Waste and Biomass Valorization
https://doi.org/10.1007/s12649-022-01891-x

ORIGINAL PAPER

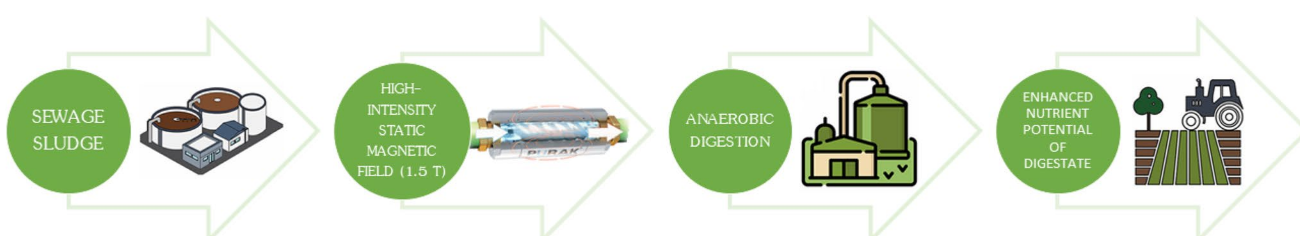
Impact of High-Intensity Static Magnetic Field on Chemical Properties and Anaerobic Digestion of Sewage Sludge

Nicola Di Costanzo[1] · Francesco Di Capua[2] · Alessandra Cesaro[1] · Maria Cristina Mascolo[3] · Francesco Pirozzi[1] · Giovanni Esposito[1]

Received: 28 January 2022 / Accepted: 25 July 2022

Abstract
The increasing production of sewage sludge at global level has addressed the search for technical solutions to take advantage from it, reducing the environmental burden originating from its disposal. Anaerobic digestion is a suitable option to handle sewage sludge in accordance with circular economy principles, as it generates a methane-rich biogas and a digestate with potential fertilizing properties. Several techniques have been proposed to enhance anaerobic digestion performances and, among these, the application of static magnetic field (SMF) has recently gained attention. Nonetheless, the effects of high-intensity SMF on the sewage sludge destined to anaerobic digestion and its impact on the anaerobic digestion process have not been evaluated yet. This study aims to determine the effects of a 1.5 T SMF on the chemical composition of sewage sludge as well as on methane generation during anaerobic digestion. The main parameters influencing the SMF (i.e., flow rate, mixing ratio of magnetized to non-magnetized sludge, number of pumping cycles, and total solid content) were varied to evaluate the impact of different exposure conditions on the chemical characteristics and methane potential of sewage sludge. An extensive exposure to the high-intensity SMF applied resulted in a 24% decrease of methane production, reduced the concentration of the monitored ionic species (i.e., NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Mg^{2+}) in the liquid phase of sewage sludge, and promoted the precipitation of compounds with valuable fertilizing properties, e.g., struvite. These outcomes suggest that high-intensity SMF, although negatively influencing methane generation, can promote the precipitation, and possibly the recovery/recycle of valuable compounds from sewage sludge, enhancing its proper management in a circular economy perspective.

Graphical abstract



Keywords Anaerobic digestion · Circular economy · Sewage sludge · Static magnetic field · Struvite

Statement of Novelty

Anaerobic digestion of sewage sludge is in line with the perspective of a more sustainable future, but still suffers from difficulties for its consolidation. Several strategies have been proposed to enhance the valorization of sewage sludge through anaerobic digestion, including different kinds

✉ Nicola Di Costanzo
nicola.dicostanzo@unina.it

Extended author information available on the last page of the article

of substrate pretreatments. Among these, the application of SMF has been poorly evaluated. No investigation of the impacts of high-intensity SMF on anaerobic digestion of sewage sludge and on sewage sludge chemical composition exists in the literature. In this study it is shown for the first time that the application of high-intensity SMF, although not beneficial in terms of methane production, can promote the chemical precipitation in sewage sludge of valuable compounds with fertilizing properties (e.g., struvite), that could improve the fertilizing potential of sewage sludge digestate or be recovered. This is an important outcome in view of the increasing application of sewage sludge in agriculture according to the circular economy principles.

Introduction

The growing demand for wastewater treatment has led to a rapid increase in the production of an unavoidable by-product, i.e., sewage sludge, holding organic matter, nutrients, and often pathogens as well as toxic substances such as organic contaminants and heavy metals [1]. Typically, sewage sludge treatment pursues a volume reduction via thickening and dehydration as well as a biological stabilization via digestion processes, usually performed under anaerobic conditions. The anaerobic digestion process generates a gaseous flow, the biogas, and a solid–liquid flow, the digestate or anaerobically digested sludge (ADS). The biogas is a well-known energetically valuable product containing around 55–65% of methane (CH_4), and it can be further processed to produce biomethane and/or thermal/electrical energy for plant operation, thereby eliminating or reducing the external supply of energy and related costs. On the other hand, ADS is a valuable source of organic matter and nutrients, and its reuse as a fertilizer is among the most attractive strategies fitting the principles of circular economy [2]. The management of this by-product represents a challenge due to the high investment and operating costs for its treatment and disposal. Both ADS management and agricultural valorization are key factors for the economic and environmental sustainability of wastewater treatment plants (WWTPs).

In the past decades, many studies have been carried out with the aim to select the best strategies to enhance the energetic valorization of sewage sludge through anaerobic digestion. These strategies include mechanical methods such as sonication [3] and lysis-centrifuge [4], thermal hydrolysis carried out at high (> 140 °C) [5] and at low temperatures (50–90 °C) [6], chemical methods such as ozonation [7] as well as biological methods such as bacterial pretreatment [8] and microaeration [9, 10]. These different strategies, although they showed good performance in improving the anaerobic digestion process, are characterized by high costs for energy and/or chemicals, which are not always compensated by an increased biogas production and prevent a wider application in WWTPs. In this scenario, it therefore seems interesting to search for innovative and more sustainable technologies.

Recently, the impact of static magnetic field (SMF) on the anaerobic digestion of sewage sludge has gained increasing interest [11–13]. In the past, some studies focused on the effects of low-intensity SMF on the aerobic degradation of organic matter and denitrification. The application of a weak SMF (13 mT) was shown to increase by 10% the efficiency of the biological decomposition of organics in activated sludge at low temperature (5 °C) [14]. Similar results were obtained by Filipič et al. [15] who demonstrated that 17 mT SMF could enhance the enzymatic activity and organic matter degradation by wastewater bacteria. In another study, it was demonstrated that a SMF with an intensity of 30 mT can improve the denitrification performance of immobilized bacteria [16].

More recently, Zieliński et al. [13] evaluated the effect of the SMF on the anaerobic digestion of municipal sewage sludge. These authors observed that a low-intensity SMF of 17.6 mT exerted a positive effect on CH_4 production efficiency and content in biogas, which was attributed to an increased proportion of methanogenic archaea in the digester mixed culture [11]. Also, the application of a weak SMF was shown to determine positive effects on solid separation, e.g., removal of sludge flocs from the bioreactor effluent, and on sludge properties, improving sludge sedimentation and dewaterability. In the literature, it is reported that these effects may depend on the SMF intensity and frequency [17], its static or oscillating nature, waveform, as well as on type and condition of the exposed cells [18]. Also, it has been proven that a strong SMF affects properties of liquids such as surface tension, density, viscosity, light extinction and wettability of solid substances [19]. Although positive impacts of low-intensity SMF on anaerobic digestion have been highlighted, the current literature lacks information regarding the effects induced by high magnetic intensities on the chemical composition and the anaerobic degradation of sewage sludge. Moreover, changes of the chemical composition of sewage sludge exposed to high-intensity SMF have not been yet investigated. As this kind of technology is used to reduce water hardness by promoting the precipitation of ionic species, its application could likely exert a similar effect on the ionic species present in sewage sludge and promote the potential precipitation of struvite, a crystalline mineral composed of magnesium, nitrogen and phosphorus with good fertilizing properties [1, 20].

The aim of this work was to determine the impact of a high-intensity (1.5 T) SMF on sewage sludge in terms of its chemical composition and CH_4 production by anaerobic digestion. The effects of the main parameters influencing

SMF intensity were investigated at laboratory scale and used to discuss practical applications of this technique for enhancing nutrient recovery and recycle from sewage sludge.

Materials and Methods

Sewage Sludge Origin and Composition

The sewage sludge was collected at the WWTP of Nola (Italy) during two sampling exercises and used to run two separate experimental phases, i.e., stage 1 (S1) and stage 2 (S2). Nola WWTP treats wastewater of predominantly municipal origin and, to a lesser extent, industrial wastewater from the nearby industrial area of Nola – Marigliano. The plant is based on a conventional activated sludge system operated at long solid retention time (> 20 days). The sewage sludge was collected from the lower withdrawal point of the pre-thickener, placed in plastic containers, transported to the laboratory, and used for the experiments. The characteristics of the sewage sludge used in this study are listed in Table 1.

Table 1 Characteristics of the sewage sludge used for the experiments

Parameter	Unit	Stage 1	Stage 2
pH	–	6.9 ± 0.1	7.0 ± 0.1
Total solids (TS)	%	5.0 ± 0.2	4.9 ± 0.15
Volatile solids (VS)	%	3.8 ± 0.3	3.6 ± 0.2
Chemical oxygen demand (COD)	mg/L	11,496 ± 62	11,579 ± 49
Soluble COD	mg/L	4887 ± 99	4990 ± 56
Ammonium (NH_4^+)	mg/L	180 ± 2	179 ± 6
Phosphate (PO_4^{3-})	mg/L	375.5 ± 3.3	357.3 ± 1.6
Nitrate (NO_3^-)	mg/L	17.6 ± 0.4	19.2 ± 2.2
Sulfate (SO_4^{2-})	mg/L	13.7 ± 1.2	15.1 ± 0.8
Magnesium (Mg^{2+})	mg/L	3.8 ± 0.3	4.2 ± 0.7

Magnetic Pretreatment of Sewage Sludge

The SMF was generated by a patented Purak magnetic polarizer provided by AMS company (Italy) (V. Ruggero, Magnetic polarizer. Italian patent company (2004) Patent N.0001351125; V. Ruggero, Magnetic polarizer. Italian patent company (2015) Patent N.102015000013842), which was composed of magnetic rings made with a mixture of rare earth metals embedded in a ceramic base and sintered. The technical parameters of the magnetic polarizer are as follows: nominal diameter = 50 mm, height = 125 mm, weight = 1.5 kg and nominal intensity of the induced SMF = 1.5 T.

Sewage sludge magnetization was applied as a pretreatment to anaerobic digestion and carried out by pumping a volume of 2L of the sludge through the polarizer. For this purpose, the magnetic polarizer was installed on a circuit (Fig. 1) made with a plastic tube (diameter = 1.5 cm) and connected to a pumping system. The latter consisted of a 520Du peristaltic pump (Watson-Marlow, UK) when the flow rate was in the lower range (0.1–0.5 L/min), while a submersible water pump (Comet, USA) was used for the higher flow rate.

Sludge pretreatment was carried out at different flow rates (Q: 0.1, 0.5 and 10 L/min) and number of magnetization cycles (number of sludge passages within the magnetic polarizer, NMC: 1 and 10) to evaluate the effect of these parameters on sludge composition and methane yields. After pretreatment, the magnetized sludge was analyzed to evaluate the effects of the applied SMF on the ionic concentrations and potential precipitation of nitrogen-, phosphorus- and magnesium-based compounds with fertilizing properties, e.g., struvite.

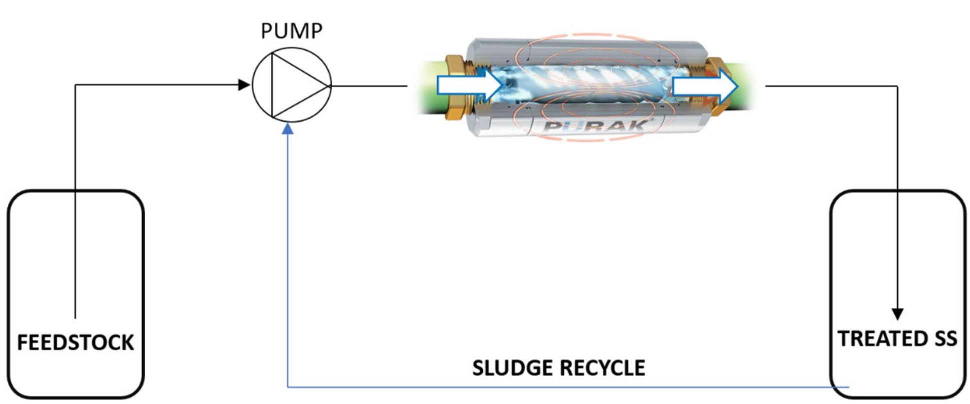


Fig. 1 Scheme of the experimental set-up for the magnetic treatment of sewage sludge

Anaerobic Digestion Tests with Magnetized Sewage Sludge

Anaerobic digestion experiments were conducted in triplicate and performed in 500 mL Schott glass bottles (Duran, Germany). Each bioreactor was sealed by screw caps with two sampling ports for daily CH_4 quantification and withdrawal of liquid samples, placed in a thermostatic bath at 35 °C and monitored for 42 days. Mixing of each bioreactor was performed manually once/day before sampling. The experimental work was divided in two stages: the first was carried out with partially magnetized sewage sludge (S1) and the second with completely magnetized sewage sludge (S2). In S1 tests, the effect of different values of magnetized sewage sludge total solid (TS) concentration (2.5% and 5%), mixing ratio (MR) of magnetized to non-magnetized sludge (0.5 and 2 in terms of VS) and number of magnetization cycles (NMC) (1 and 10) was evaluated at a constant flow rate (Q) of 0.5 L/min. In S2 the tests were carried out at Q of 0.1, 0.5 and 10 L/min, TS concentration of 2.5% and 5% and NMC of 1 and 10.

The experimental design of S1 is shown in Table 2. Experiments were carried out with 9 different tests, including a control test to which the SMF was not applied. Table S1 shows the organic load for S1 and S2 tests. From each test bottle, the daily CH_4 production was quantified 5 times/week and liquid samples (12 mL) were withdrawn once a week to measure the concentrations of volatile fatty acids (VFA), ammonium ($N\text{-}NH_4^+$), phosphate (PO_4^{3-}), nitrate (NO_3^-) and sulfate (SO_4^{2-}). These analyses, along with the chemical oxygen demand (COD) concentration, were also carried out on the feedstock after the magnetic pretreatment as well as on the digestate at the end of the tests.

Following the results from S1, in S2 the effect of SMF on the anaerobic digestion of sewage sludge was evaluated considering 8 tests with completely magnetized sludge, including 2 control tests at different TS concentrations. In S2 conditions of maximum (Q = 10 L/min, NMC = 10), medium (Q = 0.5 L/min, NMC = 10) and minimum (Q = 0.1 L/min, NMC = 1) exposure to the SMF during the pretreatment were investigated. The experimental design of S2 tests is shown in Table 3. The daily CH_4 production of each bioassay and control reactor was quantified 5 times/week. The concentrations of TAN, anions, TS, VS and COD were measured on the feedstock after magnetization and on the final digestate. Moreover, after the pretreatment, a sample (100 mL) for each condition was collected for the solid-phase analysis.

Table 2 Design of anaerobic digestion tests with partially magnetized sludge (S1)

Test	Q (L/min)	TS (%)	MR	NMC
A	0.5	5	0.5	1
B				10
C			2	1
D				10
E		2.5	0.5	1
F				10
G			2	1
H				10
Ctrl	–	5	–	–

Table 3 Design of anaerobic digestion tests with completely magnetized sludge (S2)

Test	Q (L/min)	TS (%)	NMC
A	10	5	10
B		2.5	
C	0.5	5	
D		2.5	
E	0.1	5	1
F		2.5	
Ctrl 1	–	5	–
Ctrl 2	–	2.5	–

Analytical Methods

The daily CH_4 production was quantified with the water displacement method by using a two-column system: the first column was filled with a 15% NaOH solution to allow CO_2 trapping and it was connected at the top to a second column filled with tap water. The concentrations of COD, TS and VS were analyzed according to the Standard Methods [21]. The concentration of ammonium nitrogen ($N\text{-}NH_4^+$) was evaluated as total ammonium nitrogen (TAN), being the fraction of free ammonia nitrogen (FAN) negligible (< 0.5%) at the temperature and pH conditions of the sludge during pretreatment (Table S2). TAN was determined by steam distillation followed by titration by a semi-automated distillation unit (UDK 132, VELP, Italy). The titrations were performed by using an automated titrator (TTT80 Radiometer, Copenhagen). VFA concentration was determined by high-performance liquid chromatography (HPLC) using a UVD 340U HPLC system (Dionex, Sunnyvale, CA, USA) equipped with a diode array detector and a Metrosep organic acid column 250/7.8 (Metrohm, Switzerland). Anionic concentrations were measured by ion chromatography (IC) as described by Di Capua et al. [22]. Magnesium concentration was measured by ICP-MS (Perkin Elmer Nexion 300, USA) operating in dual detector mode.

Mineralogical characterization of sewage sludge was performed by X-ray diffraction (XRD) analysis using a Philips diffractometer and Cu Kα radiation. For this purpose, films were prepared with the different samples using the Doctor

Blade Coating technique. Once the films of material were obtained, they were dried in the air for a time sufficient to achieve a constant mass.

Results and Discussion

Impact of High-Intensity SMF Pretreatment on the Chemical Composition of Sewage Sludge

The application of a 1.5 T SMF as pretreatment led to a decrease of the monitored ionic concentrations in the liquid phase of sewage sludge. Increasing the NMC from 1 to 10 during S1 pretreatment enhanced precipitation at both TS concentrations of 5% and 2.5%: in particular, all monitored ionic concentrations in the liquid phase decreased by 8–14.9% at NMC = 1 and 9.3–20.1% at NMC = 10 in the tests at 5%TS, while in the tests at 2.5%TS a 11.2–17.2% decrease was observed at NMC = 1 and a 14–31.4% decrease was observed at NMC = 10 (Fig. 2). These results show that the increase of NMC increases the tendency of the ions to form new aggregates. However, no significant differences were observed in terms of solid concentration before and after the application of the SMF (Table S3). It can be also observed that the highest reduction percentage of ionic concentration was obtained at 2.5%TS, which could be explained considering that the main effect of magnetic treatment consists in the associations of ionic species which are present in the solution, with consequent formation of precipitates, and this effect is more pronounced for solutions characterized by a lower ions concentration [23]. From this point of view, the obtained results show that sewage sludge at 2.5%TS is a less complex matrix over which the impact of the SMF can be more effective compared to sludge at 5%TS.

Figure 3 shows the data obtained from S2 tests. As observed during S1, increasing the NMC from 1 to 10 led to greater reductions of ionic concentrations at both of 5%TS and 2.5%TS. Moreover, results from S2 shows that increasing Q from 0.5 to 10 L/min at the same NMC enhanced the reduction of the ionic concentration in the liquid phase at both TS concentrations. Comparing the results obtained at Q = 10 L/min and NMC = 10 to those obtained at Q = 0.5 L/min and NMC = 10, the difference in terms of NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} removal efficiency was 1.2%, 7.4%, 0.9%, 6.2%, respectively, in the tests a 5%TS, while in the tests at 2.5%TS this difference was respectively of 1.0%, 14.8%, 0.8%, 6.2%. S2 tests also include a condition of minimum exposure to the SMF (Q = 0.1 L/min, NMC = 1), which also resulted in a reduction of NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} concentrations respectively by 15.9%, 23.9%, 7.8% and 22.7% in the tests at 5%TS, and by 12.6%, 7.3%, 4.2% and 10.6% in the tests at 2.5%TS. However, these reductions

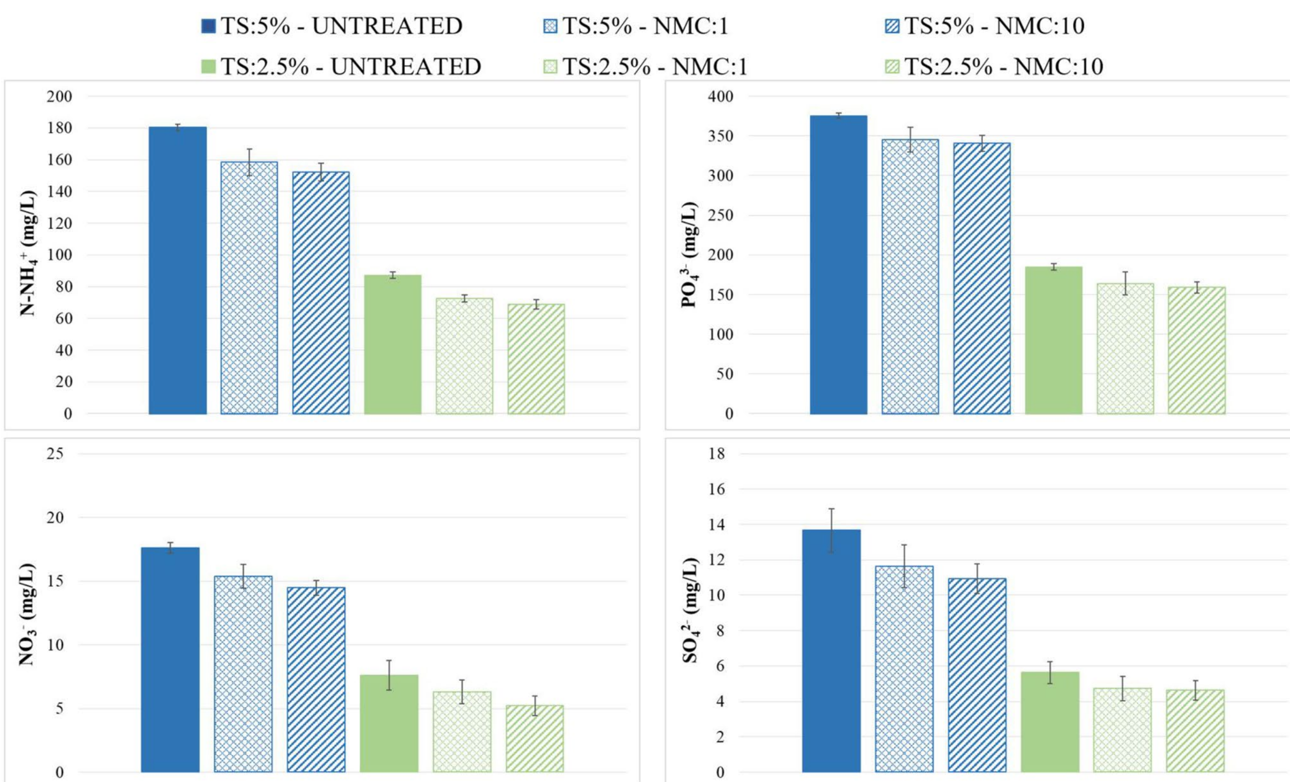


Fig. 2 Concentrations of NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} before and after SMF pretreatments in S1

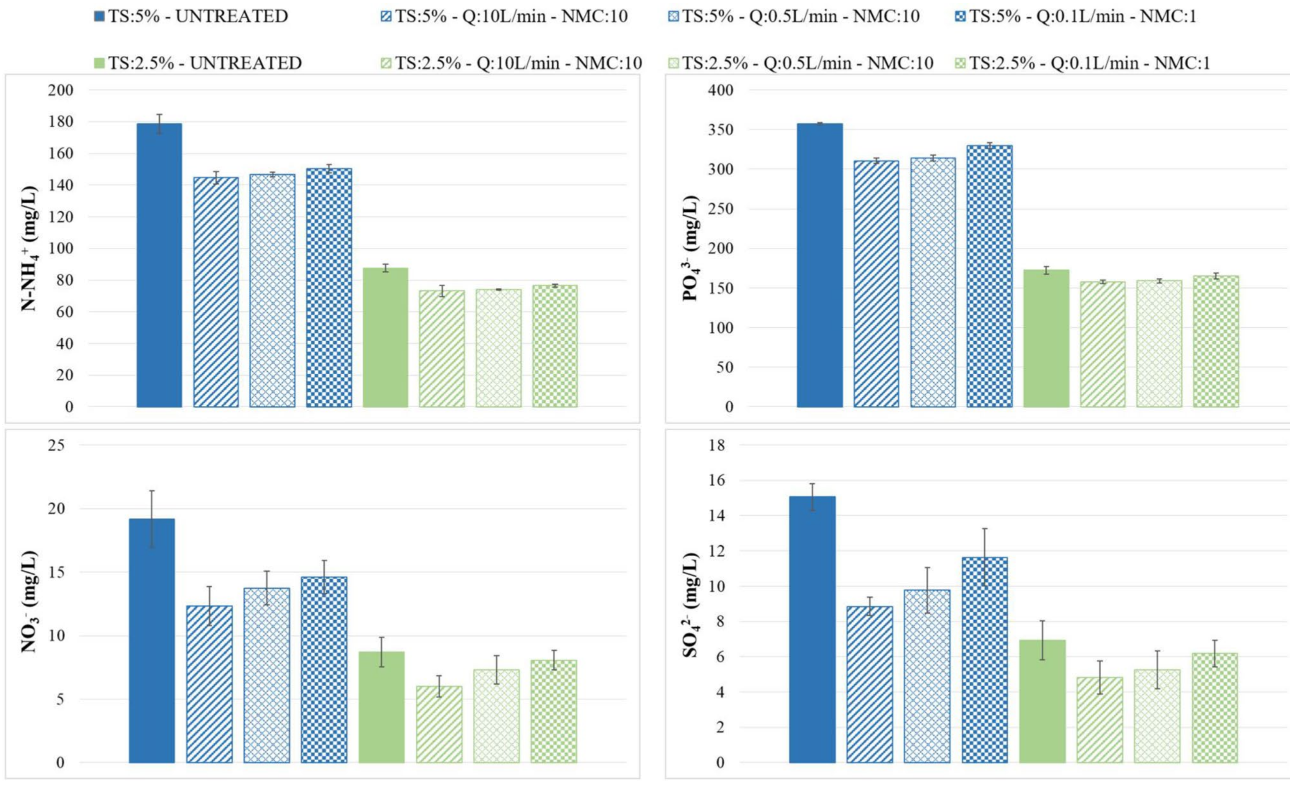


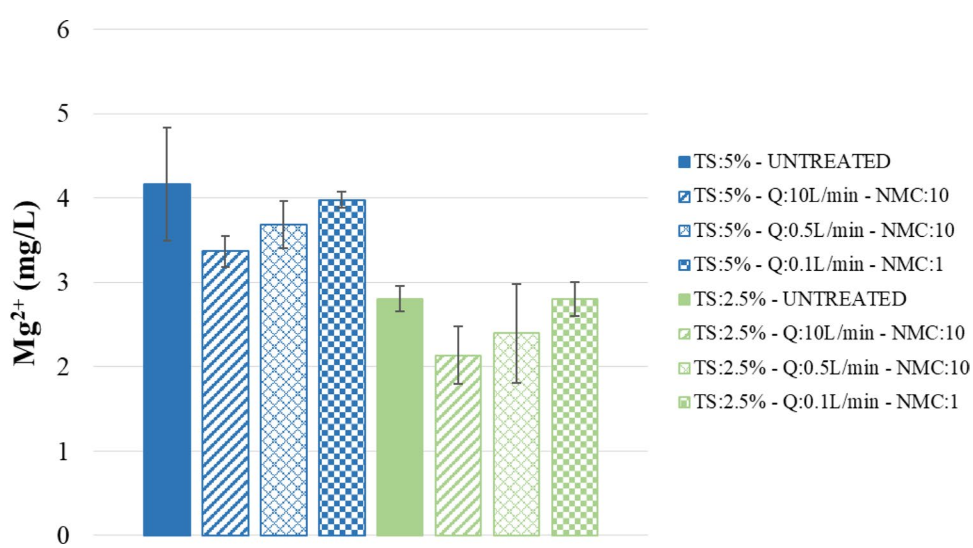
Fig. 3 Concentrations of NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} before and after SMF pretreatments in S2

were less pronounced than those obtained at higher Q and NMC values.

These results indicate that increasing sewage sludge exposure to the applied high-intensity SMF promotes the precipitation of different ionic species, which is consistent with observations on S1 experiments. Similar results are reported in studies dealing with calcium carbonate precipitates in natural waters [23, 24], where increasing the exposure of the treated matrix to the SMF resulted in an improved precipitation of calcium carbonate.

Magnesium concentration was also monitored during S2 (Fig. 4) to have an indication on the possible precipitation of struvite. Results indicate that, as already observed for the other ions, the higher reduction of Mg^{2+} in solution

Fig. 4 Concentrations of Mg^{2+} before and after SMF pretreatments in S2



was obtained at the conditions of maximum exposure to the applied SMF (Q = 10 L/min, NMC = 10), resulting in average reduction of Mg^{2+} concentration by 19.2% at 5%TS and by 23.9% at 2.5%TS, respectively.

Impact of the SMF on the Solid Phase of Sewage Sludge

A mineralogical characterization of the solid phase was carried out by XRD analysis to verify the co-precipitation of different crystalline phases due to the application of the high-intensity SMF. Figure 5 shows the XRD patterns of the solid phases related to S2 tests at 2.5%TS (Fig. 5a) and 5%TS (Fig. 5b). All samples show an amorphous band in the 2θ range equal to 15–35° due to the presence of an amorphous phase. Moreover, there are multiple diffraction peaks that can be associated with the co-presence of different crystalline phases. In particular, there are diffraction peaks of calcite ($CaCO_3$) [JPCDS card no. 1–72-1214] and quartz (SiO_2) [JPCDS card no. 1–83-2466], which were the main crystalline phases identified at both TS concentrations. Furthermore, there are other crystalline phases associable with phosphate precipitates, i.e., struvite ($MgNH_4PO_4 \cdot 6H_2O$) [JPCDS card no. 1–77-2303]), aluminum phosphate ($AlPO_4$) [JPCDS card no 1–76-226], iron phosphate ($Fe_3H_{8.5}O_{13.5}P_2$) [JPCDS card no 17–472], potassium phosphorus nitride sulfide ($K_6N_{14}P_{12}S_{12}$) [JPCDS card no 1–70-222]), iron nitrate hydrate ($Fe_4NO_3(OH)_{11} \cdot 2H_2O$) [JPCDS card no. 44–519], potassium nitrate (KNO_3) [JPCDS card no. 2–991]) and silicoaluminates ($KAlSi_3O_8$ [JPCDS card no. 1–84-1455], $Al_2H_2K_2Na_2O_8Si$ [JPCDS card no. 43–47]). As the peak area is proportional to the weight percentage of the corresponding crystalline phase, it can be observed that the amount of crystalline precipitates increases when exposure to the applied SMF increases (higher Q and NMC values). This effect is even more evident with the increase of the flow rate and, at the same flow rate, with the increase of the NMC, in agreement with the literature [23].

The application of the SMF to sewage sludge at 5%TS (Fig. 5b) has determined effects similar to those verified at 2.5%TS in terms of type of precipitates, except for struvite, being the related peaks more visible at 2.5%TS than at 5%TS. In general, peak intensities were slightly higher at 2.5%TS than at 5%TS. This is justified by the fact that the effect of the magnetic treatment on the precipitation process is more pronounced for solutions characterized by a lower concentration of ions. For this reason, to increase the quantity of precipitates in sewage sludge at high solid content it is necessary to increase the SMF intensity or sewage sludge exposure by applying higher values of Q and NMC [23].

Impact of the SMF on Methane Production

Figure 6 compares the cumulative CH_4 production obtained from the anaerobic digestion tests performed in S1. Results show that the application of 1.5 T SMF negatively affected the CH_4 production. The highest CH_4 production of 181(± 2) L_{CH4}/kg_{VS} was obtained with non-magnetized sludge (control test), while feeding the reactors with partially magnetized sludge resulted in 1.8–25.7% lower biomethane potential. The increase of MR decreased CH_4 production in all tests at similar TS concentration and NMC, e.g., at 2.5%TS and NMC = 1, only 135(± 11) L_{CH4}/kg_{VS} was produced when the MR was 2 (test H), while methane production was 162(± 3) L_{CH4}/kg_{VS} (test E) at MR of 0.5.

Observing the trend of the specific biomethane production (Fig. 6), an initial lag-phase of 2 days can be observed for each production curve subjected to the application of the SMF. This suggests that, although resulting in lower methane generation, the high-intensity SMF is not lethal for microorganisms. It is possible that the SMF induced an adaptive phase on the microbial community followed by the recovery

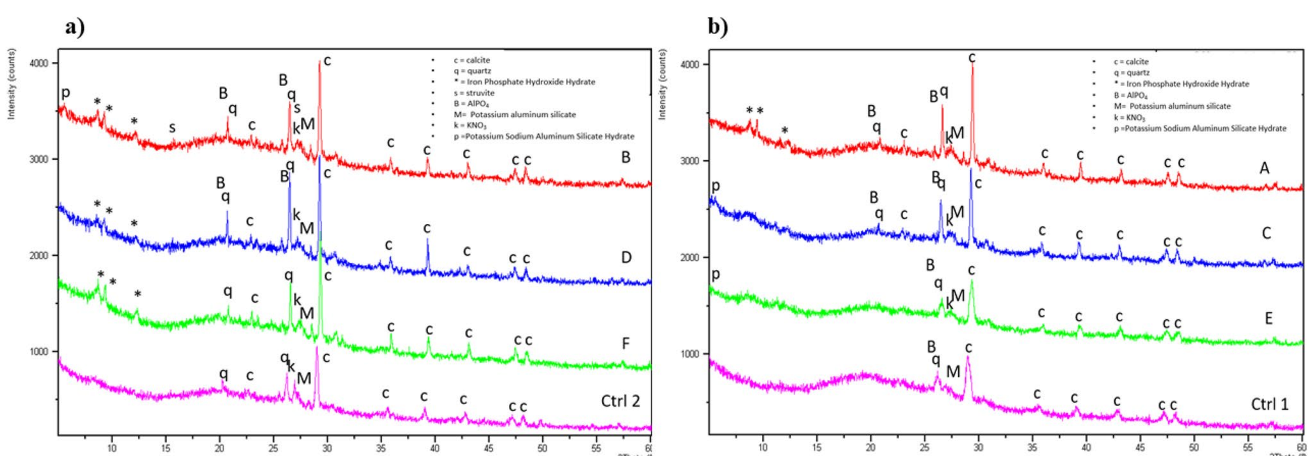


Fig. 5 XRD patterns for S2 tests (*A*–*H*) at **a)** 2.5%TS and **b)** 5%TS

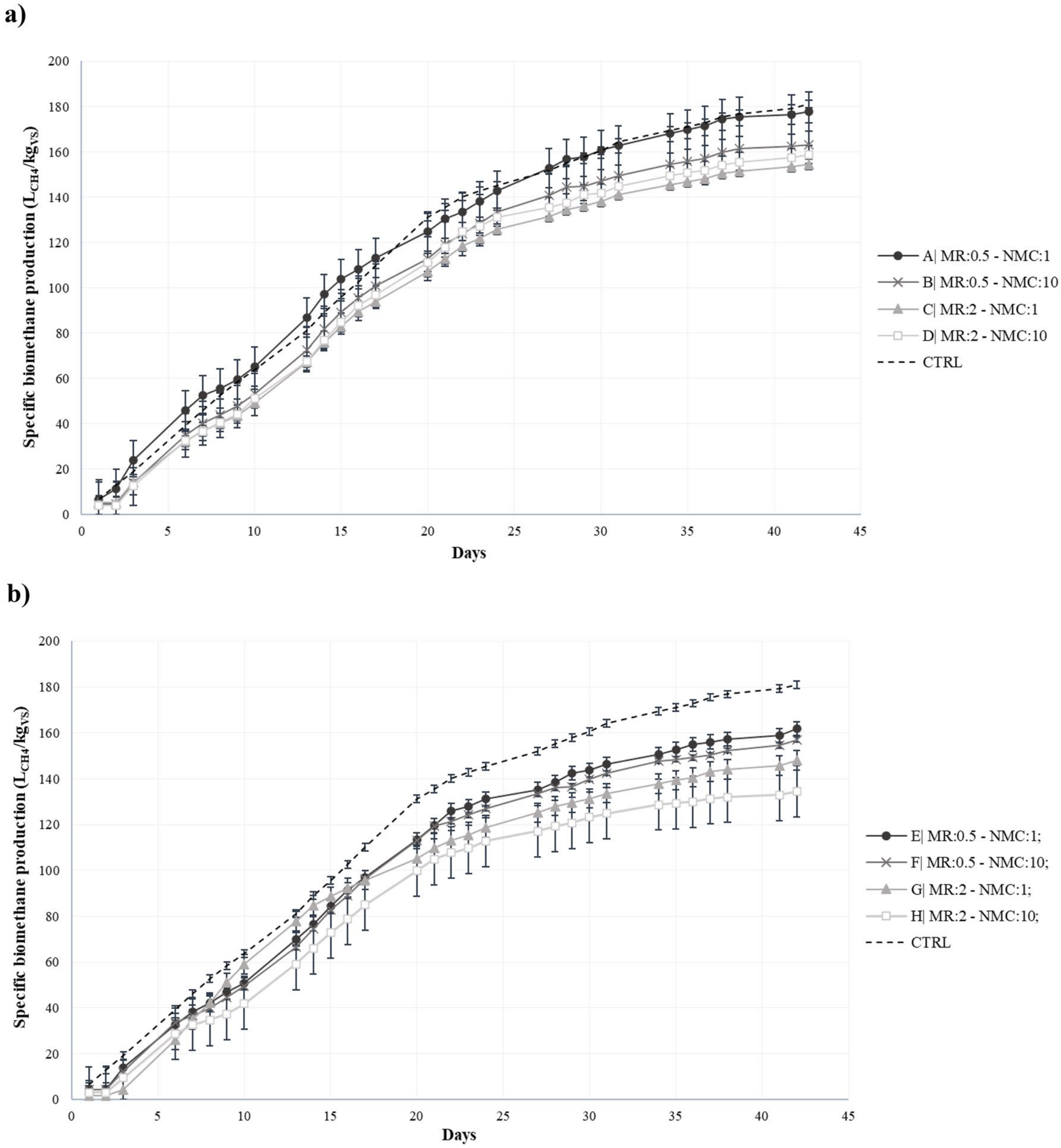


Fig. 6 Biomethane production of S1 tests at **a**) 5%TSand **b**) 2.5%TS

of CH_4 production. Comparing the different final biomethane productions (Table S4), slightly lower productions can be noted for the tests conducted at 2.5%TS compared to the tests conducted at 5%TS. This could be likely due to a lower intake of micro- and macro-nutrients available to microorganisms during the digestion process, which can be linked to the formation of precipitates discussed above and is in agreement with studies reported in the literature [25–27] highlighting that micro and macro nutrients are essential for the growth of microorganisms, to survive and carry out their cell metabolism. No significant effects of NMC were observed on CH_4 production at the tested values. Therefore, it can be concluded that the MR was the key parameter influencing CH_4 production of the magnetized sludge, as increasing the share of magnetized over non-magnetized sewage sludge negatively affected methane production. Nonetheless, the differences in methane generation at different MR values were not enormous due to the presence of a certain amount of non-magnetized sewage sludge.

Magnetization produced no differences in terms of pH, as the pH of magnetized and non-magnetized sludge of S1 was the same (6.9 ± 0.1) (Table S5). Similarly, no significant differences due to magnetization were observed in the profiles and accumulation of VFA during the anaerobic digestion process (Fig. S1). Indeed, the maximum concentration of all VFA identified in S1 tests (acetic, propionic, butyric, and citric) remained well below the inhibitory thresholds for methanogens [28]. Therefore, the detrimental impact of high-intensity magnetization to the anaerobic digestion process could depend on inhibition of bacterial growth due to direct impact of magnetic field [29, 30] and/or to the lack of micronutrients as discussed above.

The results of biomethanation tests performed in S2 confirmed the detrimental impact of magnetization, which was even more significant compared to S1 as anaerobic digestion reactors in S2 were loaded with the sole magnetized sludge under the selected operating conditions. Figure 7 shows that the highest decrease of CH_4 production over the control bioreactors was observed in test A (24%) performed at the maximum exposure conditions (Q = 10 L/min, NMC = 10), followed by C (22%) and E (9%) for the tests at 5%TS. Similar results were obtained at 2.5%TS, as the maximum reduction was observed for test B (21%), followed by D (13%) and F (3%). These results further confirm that the greater is the exposure to the applied SMF, the lower is the production of CH_4. Furthermore, it can be observed that, under the same NMC, the greater reduction in CH_4 production was obtained when the applied Q was higher (A vs C and B vs D). These results are in agreement with Mascolo [23], highlighting that the exposure to the magnetic field and the consequent induced effect is more evident at higher flow rates.

Practical Implications and Future Research Perspectives

Our study clearly indicates that the application of a high-intensity (1.5 T) SMF has a detrimental impact on anaerobic digestion in terms of methane production. However, this negative impact is reduced or even ruled out if sludge exposure to SMF is limited, i.e., when $Q \leq 0.1$ L/min, $MR \leq 0.5$ and NMC = 1 are applied for magnetization. Further research should elucidate the primary cause of anaerobic digestion inhibition following exposure to the high-intensity SMF.

On the other hand, this study shows for the first time that applying a high-intensity SMF significantly reduces ionic concentrations in the sludge and leads to the precipitation of nutrient-based compounds with potential fertilizing properties such as struvite. This suggests a potential application of high-intensity magnetization on sewage sludge digestate, which could be exploited in a circular economy perspective. Indeed, agricultural application of hygienized sewage sludge is considered a best practice, as it couples the recycling of nutrients and organic matter and reduces landfilling of sewage sludge, resulting also in lower disposal costs for WWTPs [31]. By applying magnetization directly on the digestate, struvite precipitation could be promoted after digestion, avoiding accumulation within the digester and pumping systems.

This work also shows that the TS content of sewage sludge influences the extent of precipitation, which may reduce struvite crystallization when high-solid digestate,

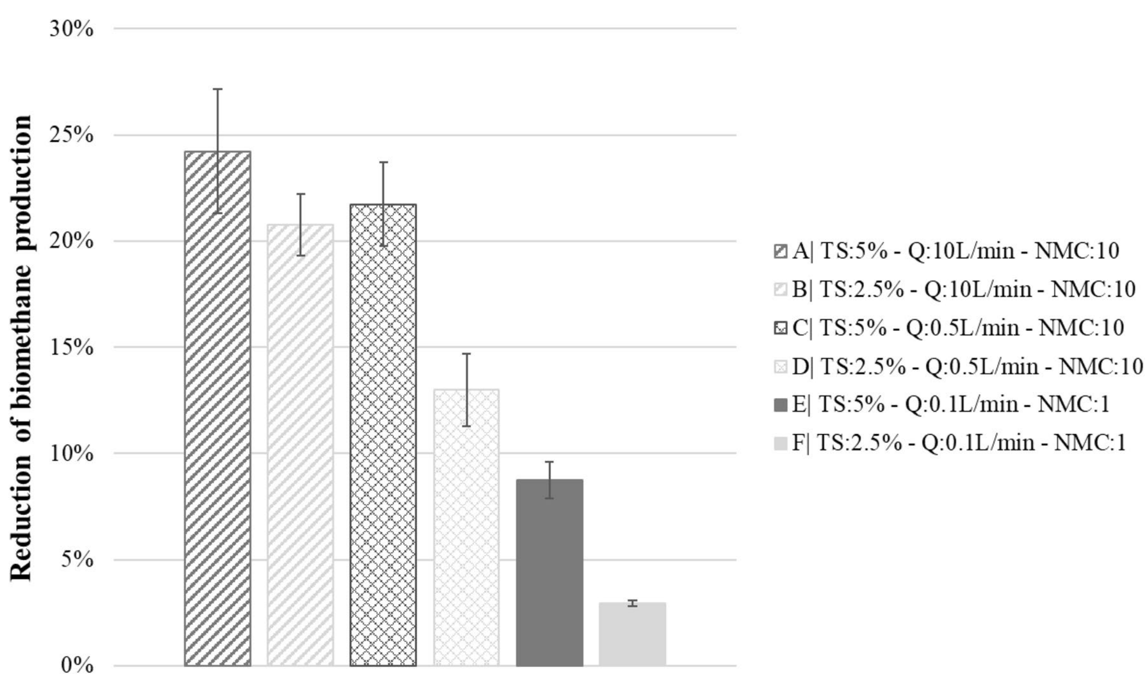


Fig. 7 Reduction in CH_4 production of anaerobic digestion tests in S2

which is often applied in agriculture, is magnetized. Additional research should be carried out to investigate the impact of magnetization on the chemical composition of sewage sludge digestate and elucidate the impact of TS content on struvite precipitation in magnetized sludge.

Conclusions

This study explores the effects of a high-intensity (1.5 T) SMF on the composition and anaerobic digestion of sewage sludge was explored. The experimental results show that the high-intensity SMF is disadvantageous for anaerobic digestion but promotes the precipitation of ionic species, including NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Mg^{2+}, and the generation of struvite. Higher exposure of sewage sludge to the SMF, provided by increasing Q, MR and NMC, resulted in the higher reduction of ionic concentrations in the liquid phase (up to 19.1% for NH_4^+, 35.7% for NO_3^-, 13% for PO_4^{3-}, 41.2% for SO_4^{2-} and 23.9% for Mg^{2+}) and in lower methane generation. The detrimental effect on anaerobic digestion could be due to an adverse impact of the high-intensity SMF on the structure/metabolism of bacterial communities as well as on the decreased availability of micro- and macro-nutrients in the liquid phase after magnetization. Notwithstanding the negative effects in terms of methane generation, experimental evidence seems promising when focused on the formation of precipitates: among others, the generation of struvite was, indeed, observed in this study in magnetized sewage sludge at low TS content (2.5%TS). This may be of strategic importance if the application of the SMF is considered as a post-treatment on ADS to improve its fertilizing properties. In this regard, further studies are necessary to better understand the mechanisms promoting the formation of target precipitates and consequently the recovery of valuable compounds according to the principles of circular economy and sustainable development.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12649-022-01891-x.

Acknowledgements The authors wish to thank AMS company for providing the magnetic polarizer used for the study. Alessandra Cesaro would like to thank the former Italian Ministry of Education, University and Research (MIUR) who provided financial support for her position as Assistant Professor in the frame of the research project entitled "Dipartimenti di Eccellenza" per Ingegneria Civile Edile e Ambientale-CUPE65D18000820006.

Author Contributions Conceptualization: NDC, AC, FDC, MCM, FP, GE; writing-original draft preparation: NDC, AC, FDC, MCM; writing-review and editing: NDC, AC, FDC, MCM, FP, GE; visualization: NDC, AC, FDC, MCM; supervision: AC, FDC, MCM, GE; lab work NDC; project administration: AC, FDC, FP, GE; funding acquisition: FDC, FP, G.E. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by Università degli Studi di Napoli Federico II within the CRUI-CARE Agreement. This research was funded by Istituto Nazionale Previdenza Sociale (INPS) and Programma Operativo Nazionale (PON) 2014/2020-BIOFEEDSTOCK Project.

Data Availability The datasets generated during the current study are available from the corresponding author on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Di Capua, F., Spasiano, D., Giordano, A., et al.: High-solid anaerobic digestion of sewage sludge: challenges and opportunities. Appl. Energy **278**, 115608 (2020). https://doi.org/10.1016/j.apenergy.2020.115608
2. Di Capua, F., Adani, F., Pirozzi, F., et al.: Air side-stream ammonia stripping in a thin film evaporator coupled to high-solid anaerobic digestion of sewage sludge: process performance and interactions. J. Environ. Manag. **295**, 113075 (2021). https://doi.org/10.1016/j.jenvman.2021.113075
3. Pilli, S., Bhunia, P., Yan, S., et al.: Ultrasonic pretreatment of sludge: a review. Ultrason. Sonochem. **18**, 1–18 (2011). https://doi.org/10.1016/j.ultsonch.2010.02.014
4. Carrère, H., Dumas, C., Battimelli, A., et al.: Pretreatment methods to improve sludge anaerobic degradability: a review. J. Hazard. Mater. **183**, 1–15 (2010). https://doi.org/10.1016/j.jhazmat.2010.06.129
5. Bougrier, C., Delgenès, J.-P., Carrère, H.: Combination of thermal treatments and anaerobic digestion to reduce sewage sludge quantity and improve biogas yield. Process. Saf. Environ. Prot. **84**, 280–284 (2006). https://doi.org/10.1205/psep.05162
6. Ferrer, I., Ponsá, S., Vázquez, F., Font, X.: Increasing biogas production by thermal (70°C) sludge pre-treatment prior to thermophilic anaerobic digestion. Biochem. Eng. J. **42**, 186–192 (2008). https://doi.org/10.1016/j.bej.2008.06.020
7. Otieno, B., Apollo, S., Kabuba, J., et al.: Ozonolysis pre-treatment of waste activated sludge for solubilization and biodegradability enhancement. J. Environ. Chem. Eng. **7**, 102945 (2019). https://doi.org/10.1016/j.jece.2019.102945
8. Merrylin, J., Kumar, S.A., Kaliappan, S., et al.: Biological pretreatment of non-flocculated sludge augments the biogas production in the anaerobic digestion of the pretreated waste activated

sludge. Environ. Technol. **34**, 2113–2123 (2013). https://doi.org/10.1080/09593330.2013.810294
9. Morello, R., Di Capua, F., Pontoni, L., et al.: Microaerobic digestion of low-biodegradable sewage sludge: effect of air dosing in batch reactors. Sustainability **13**, 9869 (2021). https://doi.org/10.3390/su13179869
10. Giordano, A., Di Capua, F., Esposito, G., Pirozzi, F.: Long-term biogas desulfurization under different microaerobic conditions in full-scale thermophilic digesters co-digesting high-solid sewage sludge. Int. Biodeterior. Biodegrad. **142**, 131–136 (2019). https://doi.org/10.1016/j.ibiod.2019.05.017
11. Zieliński, M., Rusanowska, P., Dębowski, M., Hajduk, A.: Influence of static magnetic field on sludge properties. Sci. Total Environ. **625**, 738–742 (2018). https://doi.org/10.1016/j.scitotenv.2017.12.226
12. Zieliński, M., Zielińska, M., Cydzik-Kwiatkowska, A., et al.: Effect of static magnetic field on microbial community during anaerobic digestion. Bioresour. Technol. (2021). https://doi.org/10.1016/j.biortech.2020.124600
13. Zieliński, M., Dębowski, M., Kazimierowicz, J.: The effect of static magnetic field on methanogenesis in the anaerobic digestion of municipal sewage sludge. Energies **14**, 590 (2021). https://doi.org/10.3390/en14030590
14. Niu, C., Geng, J., Ren, H., et al.: The strengthening effect of a static magnetic field on activated sludge activity at low temperature. Bioresour. Technol. **150**, 156–162 (2013). https://doi.org/10.1016/j.biortech.2013.08.139
15. Filipič, J., Kraigher, B., Tepuš, B., et al.: Effects of low-density static magnetic fields on the growth and activities of wastewater bacteria *Escherichia coli* and *Pseudomonas putida*. Bioresour. Technol. **120**, 225–232 (2012). https://doi.org/10.1016/j.biortech.2012.06.023
16. Hou, L., Liu, Y., Fan, S., Li, J.: Magnetic field enhanced denitrification efficiency of immobilized bacterial particles. Water Sci. Technol. **81**, 622–629 (2020). https://doi.org/10.2166/WST.2020.156
17. Dini, L., Abbro, L.: Bioeffects of moderate-intensity static magnetic fields on cell cultures. Micron **36**, 195–217 (2005). https://doi.org/10.1016/j.micron.2004.12.009
18. Yadollahpour, A., Rashidi, S., Ghotbeddin, Z., et al.: Electromagnetic fields for the treatments of wastewater: a review of applications and future opportunities. J. Pure Appl. Microbiol. **8**, 3711–3719 (2014)
19. Krzemieniewski, M., Dębowski, M., Janczukowicz, W., Pesta, J.: Effect of the constant magnetic field on the composition of dairy wastewater and domestic sewage. Polish. J. Environ. Stud. **13**, 45–53 (2004)
20. Di Capua, F., de Sario, S., Ferraro, A., et al.: Phosphorous removal and recovery from urban wastewater: current practices and new directions. Sci. Total Environ. **823**, 153750 (2022). https://doi.org/10.1016/j.scitotenv.2022.153750
21. Federation, W.E.: Standard methods for the examination of water and wastewater standard methods for the examination of water and wastewater. Public Health **51**, 940–940 (1999). https://doi.org/10.2105/AJPH.51.6.940-a
22. Di Capua, F., Mascolo, M.C., Pirozzi, F., Esposito, G.: Simultaneous denitrification, phosphorus recovery and low sulfate production in a recirculated pyrite-packed biofilter (RPPB). Chemosphere **255**, 126977 (2020). https://doi.org/10.1016/j.chemosphere.2020.126977
23. Mascolo, M.C.: Effect of magnetic field on calcium carbonate precipitated in natural waters with prevalent temporary hardness. J. Water Process. Eng. **41**, 102087 (2021). https://doi.org/10.1016/j.jwpe.2021.102087
24. Kobe, S., Dražić, G., Cefalas, A.C., et al.: Nucleation and crystallization of $CaCO_3$ in applied magnetic fields. Cryst. Eng. **5**, 243–253 (2002). https://doi.org/10.1016/S1463-0184(02)00035-7
25. Thanh, P.M., Ketheesan, B., Yan, Z., Stuckey, D.: Trace metal speciation and bioavailability in anaerobic digestion: a review. Biotechnol. Adv. **34**, 122–136 (2016). https://doi.org/10.1016/j.biotechadv.2015.12.006
26. Choong, Y.Y., Norli, I., Abdullah, A.Z., Yhaya, M.F.: Impacts of trace element supplementation on the performance of anaerobic digestion process: a critical review. Bioresour. Technol. **209**, 369–379 (2016). https://doi.org/10.1016/j.biortech.2016.03.028
27. Maharaj, B.C., Mattei, M.R., Frunzo, L., et al.: A general framework to model the fate of trace elements in anaerobic digestion environments. Sci. Rep. **11**, 1–19 (2021). https://doi.org/10.1038/s41598-021-85403-2
28. Wang, Y., Zhang, Y., Wang, J., Meng, L.: Effects of volatile fatty acid concentrations on methane yield and methanogenic bacteria. Biomass Bioenergy **33**, 848–853 (2009). https://doi.org/10.1016/j.biombioe.2009.01.007
29. Ji, Y., Wang, Y., Sun, J., et al.: Enhancement of biological treatment of wastewater by magnetic field. Bioresour. Technol. **101**, 8535–8540 (2010). https://doi.org/10.1016/j.biortech.2010.05.094
30. Mousavian-Roshanzamir, S., Makhdoumi-Kakhki, A.: The inhibitory effects of static magnetic field on *Escherichia coli* from two different sources at short exposure time. Rep. Biochem. Mol. Biol. **5**, 112–116 (2017)
31. Di Costanzo, N., Cesaro, A., Di Capua, F., Esposito, G.: Exploiting the nutrient potential of anaerobically digested sewage sludge: a review. Energies **14**, 1–26 (2021). https://doi.org/10.3390/en14238149

Authors and Affiliations

Nicola Di Costanzo[1] · Francesco Di Capua[2] · Alessandra Cesaro[1] · Maria Cristina Mascolo[3] · Francesco Pirozzi[1] · Giovanni Esposito[1]

[1] Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, via Claudio 21, 80125 Naples, Italy

[2] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via E. Orabona 4, 70125 Bari, Italy

[3] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via Gaetano di Biasio 43, 03043 Cassino, Italy