JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2023, 24(11), 294–302
https://doi.org/10.12911/22998993/171562
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.08.09
Accepted: 2023.08.31
Published: 2023.09.18

The Impact of Electric Current for Sewage Sludge Characteristics from Anaerobic Sequencing Bio-Electrochemical Treatment of Sewage Generated During Soilless Tomato Cultivation

Kamil Łukasz Bryszewski[1*], Joanna Rodziewicz[1], Artur Mielcarek[1], Wojciech Janczukowicz[1], Karolina Kłobukowska[1], Joanna Nowosad[2]

[1] University of Warmia and Mazury in Olsztyn, Department of Environment Engineering, Warszawska St. 117a, Olsztyn 10-719, Poland

[2] ChemProf, Department of Research and Development, Gutkowo 54B, Olsztyn 11-041, Poland

[*] Corresponding author's email: kamil.bryszewski@uwm.edu.pl

ABSTRACT

The aim of the present study was to determine: the impact of electric current density on the quantity and quality of sewage sludge produced in anaerobic sequencing bio-electrochemical reactor (AnSBBER) with an iron electrode during the treatment of drainage from soilless cultivation of tomatoes. Direct electric current (DC) effect was determined at its following densities (J): 0.63 A/m^2 (R1), 1.25 A/m^2 (R2), 2.5 A/m^2 (R3), and 5 A/m^2 (R4). Sodium acetate in (C:N) ratio of 1.0 was supplied to the reactors to ensure the proper biofilm development. Contents of elements (K, P, S, Na, Al, Cu, Fe, Mn, Mo, Zn, Mg, C, N and Ca) in the biofilm were determined. Additionally, the content of total suspended solids and the percentage share of volatile suspensions (VSS) in the sludge were determined. The study showed that the organic matter content in the sludge corresponded to the values typical of the stabilized sludge (up to 28.8% d.m. in R2).The increase in electric current density caused an increase in the concentration of phosphorus in the formed sludge (from 6.34 to 8.00% d.m. in 0.63 and 5.00 A/m^2, respectively). The analyzed sludge, compared to municipal sludge from wastewater treatment plants with biological reactors and activated sludge chambers, is richer in such elements as phosphorus, nitrogen, calcium, magnesium, potassium, sodium, and iron.

Keywords: sewage from soilless tomato cultivation, , anaerobic sequencing batch bio-electrochemical reactor (AnSBBER), sludge, macro and micro-elements

INTRODUCTION

The industrialization of agriculture entails, among other things, growing plants under complete control. An example in this case can be the soilless cultivation of plants in greenhouses or film tents, where temperature, humidity, sunlight, water supply, and composition of nutrient medium fed to the root system are continuously controlled.

Two agrotechnical treatments – irrigation and fertilization – are used simultaneously in soilless cultivation systems. These combined treatments are called fertigation. Fertigation allows, above all, to reduce the consumption of water and fertilizers and to use solutions in doses and dates optimal for plants, which promotes higher yields [Breś et al. 2012].

Breś et al. [2012] emphasized that nutrient medium doses applied in soilless cultivation systems exceed nutritional demands of plants. This is due to the need to stabilize the chemical composition of solutions in the rhizosphere as well as the pH value and electrolytic conductivity (EC) of nutrient media.

Crops cultivated in the soilless system require systematic irrigation coupled with the feeding of complete nutrient media, in which the amount of nutrients needs to be adjusted not only to cultivation system type but also to the developmental stage of the plants of a given variety and to weather conditions. The composition of the media should be precisely determined and they should be properly dosed in these cultivation systems [Dyśko et al. 2014].

Plants absorb 16 basic elements from air, water and fertilizers for proper growth and development. These include: carbon (C), hydrogen (H), oxygen (O), phosphorus (P), potassium (K), nitrogen (N), sulfur (S), calcium (Ca), magnesium (mg), iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), and chlorine (Cl). Also silicon (Si) proves useful in hydroponic tomato cultivation as it promotes plant growth when applied in small doses. Wrong amount of any nutrient upsets plant metabolism, which can lead to a crop yield decrease [Dyśko et al. 2014].

Preparation of the nutrient medium requires knowledge of the chemical composition of water. According to recommendations in force, the total salt concentration in water should not exceed 160 mg/dm^3 for highly sensitive plants and 800 mg/dm^3 for plants tolerating high salinity. When establishing the composition of nutrient media, account should be taken of all water components, with particular attention paid to the concentrations of calcium, magnesium, sulfates, and chlorides.

The highest assimilability of most elements in hydroponic crops was recorded at pH 5.5–5.8. Therefore, the pH values of nutrient media are adjusted by acid addition (usually nitric, phosphoric and hydrochloric acids). The nutrient concentration in the medium is determined based on the specific electrical conductivity (EC) of the solution and expressed in MS/cm. The average EC values of hydroponic media range from 1.5 to 4.5 MS/cm [Dyśko et al. 2014]. In addition to the macroelements shown in Table 1, microfertilizers containing 6 micronutrients are also used for media preparation (Table 2) [Dyśko et al. 2014].

The composition of wastewater discharged from facilities for soilless cultivation of plantsis a resultant of the qualitative and quantitative characteristics of the nutrient medium and the efficiency of uptake of macronutrients and micronutrients by plants. The need to treat this type of wastewater has been growing for years. It is also recommended to be recirculated and re-used in crop fertilization and irrigation. However, the owners of the facilities point to difficulties and threats associated with these processes. The main problem in the soilless cultivation with the recirculated nutrient system is the proper balancing of all nutrients and the risk of pathogens [Dyśko et al. 2014]. Therefore, it is widely believed that wastewater should be treated regardless of its intended use, even though the Directive does not specify quality requirements for effluents of this type [Dz. U. L 135 z 30.5.1991].

Among the implemented technological solutions, increasing attention is paid to reactors with a biofilm. Research conducted by Rodziewicz et al. [2019] with aerobic biological, electrochemical and bio-electrochemical rotating contactors demonstrated that such reactors have a whole range of limitations and often fail to ensure effective wastewater treatment that would allow for its discharge to the natural environment [Dz.U. 2019 poz. 1311]. But very promising results were obtained in the case of another biological membrane

Table 1. Basic macronutrient fertilizers used in the preparation of nutrient solutions

Name of fertilizer	Chemical formula	The content of nutrients
Greenhouse calcium nitrate	$Ca(NO_3)_2$	N – 15.5% (NO_3 – 14.5%, NH_4 – 1%), Ca – 19%
Potassium nitrate	KNO_3	N – 13.5%, K – 38%
Magnesium nitrate	$Mg(NO_3)_2$	N – 10.8%, Mg – 9.4%
Ammonium sulphate	NH_4NO_3	N – 34% (NO_3 – 17%, NH_4 – 17%)
potassium sulfate (IV)	K_2SO_4	K – 42%, S – 18%
Magnesium sulphate monohydrate	$MgSO_4 \cdot 1H_2O$	Mg – 16%, S – 17,2%
Magnesium sulphate heptahydrate	$MgSO_4 \cdot 7H_2O$	Mg – 9,6%, S – 13%
Monopotassium phosphate	KH_2PO_4	P – 23%, K – 28%
Monoammonium phosphate	$NH_4H_2PO_4$	N-NH_4 – 12%, P – 26,7%
Calcium chloride	$CaCl_2 \cdot 6H_2O$	Ca – 18%, Cl – 32%
Potassium chloride	KCl	K – 51,6%, Cl – 47%

Table 2. Examples of the most common micronutrient fertilizers used in hydroponic nutrient solutions

Name of fertilizer	The content of nutrients
Borax	B – 11%, Na – 12%
Boric acid	B – 17.5%
Chelate boron Symphony B	B – 20%
Zinc chelate Librel EDTA	Zn – 14%
Zinc chelate Symphony Zn EDTA	Zn – 10%
Zinc sulphate $1H_2O$	Zn – 33%, S-SO_4 – 16%
Zinc sulphate $7H_2O$	Zn – 23%, S-SO_4 – 11%
Manganese chelate Librel EDTA	Mn – 12,8%
Manganese chelate Symphony Mn EDTA	Mn – 10%
Manganese chelate Mikrovit Mn EDTA	Mn – 3%
Manganese sulphate $1H_2O$	Mn – 32%, S-SO_4 – 18%
Manganese sulphate $4H_2O$	Mn – 25%, S-SO_4 – 14%
Copper chelate Forte HEEDTA	Cu – 12%
Copper chelate Librel EDTA	Cu – 14%
Copper chelate Symphony Cu EDTA	Cu – 10%
Copper sulfate $5H_2O$	Cu – 25.2%, S-SO_4 – 12%
Ammonium molybdate	Mo – 49%, N-NH_4 – 9.2%
Sodium molybdate	Mo – 39%, Na – 18%
Chelate of molybdenum Symphony Mo	Mo – 10%
Iron chelate Librel SP DTPA	Fe – 6%
Iron chelate Librel Fe-DP DTPA	Fe – 7%
Iron chelate Librel Fe – DP6L	Fe – 6%
Iron chelate Librel Fe – HI	Fe – 7%
Iron chelate Librel Fe – LO	Fe – 13.2%
Iron chelate Tenso EDDHMA	Fe – 6%
Iron chelate Forte HEEDTA	Fe – 7%
Iron chelate Symphony Fe EDTA	Fe – 10%
Librel MIX B	Fe – 3.2%, Mn – 1.5%, Zn – 0.6%, B – 0.8%, Cu – 1.6%, Mo – 2.5%
Pionier Mikro	Fe – 1.42%, Mn – 0.54%, Zn – 0.1%, B – 0.2%, Cu – 0.1%, Mo – 0.03%

reactor – anaerobic sequencing SBBER, tested in various technological configurations (biological, electrochemical, bio-electrochemical reactors) [Bryszewski et al. 2018; Bryszewski et al. 2022; Bryszewski et al. 2021] .

Wastewater treatment by means of biological, electrochemical and bio-electrochemical processes generates a by-product, namely sewage sludge. Less sludge is produced in membrane reactors than in those with activated sludge (suspended biomass), and the volume of biomass discharged from anaerobic reactors is substantially lower than from the aerobic ones [Grady et al. 2011; Metcalf and Eddy 2014].

The volume and quality of sewage sludge is a resultant of the composition of treated wastewater, the technology used and the adopted technological parameters of processes. In the case of electrochemical and bio-electrochemical reactors, the characteristics of the sludge largely depend on the type and density of the electric current and, to some extent, on the materials the electrodes are made of. More sewage sludge is generated in the reactors with direct current (DC) flow than in those with alternative current (AC) flow [Rodziewicz et al. 2023]. Due to the composition of the treated wastewater, sewage sludge generated during the treatment of drainage from the soilless plant cultivation is expected to be rich in macroelements and microelements and can, therefore, be used as soil improver or fertilizer.

The aim of the present study was to determine: the impact of electric current density on the quantity and quality of sewage sludge produced in anaerobic sequencing bio-electrochemical reactor (AnSBBER) with an iron electrode during the treatment of drainage from soilless cultivation of tomatoes. With regard to sludge quality – the scope of the study included determination of the contents of selected macroelements and microelements and organic matter in the sludge.

MATERIALS AND METHODS

The research was conducted using four bioelectrochemical AnSBBER reactors with a volume of 2L each. The reactors contained 5 stainless steel discs (0.12 m diameter) mounted on a vertical shaft. The discs, which served as a cathode, were rotating at the speed of 14 rpm. The anode (sizes: 15 and 23 cm) made of carbon steel was mounted inside the reactor's tank. Chemical composition of discs was as follows: (chemical composition C ≤0.030, Si ≤ 0.75, Mn ≤ 2.25, P ≤0.025, S ≤ 0.01, N ≤ 0.1, Cr 17.00–19.00, Ni 13.00–15.00, Mo ≤ 2.25, and Cu ≤0.5; and that of anode was as follows: C ≤0.12, MN ≤0.60, P ≤0.045, S ≤0.045).

Direct electric current (DC) effect was determined at its following densities (J): 0.63 A/m^2 (R1), 1.25 A/m^2 (R2), 2.5 A/m^2 (R3), and 5 A/m^2 (R4) (Figure 1). The current densities adopted were based on the results of our previous study, according to which above the density current 5 A/m^2 increasing wastewater temperature (to 50 °C, at J = 10 A/m^2) [Rodziewicz et al. 2019]. The power was supplied with a Rohde & Schwarz HMP 4040 power supply device (Munich, Germany).

Figure 1 shows the operating variants of the AnSBBER (R1-R4) reactor.

Sodium acetate was supplied to the reactors to ensure the proper biofilm development. The ratio of carbon to nitrogen in the treated wastewater was C/N=1.0. The first four weeks were the period of reactors' adaptation. Activated sludge from the municipal sewage treatment plant in Olsztyn (PE 270,000) was fed into the reactors to ensure faster achievement of their target efficiency. The sludge was collected from the denitrification chamber. The actual experiment lasted two months after the end of the adaptation period. Analyses were conducted under anaerobic conditions at 20–22°C. Drainage was supplied daily, immediately after the entire reactor contents were discharged. Hydraulic retention time of drainage in the reactor was 24 h.

Contents of elements (K, P, S, Na, Al, Cu, Fe, Mn, Mo, Zn, Mg, and Ca) in the mineralized biofilm were determined via Inductively Coupled Plasma Optical Emission Spectrometry (Avio 220 ICP-OES; Perkin Elmer, USA).

The samples were mineralized in Teflon vessels with the addition of 10 mL of 69–70% nitric acid (Baker Instra-Analyzed Reagent, Phillipsburg, USA), using a microwave mineralizer (Titan Microwave Digestion Systems MPS; Perkin Elmer; USA) in four cycles (I-IV) lasting 70 minutes in total (temperature, pressure, duration, respectively): 170°C, 30 bar, 5 min in cycle I; 190°C, 35 bar, 10 minutes in cycle II; 200°C, 35 bar, 20 minutes in cycle III; and 50°C, 30 bar, 25 minutes in cycle IV.

The percentage contents of nitrogen and carbon in dried biomass from AnSBBER reactors was determined using the Flash 2000 particle analyzer (Thermo Fisher Scientific, Waltham, MA, USA).

The sludge discharged from the reactors was also determined for the contents of:

- dry residue with the gravimetric method (PN-EN 12880:2004),
- dry mineral residue and dry organic residue with the gravimetric method (PN-EN 12879:2004).

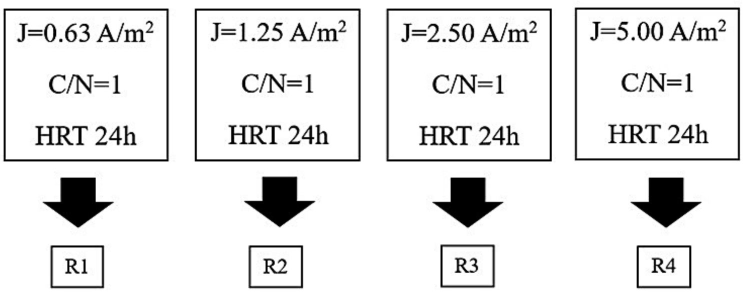

Fig. 1. Applied variants of AnSBBR reactor operation in the conducted studies: (R1-R4 reactors, J – density direct current, HRT – hydraulic retention time, C/N – the ratio of carbon to nitrogen, where sodium acetate was the external source of carbon)

In the manuscript Bryszewski et al. [2022] have been presented results of physicochemical analyses of wastewater inflowing to and outflowing from the reactors (R1-R4), as well as the efficiency of dephosphatation and denitrification processes.

Results and discussion

The content of the total suspended solids in the effluent ranged from 349.5±154.0 mg d.m./L (R1) to 760.4±134.5 mg d.m./L (R4) and increased along with increasing current density (Fig. 2 A). The content of dry organic matter ranged from 23.7% (R2) to 28.8% (R3) – (Fig. 2 B). No specific trend was observed in changes of the organic matter content in the suspended solids; however, the organic matter content below 30% indicates sludge stabilization [Metcalf and Eddy 2014]. The use of a biofilm-based reactor as well as wastewater treatment under anaerobic conditions lead to lesser sewage sludge production [Boavida-Dias et al. 2022].

Turek, Wieczorek and Wolf [2019] reported that the organic matter content of sewage sludge from the municipal sewage treatment plant ranged from 73% to 75%. Sludge stabilization with lime allowed reducing organic fraction content by 30%, i.e., to the value of 43.6%. In the study by Bartkowska et al. [2019], the content of dry organic matter determined during autothermal thermophilic stabilization of sewage sludge from 8 municipal treatment plants ranged from 29% d.m. to 59.4% d.m.

The presented volumes of the generated sewage sludge (Fig. 2) are lower than those obtained in the study by Rodziewicz et al. [2023],where the treatment of synthetic greenhouse effluents in an aerobic reactor at the same current densities generated sewage sludge volumes ranging from 3,873 mg d.m./L to 4,450 mg d.m./L at current densities of 0.63 A/m^2 and 5.00 A/m^2, respectively. In the cited study, the organic matter content in the sludge reached up to 19.88% at HRT 24h and the current density of 0.63 A/m^2, which indicates good stabilization of bio-electrochemical sludge from aerobic rotating-bed reactors. In the study by Bryszewski et al. [2021], during anaerobic treatment of greenhouse effluent using sodium acetate at a dose of C/N=1, the volume of sludge produced increased along with an increasing density of the alternating current, i.e., from 416.0±267.3 mg d.m./L at 4.4 A/m^2 to 1,079.4±251.3 mg d.m./L at 13.3 A/m^2, whereas the organic matter content reached 28.6% and 22.4%, respectively.

Qualitative analyses of sewage sludge (Fig. 3) showed certain trends in the contents of P, C, Ca and Mg, namely their increase in the sludge along with current density increase. The contents of phosphorus and magnesium in the dry matter of

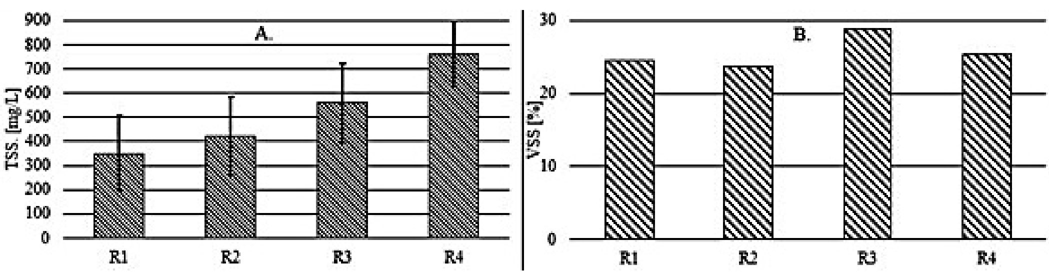

Fig. 2. Total suspended solids (A) and percentage of volatile suspended solids (B)

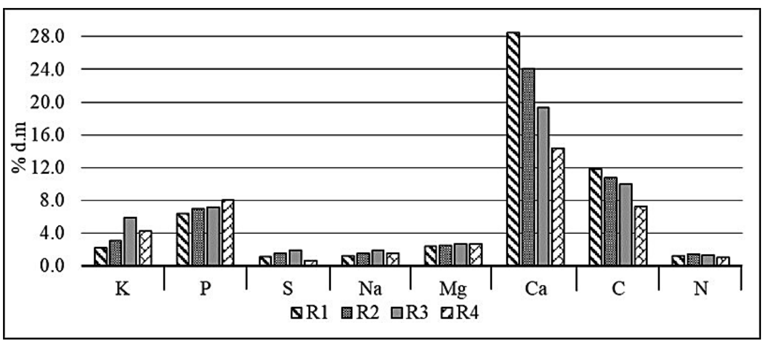

Fig. 3. The content of K, P, S, Na, Mg, Ca, C and N in the excess sludge of wastewater treatment from greenhouse

suspended solids increased with the increase in current density. The highest content of this elements was determined in the suspended solids discharged from reactor R4 (8.00% d.m) operating at the current density of 5 A/m^2, whereas the lowest one in those from reactor R1 (6.34% d.m), operating at the lowest current density tested (0.63 A/m^2). In the case of bio-electrochemical rectors, the phosphorus content in the sludge is due to the electrochemical coagulation of phosphorus, the efficiency of which depends primarily on the electric current density [Sahu, Mazumdar and Chaudhari 2014]. The percentage content of magnesium in the sewage sludge ranged from 2.40% d.m. (R1) to 2.68% d.m. (R4).

An opposite trend was observed in the percentage contents of calcium and carbon in the effluent. The highest content of calcium was determined in the sludge discharged from reactor R1 – 28.50% d.m., and the lowest one in that discharged from reactor R4 – 14.36% d.m., where the wastewater was treated at the highest current density tested. The precipitation of calcium and its diffusion to sewage sludge is affected primarily by effluent pH, which varied upon electric current flow from 5.58±0.80 (R4) to 8.57±0.72 (R1). As posited by Jóźwiak et al. [2018], the precipitation of calcium and phosphorus salts occurs at pH>6.2. The physicochemical analyses conducted in this study demonstrated that pH values measured in reactors R1 and R2 exceeded 8 [Bryszewski et al. 2022]. In the other reactors, they were below 6.2; hence, it is likely that phosphorus removal in these reactors was largely due to electrocoagulation.

The percentage content of carbon was between 7.25 and 11.79% d.m. Its highest value was determined in reactor R1 and the lowest one in reactor R4. The carbon content is due to the growth of autotrophic and heterotrophic microorganisms as a result of providing an external source of carbon in the form of sodium acetate. A lower percentage carbon content determined at higher electric current densities may result, among other things, from a higher fraction of chemical sludge.

Trends observed in the changes of the contents of the above elements are consistent with the results of physicochemical analyses of effluent described by Bryszewski et al. [2022]. Similar trends in the contents of phosphorus, carbon, calcium and magnesium have also been reported by Bryszewski et al. [2021]. The maximal contents of magnesium and phosphorus were determined at the highest AC density tested (13.3 A/m^2), i.e., 3.70% d.m. and 2.10%, respectively. In the cited work, the percentage contents of carbon and calcium decreased with current intensity increase (4.4–13.3 A/m^2) from 6.30% d.m. to 4.70% d.m. and from 31.00% d.m. to 22.55% d.m., respectively. Kłodowska et al. [2018] obtained a maximal phosphorus content of 0.17% d.m. in the sewage sludge produced during the treatment of synthetic municipal wastewater with a low C/N ratio (C/N=1.5) using citric acid as an external carbon source and electric current with a density of 210 mA/m^2.

The mean contents of phosphorus and nitrogen reported in this study are higher than in typical municipal sewage treated using activated sludge and biological reactors, which on average range from 0.9–1.5% d.m. for phosphorus and from 2.0–6.7% d.m. for magnesium [Podedworna and Umiejewska 2008]. According to Bartkowska, Biedka and Talałaj [2019], the stabilized municipal sludge contains from 1.07 to 5.60% d.m. of phosphorus, from 1.60 to 8.80% d.m. of calcium, and from 0.08% to 1.31% d.m. of magnesium.

The percentage content of potassium exceeded 5% (5.87% d.m) only in the sludge from reactor R3. The minimal content of potassium one was 2.14% d.m. (R1). Even lower values were determined for S and Na, i.e., 0.57% d.m. (R4) – 1.9% d.m. (R3), and 1.16% d.m. (R1) – 1.89% d.m. (R3), respectively. A similar percentage

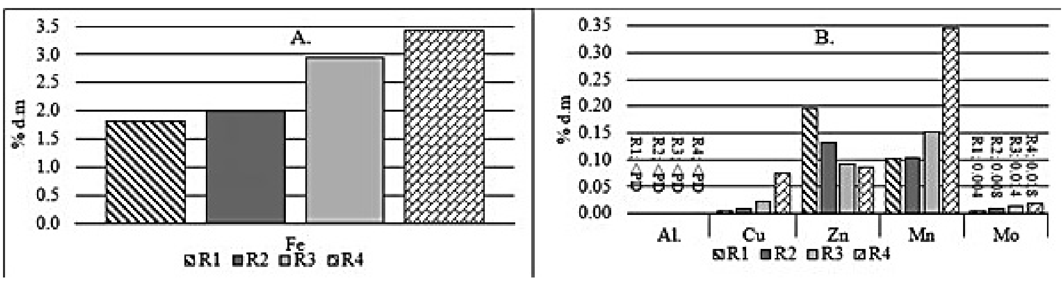

Fig. 4. The content of Fe (A) and Mn, Mo, Al, Cu, Zn (B) in the excess sludge (PD- below the detection threshold)

content of nitrogen in the sewage sludge was recorded in R2 and R3, where it reached 1.35% d.m. and 1.32% d.m., respectively. The lowest N content in the sludge (1.00% d.m.) was determined at the highest electric current density tested. The content of nitrogen in sewage sludge is due to the biomass growth. In the study by the Kłodowska, Rodziewicz and Janczukowicz [2018], the percentage content of nitrogen in the sewage sludge at C/N=1.0 increased with electric current density decrease and ranged from 0.55% d.m. (210 mA/m^2) to 0.79% d.m. (0.53 mA/m^2). Even though such a correlation was not observed in the present study, it is worth noting that the nitrogen contents determined in the sludge were almost 2–2.5 times higher, which may be due to the higher sludge production in the Kłodowska et al. [2018] research. At current densities of 0.53 mA/m^2 and 210 mA/m^2 and C/N=1.0, the volume of produced sludge was 1,150 mg d.m./L and 1,300 mg d.m./L. respectively. Although according to Bartkowska, Biedka and Tałaj (2019), an oxygen-stabilized sludge can contain from 2.43% d.m. to 7.58% d.m. nitrogen, the nitrogen concentration presented in this work is typical for biological reactors treating municipal sewage, where it ranged from 1.5 to 5.0% d.m. [Podedworna and Umiejewska 2008].

The percentage content of potassium in the sludge is significantly higher than in the excess sludge from activated sludge chambers, which is in the range of 0.1–0.8% d.m. and 0–1% d.m. as K_2O [Kominko et al. 2017]. The high potassium content in the sludge was probably due to its high concentration in wastewater, i.e., 1276.9±96.7 mg K^+/L [Bryszewski et al. 2022]. Bryszewski et al. [2021] also determined a high potassium concentration in sewage sludge, which ranged from 3.6% d.m. to 9.6% d.m. at electric current densities of 13.3 A/m^2 and 4.4 A/m^2, respectively.

Sulfur is removed upon the adsorption of SO_4^{2-} ions on metal oxides and hydroxides formed during anode dissolution due to electric current flow [Murugananthan et al. 2004].

Literature data indicates that sodium concentrations in municipal sludge are similar and equal to: 0.122% d.m. according to Antonkiewicz et al. [2019], 0.123±0.005% d.m. according to Antonkiewicz et al. [2020], and 0.14–0.73% d.m. according to Podedworna and Umiejewska [2008]. The sodium content determined in the sewage sludge in the present research is higher than that recorded in municipal sewage (Fig. 3), which may be due to the high salinity of sewage used in hydroponic crops caused by high concentrations of sodium and chlorine ions [Rozema, Gordon and Zheng 2014].

The percentage contents of iron, manganese, molybdenum, and copper increased with the increase in electrical current density (Figures 4A and B). The iron content of the sludge from the AnSBBER-type reactor ranged from 1.81% d.m. to 3.43% d.m. in the case of R1 and R4, respectively. The maximal manganese content of the sewage sludge was 0.35% d.m. (R4) and the minimal one was 0.10% d.m. (R1 and R2). In turn, the maximal copper concentration in the sludge reached 0.08% d.m. (R4).

Aluminum was absent in the sewage sludge regardless of the electric current density applied. With current density increasing, the molybdenum content in the sludge increased from barely 0.004% d.m. to 0.018% d.m. In contrast, the zinc content was observed to decrease from 0.20% d.m. to 0.09% d.m. with current density increase.

The increasing electric current density resulted also in increased contents of metal ions released into the solution as a result of anode dissolution. The released Fe^{2+} and Fe^{3+} ions form monomeric and polymeric insoluble complexes with the hydroxyl group that are capable of adsorbing contaminants [Boinpally et al. 2023]. In the research by Bryszewski et al. [2021], where an aluminum electrode was applied for the bio-electrochemical treatment of greenhouse effluents, the Al^{3+} content ranged from 0.35% d.m. to 4.5% d.m. at alternating current densities of 4.4 A/m^2 and 13.3 A/m^2, respectively. It is worth noting that despite the higher efficiency of contaminant removal by aluminum electrodes, the use of an iron electrode is justified by its lower toxicity compared to Al [Gautam et al. 2019].

The presence of copper, manganese and molybdenum in the sewage sludge may result from partial adsorption of their ions from wastewater during electrocoagulation, as well as from cathode dissolution upon the action of salts, acids and bases [Wang et al. 2022]. According to Picard et al. [2000], the dissolution of the aluminum electrode is due to the impact of hydroxyl ions on the cathode.

Zinc present in the sewage sludge was most likely removed by electrocoagulation, which resulted in its content decrease by 81% (R3 and R4) to 95% (R1 and R2) from the initial value of 1.65±0.26 mg Zn^{2+}/L [Bryszewski et al. 2022]. As Chen et al. [2018] posited, the removal of zinc during electrocoagulation is likely to be due to: (I) precipitation of hydroxides, (II) adsorption on iron hydroxide flocs, (III) cathode reduction to the metallic form, and (IV) co-precipitation of counter-charged colloidal particles formed during the electrocoagulation process. In the cited study, Zn was completely removed from synthetic sewage within 20 minutes at electric current density of 8.3 mA/cm^2 and an initial Zn concentration of 50 mg/L. Therefore, the content of this element in the sludge was below 0.2% d.m.

Bartkowska et al. [2019] reported zinc and copper contents in municipal sludge from autothermal thermophilic stabilization within the ranges from 0.075% d.m. to 0.15% d.m. and from 0.021% d.m. to 0.053% d.m., respectively It is noteworthy that the Cu and Zn concentrations determined in the sewage sludge meet the requirements for their use on arable lands in accordance with Polish regulations in force [Dz.U. 2015 poz. 257].

CONCLUSIONS

Analysis of the sludge discharged from an anaerobic bio-electrochemical reactor of AnSBBER type treating wastewater from soilless tomato cultivation allowed the following conclusions to be drawn:

- the volume of sludge produced was lower than in the electrobiological disc reactor and the anaerobic SBBER reactor operating under the flow of direct current and alternating current, respectively,
- the increase in electric current density resulted in an increased sludge production; with each current density tested the organic matter content in the sludge corresponded to the values typical of the stabilized sludge,
- the increase in electric current density caused an increase in the concentration of phosphorus in the formed sludge,
- the increase in electric current density caused iron anode dissolution, which contributed to the increase in the iron content in the sludge dry matter,
- the analyzed sludge, compared to municipal sludge from wastewater treatment plants with biological reactors and activated sludge chambers, is richer in such elements as phosphorus, nitrogen, calcium, magnesium, potassium, sodium, and iron,
- the contents of copper and zinc in the sludge did not exceed the values permitted for sludge to be used for agricultural purposes, moreover aluminum was absent in the sludge.

Acknowledgements

The work was accomplished within research project no. 2019/33/N/ST8/00955 financed from the funds of the National Science Center.

REFERENCES

1. Antonkiewicz J., Kuc A., Witkowicz R., Tabak M. 2019. Effect of Municipal Sewage Sludge on Soil Chemical Properties and Chemical Composition of Spring Wheat. Ecological Chemistry and Engineering S, 26(3), 583–595.
2. Antonkiewicz J., Popławska A., Kołodziej B., Ciarkowska K., Gambuś F., Bryk M., Babula J. 2020. Application of ash and municipal sewage sludge as macronutrient sources in sustainable plant biomass production. Journal of Environmental Management, 264, 110450.
3. Bartkowska I., Biedka P., Tałałaj I.A. 2019. Analysis of the Quality of Stabilized Municipal Sewage Sludge. Journal of Ecological Engineering, Vol. 20(nr 2), 200–208.
4. Boavida-Dias R., Silva J.R., Santos A.D., Martins R.C., Castro L.M., Quinta-Ferreira R. M. 2022. A Comparison of Biosolids Production and System Efficiency between Activated Sludge, Moving Bed Biofilm Reactor, and Sequencing Batch Moving Bed Biofilm Reactor in the Dairy Wastewater Treatment. Sustainability, 14(5), 2702.
5. Boinpally S., Kolla A., Kainthola J., Kodali R., Vemuri J. 2023. A state-of-the-art review of the electrocoagulation technology for wastewater treatment. Water Cycle, 4, 26–36.
6. Breś W., Golcz A., Komosa A., Kozik E. 2012. Horticultural Plant Nutrition. Fundamentals and perspectives (A. Komosa, Ed.). Wydawnictwo Rolnicze i Leśne, Poznań, (in Polish).
7. Bryszewski K., Rodziewicz J., Janczukowicz W. 2022. Effect of bio-electrochemical treatment of hydroponic effluent on the nutrient content. Applied Sciences, 12(19), 9540.
8. Bryszewski K., Rodziewicz J., Mielcarek A. 2018. In the Sequencing Batch Biofilm Reactor (SBBR) removal of nitrogen and phosphorus from wastewater from soilless tomato cultivation. Gaz, Woda i Tech Sanitarna, Nr 5(5), 26–28, (in Polish).

9. Bryszewski K., Rodziewicz J., Mielcarek A., Janczukowicz W., Jóźwiakowski K. 2021. Investigation on the improved electrochemical and bio-electrochemical treatment processes of soilless cultivation drainage (SCD). Science of The Total Environment, 783, 146846.
10. Chen X., Ren P., Li T., Trembly J. P., Liu X. 2018. Zinc removal from model wastewater by electrocoagulation: Processing, kinetics and mechanism. Chemical Engineering Journal, 349, 358–367.
11. Dyśko J., Kaniszewski S., Nowak J., Wójcik P. 2014. Sustainable Fertilization of Horticultural Plants (P. Wójcik, Ed.). Instytut Ogrodnictwa, Skierniewice (in Polish).
12. Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. Dz.U. L 135 z 30.5.1991, (in Polish)
13. Gautam P., Kumar S., Lokhandwala S. 2019. Advanced oxidation processes for treatment of leachate from hazardous waste landfill: A critical review. Journal of Cleaner Production, 237, 117639.
14. Grady C.P.L., Daigger G.T., Love N.G., Filipe C.D.M. 2011. Biological wastewater treatment. In Biological wastewater treatment. (3rd ed, Issue Ed. 3). Taylor and Francis Group, Boca Raton.
15. Jóźwiak T., Mielcarek A., Janczukowicz W., Rodziewicz J., Majkowska-Gadomska J., Chojnowska M. 2018. Hydrogel chitosan sorbent application for nutrient removal from soilless plant cultivation wastewater. Environmental Science and Pollution Research, 25(19), 18484–18497.
16. Klodowska I., Rodziewicz J., Janczukowicz W. 2018. Effect of Electrical Current Density and Type and Dose of the External Source of Carbon on the Quantitative and Qualitative Characteristics of Sludge Formed During Wastewater Treatment in the Sequencing Batch Biofilm Reactors. Journal of Ecological Engineering, 19(4), 143–152.
17. Kominko H., Gorazda K., Wzorek Z. 2017. The Possibility of Organo-Mineral Fertilizer Production from Sewage Sludge. Waste and Biomass Valorization, 8(5), 1781–1791.
18. Metcalf and Eddy. 2014. Wastewater engineering: treatment and resource recovery (5th ed.). McGraw Hill.
19. Murugananthan M., Bhaskar Raju G., Prabhakar S. 2004. Removal of sulfide, sulfate and sulfite ions by electro coagulation. Journal of Hazardous Materials, 109(1–3), 37–44.
20. Picard T., Cathalifaud-Feuillade G., Mazet M., Vandensteendam C. 2000. Cathodic dissolution in the electrocoagulation process using aluminium electrodes. Journal of Environmental Monitoring, 2(1), 77–80.
21. Podedworna J. and Umiejewska K. 2008. Technology of sewage sludge. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, (in Polish).
22. Rodziewicz J., Mielcarek A., Janczukowicz W., Jóźwiak T., Struk-Sokołowska J., Bryszewski K. 2019. The share of electrochemical reduction, hydrogenotrophic and heterotrophic denitrification in nitrogen removal in rotating electrobiological contactor (REBC) treating wastewater from soilless cultivation systems. Science of The Total Environment, 683, 21–28.
23. Rodziewicz J., Mielcarek A., Janczukowicz W., Tavares J.M.R., Jóźwiakowski K. 2023. Characteristics of Sludge from the Treatment of Soilless Plant Cultivation Wastewater in a Rotating Electrobiological Disc Contactor (REBDC). Energies, 16(3), 1022.
24. Rozema E.R., Gordon R.J., Zheng Y. 2014. Plant Species for the Removal of Na+ and Cl– from Greenhouse Nutrient Solution. HortScience, 49(8), 1071–1075.
25. Sahu O., Mazumdar B., Chaudhari P.K. 2014. Treatment of wastewater by electrocoagulation: A review. Environmental Science and Pollution Research, 21(4), 2397–2413.
26. The Regulation of the Minister of Environment of 6 February 2015 on the on the Municipal Sewage Sludge. Dz.U. 2015 Poz. 257, (in Polish).
27. The Regulation of the Minister of Maritime Economy and Inland Navigation of July 12, 2019 on substances particularly harmful to the aquatic environment and conditions to be met when introducing sewage into waters or into the ground, as well as when discharging rainwater or snowmelt into waters or into water equipment. Dz.U. 2019 Poz. 1311, (in Polish).
28. Turek A., Wieczorek K., Wolf W.M. 2019. Digestion Procedure and Determination of Heavy Metals in Sewage Sludge–An Analytical Problem. Sustainability 2019, Vol. 11, Page 1753, 11(6), 1753.
29. Wang J.Y., Kadier A., Hao B., Li H., Ma P.C. 2022. Performance optimization of a batch scale electrocoagulation process using stainless steel mesh (304) cathode for the separation of oil-in-water emulsion. Chemical Engineering and Processing – Process Intensification, 174, 108901.