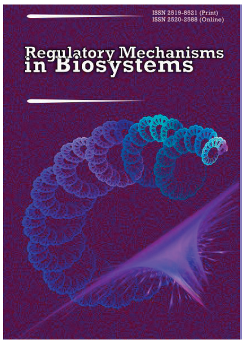

Regulatory Mechanisms in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.,
2019, 10(1), 39–44
doi: 10.15421/021906

Use of *Carex hirta* in electro-biotechnological systems on green roofs

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Article info

Received 15.01.2019
Received in revised form 27.02.2019
Accepted 02.03.2019

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Rusyn, I. B., & Hamkalo, K. R. (2019). Use of Carex hirta in electro-biotechnological systems on green roofs. Regulatory Mechanisms in Biosystems, 10(1), 39–44. doi:10.15421/021906

Production of bioelectricity from substrates with growing plants and developing microorganisms is the newest technology of alternative energetics that has great perspectives. The efforts of scientists around the world are aimed at improving biotechnology: the development of effective electrode systems for the collection of plant-microbial bioelectricity, the search for new plants, suitable for technology, testing of new substrates for the development of plants. In this paper, we presented tests of new model electro-biosystems (EBS) consisting of graphite-zinc-steelical systems of electrodes with stainless steel elements placed in plastic containers with soil substrate and planted sedges *Carex hirta*. The experiment was conducted during the year on the roofs of a university building in the climatic conditions of the Western Ukrainian region to assess the functioning of the electro-biosystems in outdoor conditions. We analyzed the different types of electrode placement in containers: with the horizontal alocation of the electrodes under the root system, with the vertical placement cathodes and anodes in a container and with the increased contact area of the cathodes with the substrate and reinforced connecting of cathodes with each other. During the experiment, we monitored the bioelectric potential of the samples which were in an open circle and under load of an external resistor. To analyze short-term voltage and current, polarization measurements were performed by changing the external resistance from 10 Ω to 5 kΩ, and the current strength, current density and power density were calculated. The conducted experiments showed *C. hirta* can be successfully cultivated on green roofs in open soil in the climatic conditions of the Western Ukrainian region. The studied electro-biosystems operate round-the-year as the plants are frost-resistant. Metereological conditions, especially the temperature and precipitation intensity, affect the electro-performance of the electro-biosystems on the roofs. The maximum average weekly current of 21.36 mA was recorded in May at optimum temperatures and a favourable humidity level, with an average temperature of 11.4 °C and rainfall of 5.39 mm/day. The electrical performance of electro-biosystems decreases during the winter and dry periods without an organized irrigation system. During the winter period, electrode systems are damaged by adverse factors. The configuration of the electrode system EBS3 is less susceptible to breakdowns due to the destructive action of water during freezing in the winter and more effective in collecting bioelectricity. The research represented in the paper is one more step towards improving bioelectricity technology on green roofs.

Keywords: electro-biosystem (EBS); plant-microbial bioelectricity; electrode system; green building; renewable energy.

Introduction

Green roofs have been used since the last centuries and nowadays are gaining popularity due to their obvious environmental benefits and the serious contribution they can make to preventing global warming on the planet. In warm weather, green roofs can significantly decrease the average temperature of a whole city, absorbing heat and reducing of the urban heat island effect (Banting et al., 2005; Getter & Rowe, 2006). In the cold season, green roofs reduce the heat loss and heating costs of buildings. At the same time, they reduce, associated with greenhouse gas emissions, energy costs for air conditioning and heating of buildings (Oberndorfer et al., 2007; Castleton et al., 2010). Improving the air quality of the city (Yang et al., 2008), landscaping, and creating a recreation area are additional benefits of green roofs.

However, since the construction of a green roof on the building of the Wageningen University, they have acquired another important environmental prospect of being a source of environmentally friendly renewable energy (Helder, 2012a). According to theoretical calculations (Strik et al., 2011), if the technology is improved, the green roof can provide energy for the whole building. In 2014, hundreds of roadside LED bulbs were lit up in Amsterdam, using only electricity extracted from plant-microbial groupings of surrounding soil (Schultz, 2014). A wireless sensor capable of monitoring environmental data, exploiting the activity of soil bacteria combined with plants for smart agriculture applications were developed in 2016 (Brunelli et al., 2016). This practical application gives rise to hope for a quick realization of the bioelectricity technology of soil with plants and microorganisms.

Research on bioelectric energy from the soil of green plantations as a variation of alternative energetics rapidly developed in the last decade (Rahimnejad et al., 2015; Behera & Varma, 2016). Since the theoretical calculated maximum power of energy of biotechnology has not yet been achieved, the work of scientists is aimed at improving technology: new electrode systems (Harnisch et al., 2009; Picot et al., 2011; Kalathil et al., 2017) and their configurations (Chen et al., 2012; Helder et al., 2012b; Wetser et al., 2017) are selected, new media (Timmers et al., 2010; Helder et al., 2011) and plants (Lu et al., 2015; Moqsud et al., 2015; Nitisoravut et al., 2017) are being searched for.

The study of the possibility of using sedge as a plant component in bioelectric systems for obtaining bioelectricity from planted soil is inspired by the unpretentiousness of *Carex hirta* and its ability to grow in all climatic zones of the globe (Gubanov et al., 2002; Jermy et al., 2007). Such properties of sedges as the ability to purify the soil and reservoirs (Wang et al., 2018), including from oil pollution (Dzura et al., 2008; Rusyn et al., 2009) and their use in landscape design (Alekseev & Novikov, 1971; Egorova, 1999; Gubanov et al., 2002) add value to sedges as bio-components of bioelectric systems together with their cosmopolitan nature and resistance to different the external conditions. The suitability of sedges for bioelectric systems may open up the possibility of arrangement on roofs of buildings or near the buildings of green areas of multiple ecological purposes: not only landscaping and climate control, but also obtaining bioelectricity and active purifying the soil environment from pollutants.

The use of plants that favour wet habitat is described in biotechnologies of the plant microbial fuel cell: Asian rice *Oryza sativa* (De

Schamphelaire et al., 2008; Kaku et al., 2008), the grass *Arundinella anomala* and giant cane *Arundo donax* (Helder et al., 2010), the common reed *Phragmites australis* (Wetser et al., 2015), cord-grass *Spartina anglica* (Timmers et al., 2010; Helder et al., 2010; Wetser et al., 2015), greater sweet-grass *Glyceria maxima* (Timmers et al., 2012), Chinese Watercress *Ipomea aquatica* (Liu et al., 2013), duckweeds *Lemna minuta* (Hubenova & Mitov, 2012), purple arrowroot *Canna indica* (Yadav et al., 2012; Lu et al., 2015), cattail *Typha latifolia* (Oon et al., 2015), and European water-plantain *Alisma plantago-aquatica* (Rusyn & Hamkalo, 2018).

Most sedges, as the listed research plants, also favour wetlands. However, hammer sedge *C. hirta* can grow on illuminated areas with different humidity, both wet and dry, on different substrates: sandy and clay, so it is the best candidate for use in electro-biosystem on a green roofs without intensific watering systems in soil substrates with the system of electrodes developed by us. We set ourselves the task of testing the model bioelectric systems with *C. hirta* and graphite-zinc-steel systems of electrodes with stainless steel elements of various configurations throughout the year on green roofs in the climatic conditions of West Ukraine.

Materials and methods

Setting of experiment

The electro-biotechnological containers with electrode systems and plants were placed on the roof of the educational building of the National University of Lviv Polytechnic to create a prototype containerized green roof. Several types of configurations of electrode systems in containers were tested (Fig. 1). Containers were kept on the roof for a year. The experiment was conducted with numerous replications.

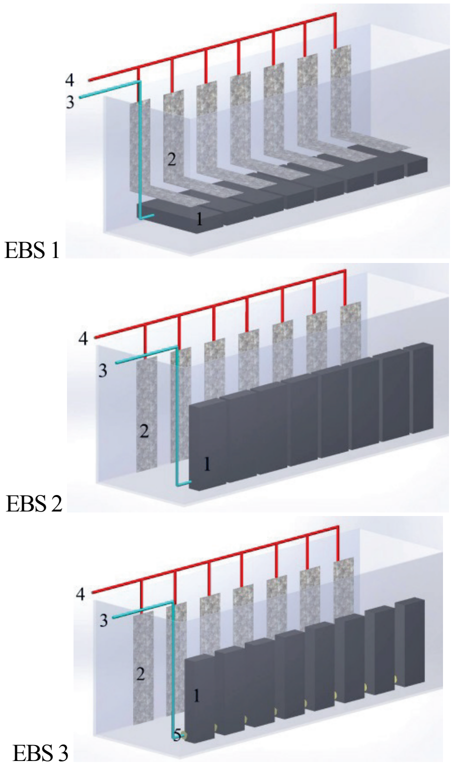

Fig. 1. Configurations of electrode systems in electro-biotechnological containers of EBS1-3: *1* – cathodes, *2* – anodes, *3* – output of the wire connecting the cathode system, *4* – output of the wire connecting the anode system, *5* – fastening elements

Electrical component of the electro-biosystem. Each system of electrodes consisted of 7 galvanized steel anodes and 8 graphite cathodes (Rusyn & Medvediev, 2018), interconnected by copper multi-conductor wires with a cross section of 1.5 mm (Rusyn & Medvediev, 2016).

The anodes were plates of 292 x 30 x 0.8 mm, curved at right angles in the form of L or folded three times in the form of letters I (Fig. 1) (Rusyn & Medvediev, 2015).

The cathodes were graphite plates 90 x 30 x 15 mm in size, connected between them by a wire almost without spaces in the form of an integrate plate in EBS1 and EBS2 and at a distance from each other, to increase the contact area of cathodes with soil in EBS3 (Fig. 1) (Rusyn & Medvediev, 2015). In EBS1, cathode electrode systems were placed in containers horizontally under the anodes and roots of the plants, and in EBS2 and EBS3 – vertically, parallel to the anodes under the roots of the plants (Fig. 1). Placement of electrode systems in the zone of association of roots of plants with soil microorganisms is due to the emission zone of electrons and protons. In EBS3, the connection between the cathodes was additionally enhanced by stainless steel fasteners (Fig. 1). The anodes were located vertically in the thickness of the substrate at a depth from 2 to 12 cm.

Biological component of the electro-biosystem. Plants of hammer sedge *C. hirta* from the places of natural growth in the Lviv and Volyn regions were planted in a plastic container with an area of 0.0525 m^2 with an electrode system in the depth of the container. The medium for plant development consisted of a universal substrate (Fig. 2).

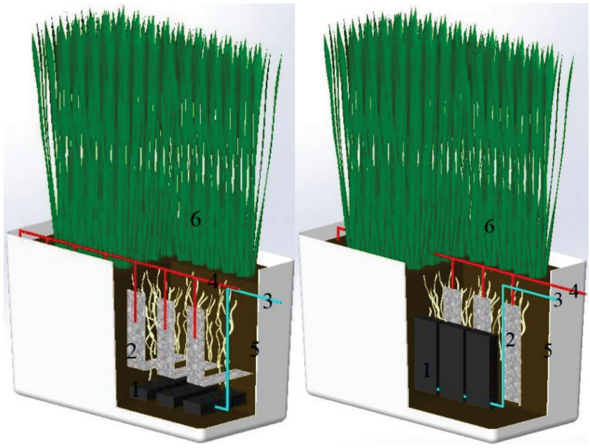

Fig. 2. Electro-biosystems with electrodes and plants: *1* – cathodes, *2* – anodes, *3* – the output of the wire connecting the cathode system, *4* – the output of the wire connecting the anode system, *5* – the container with the substrate, *6* – sedge

Measurements and calculations. Bioelectric potential and current strength were measured daily using a digital multimeter. Probes of the multimeter were connected to wires proceeding from a system of electrodes located in the depths of a container.

Bioelectric potential was monitored in time over the process of the electro-biosystem which was in an open circle. Polarization measurements were perfomed by changing the external resistance from 10 Ω to 5 kΩ for the analysis of short-term voltage, current and power generation. The polarization curves were obtained by changing the external resistors from 10 Ω to 5 kΩ. The voltage was recorded through the external load, periodically connected to the circle for 15 minutes. Polarization analysis was conducted several times.

In order to determine the electrical performance of the electro-biosystems under load conditions, voltage was measured when an external resistor was continuously connected for several days.

The current strength was measured using resistors and also was calculated theoretically through practically measured voltage and resistance according to the formula: I (A) = U (V) / R (Ω). The current density was calculated by the formula: J (A/m^2) = I / S (m^2), where: U – the measured voltage, R – the external resistance, S – the experimental area covered by the electrodes. Power density was counted accordingly to the definition: P (W/m^2) = J (A/m^2) · U (V).

The average bioelectric potential and current strength were calculated daily, weekly and every two weeks. The current density and power density were normalized to the 1 m^2 of experimental area planted by sedges and covered by the electrode systems.

The values of temperature and amount of atmospheric precipitation during the experimental period were obtained from the rp5.ua archive of the meteorological station Lviv. The average daily and weekly temperatures were calculated, the total rainfall every week and the average daily rainfall of each weekwere measured.

Results

Effect of the temperature and atmospheric precipitation on the generation of bioelectricity by electro-biosystems with sedge on roofs during the year. Meteorological conditions, especially the temperature of the environment and intensity of precipitation, have an impact on the electro-performance of electro-biosystems on the roofs. Electro-biosystems react sensitively to arid periods and intense precipitation, increase and falling in ambient temperature.

The current strength was set at the average weekly level of 19.25 mA after the installation of the electro-biosystem in September at the average weekly temperature of 15.38 °C and an average weekly precipitation of 4.19 mm/day (Fig. 3). With a subsequent decrease of rainfall at the end of September and early October, the current strength was reduced.

The most expressive increase in the average daily values of bioelectric potential and current strength occurred after intense precipitation during favourable positive temperatures that followed after prolonged arid periods. For example, in the end of October, after a 22-day dry period, during the next 10 days of precipitation, when the total amount of rainfall was 92.7 mm, there was a rise in the values of bioelectricity of electro-biosystems, especially a pronounced increase of current by 2.16 times (Fig. 4). The frost stopped further growth of the values of the current strength with increasing rainfall and the current strength was reduced (Fig. 4).

In the late-autumn and winter periods, the limiting factor of bioelectricity production is low temperatures (Fig. 3). During this period both the level of bioelectric potential and current strength was reduced. During frosts during the winter period, the current strength did not exceed 3 mA (Fig. 3). With the growth of the ambient temperature in the early spring, the current strength increased again and at temperatures above 10 °C it grew to the original values (Fig. 3). The average weekly current in the first half of May was higher than 20 mA at an average daily temperature of 11.43 °C. The strength of the current was maintained further at a high level and dropped during droughts.

The influence of rainfall on the level of bioelectricity was most significant in the spring, summer and autumn periods, when the plants developed, and the average daily temperatures did not drop below 0 °C. Prolonged arid periods during optimal positive temperatures in June and August, led to a sharp decrease in the current strength (Fig. 3).

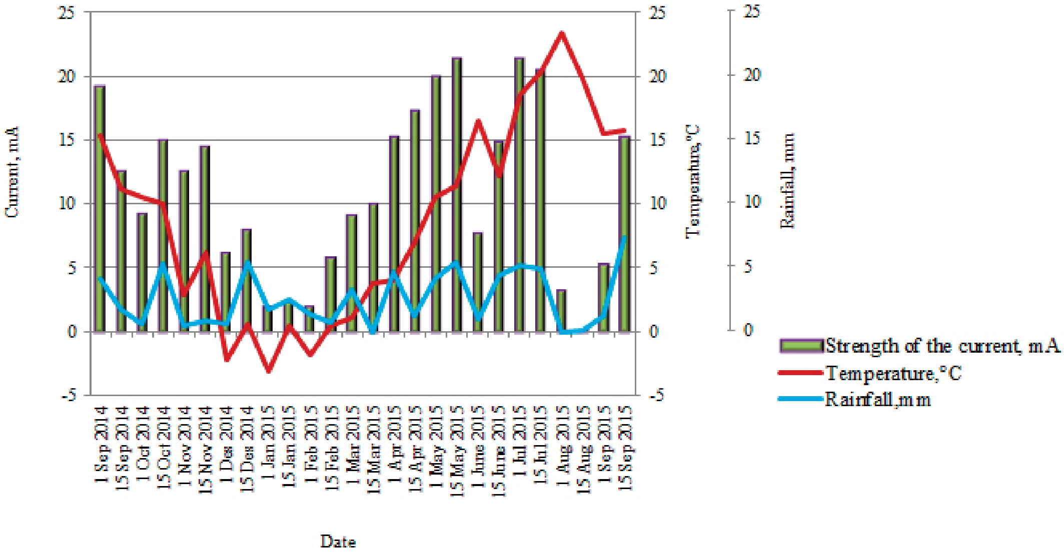

Fig. 3. Dynamics of current strength depending on the influence of meteorological factors during the year in round-the-year-effective electro-biosystems: the current strength is essentially lowered during minus temperatures and prolonged arid periods

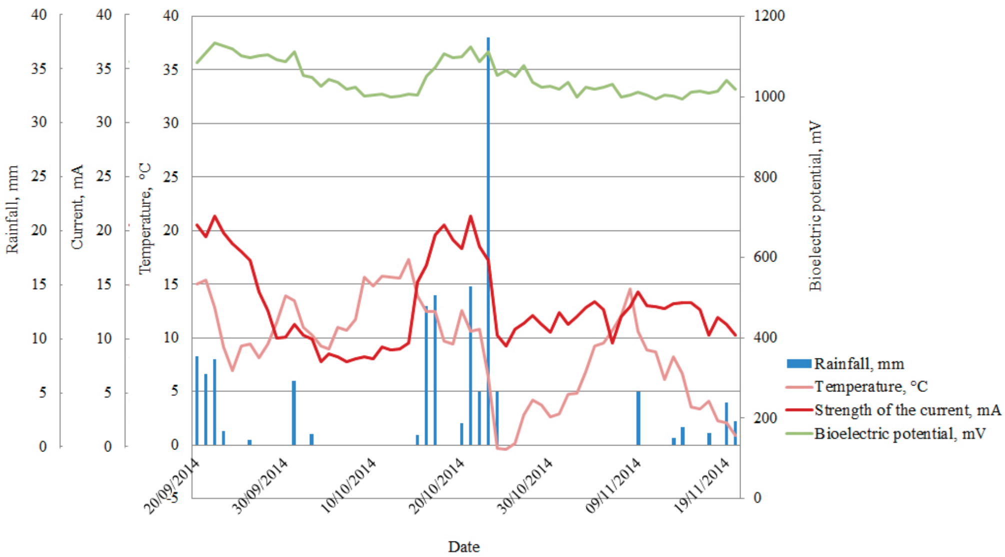

Fig. 4. Average bioelectric potential at open circle and current strength of electro-biosystems during intense precipitations and arid periods in the autumn: the decrease of current strength and bioelectric potential was recorded in early October during a few weeks of arid period and at the end of October, with a decrease in the average daily temperature below 0 °C and drought

Thus, the average weekly current of 21.36 mA at favourable temperatures and sufficient precipitation, 5.39 mm/day, during the last two weeks of May, in the following drying 2 weeks of June with a rainfall reduced to 1 mm/day, despite the favourable temperatures, 16.55 °C, dropped to 7.78 mA (Fig. 3).

During July, at optimum temperatures and a favourable humidity level, at an average daily temperature of 18.51–20.32 °C and rainfall 4.95–5.22 mm/day, the average weekly current strength rose to 20.48–21.35 mA. During August, at similar, favourable temperatures, but low humidity, at a average daily temperature of 19.87–23.34 °C and rainfall of 0.00–0.13 mm/day, the current strength dropped practically to zero, to 0.11–3.23 mA (Fig. 3). However, in September, the current strength again renewed its level with an increase in the amount of precipitation, 4.65 mm/day at a temperature of 11.08 °C (Fig. 3).

Plant metabolism is activated in the zone of comfort of positive temperature and sufficient moisture, and as a result, active photosynthesis is accompanied by release of roots' extracts – substrates for the development of electro-generating microorganisms, obviously, therefore, in these conditions, the strength of the current increases.

The long-term maintenance of minus temperatures and prolonged droughts are unfavourable factors for work of electro-biosystems. Current strength was reduced by 91.5% of the maximum values during frosts and practically to zero during prolonged droughts, and fully restored its level when temperature rose and precipitation was restored. Regular precipitation of about 5.1 mm/day and a positive temperature are optimal for EBS operation. If we are not able to influence the temperature regime on the green roofs, then by ensuring regular watering of plants it is possible to achieve effective work of the EBS all the year-round except for a period of prolonged winter frosts.

Breakdown of electro-biosystems in the winter period. The hammer sedge as a component of the EBS is a winter-proof plant and survived the impact of severe winter weather conditions. However, a significant part of electro-biosystems were damaged in winter period (Table 1). In the winter, the electro-performance of systems was reduced and only a small fraction of the EBS was generated (9.8–25.6%) in the spring restored the initial level of bioelectricity (Table 1). Model electric biosystems, in the main EBS1 and EBS2, failed after the winter period and required the restoration of the connections between the electrodes. In winter, the power of expansion of frozen water damaged the contacts between the electrodes. EBS3 with reinforced joints was somewhat more resistant to its damaging action (Table 1).

The EBS with replaced electrode systems in the spring and with preservation of vegetation continued to work effectively (Table 1).

The role of electrode system configurations in the work of hammer sedge electro-biosystems. The long-term effect of the external resistance of 500 Ω caused a more than twofold decrease of the bioelectric potential, at 2.21–2.26 times, which recovered within a day after the removal of the external resistor in all electro-biosystems regardless of the configuration types (Fig. 5). The decrease of bioelectric potential in the EBS3 was somewhat less than EBS1 and 2 (Fig. 5).

Table 1
Electro-performance of electrical biosystems during year ($P < 0.05$)

Type of electrical biosystems	EBS worked efficiently a year-round, %	Average open-circuit bioelectric potential, mV			
		September 2014	April 2015		
			EBS without failures	EBS with breakdowns	EBS after repairs
EBS1	9.8	1031.1	1018.5	717.1	1077.0
EBS2	11.3	1026.2	1042.9	850.1	1085.5
EBS3	25.6	1049.1	1056.1	894.3	1071.1

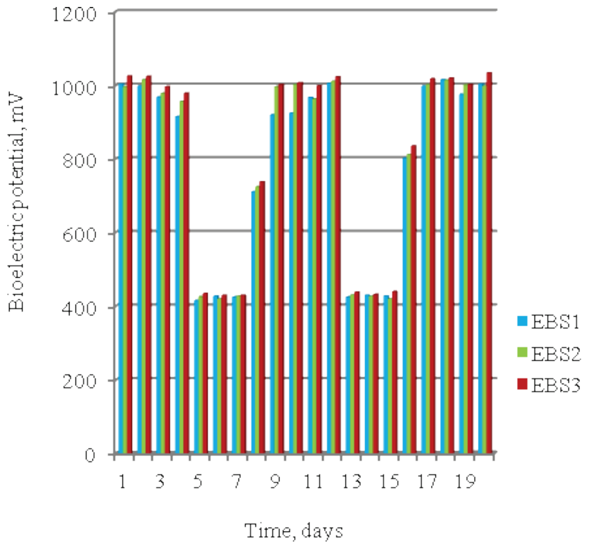

Fig. 5. Effect of external resistance 500 Ω during 3 days on electro-biosystems (EBS) work with different configurations of electrode systems and sedge

During a short-term load, the power density in electro-biosystems without additional cathode-fastening elements fell from 0.95 W/m^2 (EBS3) to 0.79 W/m^2 (EBS1) (Fig. 6). The highest power density was recorded in the short-term use of an external 50 Ω resistor.

The highest values of the bioelectric potential were recorded with the application of the highest external resistance and were decreased with connections of lower loads.Thus, at a short-term connection of 12 kΩ external resistor, the average bioelectric potential of the electro-biosystems ranged from 970 mV (EBS3) to 952 mV (EBS1) and dropped an average to 107 mV (EBS3) – 98 mV (EBS1) when using an external resistance of 10 Ω (Fig. 6).

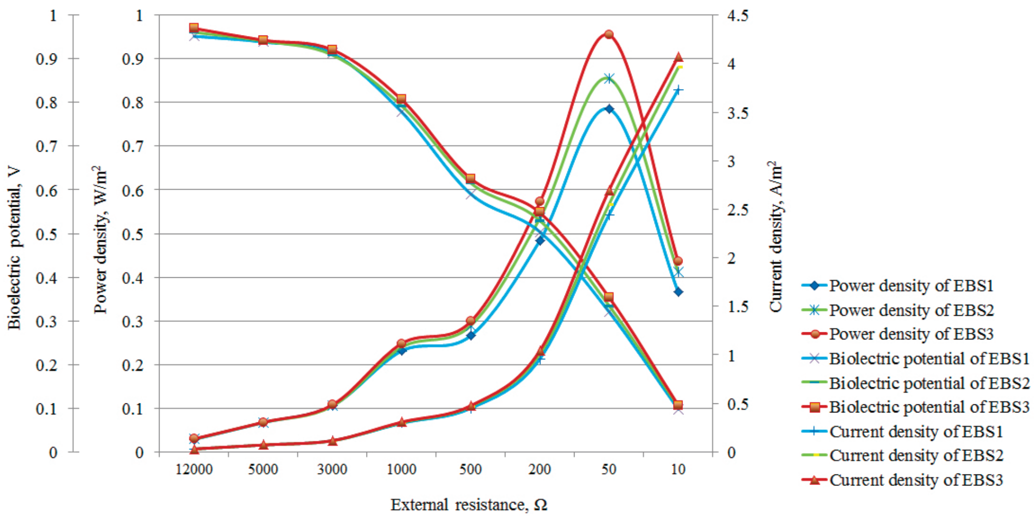

Fig. 6. Influence of short-term action of external resistance on bioelectric potential, power density and current density of electro-biosystems with sedge

The current density, normalized to 1 m^2 of the surface covered by plants and electrodes, was 0.960 A/m^2 (EBS1) – 1.044 A/m^2 (EBS3) with a short-term application of an external resistance of 200 Ω (Fig. 6).

Bioelectricity production by bioelectric systems at short and long-term load almost did not differ and was slightly higher in EBS3 (Fig. 5, 6). EBS3 was also more resistant to damage by adverse weather conditions of the winter period and worked more efficiently the year-round. 25.6% of the electro-biosystems with the configuration 3 after the winter period restored the initial values of the bioelectric potential and current strength (Table 1).

Discussion

The currently developed electrobiological systems contain electrode systems based on various materials, for example, platinum vs. iron (II) phthalocyanine based electrodes (Harnisch et al., 2009), but carbon nanotubes and graphene are the most commonly used materials (Chen et al., 2019). Choice of materials, optimal configuration of electrodes and suitable plants can improve the perfomance of plant-microbial electrobiosystems (Nitisoravut et al., 2017). The novelty of the electro-biosystem developed by us consists in the application of new materials for electrode systems, graphite – zinc – steel with stainless steel, their new configurations, and the new biocomponent, sedge plant *C. hirta*. This electro-biosystem has some similar characteristics, described in the literature, with another types of electro-biosystems. We noted the dependence of the decrease in the value of the bioelectric potential with a decrease in resistance during short-term connection of resistors, as described in electro-biosystems by Cheng et al. (2006). The current density was 1.02 A/m^2 with a short-term application of an external resistance of 200 Ω (Fig. 8), which is close to that recorded in other bioelectric systems with distinguishing electrode systems and media: 1.60 A/m^2 in a synthetic medium (Helder et al., 2012b) and in an aquatic environment of 1.62 A/m^2 (Hubenova & Mitov, 2012). The maximum values of the current strength are lower than those recorded in the *Alisma plantago-aquatica* similar electro-biosystem in marshy substrate (Rusyn & Hamkalo, 2018), probably due to the use of a medium with lower conductivity. In addition, the influence of the medium on the electrical efficiency is very significant, since its structure, pH, determines the type of microbial community generating bioelectricity (Nitisoravut et al., 2017).

Placement of electrodes in substrate with plant roots and soil microorganisms, configuration design overall affected the power output of the electro-biosystem (Nitisoravut et al., 2017). So, with the use of flat-plate design instead of traditional tubular electro-biosystem design, currents were increased almost by 10 times and power density by two times per planting area (from 0.15 to 1.60 A/m^2 and from 0.22 to 0.44 W/m^2) (Helder et al., 2012b). The depth of the location of the electrodes is essential. It has been reported that the power output is more at 5 cm of dipped anode and deeper in comparison with the surface positioning of the anode at a depth of 2 cm (Takanezawa et al., 2010; Deng et al., 2014).

We used a variation of flat-plate configuration with different types of arrangement of electrode systems in containers: with vertical placement of anodes in a substrate at a depth 2–12 cm, with horizontal and vertical placement of cathodes, with cathode sticks, connected in the form of an integral plate and separately placed graphites with their strengthened fastening. Among all variants of configurations, the greatest impact on the performance of bioelectric systems was made by the distance between the cathodes and their enhanced fastening with wire. EBS3 with cathodes located separately, was characterized by higher values of bioelectricity in both short-term and long-term loads (Fig. 5, 6). Probably, the increased contact area of the electrodes with the electrons and protons emitted into the ground played a positive role, as well as the stronger contact of wire and graphites by an additional stainless steel fastener, which allowed the system to collect electrons with the least losses. EBS3 was also more resistant to damage by unfavourable meteorological factors in winter (Table 1).

The percentage of electro-biosystems, effectively working all the year-round is low, but the fact that the plants withstand frost and restore their growth in the spring is a significant achievement. The literature describes the death and freezing of plants on green roofs during the winter period (Helder et al., 2013). The sedge *C. hirta* is a cold-resistant plant and electro-biosystems with *C. hirta* can be exploited round-the-year on roofs in the climatic conditions of the Western Ukrainian region.

In the above-described studies, we demonstrated that the work of electrical biosystems depends on the temperature of the environment. Fall in the temperature below 10 °C was accompanied by a signifycant decrease in the current strength level. Obviously, the reduced level of photosynthesis under these conditions led to a weakening of the root-soil flow of organic matter, which affected the development of the electro-producing microorganisms of the soil. Testing of electro-biosystems with another type of electrode system under laboratory conditions showed similar results of inhibition of the electro-productivity of systems at temperature below 10 °C (Hong et al., 2009; Li et al., 2013).

At optimal positive temperatures, the amount of precipitation is the limiting factor for the work of electro-biosystems. Prolonged arid periods lead to a sharp decreasein level of the current. A similar bioelectricity dynamic is described in the work of the group of researchers Dai et al. (2015), which showed the effect of the seasonal arid period on the reduction of the current of electric biosystems *in situ*. Regular irrigation during arid periods can provide effective EBS operation all the year-around, except for the period of prolonged winter frosts.

Conclusion

C. hirta can be cultivated all the year-round on the roofs of buildings in the composition of the electro-biosystems in the metereological conditions of the Western Ukraine. *C. hirta* is the optimal biocomponent of electro-biosystems on roofs, as it is winter-resistant, survives in arid conditions and restores its electro-activity after moistening of the soil substrate. Meteorological conditions have a significant impact on the functioning of electrical biosystems. Ambient temperature below 0 °C is the limiting factor for the operation of the electrical biosystem in winter and long dry periods decreased their functioning at favourable positive environmental temperatures in the spring, summer and autumn. The electrical performance of EBS in drought conditions and in the winter frosts was not high. For effective work of electro-biosystems, regular humidification, about 5.1 mm/day, and positive temperatures above 10 °C are required. Among the considered electrode configurations, EBS3 with an increased contact area of cathodes with the substrate and an enhanced fixing of electrodes by stainless steel elements is the most promising model of electro-biosystems with sedge. EBS3 is more effective for collecting bioelectricity, works more efficiently under conditions of both short-term and long-term load, and is also more resistant to damaging effects of adverse weather conditions on electrode systems. Further improvement of EBS electrode connections, the use of irrigation systems and the overall increase in the power energy will make it possible to use electro-biosystems with *C. hirta* on green roofs of buildings to obtain bioelectricity. Electro-biosystems with graphite – zinc – steel electrode systems with stainless steel elements and *C. hirta* are a promising source for renewable and stable generation of green energy.

We express our sincere gratitude to Oleksandr Valentynovych Medvediev for consultations regarding the technological stage of work implementation.

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