favoured methanogenesis under the constant electromagnetic field of 7.5 with a 21.5% increase in the accumulated production in relation to the control.
2. The delay phase was shorter when the 10 mT magnetic field was applied. The start of methane production in the magnetized reactors occurred 171 min before the control reactors.
3. The values obtained for the COD consumption of the tests under an electromagnetic field of 7.5 mT showed a 15% increase in the average removal for the reactors, when compared to the mean of the control reactors. The highest value of the three fields was tested.
4. However, further studies are needed in order to validate the effect of the magnetic field on anaerobic digestion, as well as its performance in the biological system.

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