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Constructed wetlands as nature based solutions – hands-on activities to highlight their potential to minimize ocean pollution

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Abstract
This work presents an engaging hands-on activity designed to teach school students about nature based solutions (NBS) and their role in achieving high-quality water systems within a sustainable circular economy. Through this activity, students actively participate in building a small constructed wetland (CW) and test its effectiveness under various contamination scenarios. The activity was tested with school teachers, undergoing refinements based on their feedback. This iterative development process has ensured the activity's effectiveness in engaging both school students and the public. Further, the CW model can be scaled-up for specific school projects focused on improving water quality. This activity offers valuable opportunities to enhance ocean literacy, promote understanding on NBS and raise awareness about aquatic ecosystems contamination and the importance of environmental sustainability.

Keywords Educational kits · Constructed wetlands · Contamination of aquatic environments · Environmental sustainability

Introduction

The European Commission is set, through its Green Deal, to decrease pollution, restore damaged ecosystems and bring nature to its environments, from cities to agricultural land and from forests to the ocean (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en). Nature based solutions (NBS) can be key to attain these aims. NBS stand as an engineering approach designed to integrate natural ecosystems and their functions and services into urban, landscape and seascape environments. They are integrated with existing natural systems and provide multiple stakeholder benefits, being cost-efficient, resilient, adaptable and sustainable (van der Meulen et al. 2023). NBS are globally scalable and represent a holistic response to the increasing pressures of chemical and biological contamination faced by diverse ecosystems. Notably, different approaches can be used for addressing these challenges, such as natural wetlands and constructed wetlands (CWs).

For example, estuarine salt marshes, recognized for their exceptional ability to improve water quality, stand as a prominent example of the important role natural wetlands play in ecosystem conservation (Cunha et al. 2024). CWs are engineered wetlands that imitate natural wetlands, optimising natural processes within a controlled environment. These systems utilize natural processes involving soil/substrate, wetland vegetation and associated microbial communities for the treatment of wastewaters or other polluted water sources, acting as an exemplary NBS. Through a combined action of plants, microorganisms and substrate/soil components, CWs can effectively reduce the concentration of harmful compounds to levels safe for aquatic life and the environment (Almeida et al. 2017a). Physical, chemical and biological processes, such as volatilization, photodegradation, sorption and sedimentation, plant uptake and microbial degradation, may occur simultaneously, contributing to eliminate different compounds (Almeida et al. 2017a). CWs are among the most widely adopted NBS for wastewater treatment, being also relevant for the nexus water-carbon (Jamion et al. 2023).

Despite the growing recognition of the environmental and social significance of NBS and the significant technological

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innovations and advances in CWs, school students and the public in general are still highly unaware of their benefits. Moreover, there is a lack of activities fostering their understanding and preparing the mind-set and creativity of our future generations for the need to adopt and develop co-solutions promoting environmental and ocean sustainability (Correia et al. 2020; Gravina et al. 2019; European Commission, 2022).

The aim of this work was thus to develop a kit and hands-on experimental activity based on the CW concept that could be used in the class room for teaching. The ultimate goal was to offer teachers and other educators sound resources to integrate environmental and ocean sustainability into their students curriculum, and disseminate the value of nature in which we are all part off.

Materials and methods

Assembling of the CW model

Before assembling the CW model, a CIIMAR researcher expert made an oral presentation on the topics of bioremediation and phytoremediation and natural and constructed wetlands and on the use of these biotechnologies as NBS. This presentation was followed by the practical session in which the participants assembled the CW model and tested it. The CW model was built using the following materials: transparent boxes of 10–20 L, faucets, perforated silicone tubes fitting the faucets, gravel, expanded clay or other porous material (e.g. lava stone), sand, water, plants (e.g. lilies or pitchers or other easily-to-obtain plants that support wet medium) (Fig. 1). The detailed hands-on protocol was developed based on the lab scale CW microcosms used in research (Fig. 2 and Supplementary material).

Petshop kits were used for quantification of phosphates, ammonia and nitrites ions, and of pH in the water going in and out of the CW model assembled by the participants. Water, doped with known amounts of nutrients (by adding ammonium and phosphate salts), was firstly prepared and given to the teachers before the activity. After assembling the model, participants added the nutrient doped water to system. Water was poured on top, flooding the system through the layers, until it was saturated. Aliquots of water were collected through the faucets placed at the bottom immediately after assembling the system and after two hours in the system, and nutrients levels were quantified.

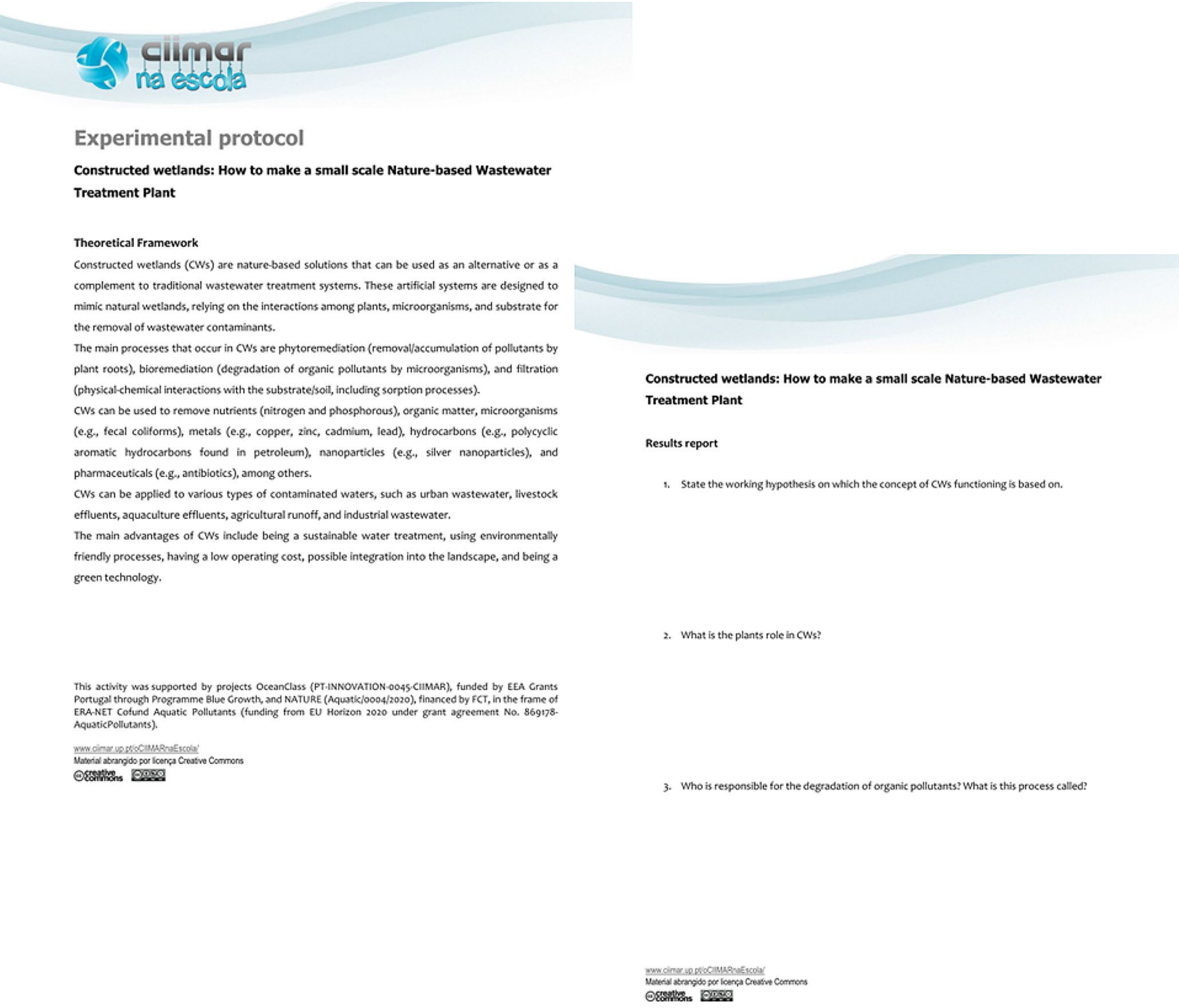
Qualitative and quantitative assessment of the activity

To evaluate the potential contribution of the CW kit in improving knowledge and design future ocean literacy actions, the hands-on activity was tested with 31 Portuguese teachers of basic and secondary learning cycles from schools of Porto and Aveiro districts (Northern Portugal 15 teachers) and from schools of the Azores Islands (16 teachers). The teachers were participants of the life-long training action focused on ocean literacy offered freely through the OceanClass project (funded by the Blue Programme of the EEA Grants, https://ociimarnaescola.ciimar.up.pt/OceanClass.php).

A qualitative assessment of the activity was done using simple questions expressed without preconceived hypotheses. At the end of the activity, three general questions were asked orally to the participating teachers:

- *What are your thoughts about the experiment you did?*
- *What impressed you most?*
- *What do you think about NBS and their importance to water quality?*

Fig. 1 Assembling a CW lab scale model. Protocol and video in https://ociimarnaescola.ciimar.up.pt/OceanClass.php



Experimental protocol

Constructed wetlands: How to make a small scale Nature-based Wastewater Treatment Plant

Theoretical Framework

Constructed wetlands (CWs) are nature-based solutions that can be used as an alternative or as a complement to traditional wastewater treatment systems. These artificial systems are designed to mimic natural wetlands, relying on the interactions among plants, microorganisms, and substrate for the removal of wastewater contaminants.

The main processes that occur in CWs are phytoremediation (removal/accumulation of pollutants by plant roots), bioremediation (degradation of organic pollutants by microorganisms), and filtration (physical-chemical interactions with the substrate/soil, including sorption processes).

CWs can be used to remove nutrients (nitrogen and phosphorous), organic matter, microorganisms (e.g., fecal coliforms), metals (e.g., copper, zinc, cadmium, lead), hydrocarbons (e.g., polycyclic aromatic hydrocarbons found in petroleum), nanoparticles (e.g., silver nanoparticles), and pharmaceuticals (e.g., antibiotics), among others.

CWs can be applied to various types of contaminated waters, such as urban wastewater, livestock effluents, aquaculture effluents, agricultural runoff, and industrial wastewater.

The main advantages of CWs include being a sustainable water treatment, using environmentally friendly processes, having a low operating cost, possible integration into the landscape, and being a green technology.

This activity was supported by projects OceanClass (PT-INNOVATION-0045-CIIMAR), funded by EEA Grants Portugal through Programme Blue Growth, and NATURE (Aquatic/0004/2020), financed by FCT, in the frame of ERA-NET Cofund Aquatic Pollutants (funding from EU Horizon 2020 under grant agreement No. 869178-AquaticPollutants).

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Results report

1. State the working hypothesis on which the concept of CWs functioning is based on.
2. What is the plants role in CWs?
3. Who is responsible for the degradation of organic pollutants? What is this process called?

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Fig. 2 Protocol to assemble a lab scale CW

Participants were asked to talk freely as much as they wanted to express their subjective views and impressions.

A preliminary quantitative analysis of the activity was also done by asking a simple question, with five optional answers:

1. *Constructed wetlands (CWs) are nature-based solutions that can be used as an alternative or as a complement to traditional wastewater treatment systems. Select the correct statement(s)*:

A. CWs have high costs and are based on a concept that requires the installation of highly complex machinery that causes great impact on the environment.
B. The main advantages of CWs are their low cost of operation, the possibility of integration in the landscape and the fact they are a green technology.
C. CWs are artificial systems designed to mimic natural wetlands.
D. CWs can only be applied to contaminated water with very specific characteristics.
E. Nature-based solutions allow creating new ecosystems with new functions and services.

The question was presented to the participants before and after the module related with Biotechnologies of the lifelong training action. All responses of the participants were anonymous. Correct answers were the options B, C and E. Scores were given as the overall proportion of correct answers provided.

Statistical analysis

A factorial analysis of variance (ANOVA) was carried out to assess the potential contribution of the CW kit in improving teachers' knowledge. The score of the participants in the quantitative question was taken as dependent variable and the time of assess and region of origin were taken as factors. The arcsin transformation was applied to the data to achieve normality and homogeneity of variances. The significance level was 0.05 and the analysis was performed in SPSS v21.

Results and discussion

Assembling of the constructed wetland model

Participants assembled a small model of a CW using simple supermarket materials and easy to get plants (Fig. 1). The assembling was done according to the protocol specifically developed to support classroom teaching (https://ociimarnaescola.ciimar.up.pt/images/cw.pdf; Supplementary material). A video was also done to help build the model (https://www.youtube.com/watch?v=MSiJ18CfmW8&t=3s).

For the activity, a nutrient enriched water was used to fill the CW and the participants were instructed to measure nutrient levels in the water collected right after assembling the system and collected after two hours in the system.

The lab-scale CW model was based on CW microcosms used in research with the aim of evaluating CW potential to remove pollutants, such as organic matter, nutrients, metals, antibiotics and pathogenic bacteria, from livestock wastewater (Almeida et al. 2017b; Santos et al. 2019; Dias et al. 2020; Bôto et al. 2023) and aquaculture effluents (Gorito et al. 2018; Bôto et al. 2016). The CW microcosms were assembled with a layer of gravel, a layer of either lava rock or expanded clay, and a layer of sediment and/or sand to support plant roots. During the initial phase, the systems were acclimated for one or two weeks with a nutrient solution. Then the contaminated water was treated in the CW system during one or two weeks cycles. The plant commonly used was *Phragmites australis*, but experiments with *Typha latifolia* were also carried out, obtaining similar results. For instance, ammonia removal rates up to 98% and phosphate removal rates up to 93% were achieved (Almeida et al. 2017b; Dias et al. 2020).

In the CW model assembled by the teachers, the decrease in nutrients during the treatment in the CW was helpful to understand CW functioning and applications.

The protocol supporting the activity contains a part with indications and instructions for teachers to prepare their lectures about this topic and an experimental log sheet for the students (Fig. 2, Supplementary material). The experimental log sheet was designed to facilitate students understanding of the concept and function of each component within the CW model. It also aimed to guide them in summarizing their learning and encourage discussions about NBS, CWs, and their real-world applications. During the activity, teachers were invited to fill in the experimental log to evaluate its usefulness.

Assessment of the activity

Qualitative assessment revealed that participants highly valued the hands-on nature of the activity, which allowed them to delve deeper into the topic and its real-world implications for water scarcity and quality. The possibility of using such NBS solutions to treat effluents for example from aquaculture or farming facilities or wastewaters, came up as a relevant aspect. Participants considered that the experiment was simple, attractive and especially useful to understand the physical and biochemical processes occurring in wetlands as well as those associated to CWs operation. The opportunity of exploring those concepts and processes through a simple model that can be used in the classroom with multiple experimental and environmental sustainability purposes was a significant plus. Furthermore, the CW model aligns with the principles of green technologies and NBS principles and to their potentialities to mitigate ocean problems, particularly when applied in transition systems like estuarine areas. For instance, one can explore the role of wetlands in removing estuarine pollutants, preventing them from reaching the Ocean and, therefore, protecting our Ocean.

Regarding the quantitative assessment, the two groups of participants were similar in age and gender (Fig. 3). Their age ranged from 43 to 62 years (mean 52 ± 5) in those from Porto/Aveiro region and from 40 to 60 years (mean 48 ± 6) in those from the Azores Islands. Teachers from the mainland were all from the Biology and Geology group of the 3rd Cycle of Basic Teaching and Secondary Teaching. Teachers from the Azores Islands were distributed among the 2nd Cycle of Basic Teaching (Mathematics and Natural Sciences), as well as the 3rd Cycle of Basic Teaching and Secondary Teaching (Biology and Geology and Farming Sciences).

The ANOVA analysis showed a significant main effect of the time of the quantitative assessment ($p < 0.0001$) and of the interaction of time and region ($p = 0.003$) (Table 1). Overall, the results suggest that the activity was effective in improving knowledge on CWs for teachers from both regions, although more strongly for those from the mainland (Porto and Aveiro regions) (Fig. 4). Results also indicate that teachers from Azores Islands appear to be more aware and knowledgeable about the topic than their mainland

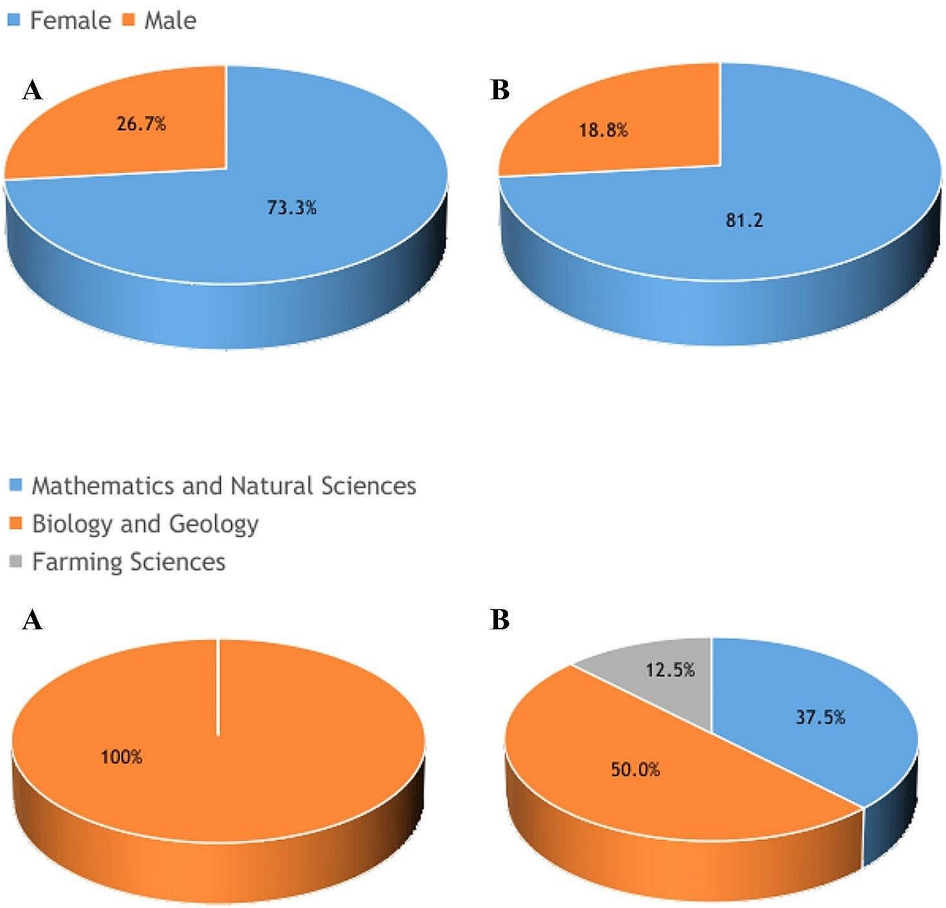

Fig. 3 Main characteristics of the two participant groups from the mainland (Porto/Aveiro region) (**A**) and the Azores Islands (**B**)

Table 1 Results of the ANOVA analysis performed to evaluate the effect of the activity on the teachers' knowledge about constructed wetlands

Source of variation	Degrees of freedom	Mean Square	*F*	*p*
Time	1	13.485	30.02	< 0.0001
Region	1	0.049	0.109	0.742
Time * Region	1	4.354	9.693	0.003
Error	58	0.449		

colleagues, possibly due to their different teaching areas and/or the fact they are islanders.

The participant teachers were additionally interested in the CW model for the chance to provide their students with state-of-the-art knowledge and developments about urgent environmental challenges and about the research and technology co-solutions under development. The log sheet was saw as helpful to consolidate the new knowledge acquired. University students often work with similar models for their training or research. Though, to our knowledge, activities that natural sciences and biology teachers can use to address the topic and prepare the students for their final exams are not easily available but are much needed (Saiote et al. 2014). There is a strong need for tools to address the scientific method, quantitative interpretation, and most important to develop students' critical thinking, and environmental and co-creation skills (European Commission, 2022). Involving chemistry and mathematics teachers in the activity can also broaden its scope and appeal, transforming it into a multidisciplinary learning experience. Chemistry teachers can offer additional methods and deeper understanding of water quality parameters, linked to their core biological importance to living species. Math teachers can take advantage of the data gathered by the students and introduce them to inferential statistics. Philosophy and social science teachers can also enrich the learning by facilitating discussions on the importance of environmental sustainability for our planet´s future, exploring the social and economic benefits of NBS and CWs. These are all valuable aspects for discussion with students in an interdisciplinary setting.

Moreover, the model allows also to address issues regarding water scarcity and reuse. Water scarcity, a major challenge of our times, sits at the forefront of the United Nations' Sustainable Development Goals (SDGs) for 2030. Extreme weather events, climate change, and unfavourable geography make freshwater resources highly vulnerable in many countries. The United Nations Organization and the

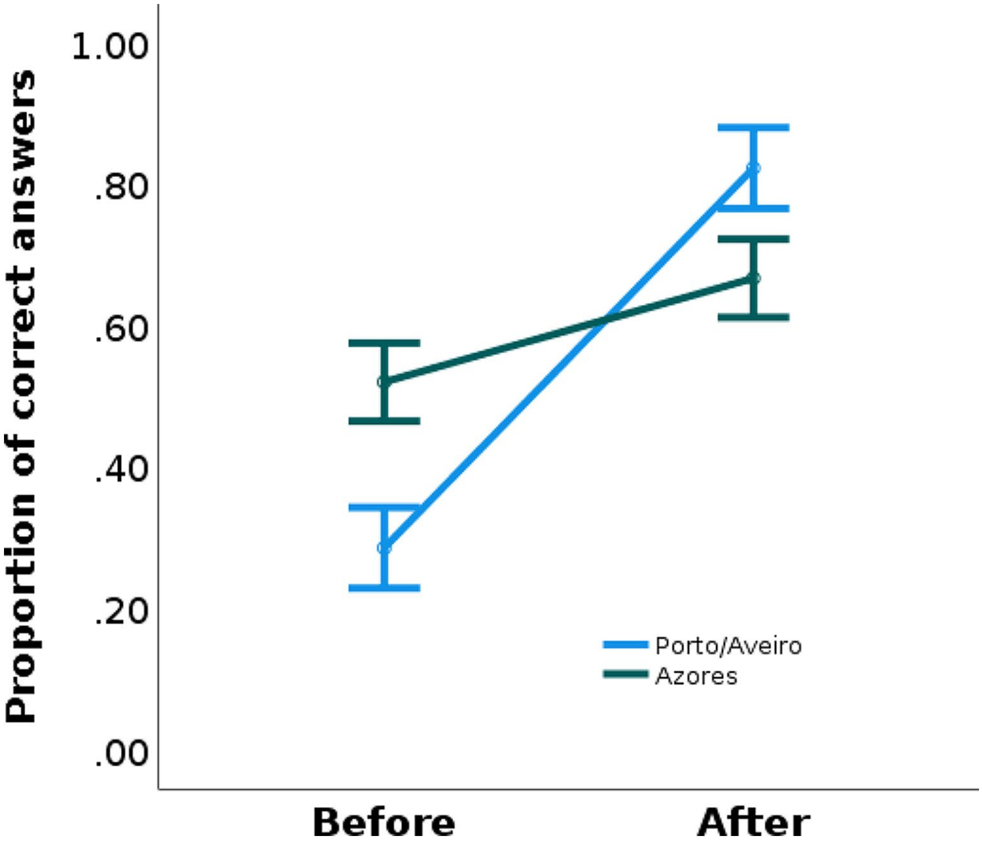

Fig. 4 Proportion of correct answers before and after performing the activity of teachers from mainland Portugal (Porto and Aveiro regions) and Azores Islands ($N=31$). The values represent the mean score and respective standard error

European Union have prioritized water reclamation and reuse as a strategic approach to mitigate the global shortage of clean freshwater for human consumption and agriculture. Implementing this plan requires the development of efficient, affordable and environmentally sustainable solutions for water treatment. Conventional water treatment methods (e.g. ozonation, membrane filtration) are often expensive, requiring specialized infrastructures, personnel and equipment, and consuming significant amount of energy. This creates access limitations for many populations worldwide and hinders the ability to meet growing water treatment needs. Therefore, exploring alternative technologies is crucial and eco-technologies can be a suitable choice. In light of the current search for alternative water treatment solutions and technologies, NBS like CWs stand out as promising and attractive options. NBS are usually considered to be cost-efficient in the initial investment and ongoing operation and maintenance, making them accessible to a wider range of communities.

Overall, the results are highly encouraging and warrant further investigation. A deeper quantitative assessment, including comparisons within groups, would be valuable in refining the developed model for teaching about water treatment and reuse, as well as on ocean literacy, to teachers and their students. Further questions that maybe included in the assessment are related to CW processes and the relevance of microorganisms, plants and the substrates in those processes (e.g., Table 2) and their overall importance in terms of sustainability.

Overall, this versatile hands-on experiment readily adapts to available classroom time. When there are time constrains, in the classroom or in the training sessions, a cooking-show approach can be easily used. By using a pre-assembled and stable system, participants can immediately measure water quality parameters while assembling another CW system, maximizing learning efficiency. The measurement of the water quality parameters can also be done on different days, like an exhibition set, allowing the students to investigate the impact of different factors.

From our experience, recognizing the different components and building the CWs model provides deeper understanding of ecosystem functioning, ocean sustainability and NBS contribution to address crucial societal challenges. NBS can be key for instance for coastal protection (van der Meulen et al. 2023) The hands-on experiment also facilitates a clear understanding of basic concepts and principles related to, for example, eutrophication, biodiversity and the water circular economy. It covers Essential Principles of Ocean Literacy (Ocean Literacy 2013, 2020; Santoro et al. 2017) and fits sustainable development goals (SDG) of the Decade of Ocean Science for Sustainable Development (2021– 2030), proclaimed by the United Nations; SDG 4

Table 2 Further possible questions to include in a deeper quantitative assessment of the experimental activity developed herein

Phytoremediation involves different processes of removal/degradation/elimination of pollutants, being divided in phytoextraction, phytostabilization, phytodegradation, phytovolatilization, phytofiltration and phytostimulation (or rhizoremediation). Select the correct statement(s):

A) Phytoextraction promotes the removal of pollutants through their accumulation in plant tissues *Correct statement*

B) Phytostabilization promotes the removal of pollutants through their accumulation in plant tissues In*correct statement*

C) Phytostimulation is directly related with the microbial activity in the rhizosphere of the plant promotes the removal of pollutants through their accumulation in plant tissues *Correct statement*

D) Phytovolatilization promotes the accumulation of pollutants in plant aboveground tissues *Incorrect statement*

E) Phytoextraction promotes the removal of pollutants through their accumulation in the soil surrounding layers. *Incorrect statement*

Chose the option that completes the next sentence so that it becomes an incorrect statement: Constructed wetlands are a useful wastewater treatment technology that:

A. presents high costs of implementation and maintenance.

B. is based on a technological concept that required the assembling of sophisticated machinery.

C. demands installing complex equipment that has a high environmental impact.

D. involves pollutant removal processes carried out only by microbial communities.

E. all of the above options Option to be selected

Select the correct option. In constructed wetlands the main players are:

A) plants alone

B) microorganisms alone

C) plants and microorganisms

D) plants, microorganisms and substrate Option to be selected

E) Plants and substrate

(Quality education), SDG 6 (Clean water and sanitation) and SDG14 (Life below water).

This hands-on activity can also be used in museums and public science centres during workshops and exhibitions. Effective knowledge transfer and capacity building, achieved through communication actions with and for the general public and students, are essential for ensuring the sustainable exploitation of the ocean and coastal resources. Utilizing experimental hands-on dissemination and communication activities can actively engage school students in understanding the benefits and functioning of NBS. These approaches are very relevant to involve the younger generations in the protection of nature, and ultimately of the ocean. They also provide a means to inspire students creativity towards the development of environmentally sustainable technologies and business innovation in the future.

The application of eco-technologies as CWs can be key in increasing the use of NBS systems, in line with the current European Green Deal and with the ambitions to restore biodiversity and achieve zero pollution.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s11852-024-01044-3.

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