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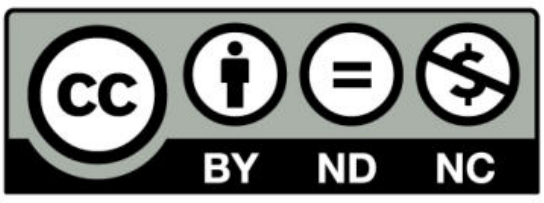

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ENERGYCOMPO II: Design of a hydroponic battery-pot system that generates electricity using pepper plants cultivated with bio-waste compost

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Summary

Plants require water, nutrients, and a growing media for their growth and development. The rhizosphere is the region where plant roots transform soil chemical compounds for their assimilation. During this phenomenon, an electrons flow occurs, which can be used to obtain electricity similarly to an electrochemical battery. This is known as biophotovoltaic energy, and its interest as an environmental biotechnology is increasing. In this research, we designed a hydroponic battery-pot system to produce electricity during the growth of pepper plants. We studied the effect of moisture content and salt concentration in the growing substrate. Also, we evaluated the addition of bio-waste compost to increase plants´ growth and development, as well as electricity production. According to our data, humidity is crucial for electrical conductivity, as is salinity in the substrate. To achieve these goals, installing a hydroponic system in the battery-pots was essential. Finally, the addition of bio-waste compost improved plant growth and development, and consequently, electrical intensity.

Keywords: Copper tubes, electrical intensity, food scraps, metallic mesh, moisture, salts, voltage.

INTRODUCTION

The rhizosphere is defined as the region where soils and roots are directly in contact [1]. The biological activity in the rhizosphere is quite significant because it is where chemical reactions necessary for the transformation and assimilation of nutrients by the roots take place [1]. During this process, an electrons flow is generated, which, similar to an electrochemical battery, can be used to generate electricity. This phenomenon is known as biophotovoltaic energy and it is currently under research and development as a sustainable technology [2]. In fact, there are already several examples of its application, such as "Plantalámparas: Plants that give light", from the Universidad de Ingeniería & Tecnología (UTEC) of Peru [3] or the Plant-e project [4].

Plant growth is enhanced by compost, a material produced by waste recycling that provides a large amount of organic matter, nutrients, and beneficial microorganisms that promote plant growth. In the CAOS project "Biological insights of Estación Experimental del Zaidín (EEZ) bio-waste composting" [5], we studied the biological process of composting of the bio-waste generated by the Estación Experimental del Zaidín (EEZ-CSIC), and demonstrated that this compost is an excellent organic fertiliser that stimulates the biological activity of plants.

In the CAOS project "Plants can be used as electrical batteries", we investigated the generation of biophotovoltaic energy by onion plants grown with compost from the EEZ-CSIC [6]. Although the compost improved plant development, we did not observe its effect on the electrical potential. This could be due to the experimental system used was not suitable because the pots and electrodes were too small. Continuing with this idea, in the last CAOS project [7], we evaluated the effect of compost on pepper plants using two types of electrodes. We obtained the best results with electrodes which had the largest area. As in the previous projects, we did not see the effect of compost on electricity generation, although it did improve pepper´s plants growth.

All these results led us to believe that the design of our energy system was not optimal. For this reason, the aim of this research was to optimize a battery-pots system in order to test if the compost can improve the biophotovoltaic energy production.

MATERIAL AND METHODS

1. Hydroponic battery-pots design and electric measurements

The battery-pots used in this research were designed according to previous results [5,6] but with some modifications. We used plastic 0.5 L pots with a foam of 1cm height placed between anode and plant substrate to ensure water retention (Figure 1A and B). Electrodes were copper tubes and metallic mesh as cathodes and anodes, respectively (Figure 1C). The hydroponic system was designed with two paper strips embedded at the bottom of each pot, which were inserted in plant nutrient solution to ensure proper watering (Figure 1D).

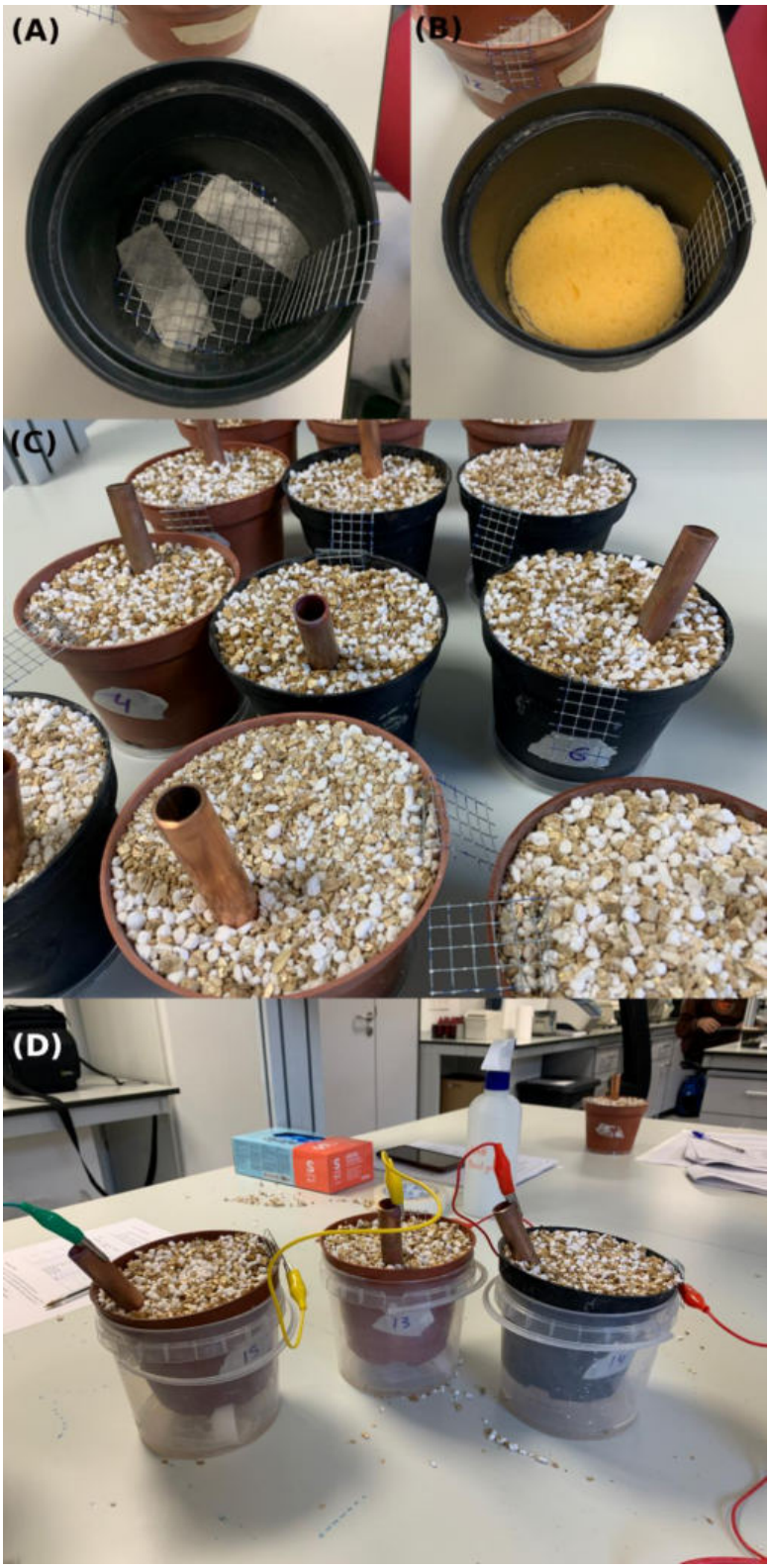

Figure 1. An overview of the battery-pot systems used in this research: metallic mesh placed at the button of the pot (A), a 1 cm height foam (B), battery-pots with electrodes (C) and hydroponic system (D)

Two mixtures of plant substrate were assayed in this research (Figure 2):

- Substrate 1: perlite/vermiculite (1:1, v/v)
- Substrate 2: perlite/vermiculite/compost (1:1:1, v/v). The compost was made with bio-waste from Estación Experimental del Zaidín (EEZ-CSIC), as previously described [5].

Electric potential difference (or voltage; V) and electrical intensity (I) was recorded as Pérez et al. recommended [5] by using a professional digital multitester. Electric recordings were made after connecting 4 hydroponic pots in series as a battery-pot circuit by using a LED lamp (Figure 2).

Figure 2. An overview of the plant substrates: Substrate 1, perlite/vermiculite (A); Substrate 2, perlite/vermiculite/compost (B); and the hydroponic battery-pots system used during peppers growth experiment (C).

2. Plant experiments

15 days-old pepper plants (*Capsicum annuum* L.) were transplanted to the hydroponic battery-pots and grown at the Greenhouse and Growth Chamber Service facilities of the EEZ-CSIC for 3 days. Tap water was used as nutrient solution and it was renewed in the hydroponic pot every week according to plant requirements. The V and I were also recorded every week as it was described above. After harvesting, height, number of leaves and flowers, shoot (SFW) and roots fresh weight (RFW) were recorded as it was described in [2].

3. Experimental design

Three consecutive experiments were carried out in this research:

- Experiment 1 (Effect of water). In order to know the effect of moisture substrate in the electric measurements, four tap water volumes (0, 50, 100 and 150 mL) were added to pots with and without hydroponic system, and V and I were registered after 15 minutes.
- Experiment 2 (Effect of salt). Four NaCl solutions (0, 1, 2 and 3 g L^{-1}) were tested after addition to pots without hydroponic system. The added volume to each pot was decided according to Experiment 1 results.
- Experiment 3 (Effect of compost). In order to evaluate if compost can improve plant development and electricity production, pepper plants were grown in pots with hydroponic system and with and without compost according to the following treatments (Figure 2):
    - T0: Hydroponic battery-pots filled with substrate 1 without plants
    - T1: Hydroponic battery-pots filled with substrate 1 with plants
    - T2: Hydroponic battery-pots filled with substrate 2 with plants

A total of 12 hydroponic battery-pots were used in each experiment, 4 per treatment (Figure 2). Data were expressed as arithmetic mean.

RESULTS

In Experiment 1, we explored the effect of water content in plant substrate on the V and I produced by the battery-pots (Figure 3). To do this, we added four volumes of tap water to pots (0, 50, 100 and 150 mL), which represented approximately < 5, 10, 25 and 30 % of substrate moisture. According to the results, water strongly affected the voltage in the battery-pot system (Figure 3A). Apparently, electricity did not flow properly with less than 25 % of moisture. Similar results were found in electric intensity, which exponentially increased with water addition to the pots (Figure 3B). The more water the plant substrate contained, the higher the electrical intensity was. In parallel, a hydroponic system coupled in the battery-pots was evaluated. In this device, 150 mL of tap water were added, which represented more than 30 % of the substrate moisture. In this system, maximum records were recorded, close to 40 µA.

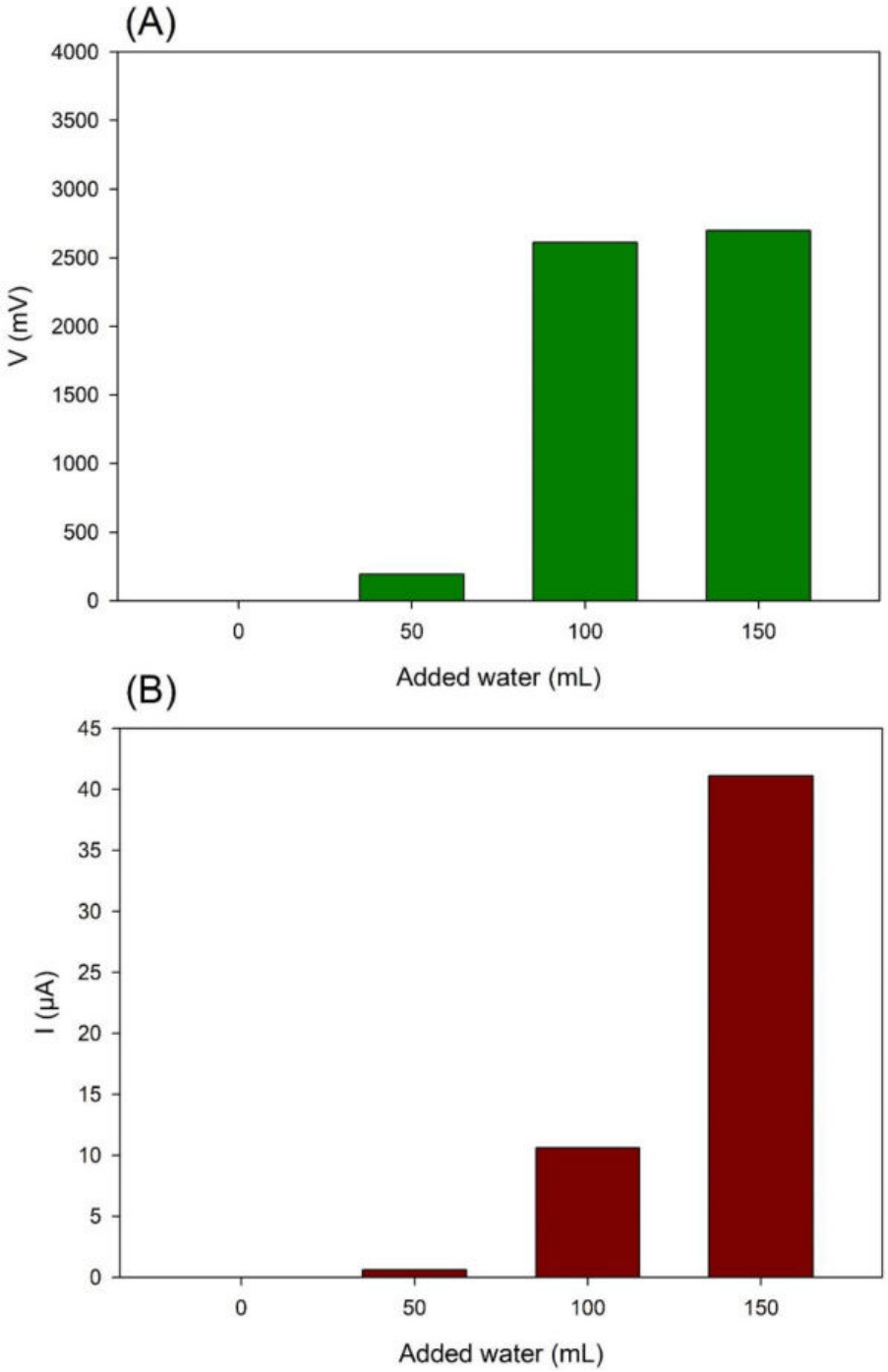

Figure 3. Results of the Experiment 1: effect of water addition to battery-pots on its electrical potential difference (or voltage; V) (A) and electrical intensity (I) (B).

Results from Experiment 2 showed that salt content in plant substrate was also relevant for the electricity flow in our battery-pots devices (Figure 4). While the voltage remained constant with salt addition (Figure 4A), the electrical intensity increased linearly with the NaCl concentration added to the battery-pots (Figure 4B). Accordingly, the maximum I values were registered after addition of 150 mL of NaCl at 3 g L^{-1} to battery-pots, producing approximately 15 µA.

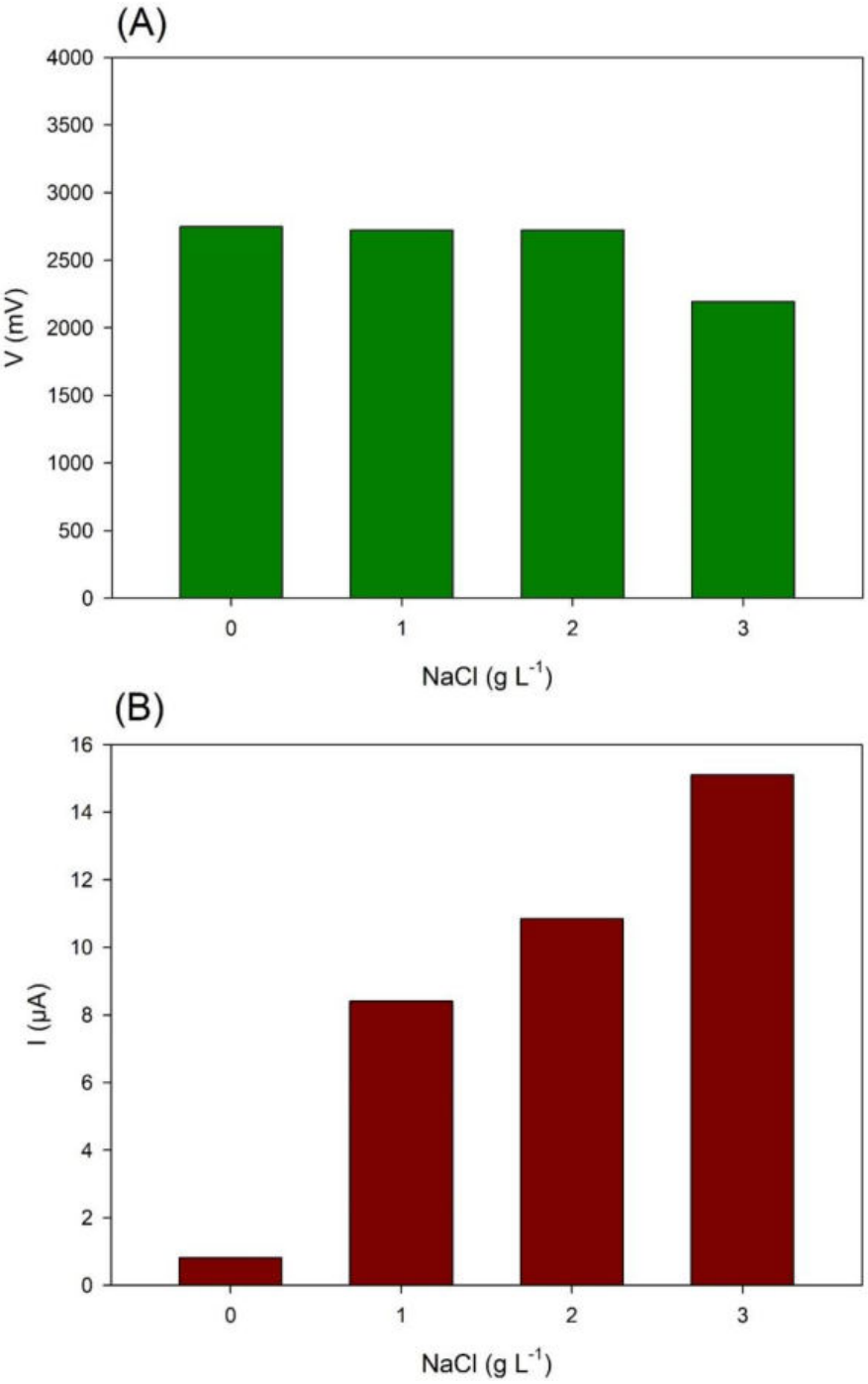

Figure 4. Results of the Experiment 2: effect of salt concentration added to battery-pots on its electrical potential difference (or voltage; V) (A) and electrical intensity (I) (B) of battery-pots.

Data from Experiment 1 and 2 allowed us to determine the experimental conditions for the electrical production during plant cultivation. Based on our results, we used a hydroponic system to maintain the correct level of moisture in the growing substrate. Also, we added compost due it its organic matter and nutrients content. Compost provided salts, which could contribute to improving the electrical flow in the battery-pots as noted in the electrical conductivity measurements. Substrate 1 (perlite/vermiculite) used in T0 and T1 treatments was 751 ± 23 µS cm^{-1} and 5140 ± 154 µS cm^{-1} in Substrate 2 (perlite/vermiculite/compost) (T2

treatment), being close to 5 fold higher. Pepper plants were grown for 35 days and V and I were recorded weekly (Figure 5).

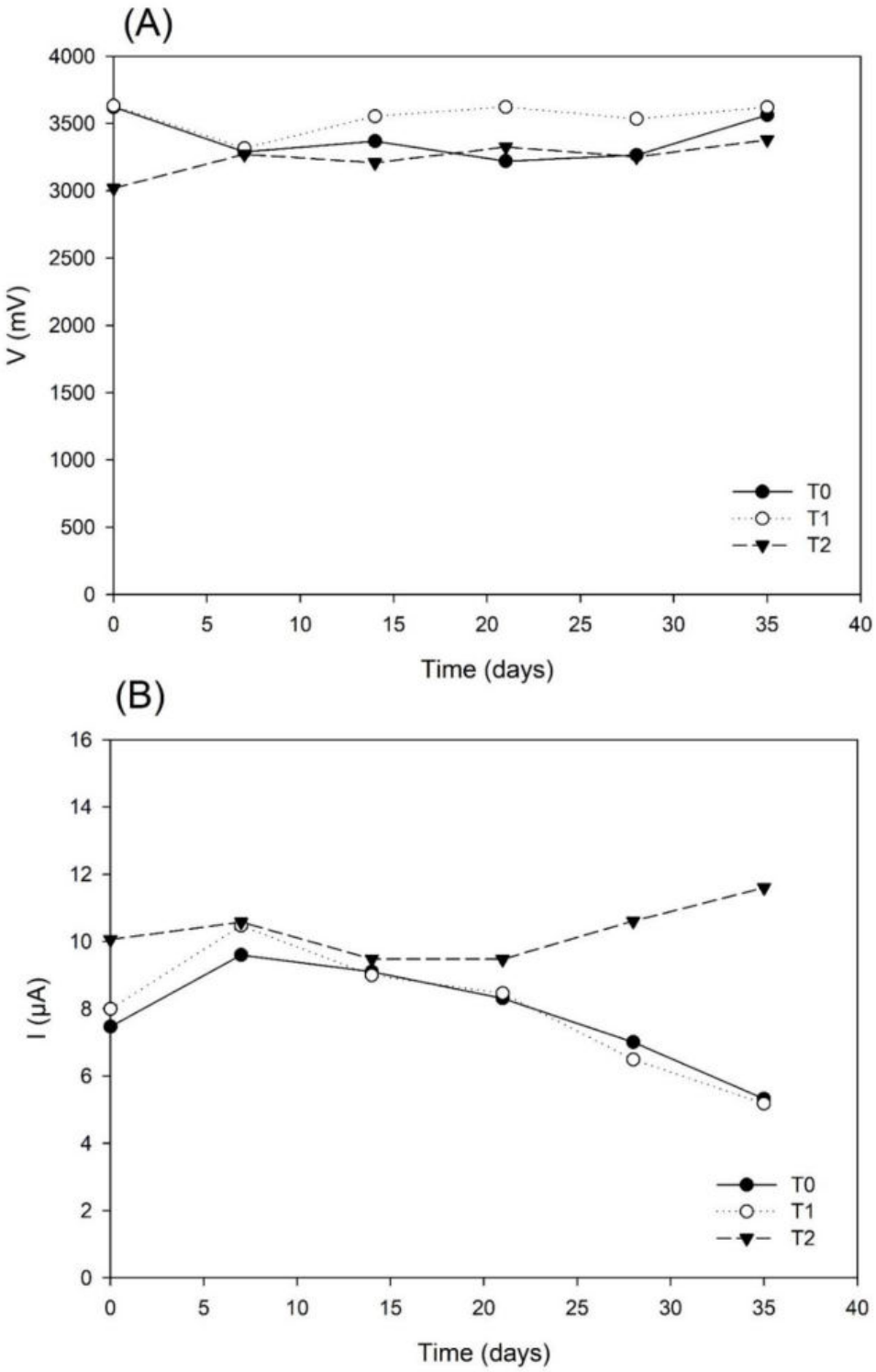

Figure 5. Results of the Experiment 3: evolution of electrical potential difference (or voltage; V) (A) and electrical intensity (I) (B) of battery-pots during peppers growth. T0, control treatment without plants; T1, pepper plants without compost and T2, pepper plants with compost.

Neither compost nor the plants affected voltage during growth (Figure 5A), which were ranged between 3000 and 3500 mV. In contrast, compost strongly affected electrical intensity (Figure

5B), especially after 3 weeks of growth. Pepper plants of T2 grew and developed notably compared to T1 treatments (Figure 2) and I values were increased from 9 to 11 μA, three times higher than T0 or T1 treatments. Compost addition not only improved electricity production but also plant growth and development (Table 1) by increasing height, number of leaves and flowers, and plant biomass (SFW and RFW) compared to T1 treatment (Table 1).

Table 1. Physiological parameters of pepper plants grown with or without compost after harvesting. T0, control treatment without plants; T1, pepper plants without compost and T2, pepper plants with compost.

Treatments	Height (cm)	Number of leaves	Number of flowers	SFW (g)	RFW (g)
T0	0.0 ± 0.0	0 ± 0	0 ± 0	0.0 ± 0.0	0.0 ± 0.0
T1	20.4 ± 1.0	7 ± 1	0 ± 0	3.0 ± 0.2	4.0 ± 0.7
T2	34.4 ± 3.0	13 ± 1	3 ± 2	11.0 ± 2.5	9.0 ± 2.5

SFW: shoots fresh weight, RWW: roots fresh weight.

DISCUSSION

In this research, we have optimized a battery-pot system for the electricity production during plants growing. According to previous research, several parameters can modulate the electricity flow through the system, such as electrode material and dimensions, pot size, root plants, and growing substrates, among others [6, 7]. In this research, we have evaluated moisture, salt content and compost addition to the plant growing substrate.

Our results showed that the battery-pots have to be properly watered to ensure the circulation of electrons, and consequently, electricity production. Although water is not a good conductor of electricity, it is the universal solvent [8], which means that dissolved salts are responsible for the electrons transfers in the battery-pot. Salts are essential for the flow of electrons in a battery [9]. Plants watered with a nutrient solution with more nutrients, and thus higher electrical conductivity, will enhance the process and compost can provide both. Food scraps are characterized for its high salt content, especially after cooking [10]. For that reason, bio-waste compost typically has high electrical conductivity [5, and our data].

As demonstrated by our results, the hydroponic system installed to battery-pots ensured constant humidity during the growth of the peppers. Also, the compost provided salts and nutrients which improved electricity production. Therefore, the main conclusions of this research are:

1. Humidity is key for electrical conductivity, and a hydroponic system can ensure this in a battery-pot.
2. Salinity increases conductivity, and a compost with higher salt content also can improve electrical intensity. An example is bio-waste compost.
3. Bio-waste compost improves electrical intensity, thereby enhancing plant growth and development. This suggests that a battery-pot can be improved by fertilizing the plants with bio-waste compost.

Taking all these findings into account, some future researching lines are proposed:

- It could be interesting to investigate whether a different type of plant, such as succulents, would create a higher intensity due to their higher water content.
- We observed that the plant roots were trapped in the foam. To avoid that, we propose a new battery-pot system without a sponge. It would be interesting to observe how the roots will grow around the electrode itself.
- Finally, it would be compelling to test if increasing the soil biological activity with worms could enhance electricity production.

Acknowledgements

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MY OWN IDEAS

Carla González Gutiérrez

Initially when we were introduced to the ENERGYCOMPO II project, I saw the whole project very far away and had little idea about what we were going to do and what it was going to consist of, so I did not find it really interesting. But from the moment we started to introduce ourselves deeply into the project, I started to see everything clearer and I found it really interesting. The moments that I highlight of this project would be the days in the EEZ-CSIC, since I had a lot of fun and also learned a lot, another highlight would be the conference that despite being quite long was very entertaining and enriching since we undertook much of the other experiments, at the time we had to present our project, even though we were very nervous at first, in the end we did quite well and we knew how to perfectly expose the work we had carried out for months. In conclusion, I found it a really enriching activity in which at the same time that we learned we had fun, so I would recommend it to anyone.

Carmen Lorente Calvo

This project has been very interesting, I really liked the idea we were proposed and the questions that we were given, as I think they invited us to think more and they also were related to the contents we saw in class.

I personally think that the project was very well thought out, I really liked the different experiments and how we discussed the results obtained at the end of the whole process. By discussing between us we learned more and increased our curiosity. It also made us feel proud of ourselves for achieving interesting results. I think the project overall made us realize that there were fun methods to learn science and that what we are learning in school can be really useful.

It was very fun going to the laboratory and doing there the experiments, because we really felt like real scientists. Although I would have liked seeing the whole building, I understand it was not possible because of the time restriction and other things. The project wasn't finished when we did all of the experiments, we needed to do a document in which we explained the project and then a presentation that we would present in a congress. Doing the document and the presentation in class was a bit tedious but overall not too bad. It helped us learn how to do scientific papers and everything so it wasn't useless. The congress on the other hand was a very fun experience and it was a great way for most of us to improve our public skills. For me for example, I felt a lot of pressure when I needed to talk, and although it could've been better it wasn't that bad. All in all, it was a great experience and I would love to repeat it. I learnt many things and I think it made us all fonder of science. Even the part in which we did not experiment was good, so I'm willing to do more projects like this in the future.

Nicole Elizabeth Mergen

When our physics and chemistry teacher Marta proposed the ENERGYCOMPO II project, I was initially doubtful. I believed that working in a lab would be unrewarding, but it has been the contrary to that. Working in this semi-professional experiment has rewarded me deeply and made me look at science in a new and more positive light. I will always be deeply grateful for this experience and shall never forget the fun moments of the project we got to take part in. Working alongside professionals and my classmates has been wonderful and the experiments proposed to us were thoroughly explained which was the best part, as I was able to understand what I was doing and carry it out effectively and well. Understanding a project like this was also the key to enjoying it. Without the help of my teacher, Marta Torres and Germán Tortosa from EEZ-CSIC, I wouldn't have had a fraction of the understanding or enjoyment of this experiment. I also think this project has given us a bigger understanding of work and has given us experience, which, in my opinion, the school I go to can't offer as I have more to do with a work oriented atmosphere. To end this project, we had to present it in a congress and explain it to other people our age, which I found a very good ending to this experiment.

Olalla Pérez Luque

Taking part in the ENERGYCOMPO II project has been an incredibly enriching experience for me. Being involved in a semi-professional experiment and working with an experienced researcher has provided

me an enormous amount of knowledge. One of the most important things of this project was to have the chance of working in a real laboratory, EEZ-CSIC. The opportunity of using experimental equipment, which is not available in our school, has greatly improved my understanding of scientific research and gave me skills that are important for any who wants to work in something related to this subject. The project also emphasized the importance of teamwork. Our group worked closely helping each other to achieve good results. I am so glad we had Germán Tortosa and Marta Torres as our leaders since they did an incredible job during this experience. They always motivated us and created a grateful work environment, which I fully enjoyed. Additionally, the experience of presenting our findings at a congress helped me improve my presentation skills. I am grateful for the opportunity to participate in the ENERGYCOMPO II project. If they give me the chance, I would gladly take part in similar projects in the future, as they provide a unique and practical learning experience that goes beyond traditional classroom education.

Gonzalo Piédrola Romero

What started like normal trips to have fun turned out to be a one time experience, the project that have offered us knowledge and have teach us lot of things was mainly direct by our physics teacher, Marta Torres and by the CSIR researcher German Tortosa, which have become two of our friends thanks to all the fantastic experiences. This experiment, which at first we hadn't any idea, turned fast into a lovely thing to do. The materials used, which were new for us, German was in charge of explaining to us how to do everything, he explained the objective and the steps to reach it. We learn new vocabulary and science facts that we didn't have any idea about. Every trip to the EEZ-CSIC was fun and taught us different things, it was all fun and learn until we discovered a new fear, the presentation in front of all the schools who had made any science project, we needed to learn everything and prepare, we thought it was going to be the worst but it turned out to be very exciting and fun, there was food and laughs. To summarize everything, it was a very exciting experience and a great time with teachers and friends. I absolutely recommend it to everyone that wants to try it because you are not going to regret it.

Javier Ruano Algar

In the last years I have been watching different classes starting this project, and I was observing patiently waiting for my turn. This year in 4°ESO our physics and chemistry class had the opportunity to take part in this project called ENERGYCOMPO II proposed by Germán Tortosa, a CSIC researcher. The first two classes were of introduction where Germán with the help of our teacher explained the project and the schedule we would follow in the next 5 sessions. These sessions took place in the EEZ-CSIC and they lasted about three months in total considering that we went twice a month. During this day of experimentation, we had the opportunity to observe the growth and progression of our crops, just as we measured their electrical performance with the help of some LED lights.

The good thing about this project is that while you acquired new knowledge about the operation of electrical circuits and the growth of plants, you learned to solve all kinds of problems that could arise at a given moment and unexpectedly, such as machines measures don't work, or that the results don't make sense or don't look like your hypothesis, which makes you think that you have to repeat it again, but instead of seeing this as something terrible, we see it as something fine, since it teaches you that failure is not bad, is normal, and worst is to give up. At the end of these sessions we had a congress where we presented our work while we heard about other experiences that other schools had carried out not only in Granada but also in other parts of Andalusia. This was an incredible opportunity to learn things that are not taught in school and that are very unique and important for young people like us. I have learned a lot and I would definitely recommend it to anyone who has even the slightest interest in science and innovation.

Gabriel Enriquez

In the previous months, our Physics teacher introduced EnergyCompo project to us. We began with tons of excitement when we met Germán Tortosa for the first time; he explained to us what we were supposed to do and what the project consisted of. Germán is the researcher who helped us carry out this project. During the last months, we did many visits to the EEZ-CSIC where we learned about how to work in the laboratory. In the laboratory, Germán explained to us what we needed to do and we managed to do it

efficiently. Although we used materials that we had not seen before, he patiently taught us how to use them well. Finally, we measured the plants and the energy they produce depending on the materials and methods that we introduced to the different treatments. After that, we prepared ourselves to attend a congress in which schools from Granada and Andalucía told us about their projects and research. In my opinion, I consider this project offers lots of benefits, such as the possibility to work in groups in a laboratory with lots of equipment. We also improved our teamwork skills, because each group had assigned tasks and everyone must contribute. It was a great experience for all of us, because we always had a great time and we obtained lots of new knowledge and skills thanks to this project.

Adrián Tejedor García

The possibility of taking part in a project like this came unexpectedly, but although at the beginning I found it kind of boring, I ended up really enjoying experimenting in a real laboratory with a real scientist in order to end up with our final conclusions. I love how interactive and well explained the sessions in the experimental center were, despite the fact that we were a bit too slow in my opinion. However, we were able to learn new things and find the practical side of them anyways, which I think is the most valuable aspect of this experience. Even when we found an obstacle, we worked as a team (and were helped by Marta and Germán) to find a solution. A remarkable example of this is the session in which we accidentally switched the amount of salt between two different treatments and ended up with weird results. Although this may be a problem, it actually was an advantage because thanks to it we got to learn how to measure salt concentration in water. Overall, I highly recommend participating in this project as it makes you learn a lot about science and it provides useful experiences and knowledge. I am thankful to have had the opportunity to be part of it.

Sara Vargas Montoya

I personally think this project was very interesting. I was able to work with materials that I didn't even know they existed and I also am very grateful because our teacher thought of us and knew that we were really going to enjoy it. I think it's a great idea to create electricity by using the energy from a plant; it is not only original but also good for the environment. This electricity doesn't pollute or contaminate our planet, so in the future it will probably be very useful.

About the experiment, it was very entertaining. I really like the fact that we were able to make the experiment ourselves instead of just writing down the results. We used many laboratory materials and they explained to us what they were for. We also experimented with different compounds, by adding more or less water, calculating if salt increased electricity and at the end we realized salt really helped with electricity so we added compost that came out of organic matter from the food we eat because it had salt. Then, we made a presentation about this project and finally, we showed it to many people.