Exploring the effects of static magnetic fields for the enhanced valorization of sewage sludge by anaerobic digestion

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Abstract

Anaerobic digestion (AD) is an interesting and sustainable option to handle sewage sludge (SS), as it generates a methane-rich biogas and a digestate with potential fertilizing properties. Several strategies have been proposed to enhance AD performances and the valorization of SS. Among these, the application of a static magnetic field (SMF) has been poorly evaluated and recently gained attention. This work investigated the effect of low-intensity SMF (20-50 mT) on methane production from AD of SS, comparing it to the effect deriving from the application of a high-intensity SMF (1.5 T). Magnetic pretreatment at 20 mT was particularly effective, as it increased biomethane production up to 12.9% compared to the control test. On the contrary, 1.5 T was detrimental in terms of cumulative methane production, as it resulted in a 20.9% decrease. These outcomes suggest that SMF intensity is inversely related to biomethane generation and that further investigations are worthy to understand the mechanisms underlying AD enhancement by SMF application.

Keywords: static magnetic fields, sewage sludge, anaerobic digestion, biomethane, nutrient recovery.

1. Introduction

Sewage sludge (SS) is an inevitable by-product of municipal wastewater treatment and represents a key issue in many countries due to its increasing volume and the impacts associated with its disposal. In addition, the management of huge sludge quantities stands as a significant part of the operating costs of wastewater treatment plants. For this reason, appropriate management strategies that are sustainable from an environmental and economic point of view are needed. In this perspective, anaerobic digestion (AD) is considered an effective, economical, and eco-friendly technology. AD stabilizes sludge, aids in odor and pathogen removal (Nguyen et al., 2021), and noticeably generates a methane-rich biogas, which can be recovered for energy purposes (Cesaro et al., 2019). The generation of biogas comes along with the production of anaerobic digestate with potential fertilizer properties due to the significant content of both macro- and micro-nutrients (Di Costanzo et al., 2021). To improve AD efficiency, several studies have implemented pretreatment processes increasing biodegradability, dewaterability of sewage sludge, and, consequently, biogas production. Among these, the application of static magnetic field (SMF) has been poorly evaluated. Traditionally, this technology has been applied for calcium carbonate precipitation in water (Mascolo, 2021) and, more recently, it has been proposed in combination with aerobic biological processes (Wang et al., 2021). The application of a SMF to SS destined to AD is expected to impact both the generation of methane and the quality of the digestate, leading to the possible precipitation of compounds that may enhance the fertilizing properties of SS (Di Costanzo et al., 2022).

The aim of this work was to establish the effects of SS exposure to the SMF in terms of AD performance, comparing the impact generated by a low-intensity (20-50 mT) and high-intensity (1.5 T) SMFs on both biomethane production and chemical composition of the digestate. Batch AD tests were carried out on both untreated and pretreated SS samples and experimental results were discussed to identify the possible integration of this novel technology within AD processes.

2. Materials and methods

2.1. SS origin, composition and magnetic pre-treatment

The SS used in this study was collected at the wastewater treatment plant in Mercato San Severino (Italy) from the pre-thickener, collected in plastic containers and immediately used for the experiments. The characteristics of the SS used are listed in **Table 1**.

Table 1. Characteristics of the SS used for the experiments.

Parameter	Unit	Value
pH	-	7±0.1
Total solids (TS)	%	3.6±0.3
Volatile solids (VS)	%	2.4±0.1
Chemical oxygen demand (COD)	mg/L	6706±10
Soluble COD	mg/L	1146±25
Ammonium (NH_4^+)	mg/L	77.5±0.7
Nitrate (NO_3^-)	mg/L	2.7±0.1
Phosphate (PO_4^{3-})	mg/L	3.9±0.1
Sulphate (SO_4^{2-})	mg/L	2.3±0.1
Magnesium (Mg^{2+})	mg/L	5.9±0.2

The SMF was generated by a magnetic polarizer provided by AMS company (Italy) installed on a circuit as described by Di Costanzo et al., (2022). SS magnetization as AD pretreatment was carried out by pumping 2 L of sludge, with a flow rate of 0.1 L/min, through the polarizer with a nominal SMF intensity of 20 mT, 50 mT and 1.5 T.

2.2. AD Tests with magnetized SS

AD experiments were conducted in triplicate under mesophilic conditions (37±1 °C) and performed in 250 mL serum glass bottles (OCHS, Germany). Each bioreactor was sealed by a cap composed of rubber septum, aluminum crimp, and needles equipped with 1-way stopcocks (Masterflex, Germany) for gas and liquid sampling. Mixing of each bioreactor was performed manually once a day before sampling. Each bottle was filled with only treated sludge, leaving 100 mL as headspace volume for the biogas accumulation. To ensure anaerobic conditions, each bottle was flushed with argon gas for 1 min and then vented to reach atmospheric pressure. Control tests, containing only sludge, were simultaneously carried out to evaluate the methane generation obtained from the sludge without magnetic pretreatment. The experimental design used for the tests is shown in **Table 2**.

Table 2. Design of AD tests.

Test	SMF Intensity [mT]	Q [L/min]	NMC
A	20	0.1	1
B	50	0.1	1
C	1500	0.1	1
CTRL	-	-	-

From each test bottle, the daily methane production was quantified 5 times/week and was recorded for 35 days. In addition, liquid samples (2 mL) were withdrawn once a week to measure the concentrations of volatile fatty acids (VFAs), NH_4^+, PO_4^{3-}, NO_3^-, SO_4^{2-} and Mg^{2+}.

2.3. Analytical methods

The concentrations of COD, TS, and VS were analysed according to the Standard Methods while NH_4^+ concentration was determined spectrophotometrically using the method described in APAT CNR-IRSA, (2003). Anionic concentrations were measured by ion chromatography as described by Di Capua et al. (2020). Magnesium concentration was measured by ICP-MS (Perkin Elmer Nexion 300, USA) operating in dual detector mode.

2.4. Statistical analysis

Statistical comparison of the reported data from the control and each samples under the different treatment conditions were compared by one-way analysis of variance (Lee and Lee, 2018). All analyses were performed with Minitab 17 Statistical Software (Minitab LCC, USA), where a difference marked with a p-value lower than 0.05 was considered statistically significant.

3. Results and discussion

Figure 1 reports the specific biomethane production after 35 days of AD tests. The control test, with untreated sludge, showed a maximum achievable specific biomethane production of 244.7 L_{CH4}/kg_{VS}. The low-intensity pretreatments, under both intensity (20-50 mT) significantly increased the methane production compared to control test ($p<0.05$). In particular, the specific biomethane production reached 281 L_{CH4}/kg_{VS} for an intensity of 20 mT and 254 L_{CH4}/kg_{VS} for an intensity of 50 mT. On the other hand, the use of a high-intensity SMF (1.5 T) pretreatment resulted in a decrease of specific methane production by 20.9% compared to the control test, reaching 202.4 L_{CH4}/kg_{VS}. This result is in line with those outlined in a previous work (Di Costanzo et al., 2022), where high-intensity SMF (1.5 T) resulted in lower methane generation of 23.9% compared to tests with untreated sludge. The detrimental effect of high-intensity SMF on AD could be due to a decreased availability of micro- and macro-nutrients in the liquid phase after magnetization. In fact, as shown in **Figure 2**, after the pretreatment there is a greater reduction of the ionic concentrations in liquid phase as the exposure of the sludge to the magnetic field increases. In particular, high-intensity SMF produces a maximum reduction of 27.8%, 45.2%, 25.7%, 40.5% and 11.6% for NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Mg^{2+}, respectively. Moreover, it can be observed that this reduction remains unchanged throughout the duration of the AD tests. This effect, as reported in literature (Mascolo, 2021), can be linked to a magnetization memory, i.e., the persistence of the magnetization with time. On the other hand, from **Figure 2** it can be observed that even a low-intensity SMF produces a reduction in the liquid phase of all the observed ionic concentrations, but more limited (i.e., 5.4% for NH_4^+, 2.7% for NO_3^-, 8.3% for PO_4^{3-}, 18.0% for SO_4^{2-} and 1.7% for Mg^{2+}). Another possible explanation is that SMF influences the biological activity of bacteria and archaea involved in methane production. From these results, the need to implement future studies aimed at clarifying and establishing the contextual effect on the structure and metabolism of bacterial communities, appears necessary.

4. Conclusions

Our study demonstrates that low-intensity SMF pretreatment is an effective technique for enhancing AD performance, attaining 12.9% and 3.7% improvements of methane production at 20 and 50 mT compared to the untreated SS. On the other hand, applying a high-intensity SMF (1.5 T) is detrimental. Specifically, even at a minimal exposure, the latter determined a reduction in methane production of 20.9%.

This study therefore proposes an innovative treatment opening up to future perspectives aimed at creating a system integrating SMF and AD for the valorisation of SS in a circular economy perspective.

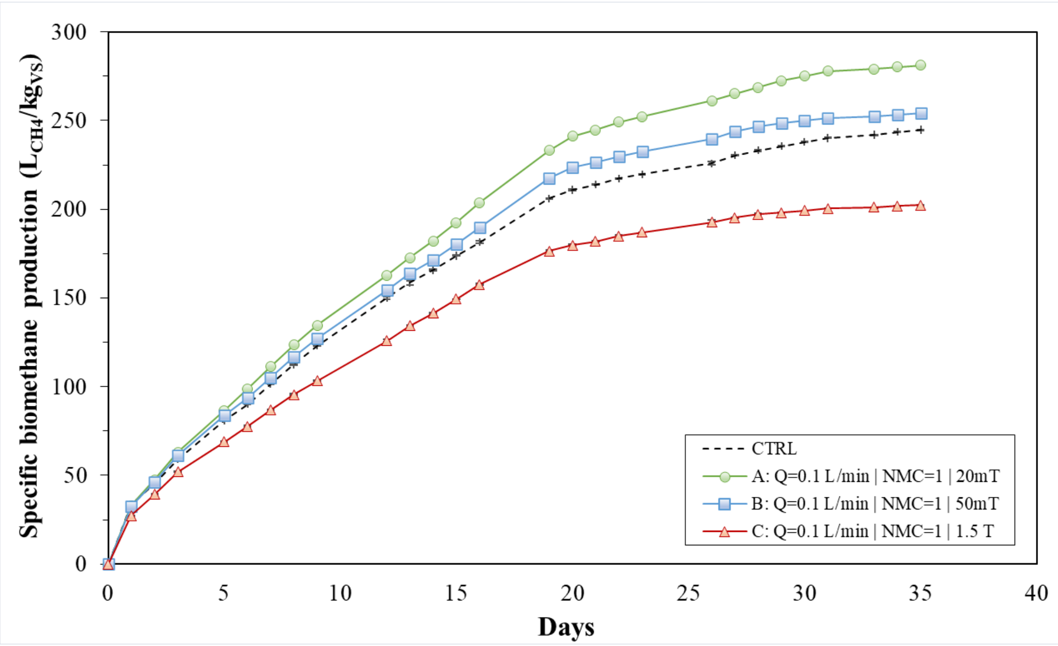

Figure 1 - Specific biomethane production in AD tests.

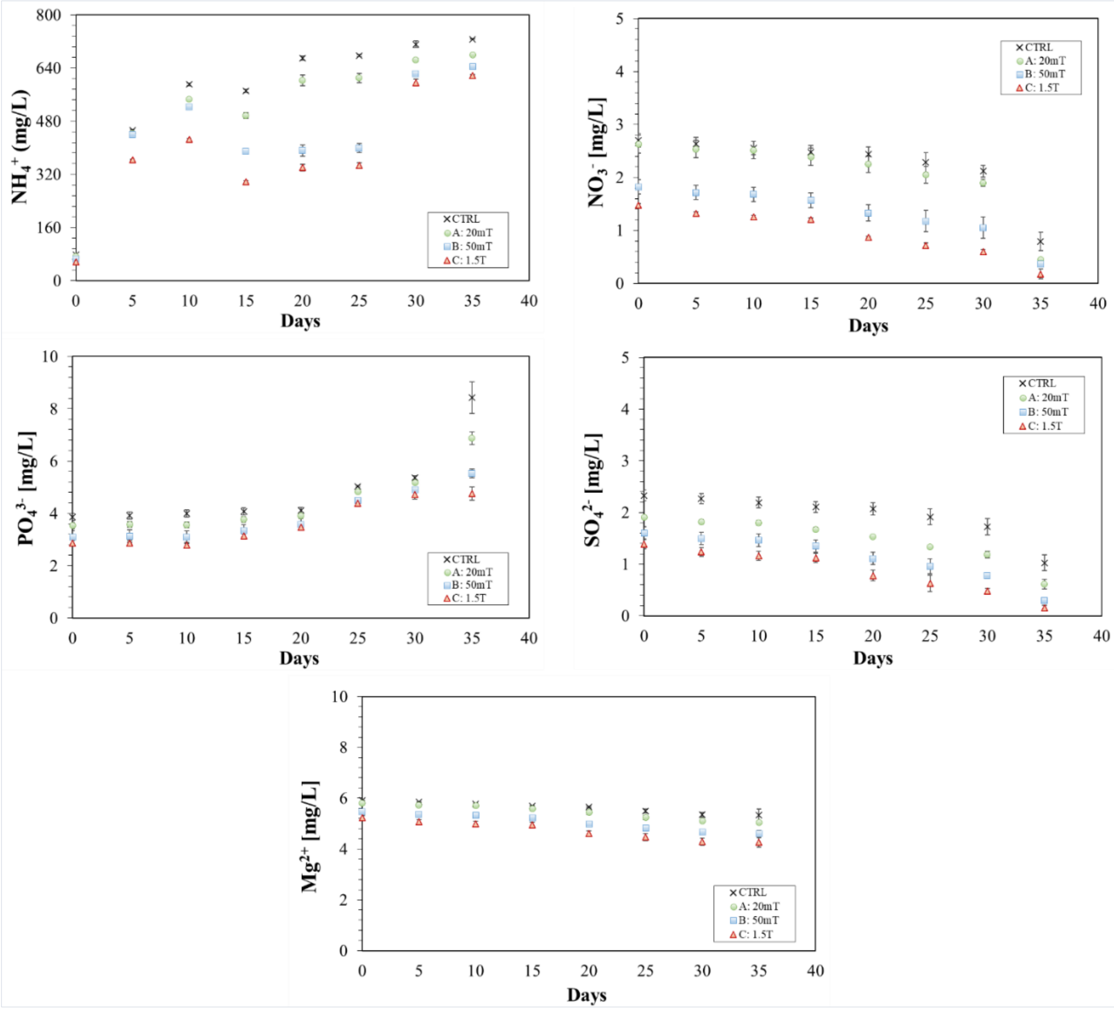

Figure 2 - Concentrations of NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Mg^{2+} during AD tests

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