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Characteristics of Sludge from the Treatment of Soilless Plant Cultivation Wastewater in a Rotating Electrobiological Disc Contactor (REBDC)

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Abstract: Due to the high nitrogen and phosphorus concentrations in wastewater from soilless cultivation of tomatoes, the sludge formed during wastewater treatment can be used as a source of nutrients in agriculture. The effect of electrical direct current (DC) density (J) and hydraulic retention time (HRT) in a rotating electrobiological contactor (REBDC) on the quantity and quality of sludge generated in the process of tomato soilless cultivation wastewater treatment was determined. The cathode consisted of discs immobilized with biomass, while the anode was an aluminum electrode. HRTs of 4 h, 8 h, 12 h, 24 h and (J) of 0.63, 1.25, 2.50, 5.00, and 10.00 A/m^2 were applied. The study showed that the increase in (J) caused an increase in the amount of sludge generated. The increase of (J) contributed to increased concentrations of biogenes in the sludge, whereas extension of HRT at a given current density contributed to increased concentrations of nitrogen and phosphorus (up to 6.2% and 0.8% respectively) and to the reduced content of organic matter (up to 23.04%). The examined sludge was stabilized, sanitary, and safe, and may be an alternative to mineral fertilizers. This study showed that larger sludge amounts are produced in a DC mode aerobic REBDC than in an alternating current anaerobic one.

Keywords: tomatoes; soilless cultivation wastewater; rotating electrobiological contactor; sludge; phosphorus and nitrogen content; aluminium and iron

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1. Introduction

Soilless cultivation of plants (SCP) is currently considered the basic method of plant production under cover, leading to the dynamic growth of this area around the world. In a soilless system, plants are rooted in a special substratum and fed an aqueous solution of nutrients. This system is characterized by high efficiency and good product quality, and can be operated almost 10 months per year [1].

Soilless cultivation of plants generates nutrient-rich wastewater that in most cases is discharged into groundwater or surface water. Thus, fertilizer components are irretrievably lost. Production of tomatoes on mineral wool takes 9–10 months, during which period nitrogen and phosphorus are released into the environment: 23–245 kg N/ha and 2–54 kg P/ha each month [2]. The same applies to other crops. In the case of roses, the lost nitrogen may amount to 2000 kg N/ha in a year, which is 60% of the mass of nitrogen supplied to the plants [3]. Regarding cucumbers, these amounts are 33–43% and 35–47% for nitrogen and phosphorus, respectively. Soilless cultivations should be carried out with an excess of nutrient solution. Usually, this is 25–45%, which results in generating about 4.5 L/m^2 of SCP wastewater (SCPW) with a high concentration of nutrients [2]. The importance of the environmental problem is demonstrated by the concentration of phosphorus in wastewater from tomato cultivation, which ranges from 35.4 to 104.0 mg P/L, whereas for nitrogen-based pollutants it ranges from 270.0 to 614.9 mg N/L [2]. At the same time, COD is usually below 50 mgO_2/L [2,3]. The high N and P concentrations make SCPW a potential substrate for N and P recovery [4]. In addition, the sludge formed during wastewater treatment can be such a source or can be used as a source of nutrients in soil plant crops [5].

The issue of sewage sludge generated during SCPW treatment has rarely been addressed in the scientific literature [5,6]. The scarcity of data is due to the specific nature of the conventional SCPW treatment technologies applied thus far, which either result in low sewage sludge loads produced (reverse osmosis and ion exchange membranes [7–9]) or do not pose any technological problems, as in the case of constructed wetlands and biofilters [8–13]. An exception in this case is phosphorus removal technology involving the use of hydrate lime for its precipitation [14–16]. This treatment technology acts selectively and is deployed sporadically; it additionally results in the removal of part of the microelements, however, it has no significant effect on the concentration of nitrogen compounds.

Our previous investigation proved that SCPW may be pre-treated in bioelectrochemical reactors (BERs) such as an aerobic REBDC [17,18] or anaerobic SBBER [6,18].

The flow of electric current through BERs ensures good conditions for the simultaneous removal of phosphorus and nitrates. Phosphorus is mainly removed by the electrocoagulation process, while nitrates are mainly removed as a result of heterotrophic and hydrogenotrophic denitrification and electrochemical nitrate reduction [17]. Hydrogenotrophic denitrification in bioelectrochemical reactors is the result of the flow of electric current between the electrodes placed in the reactor. The hydrogen, produced from water by electrolysis, is an energy source for autotrophic bacteria. The carbon dioxide derived from heterotrophic denitrification is a source of inorganic carbon in autotrophic denitrification. At current densities above 2.5 A/m^2, a greater share of hydrogenotrophic denitrification in nitrogen removal was observed, and a reduced efficiency of heterotrophic denitrification and electrochemical nitrate reduction in REBDC was found [17]. The electric current flow causes dissolution of the aluminum anode and the removal of phosphorus in the process of electrocoagulation. Aluminum ions coming from the electrode combine with the hydroxide ions. The aluminum hydroxides bind the phosphorus, which then settles out as sludge [19]. This sludge flows out the reactor together with the exfoliating biofilm.

The qualities of sludge discharged from BERs depends on many factors, such as the SCPW characteristics, reactor type (i.e., aerobic or anaerobic), technological parameters of the reactor (hydraulic retention time (HRT), temperature, type of current (alternating, direct), electric current density, the material from which the electrodes are made, the external source of carbon dose, and its type [20,21]), and the share of processes involved in the reactor treatment process [17]. According to Bryszewski et al. [6], the sludge generated during SCPW treatment in a bio-electrochemical reactor with alternating current (AC) was rich in phosphorus and nitrogen as well as in other elements such as calcium, potassium, and magnesium. However, phosphorus is the key element, as over eighty percent of the world's P-based fertilizers are produced from phosphate rocks (apatites and phosphates) which will run out within 100 years [12].

The sludge resulting from SCPW treatment in a bioelectrochemical reactor, regardless of the type of electric current flowing through it, is "polluted" with the metal ions that the electrodes and other reactor elements are made up of [6]. As shown in a previous study [22], electrodes are consumed much faster in DC mode reactors than in AC mode ones as a result of uniform dissolution of electrodes during the process conducted in the latter, which may indicate a higher concentration of elements the electrodes are made up of in the sludge [22].

A study conducted by Rodziewicz et al. [17] demonstrated that the removal efficiencies of nitrogen and phosphorus compounds in an REBDC with DC depend on the electrical current intensity (I: 0,35 A, 0,7 A, 1,4 A, 2,8 A and 5,6 A) and HRT(4 h, 8 h, 12 h and 24 h). Therefore, it is to be expected that an increase in current intensity contributes to changes in the sewage sludge load produced as well as in the concentrations of carbon, nitrogen, and phosphorus compounds in the sludge. In addition, it may be posited that these parameters will produce an increase in the aluminum and iron concentrations in the sludge due to electric dissolution of the aluminum anode and dissolution as a result of spontaneous corrosion of the disks and casing [23].

The present study aims to determine the effects of the electrical current density (J) and hydraulic retention time (HRT) in a rotating electrobiological contactor with direct current flow on the amount and quality of sewage sludge generated during SCPW treatment. The scope of our qualitative analyses of the sludge included determination of the concentrations of nitrogen, phosphorus, organic matter, volatile solids, aluminum, and iron. In turn, our quantitative analyses aimed to determine the dry matter content of the biofilm overgrowing the contactor's disks and the total concentration of suspended solids in the effluent.

2. Materials and Methods

This research was conducted on four rotating electro-biological disc contactors (REB-DCs). The disks covered by biofilm provided a cathode, while an aluminum electrode placed in the contactor served as an anode (Figure 1).

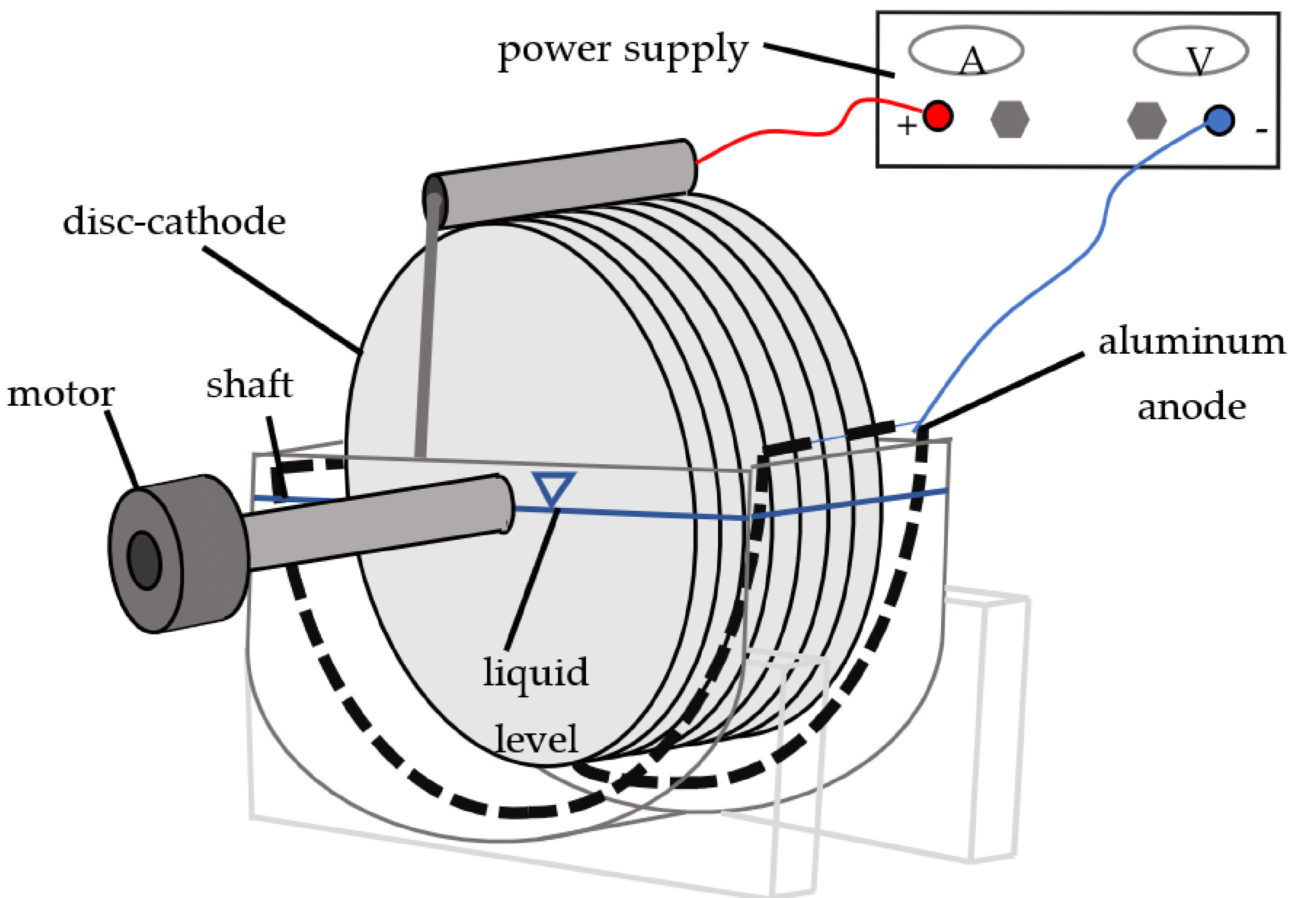

Figure 1. Scheme of unit experimental model.

The technical parameters of the REBDCs used during the experiment are provided in Table 1.

All research was conducted in the laboratory at a temperature of about 20.0, ± 1 °C. The following HRTs were applied: 4 h, 8 h, 12 h, and 24 h. The following J values were used during investigation for each HRT value: 0.63 A/m^2, 1.25 A/m^2, 2.50 A/m^2, 5.00 A/m^2, and 10.00 A/m^2. Electric current density values were adopted on the basis of a previous study [24].

Biomass from the denitrification section of the WWTP in Olsztyn, Poland was applied as the inoculum.

Table 1. Technical parameters of rotating electrobiological contactors.

Parameter	Value
Number of discs	8
Single disc diameter [cm]	22
Discs total area [m^2]	0.56
Percent immersion of the discs [%]	40
Flow tank volume [L]	2.0
Rotation speed [rpm]	10

2.1. Wastewater Composition

Wastewater with characteristics similar to wastewater from soilless tomato cultivation was used [2,25].

Sodium acetate was added to the wastewater as a source of carbon. A C:N ratio of 0.5 was used to ensure biofilm growth and autotrophic denitrification [17,26].

The wastewater characteristics are shown in Table 2.

Table 2. Synthetic wastewater concentration after addition of sodium acetate.

Parameters	Value Mean	Standard Deviation
COD [mg O_2/L]	259.5	39.7
Total nitrogen [mg N/L]	470.3	14.7
Total phosphorus [mg P/L]	74.4	10.0
pH	6.98	-

2.2. Experimental Model

Minipulse 3 peristaltic pumps (Gilson, Middleton, WI, USA) pumped wastewater to the reactors. An aluminum anode was placed in every reactor. Disks made of stainless steel were used as cathodes. A laboratory power supply (HANTEK PPS2116A, Qingdao, China) was used as a source of direct electric current. Aluminum electrodes were used in the study because, as indicated in the literature, they are more efficient in removal of phosphorus compounds compared to electrodes made of iron. In the case of aluminum, phosphorus compounds are removed during both precipitation and adsorption, whereas in the case of iron the mechanism of adsorption is less effective. In addition, the use of an iron electrode results in higher turbidity of the solution being treated [27]. The use of an aluminum electrode additionally enables simultaneous removal of nitrates as a result of their electrochemical reduction [28].

The inflowing wastewater and the effluent were each analyzed for their concentrations of:

- Total nitrogen, measured on a Total Organic Carbon Analyzer TOC-L CPH/CPN with TNM-L device (Shimadzu Corporation, Kyoto, Japan) using the method of oxidative combustion chemiluminescence;
- Total phosphorus (measurement accuracy to 0.01 mgP/L), measured on a UV-VIS 5000 DR spectrophotometer (HACH Lange, Düsseldorf, Germany) using the HACH Lange LCK 348–350 method;
- Organic matter, expressed as the COD value and measured with the bichromate method (PN-74/C-04578/03);
- Total suspended solids, measured using the gravimetric method (PN-EN 872:2007);
- pH value (measurement accuracy to 0.01 pH), temperature (exact to 1 °C), measured using a CP-105 pH meter (Elmetron, Zabrze, Poland).

The following indicators were determined in sewage sludge:

- Total nitrogen, by oxidative incineration chemiluminescence (Total Organic Carbon Analyzer TOC-L CPH/CPN) with a TNM-L device (Shimadzu Corporation, Kyoto, Japan)
- Total phosphorus, with the sludge digested using perchloric and nitric acids and measured with the HACH Lange LCK 348–350 method and a UV-VIS 5000 DR spectrophotometer (HACH Lange, Düsseldorf, Germany);
- Dry residue, using the gravimetric method (PN-EN 12880:2004);
- Dry mineral residue and dry organic residue, using the gravimetric method (PN-EN 12879:2004),
- Aluminium, with the sludge digested by perchloric and nitric acids, measured by the HACH Lange LCK 301 method using a UV-VIS 5000 DR spectrophotometer (HACH Lange, Düsseldorf, Germany),
- Iron, with the sludge digested by perchloric and nitric acids, measured using the HACH Lange LCK 321 method with a UV-VIS 5000 DR spectrophotometer (HACH Lange, Düsseldorf, Germany).

The investigation scheme is shown in Figure 2.

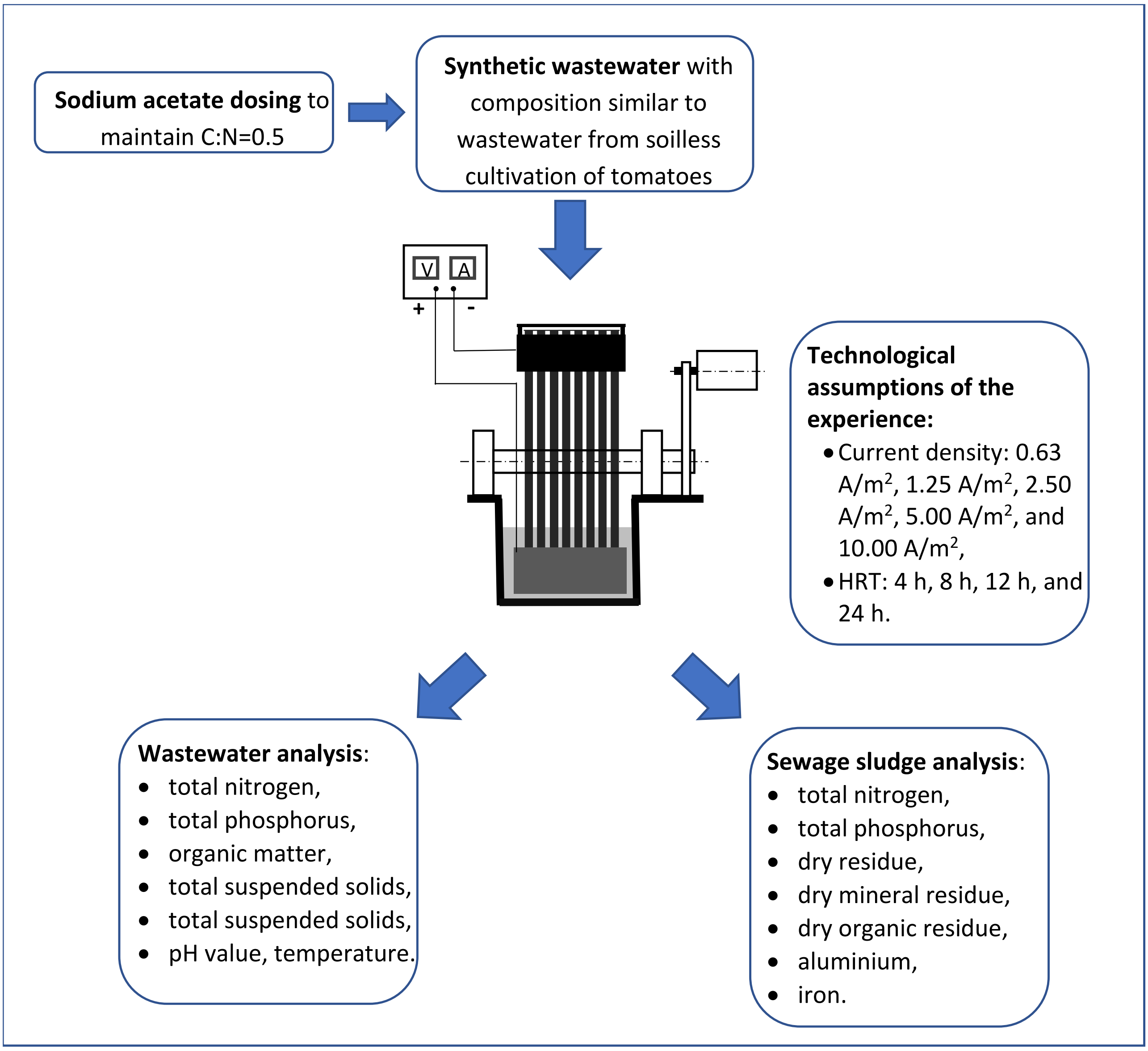

Figure 2. Research scheme.

3. Results and Discussion

3.1. Characteristics of the Biofilm Immobilized on the Disks

In each analyzed variant, biofilm hydration exceeded 94.0% and was observed to increase with extension of the HRT. The dry matter content, expressed per m^2 of disk surface area, increased with extension of the HRT and increasing electrical current density, i.e., from 5400 ± 356 mg DM/m^2 at HRT = 4 h to 15,950 ± 988 mg DM/m^2 at HRT = 24 h. These values are comparable to the characteristics of rotating biological contactors with low organic loading rates [29,30].

3.2. Quantitative and Qualitative Characteristics of Sewage Sludge Generated in the Electrobiological Disk Contactor

The amount of sewage sludge (i.e., total suspended solids concentration (TSS) in the effluent) generated during the treatment process in the electrobiological disk contactor depended on both J and HRT (Figure 3, Table 3). At all current densities tested, the concentration of suspended solids in the effluent from REBDC decreased along with HRT extension, which was due to their aerobic stabilization, the effectiveness of which is determined by the hydraulic retention time [31]. At an electrical current density of 0.63 A/m^2, it ranged from 4718 mg DM/L at HRT = 4 h to 3873 mg DM/L at HRT = 24 h (the lowest value determined throughout the study). It was additionally observed that increasing current density resulted in a greater amount of generated sludge. This effect was due to the electrocoagulation of organic compounds and phosphorus, the effectiveness of which increases with increasing current density [32]. At the highest current density tested, i.e., 10.00 A/m^2, the concentration of suspended solids in the effluent ranged from 5215 mg DM/L (the highest value noted throughout the study) at HRT = 4 h to 4580 mg DM/L at HRT = 24 h.

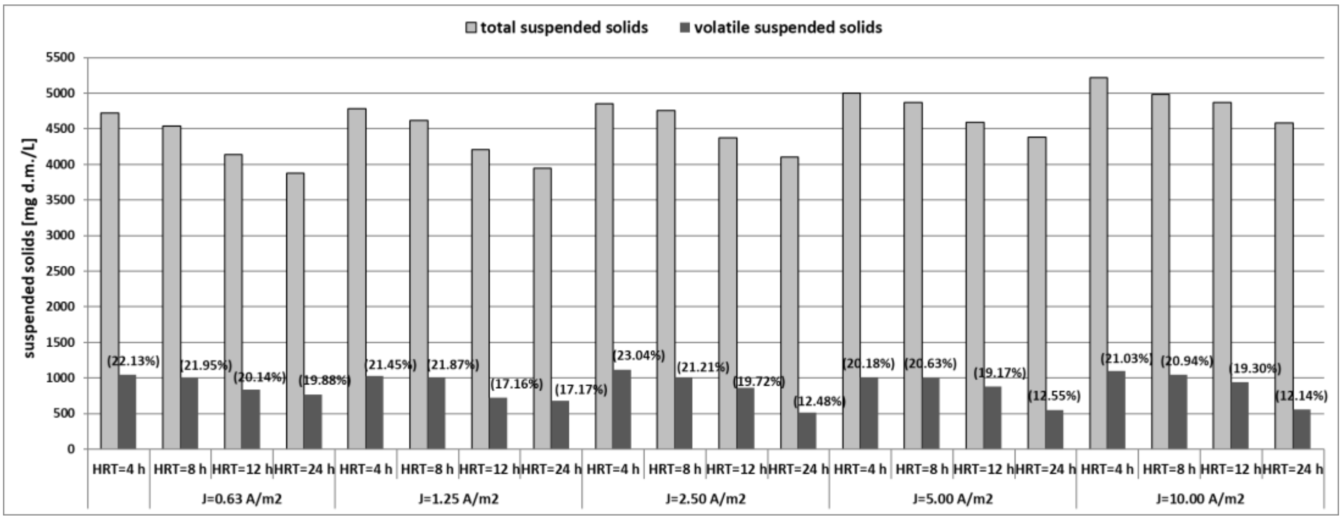

Figure 3. Total suspended solids and volatile suspended solids.

Table 3. Total suspended solids amount depending on electric current density and HRT.

HRT [h].	Electric Current Density [A/m^2]				
	0.63	**1.25**	**2.50**	**5.00**	**10.00**
4	4718	4783	4853	4996	5215
8	4542	4614	4757	4871	4980
12	4136	4207	4370	4590	4870
24	3873	3944	4102	4384	4580

The volume of sludge produced was significantly higher compared that determined by Bryszewski et al. [6], in the range from 416.0 ± 267.3 mg DM/L to 1079.4 ± 251.3 mg DM/L.

Worthy of notice is that the cited experiment was conducted in anaerobic reactors with real wastewater, higher external carbon source input (C/N = 1.0), and electrical current densities of 4.4–13.3 A/m^2. Anaerobic reactors ensure smaller biomass growth compared to aerobic ones [33]. This experiment was additionally conducted with alternating current (AC), which, as claimed by Dehghabi et al. [34], contributes to a smaller volume of sludge produced than under conditions of direct current (DC) flow. The study described in this manuscript was performed in aerobic reactors with synthetic wastewater at C/N = 0.5 and with direct current (DC), and moreover had a density of 0.63–10.0 A/m^2 flowing through the reactors.

A typical feature of anaerobic reactors, both those with suspended biomass and with biofilm, is noticeably smaller biomass growth [33] than in aerobic reactors, which explains the difference between the results obtained by Bryszewski et al. [6] and those in the present study. A greater amount of sludge produced in BERs with DC than in those with AD was reported by Hoseinzadeh et al. [35,36] and Dehghani et al. [34], who demonstrated that bio-electrochemical processes supplied by AC were characterized by lower sludge production compared to reactors operating in AD mode.

The mass of sludge produced in our study was higher than that established by Kłodowska et al. [37] in their experiment with an anaerobic sequencing batch biofilm reactor (SBBR) with and without passage of electrical current, where the quantities of the formed sludge were below 1400 mg DM/L. This is mainly due to the differences in the type and quality of the treated wastewater (municipal sewage subjected to mechanical and biological treatment processes including nitrification) and the type of external carbon source used (citric acid, potassium biocarbonate). It is not less important that Kłodowska et al. [37] used substantially lower densities of electrical current (53, 105, 158, and 210 mA/m^2), which ensure lower electrocoagulation effectiveness, and ultimately make for a lower concentration of suspended solids in the effluent [38]. At the same time, the volume of sludge produced was similar to that determined in the study conducted by Aykol [39], where the sludge amounts were 4570 mg DM/L and 5330 kg DM/L in the effluent from a reactor treating paint manufacturing wastewater by electrocoagulation at current densities of 5 A/m^2 and 10 A/m^2, respectively. Likewise in the work of Kłodowska et al. [37], the results obtained by the above-cited authors confirm that an increase in electrical current density in the BER with an external carbon source leads to higher concentrations of TSS in the treated wastewater, and ultimately to greater amounts of sludge being formed. In addition, they found that increasing current density in the same reactor without an external carbon supply (electrochemical reactor) led to a decrease in sludge generation.

According to the literature, one effective method for sludge volume mitigation during wastewater treatment is the application of bioelectrochemical systems. These can decrease the microbial growth yield (mg TSS/g ΔC), which represents the ratio of the amount of biomass produced (mg TSS) to the amount of substrate consumed/removed (g ΔCOD) [40]. The values of the sludge yield coefficient (Y) obtained in the present study range from 17.8 to 25.6 mg TSS/g ΔCOD at HRT = 4 h and current densities from 0.63 to 10.0 A/m^2 to 16.1 to 19.7 mg TSS/g ΔCOD at HRT = 24 h and current densities from 0.63 to 10.0 A/m^2. These values are comparable to the results presented by Wilson and Kim [40], who reported Y = 20 mg VSS/g ΔCOD in a microbial electrolysis cell (MEC) reactor. According to these authors, small amounts of waste sludge are produced in bioelectrochemical systems because anaerobic exoelectrogenic bacteria form highly populated biofilms on the anode [40]. However, in the aforementioned study the Y parameter was expressed as VSS (volatile suspended solids) and not as TSS (total suspended solids), which means that if TSS had been assumed as the point of reference, then the Y values determined in the study by Wilson and Kim [40] would undoubtedly be higher than 20 mg TSS/g ΔCOD.

In turn, the sludge yield value was about 92.0 mg TSS/g COD in the experiment conducted by Moghiseha et al. [5] in a bioelectrochemical reactor, where phenol was used as a carbon source at C/N = 0.5. However, this experiment was performed in an aerated bioreactor that differed significantly in terms of design from REBDC-type reactors and had different electrodes (steel wool and carbon cloth); furthermore, the treatment process was mainly targeted at the removal of carbon compounds. In the present study, sodium acetate fed to the reactor was mainly consumed in heterotrophic denitrification, where biomass growth was substantially less intensive than in the process of carbon compound (COD) removal [33]. According to the literature [41], the concentration of TSS in the effluent from bioelectrochemical systems is much lower than from aerobic and anaerobic bioreactors. The sludge yield determined in the cited work was at Y = 80 mg TSS per g ΔCOD, whereas in MFCs (microbial fuel cells, i.e., one type of microbial bioelectrochemical system (BES)) treating effluent from primary settling tanks [42] the sludge production was 111–134 mg TSS/g ΔCOD. For comparison, the excess sludge production was 279 mg TSS g ΔCOD in a typical aerobic activated sludge reactor operated under the same conditions as in [41]. According to Batstone et al. [43], reactors with anaerobic microorganisms have a low sludge yield coefficient, i.e., 40–100 mg TSS/g ΔCOD, compared to aerobic microorganisms, with 670 mg TSS/g ΔCOD for heterotrophs and 240 mg TSS/g ΔN for autotrophs [44].

The present study demonstrated the effect of J and HRT on the percentage content of organic matter in sewage sludge dry matter (Figure 3). At the lowest current density and the shortest HRT (i.e., 0.63 A/m^2 and HRT = 4 h, respectively), organic matter (VSS) accounted for 22.13% of sludge dry matter. Under the flow of electrical current with a density of 10.00 A/m^2 and at HRT = 24 h the percentage content of organic matter was substantially lower, reaching 12.14%, which was due to the effect of the hydraulic retention time on the efficiency of aerobic stabilization of the sludge [33].

In the case of organic compounds, their percentage content in sludge dry matter was affected primarily by the hydraulic retention time. At the highest HRT tested, i.e., HRT = 24 h, the percentage content of organic matter reached 19.88% and 12.14% at 0.63 and 10.00 A/m^2, respectively, whereas at HRT = 4 h the respective values were 22.13% and 21.03%. The values presented above point to wastewater stabilization, as it is commonly believed that the organic matter content in stabilized wastewater ranges from 30 to 50% [31].

The percentage content of organic matter in sludge dry matter was lower than the values reported by Bryszewski et al. [6] at electrical current densities of 4.4, 8.8, and 13.3 A/m^2 and HRT = 24 h, where the percentage of organic matter in dry matter in the reactor with the lowest electric current density tested (4.4 A/m^2) was 28.6%, subsequently decreasing to 22.4% at the highest density of alternating current. As in the present study, the percentage content of organic matter decreased along with increasing current density, which is typical of BER-type reactors, in which the effectiveness of aerobic stabilization of a biofilm is the coupled effect of hydraulic retention time and reactor temperature resulting from current density. This effect is due in part to the aerobic conditions occurring in the flow-through tank of the REBDC reactor, which when coupled with long hydraulic retention time and high temperatures can facilitate aerobic stabilization of the sludge [17].

HRT and electrical current density affect the content of nutrients (nitrogen and phosphorus) in the sludge as well. At a current density of 0.63 A/m^2, phosphorus accounted for 0.68% (the lowest value recorded in the studied range of current densities and HRTs) to 0.70% of sludge dry matter at HRTs from 4 h to 24 h, respectively (Figure 4). This means that extending the hydraulic retention time of wastewater and sludge in the contactor increased the phosphorus concentration in the sludge. Similar dependencies were noted at the other current densities tested. At the same time, it was noticed that increasing the electrical current density at the same HRT contributed to an increase in phosphorus content in the dry matter of the suspended solids. The highest P content, accounting for 0.84% of the sludge, was achieved at a current density of 10.0 A/m^2 and HRT = 24 h.

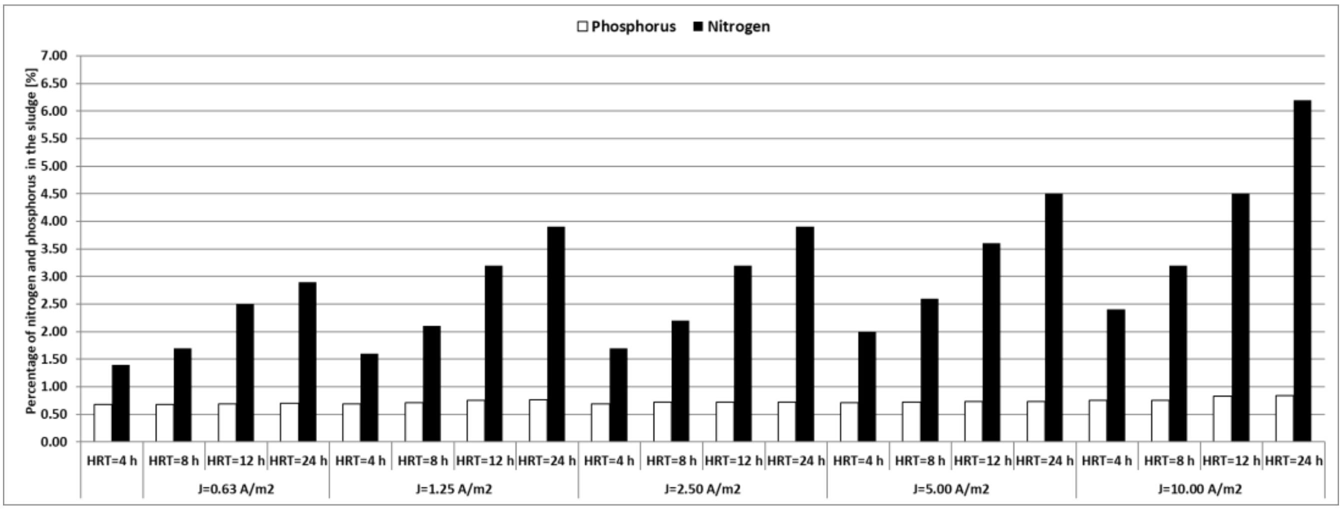

Figure 4. Percentage of nitrogen and phosphorus in the sludge.

The achieved values are lower than those reported by Bryszewski et al. [6], who noticed that when the alternating J increased, the content of P increased from 2.6% DM to 3.9% DM in an anaerobic electrochemical sequencing batch biofilm reactor and from 1.3% DM to 2.1% DM in a bio-electrochemical reactor with an external carbon source. It needs to be noted, however, that the present study was performed with synthetic wastewater, whereas the above-cited author used wastewater from a greenhouse used for soilless plant cultivation. In addition, the concentration of total suspended matter in the effluent from the REBDC in the present study was substantially higher that from the reactor used by Bryszewski et al. [6]. Furthermore, they applied a higher C/N ratio (1.0), and the reactor was a non-flow-through sequential-type reactor, which facilitates the binding of phosphorus compounds [45]. At the same time, the phosphorus content determined in the present study was several times higher compared to the value reported by Kłodowska et al. [37]. In the cited study, the phosphorus content determined at the highest electric current density (210.0 mA/m^2) and the highest C/N value (1.5) was 0.17%. This difference is due to a significantly lower phosphorus concentration in raw wastewater (5, 2, and 74.4 mgP/L) and substantially lower electrical current density (53–210.0 mA/m^2; 0.63–10.0 A /m^2), which are the main factors affecting phosphorus concentration in the sludge generated in BER-type rectors [46]. The percentage content of phosphorus in the excess sludge formed in activated sludge tanks of municipal wastewater treatment plants ranges from 0.9 to 1.6%.

Similar observations were made for the nitrogen concentration in the suspended matter outflowing from the REBDC. It increased along with increasing current density and extending HRT. At a current density of 0.63 A/m^2, it reached 1.4% N at HRT = 4 h. HRT extension at a stable current density led to an increase in the percentage content of nitrogen, from 1.7 through 2.5 to 2.9% N at HRT 8, 12, and 24 h, respectively. Similar tendencies were noticed at current densities of 1.25 A/m^2, 2.50 A/m^2, 5.00 A/m^2, and 10.00 A/m^2. At current density 1.25 A/m^2, the percentage content of nitrogen in sludge dry matter ranged from 1.6% for HRT = 4 h to 3.9% for HRT = 24 h, while at 2.50 A/m^2 the respective values were 1.7 and 3.9% and at 5.00 A/m^2 they reached 2.0 and 4.5%, respectively. The highest values, ranging from 2.4 to 6.2%, were determined at the highest current density tested (Figure 4).

The values obtained in the present study fall within the ranges typical of the excess sludge from a municipal wastewater treatment plant with activated sludge tanks (3–10.0%). In addition, the concentrations of nutrients in the sludge from the REBDC were lower than the typical values for artificial fertilizers used in agriculture (5% N and 10% P) [45]. At the same time, at HRT = 24 h and J over 1.25 A/m^2, they were higher than those reported by Bryszewski et al. [6] at 1.4% to 3.0% DM, and comparable with those determined by Kłodowska et al. [37], whose results ranged from 4.2 to 10.1% at the same HRT and

N/C ratio. Unlike in the present study, in the above-cited experiments performed by Bryszewski et al. [6] and Kłodowska et al. [37], the increase in current density contributed to a decrease in the percentage of nitrogen content in the sludge, which was due to different oxygen conditions in the reactors (anaerobic and aerobic) [47].

The concentrations of nitrogen, phosphorus, and organic matter in sewage sludge are determined by the effectiveness of their removal from wastewater and by the consumption rate of the external carbon source fed to the reactor. The data presented in Figure 5 show explicitly that the extension of HRT at a stable current density resulted in reduced concentrations of nitrogen, phosphorus, and organic compounds (COD) in the effluent. At the same time, increasing the electrical current density contributed to the increased effectiveness of nutrient removal from wastewater, and affected the extent of consumption of the carbon compounds fed to the reactor, ultimately translating into their lower concentration in the effluent (Figure 5).

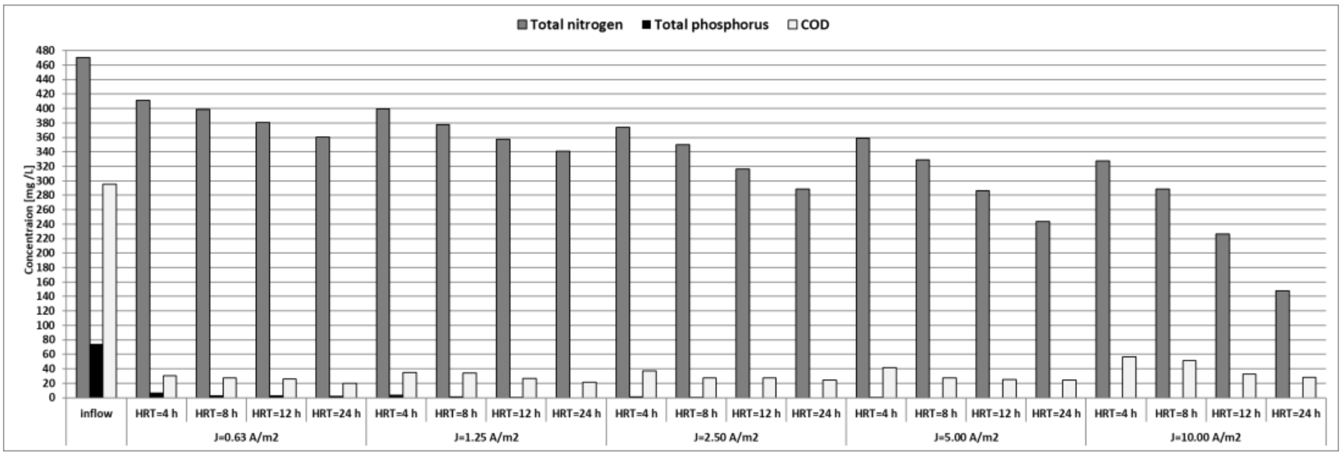

Figure 5. Effluent concentration of total nitrogen, total phosphorus, and COD.

Under conditions of electrical current flow, both iron and aluminum were detected in sludge dry matter (Figure 6). Their concentrations were observed to increase along with HRT extension at each current density tested. In addition, increased current density contributed to higher concentrations of iron and aluminum in suspended solids and in the sludge. These tendencies are due to the fact that electrical dissolution of the aluminum anode and dissolution as a result of spontaneous corrosion of the contactor's disks and casing depend on both the electrical current density and the HRT [23,37]. At the lowest current density tested (0.63 A/m^2), the aluminum content reached 0.1 mg/g DM at HRT = 4 h and HRT = 8 h. At longer HRTs, i.e., HRT = 12 h and HRT = 24 h, the content was two-fold and three-fold higher (0.2 and 0.3 mg/g DM, respectively). The flow of electrical current with a higher density, reaching 1.25 A/m^2, caused an increase in aluminum content, from 0.2 to 0.4 mg/g DM at HRT = 4 h and HRT = 24 h, respectively. In turn, at a J of 2.50 A/m^2, the aluminum content ranged from 0.4 to 0.8 mg/g DM, and at 5.00 A/m^2 it ranged from 0.5 to 1.6 mg/g DM The highest aluminum content, reaching 2.0 mg/g DM, was determined at a current density of 10.00 A/m^2 and HRT = 24 h. For the shorter HRTs tested (4, 8, and 12 h), the aluminum content in the sludge ranged from 0.5 to 1.4 mg/g DM.

Similar tendencies were observed for iron content in the sludge dry matter. The extension of HRT at a stable J contributed to increased iron content in both the suspended matter of the effluent and the sewage sludge. In turn, increasing the current density caused the iron concentration in the suspended matter and the sludge to increase. At a current density of 0.63 A/m^2, iron content reached 0.3 mg Fe/g DM at HRT = 4 h and HRT = 8 h, and reached 0.5 mg Fe/g DM at HRT = 12 h and HRT = 24 h. At J of 1.25 A/m^2, the iron content ranged from 0.4 to 0.7 mg/g DM, whereas at current densities of 2.50, 5.00, and 10.00 A/m^2, it was similar and ranged from 0.4 to 0.9 mg/g DM.

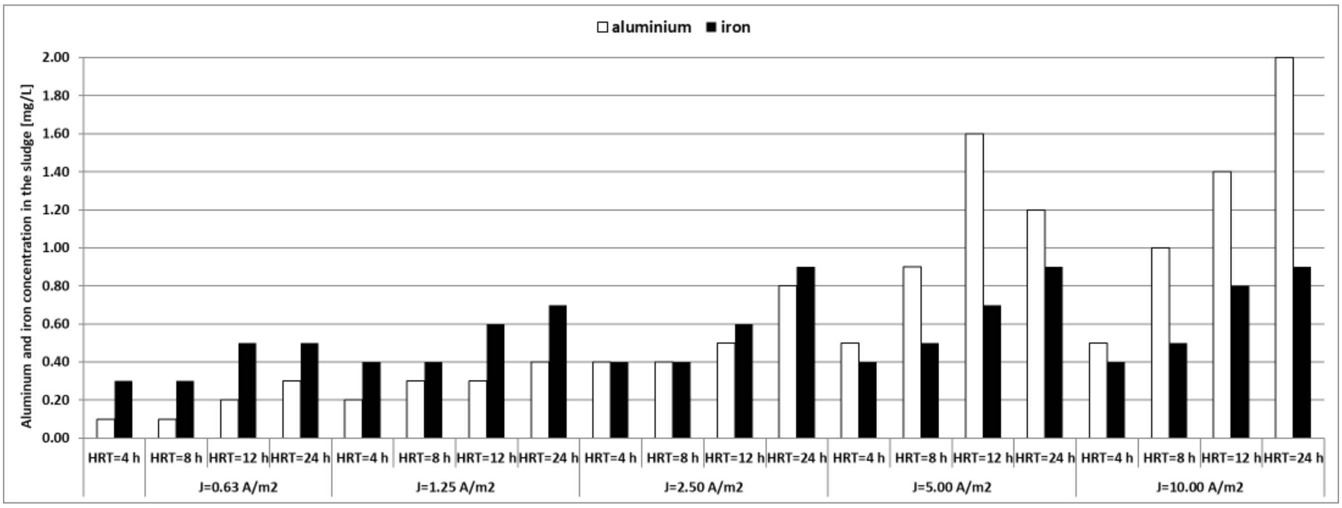

Figure 6. Aluminum and iron concentration in the sludge.

A previous study by Rodziewicz et al. [32] demonstrated that iron concentration in the effluent did not exceed 0.2 mg/L at current densities below 2.50 A/m^2 or 0.3 mg/L at the other current densities tested. Similar values were determined for aluminum, i.e., at current densities of 0, 63, and 1.25 A/m^2, its concentration in the effluent was at the limit of detection, whereas at higher current densities tested it ranged from 0.1 to 0.3 mg/L. In addition, these authors observed that HRT extension at a given current density and current density increase increased the aluminum concentration in the effluent from REBDC. The reported concentrations of both metals in suspended solids and in the effluent prove that aluminum derived from the anode is mainly consumed in the electrocoagulation process, whereas iron derived from disk and casing dissolution is mainly bound by the biofilm.

The concentrations of aluminum and iron in the sludge were lower than the values determined by Bryszewski et al. [6], i.e., from 0.3% DM at a current density of 4.4 A/m^2 to 4.5% DM at a current density of 13.3 A/m^2 for aluminum and from 0.09% at 4.4 A/m^2 to 0.23% DM at 13.3 A/m^2 for iron. These differences are due to the fact that in DC-based reactors (such as REBDC), a layer of impermeable oxides is formed on the electrodes, which causes lower iron and higher aluminum concentrations in the sludge [48]. At the same time, in AC-based reactors (such as that used by Bryszewski et al. [6]), the passivity of the cathode and anode is minimized by using AC, in which the electrodes are switched periodically. This creates better conditions for even dissolution of the electrodes in AC-mode reactors [22]. Likewise, in the study conducted by Bryszewski et al. [6], the concentrations of both metals in the sludge increased along with increasing current density. The is due to the fact that J regulates both anodic dissolution, which determines the amounts of aluminum released into wastewater and sludge [27], and the corrosion of the contactor's disks (cathode) and REBDC inflow chamber [23].

The Polish regulations (resulting from the Directive of the Council 86/278/EWG of 12 June 1986 on the protection of environment, soil in particular, in the case of sewage sludge use in agriculture [49]) set no limits for the use of sewage sludge based on its aluminum and iron contents [50]. Only concentrations of heavy metals and sanitary conditions (contamination with eggs of Ascaris sp., Trichuris sp., and Toxocara sp. parasites and pathogenic bacteria from the Salmonella genus) are strictly monitored. Due to the lack of a potential biological source of sludge contamination (household wastewater is not mixed with SCPW in facilities for soilless plant cultivation), there is no risk of sanitary contamination, which would make its application for agricultural purposes and for reclamation of soils intended for agricultural use impossible [50].

Taking into account the composition of the medium provided to plants in the facilities for soilless tomato cultivation, iron as well as minute amounts of copper and zinc are present in the effluent from REBDC and in the sludge formed in the treatment process;

however, their presence is not due to the corrosion of contactor's disks. Concentrations of copper and zinc in the medium are low enough (below 1 mg/L) that they pose no risk of exceeding permissible levels in the sludge [50,51].

Sludge formed during SCPW treatment in the rotating electrobiological disc contactor at the highest J tested (10.0 A/m^2) and the longest hydraulic retention time tested (HRT = 24 h) has the highest concentrations of nitrogen and phosphorus and the lowest of organic matter. It does not require stabilization; however, it may require dewatering depending on the method of its application to the soil. This should not be technologically challenging because, as demonstrated by Kłodowska et al. [37], sludge from electrobiological biofilm reactors is characterized by very high dewaterability (capillary suction time (CST) below 10 s). Sludge in either liquid or dehydrated form may be deployed in agriculture and for the reclamation of soils intended for agricultural purposes.

Further research is necessary to determine the volume and quality of sludge formed in REBDC in the case of using other doses of the external carbon source ensuring higher effectiveness of denitrification.

4. Conclusions

The results of this study, performed in REBDCs treating SCPW, confirmed the assumed hypothesis that an increase in electrical current density would cause an increase in the amount of sludge generated in the treatment process. The results further confirmed that current density increase would affect concentrations of biogenes and carbon compounds in the sludge. Increased J contributed to increased concentrations of N and P in the sludge, whereas extension of the wastewater hydraulic retention time in the reactor at a given current density led to increased concentrations of biogenes in the sludge and to reduced content of organic matter.

In addition, it was found that:

1. Increasing the electrical current density in the rotating electrobiological contactor resulted in increased percentage content of phosphorus and nitrogen in the dry matter of the suspended solids. Phosphorous content accounted for 0.7% to 0.8%, whereas nitrogen content accounted for 1.4% to 6.2% of sludge dry matter.
2. The increase in electrical current density caused an increase in the volume of sludge outflowing from the REBDC, whereas HRT extension at a given current density resulted in a lower volume of sludge produced and in a lower percentage content of organic substances.
3. The very low percentage content of organic matter in the suspended solids in the effluent from the rotating electrobiological contactor (from 12.14 to 23.04%) means that the sludge formed during treatment of wastewater from soilless tomato cultivation is stabilized and does not require additional stabilizing measures if intended for use in agriculture.
4. Due to the lack of a potential source of sanitary contamination of the sludge, there is no risk of it being contaminated with eggs of *Ascaris sp.*, *Trichuris sp.*, or *Toxocara sp.* parasites or pathogenic bacteria from the genus Salmonella, which would exclude its application in agriculture and for reclamation of soils intended for agricultural purposes.
5. Sludge from soilless tomato cultivation may be used as a source of nitrogen, phosphorus, and carbon, and may serve as a viable alternative to conventional mineral fertilizers applied in agriculture.
6. The present study results confirm that larger amounts of sludge are produced in direct current (DC)-mode aerobic REBDCs than in alternating current (AC)-mode anaerobic reactors.

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