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Optimizing Local Materials in Green Roofs Through Citizen Science Activities at a Primary School in Azores

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Abstract: Green roofs are a fundamental technology in the transformation of urban centers into more sustainable environments, with a positive impact on buildings, cities, and their inhabitants. Yet, green roof technology may require the use of materials with a high environmental impact, namely, when associated with large transport distances. The present work arises from the need to find an environmental solution to use in an eco-school on one of the Azores islands. It tests green roofs on a wooden structure using local and sustainable materials. Prototypes were built to monitor their performance and to complement the theoretical information investigated regarding the construction systems of green roofs with alternative materials. The installation of the prototypes was accompanied by the school community, and the performance was monitored. The pumice stone proved to be an efficient solution for the drainage layer of the green roof. The use of local soil (volcanic origin) instead of a commercial substrate proved to work properly, both for drainage and for vegetation growth. Finally, the results also contribute to a better understanding of green roofs on wooden structures and encourage the use of local materials in future projects, with a view towards a circular economy.

Keywords: green roof; local materials; wooden structure; sustainability; Azores; eco-school

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1. Introduction

With the growth of the population and the consequent increase in urbanization observed in recent years [1,2], there has been a decrease in green spaces in urban contexts [3]. Green roofs have emerged as one of the responses to the need to introduce green spaces in fully built-up areas [4], as building roofs represent about 32% of urban horizontal surfaces [5]. Therefore, in urban contexts, this technology allows for the creation of green areas without requiring additional urban surface use [6,7]. Green roofs are mentioned in the EU Biodiversity Strategy 2030 as key urban strategies to stop the loss of green urban ecosystems [8–10].

Green roofs can be classified as extensive, intensive, or semi-intensive, depending on the type of vegetation, their properties, and the intended use [3]. Green roof systems consist of different layers with distinct functions [11] and, depending on the needs and characteristics of the roof, these layers can also assume different positions within the system [4].

Green roofs offer various social, environmental, and economic benefits, such as the conservation of ecosystems and biodiversity preservation, improvement in air quality, reduction in urban noise pollution, and enhancement of physical and mental health of inhabitants [3,12–16].

Another benefit mentioned in the literature is stormwater retention. [14] shows, based on the analysis of various studies, that the reduction in stormwater runoff is, on average, 57% in extensive green roofs and 79% in intensive green roofs. Traditional roofs are typically made with impermeable materials, lacking the ability to retain water. Green roofs, depending on characteristics such as the type of vegetation, the thickness and composition of the substrate, and the slope, offer qualities favorable for water retention [17–19]. Atmospheric conditions also influence the water retention capacity of green roofs, with a decrease in water retention capacity being observed in humid environments [20–22].

According to [23], green roofs act like natural reserv–oirs by capturing, storing, and slowing down rainwater, while also promoting its evaporation and transpiration. This process reduces the amount of rainwater released, delays its flow, and lowers the peak levels of runoff. Green roofs, when combined with rainwater-harvesting systems, help reduce the volume of stormwater drained into the drainage system and allow non-potable water demands to be met through the reuse of rainwater. These technologies and solutions for water recovery and treatment can play a key role in significantly reducing the consumption of potable water in buildings [14].

Some studies, such as [24–26], show that the water passing through green roofs typically exhibits better quality, with the vegetation acting as a natural filter. It absorbs pollutants, improves sediment capture, and helps with the retention of nutrients. Additionally, a green roof reduces surface runoff, lowering the number of contaminants that reach water bodies. As a result, the filtered water is cleaner and less polluted, contributing to a more sustainable environment. In the study [27], it was noted that the substrate, vegetation composition, and moisture content can influence the quality of runoff water. Additionally, it was observed that green roofs, especially those containing recycled construction materials, do not negatively impact hydrological performance or water quality. The study highlighted that recycled construction materials may even enhance drainage during dry conditions without compromising water quality.

There are still some reservations regarding the sustainability of using green roof technology on a large scale, specifically due to the impact of using certain types of materials [28]. Ref. [29] state that the materials used must not have polluting effects and that regulations concerning pollution and environmental compatibility must be respected. These standards also add that, in the construction of green roofs, "When selecting materials, recycling or disposal should be taken into account". The construction of green roofs requires more resources than conventional roofs, and the production of some of the materials that constitute their layers is high energy consumption [30]. Ref. [30] analyzed the types of materials used in the different layers of green roofs from the perspective of life cycle assessment across various studies. The growing medium for green roofs typically consists of organic matter and porous minerals, and the filter, drainage, and roof barrier layers are made from polymeric materials. The water retention layer is made from various materials, including polymeric and recycled textile fibers, rock wool, expanded perlite, polyethylene, and polyvinyl chloride. As for the waterproofing layer, bitumen or PVC membranes are commonly used. Some of these materials, especially those derived from polymer manufacturing, are associated with negative environmental impacts. Therefore, it is essential to seek more sustainable materials [28] in an attempt to reduce the impact of the construction industry [31]. The use of local materials in the construction of green roofs is suggested in the literature [30] as a possibility to mitigate the impacts associated with their production and transportation [32]. In fact, the European Climate Pact—part of the European Green Deal—refers to locally sourced materials as a way to make a new construction greener and to minimize its environmental impact [33,34].

The EU Climate Pact was launched to help citizens understand the need for climate action and facilitate the green transition at all levels of society, so community engagement is necessary to achieve the goal proposed by the European Green Deal to be the first climate-neutral continent in the world by 2050 [35]. It is seen as essential to "help education and training institutions to integrate sustainability into teaching and learning and across all aspects of their operations" [36]. In 2022, the Council of the European Union stated that sustainability should be integrated into the education policies of the Member States [36] and that green transition should be a priority in education programs for all levels of education and learners of all ages (e.g., local staff, local authorities, youth organizations). They also emphasize the need to create learning environments that “enable teaching and learning that is hands-on, interdisciplinary, and relevant to local contexts” [36].

The present work contributes directly to this purpose by evaluating the use of local materials in green roofs’ layers through citizen science activities involving students, staff, and parents of a primary school in Azores. It evaluates the performance of different materials in green roofs to optimize the use of local materials in their construction and the maximization of sustainability. Azores is a series of volcanic islands providing local materials with competitive drainage and vegetation growth characteristics. The support layer is a wooden structure, and the proposals must meet the functional requirements of green roofs and the requirements of each layer. Green roof prototypes were built by the school community, and data on water management in school activities were also recorded. This is also a central input of this work—contributing directly to community engagement with positive feedback from the school community and being useful for future projects.

2. Materials and Methods

2.1. Eco-School

This study arises in the context of a collaboration with the team of the pedagogical innovation project “Novas Rotas” with the aim of developing a green roof on a wooden structure for the development of a new school. This is a pioneering and innovative project, which aims to use local materials and follow sustainable principles in its construction based on the involvement of the community and nature. The eco-school will be implemented at Quinta do Norte, in the village of Capelas, on the island of São Miguel, in the Azores (Figure 1).

The eco-school will be energy-efficient and autonomous, offering various economic and environmental benefits, in addition to cultural ones [37]. The project will adopt bioclimatic strategies integrated into the architecture and landscape, such as rainwater harvesting and treatment [38], the use of renewable energies (with the installation of photovoltaic panels), and green roofs. Additionally, local and natural materials that are easily recyclable and have no impact on the landscape will be used, and solar orientation will be maximized as a means of obtaining energy, thermal comfort, and natural light.

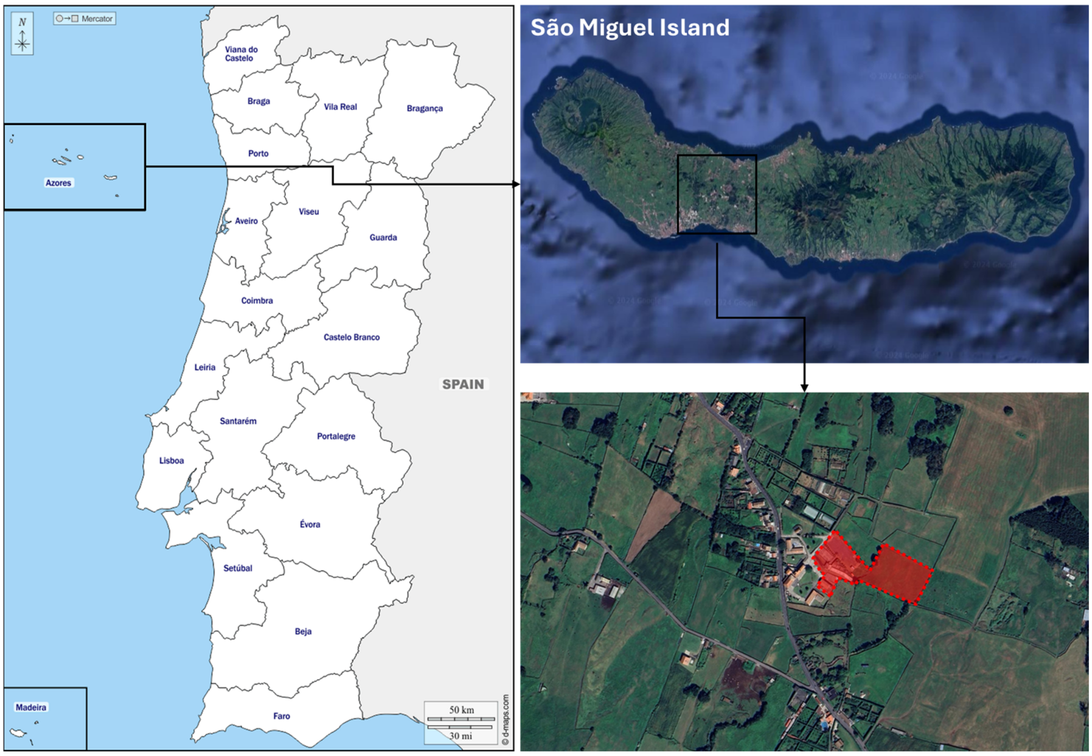

Figure 1. The geographical location of the eco-school on the island of São Miguel, Azores—adapted from [39] and Google Earth.

The building features modular architecture (Figure 2), allowing spaces to be defined by function or environment, and future expansion of the school. Each module is represented by a hexagonal prism. The modules oriented to the south, receiving more sunlight, will be used for classrooms, while the modules to the north will serve as reception areas, offices, and a gym, with the central core reserved for social and dining areas. The ground floor has an area of 1363 m^2, and the elevated floor 1 has an area of about 390 m^2. The modules to the north and south have green roofs that blend with the surrounding landscape, and the central core has a wooden roof with glass applications.

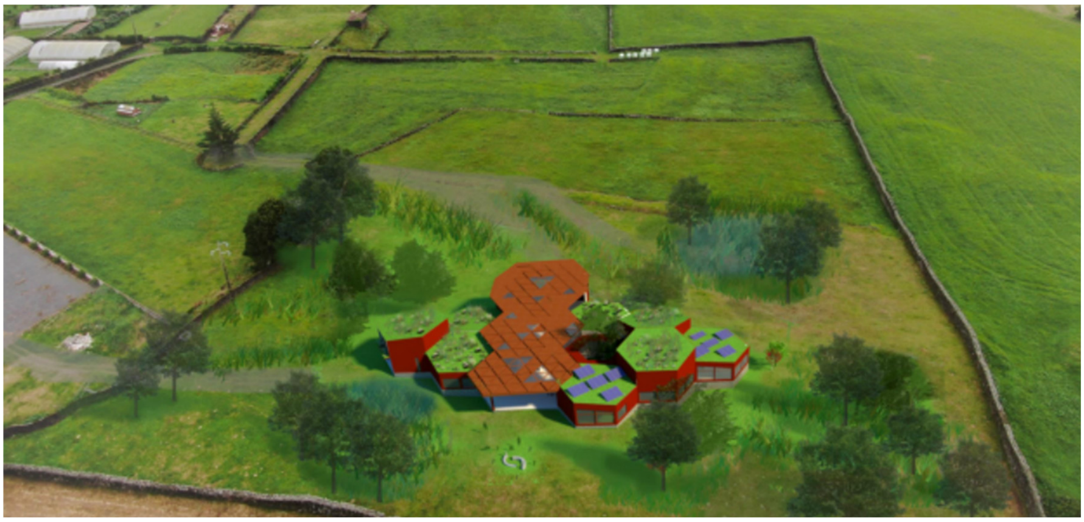

Figure 2. The 3D model of the eco school—source: [40].

The implementation of green roofs in the school, in addition to reducing pollution and improving air quality [41], increases the durability of the roof. Photovoltaic panels are planned to be installed on two of the green roof modules, oriented to the south to maximize solar and consequently energy utilization. The panels will allow water heating by capturing solar radiation, which will be converted into thermal energy, enabling the eco-school to be fully supplied.

2.2. Materials

Currently, wooden structures present an excellent alternative to concrete or metal structures [42], with studies encouraging their use [43,44]. As a result, projects with proposed wooden structures are starting to emerge, such as the eco-school.

In a wooden structure, after a preliminary verification and analysis of the support, it is recommended to treat the existing joints between the roof wooden panels by filling them with a high-modulus, fast-hardening sealant that absorbs the deformations.

In the construction process of the school, the aim is to use local materials combined with traditional and contemporary construction techniques with a lower environmental impact.

According to [45], there are available mineral resources (basalt stone, pumice stone, etc.), woody resources (cryptomeria wood, etc.), and fibrous resources in the Autonomous Region of the Azores, which can be applied in civil construction.

Cryptomeria, also known as Japanese cedar, is one of the main wood types in the archipelago, mainly used in cladding, flooring, and structural applications. It is considered a soft, light, and durable wood with good adhesion properties, strong joints, and good reception to metallic elements. Its use is varied, from laminate and plywood to cladding and structural elements [45].

Basalt stone and pumice are available materials given the volcanic nature of the island. Natural fibers are emerging as a developing alternative to conventional synthetic fibers, and, in this case, they come from raw materials important to the regional economy. Examples include fibers from pineapple, banana, conteira, and cryptomeria, of plant origin [45].

Considering the characteristics of some of these materials, an analysis was conducted on how they could be used in the composition of the layers that make up green roofs. An eight-layer green roof solution was considered (ordered from bottom to top): support layer, thermal insulation layer, waterproofing layer, waterproofing protection layer, drainage layer, filtering layer, substrate, and vegetation. Analyzing information from [46–49] on the cost and ease of application of the materials, cryptomeria wood can be used in the support layer, pineapple fiber in the waterproofing protection and filtering layers, pumice stone in the drainage layer, and Azorean soil in the substrate layer.

2.3. Prototypes

Based on the characteristics of the available local materials, green roof solutions as alternatives to traditional ones were formulated, using local and sustainable materials. These alternative solutions involve the incorporation of expanded clay or pumice stone in the drainage layer and the use of a non-woven geotextile or pineapple fiber geotextile in the protection and filtration layers. However, pineapple fiber geotextile is a non-recurring material with limited availability. Therefore, as a short-term solution was sought, no prototypes were made to test this material. In Figure 3 it is possible to visualize the suggested materials for each layer of the prototype.

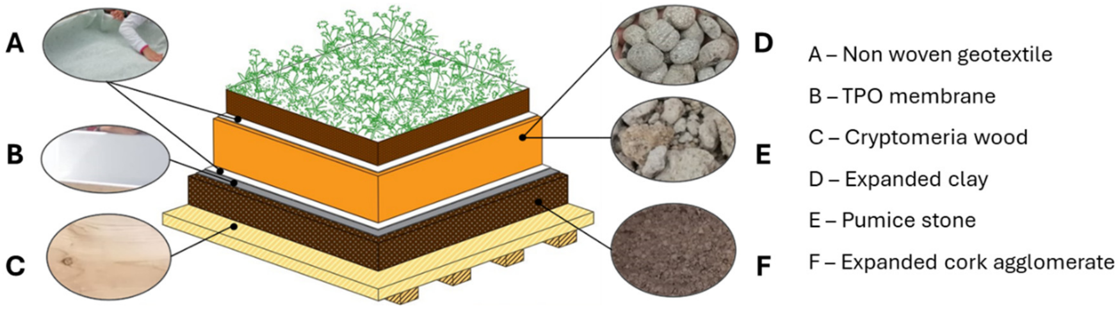

Figure 3. Different materials that could be used in each of the layers.

Two prototypes were developed with the aim of implementing and monitoring them in order to understand if the use of these materials is viable so they can be applied to a real roof, specifically at the eco-school. These prototypes differ only in the material used in the drainage layer: either pumice stone or expanded clay. The prototypes were installed on the school grounds with the aim of simulating the climatic conditions to which the roof will be subjected and were executed in accordance with the available materials and provided funding.

The layers of the prototypes are composed of the following materials: The support layer consists of cryptomeria wood, the thermal insulation layer consists of expanded cork particle boards, the waterproofing layer consists of TPO (thermoplastic polyolefin) membranes, the protection layer is a non-woven geotextile, the drainage layer is either expanded clay or pumice stone, and the filtering layer consists of a non-woven geotextile. Finally, the substrate layer uses local substrate, and the vegetation layer uses succulent plants.

The geotextile, the TPO and the expanded cork were offered by Spitex II Lda, Azores, Portugal. The expanded clay was offered by Agriloja Lda, Azores, Portugal. Finally, the pumice stone was offered by the Municipality of Ponta Delgada, Azores, Portugal. All other materials were extracted from the existing campus of the eco-school.

Figure 4 provides a more detailed presentation of the prototypes, with Prototype 1 featuring a drainage layer composed of expanded clay and Prototype 2 featuring a drainage layer composed of pumice stone.

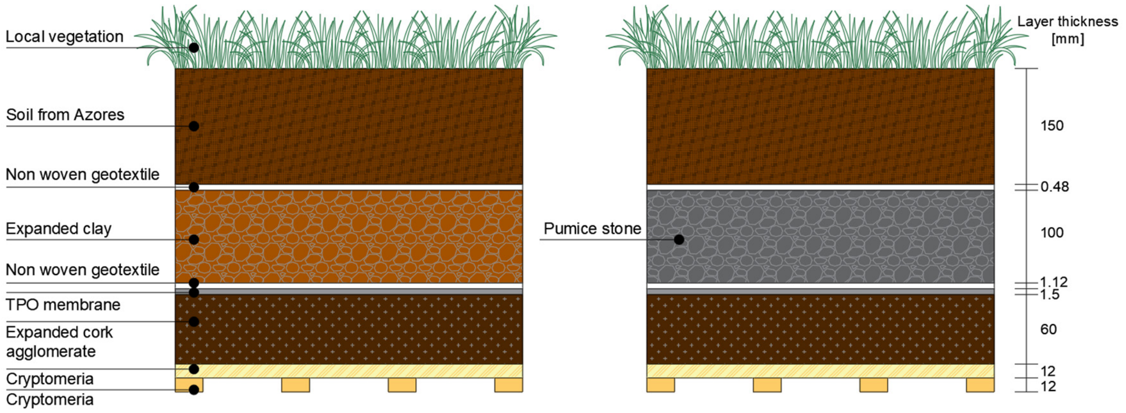

Figure 4. Constituent materials of each of the prototypes: Prototype 1 (**left**) and Prototype 2 (**right**).

The prototypes were assembled on trays using local materials. The wood used is reclaimed cryptomeria. The materials composing the different layers of the green roof were sourced from local suppliers and the Municipal Council, and the assembly of these trays was carried out with the assistance of local companies.

Figure 5 presents a schematic representation of the prototypes.

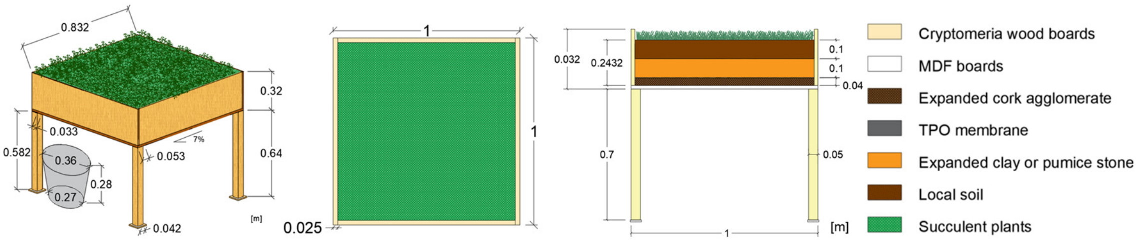

Figure 5. Schematic representation of the prototypes, with the materials and dimensions of their components.

A hole was also made for the drainage of the prototype, from which the drained water was collected in buckets for subsequent monitoring. A green roof cannot have only one drainage point, but this option was chosen to facilitate monitoring, considering that it is a small-scale prototype.

After the installation of the expanded cork panels (thermal insulation layer) and TPO membranes (waterproofing layer) by a specialized company, the remaining layers of the green roof were installed with the assistance of the school's students and teachers (Figure 6).

2.4. Data Gathering

After the assembly of the prototypes, the monitoring of them was proposed to the Nova Rotas team, the parents association, the students, and the teachers of the eco-school. In this project, the aim was to involve the community, both in seeking solutions and testing, as well as in future construction.

As previously mentioned, the engagement of communities and the inclusion of content about environmental sustainability in education are very important to achieve the goal of a more sustainable future [36]. The European Union refers to citizen science as a way to help citizens work better together and with institutions [35], highlighting that in recent years it has been one of the major providers of knowledge and data [50], and it is a method that allows people to help improve environmental sustainability [51]. Citizen science allows citizens to work together with professionals, playing an important role in experiments, data collection, analysis, and scientific discoveries. It enables experts to gather more data than they would otherwise, benefiting professionals and citizens who engage in research projects [51].

Figure 6. Installation of the expanded cork panels (**top left**), TPO membranes (**top right**), and the remaining layers (**bottom**).

To assist in the correct monitoring of the prototypes, a monitoring sheet was developed with the aim of:

☐ Assessing the total weight of the solution (dry and wet);
☐ Monitoring the saturation of the prototypes;
☐ Comparing the performance of expanded clay and pumice stone in terms of drainage and vegetation development;
☐ Verifying if the soil from the Azores is suitable as a substrate for the green roof;
☐ Evaluating maintenance needs.

These sheets allowed for a detailed and organized analysis and monitoring of the prototypes (Figure 7). The analysis of saturation is crucial, considering that the aim is to use local soils.

Figure 7. Monitoring of the prototypes by the students of the school, using the monitoring sheet.

This monitoring consisted, first and foremost, of measuring the weight of a sample of substrate in a standard measuring cup before (dry substrate) and after watering (wet substrate). The watering was also standardized, using 65 L of water, and the dry substrate sample was removed from the prototypes one day before the monitoring so that it could dry. Next, the prototypes were analyzed in terms of waterlogging, checking for permanent puddles of water, and in terms of drainage, verifying the capacity to drain water from the surface. Finally, the color of the drained water was analyzed, and the development of the planted vegetation and the maintenance required throughout the monitoring period were also analyzed. Figure 8 shows some of the steps in the substrate-monitoring process.

Figure 8. Wet and dry substrate (**left**), weighing the substrate (**center**), and watering the prototype (**right**).

Ten monitoring sessions were conducted in total, the first one on 29 September and the last on 28 October 2022. The sessions took place between 1:30 PM and 3:00 PM, the period of greatest solar exposure for the prototypes.

3. Results and Discussion

In Table 1, the results obtained from the measurements of the substrate before and after watering in each of the monitoring sessions are presented.

Table 1. Weights of the substrates in the pumice stone and expanded clay prototypes; incomplete measurements are designated as NA (not assessed).

Monitoring Number	Pumice Stone Prototype			Expanded Clay Prototype		
	Cup Weight + Dry Substrate (g)	**Cup Weight + Wet Substrate (g)**	**Wet Substrate − Dry Substrate (g)**	**Cup Weight + Dry Substrate (g)**	**Cup Weight + Wet Substrate (g)**	**Wet Substrate − Dry Substrate (g)**
1	NA	727	NA	NA	691	NA
2	404	901	497	424	860	436
3	731	NA	NA	539	NA	NA
4	770	937	167	792	782	NA
5	780	873	93	399	743	344
6	669	780	111	574	893	319
7	758	719	NA	944	740	NA
8	530	932	402	590	761	171
9	726	969	243	519	791	272
10	876	832	NA	542	853	311

The weather conditions on the day before and the day of the prototype monitoring are shown in Table 2. It is noted that precipitation occurred on the day of or the day before the test in several of the monitoring sessions. As a result, the values obtained for the dry substrate in Table 1 may show discrepancies from the actual value.

The values described in Table 1 were obtained by the eco-school students. The difference between the cup weight + wet substrate and the cup weight + dry substrate was calculated to determine the water-holding capacity of that substrate.

Given that many of the data presented in Table 1 are incomplete, and due to the highly variable weather, typical of the Azores archipelago, it is not possible to draw many conclusions from these tests. It was observed that in the fifth and sixth monitoring sessions, where there was no rain, the pumice prototype showed a smaller difference between the dry and wet substrate, while the expanded clay prototype showed a larger difference. However, in the eighth monitoring session, where it rained the day before the monitoring, the opposite occurred. This could indicate that the pumice prototype substrate retains more water when it rains. When it does not rain, the expanded clay prototype substrate retains more water. However, given this discrepancy in the data and external factors, this possibility needs further study. Moreover, as observed in the ninth monitoring session, where it rained the day before, both the pumice substrate and the expanded clay substrate had very similar values for the difference between the wet substrate and the dry substrate.

Table 2. Weather conditions on the day of monitoring and the day prior to it.

Monitoring Number	Monitoring Day	Current State of Weather	Weather the Day Before
1	29 September	Covered up	Covered up
2	30 September	Showers	Covered up
3	3 October	Covered up	Covered up
4	6 October	Covered up and showers	Covered up and showers
5	10 October	Covered up	Sun
6	13 October	Sun	Sun
7	17 October	Covered up, showers, and strong wind	Sun
8	20 October	Sun	Showers and strong wind
9	24 October	Sun	Rain
10	28 October	Sun	Sun and rain

Relative to the analysis of waterlogging and drainage, the pumice stone prototype clogged three times. It is expected that the origin of the clogs is due to the need to fix both the protective layer and the filtering layer of the geotextiles. The protection layer proved to be working as a tampon. After raising the layer, the prototype was immediately drained.

The suggested maintenance for the prototypes under study includes securing the geotextile, filtering, and protective layer. Solving this issue avoids the prototype clogging due to the passage of fine particles through the geotextile.

The prototypes presented a similar amount of flow, differing in the color of the water displayed by it, as shown in Figure 9. In the pumice stone prototype, it was possible to observe a more translucent flow of water compared to the expanded clay prototype, which was cleaner to the naked eye.

Figure 9. Drainage of the pumice prototype (**left**) and the expanded clay prototype (**right**) during the second monitoring session.

These results align, to some extent, with the literature and what is expected from these materials. Pumice stone and expanded clay are commonly used in green roofs due to their lightweight and porous characteristics. Pumice stone, with its high porosity, enhances water retention while also facilitating drainage, thus improving the efficiency of green roofs in managing excess rainwater and ensuring that the substrate remains well aerated. Expanded clay also offers a similar balance. Its main advantage is providing good drainage and aeration for plant roots. Additionally, expanded clay contributes to stormwater retention and filtration, improving water quality by reducing runoff pollutants [52].

The Azores soil used in the substrate layer proved to be a good alternative solution to the technical substrate, given that the clogging that occurred in the prototypes did not occur due to it, as would be expected.

Throughout the monitoring sessions, good development of the planted vegetation was observed. Qualitatively, in the initial phase, the vegetation in the pumice prototype appeared to have slightly greater development than that in the expanded clay prototype. As the monitoring progressed, it was observed that the vegetation in both prototypes showed positive development. On 12 January 2023, during a site visit, it was noticed that the expanded clay prototype had been severely damaged and further monitoring sessions could not be conducted. Five months after this date, it was found that the vegetation in the pumice prototype had experienced significant growth.

4. Critical Analysis and Main Conclusions

This study aimed to collaborate with the eco-school team from Novas Rotas in Ponta Delgada, Azores, to create a green roof using local and sustainable materials for the new eco-school. It was possible to address this need, presenting a viable proposal that can be implemented on the eco-school's roof.

In the initial phase, despite the limited information available on green roofs over wooden structures, four possible solutions were proposed. These construction solutions, in addition to providing the usual benefits, promote a circular economy connected to sustainability and the use of local materials. Leveraging the survey of local materials from the Azores, the layers of the prototypes were defined. However, due to the associated costs and the materials available for the execution of the prototypes, and given the need for a short-term solution, two of these solutions were implemented.

Throughout the development of this project, various constraints emerged that delayed the study. The search for materials for the execution of the prototypes was intensive, both in terms of information regarding local construction materials and the availability of acquiring them in small quantities and specific dimensions. The logistics of shipping materials to the Azores proved to be one of the main challenges. The assembly and monitoring of the prototypes were carried out remotely, with the assistance of parents, teachers, and students, which complicated the assembly and analysis process.

The collaboration of parents, teachers, and students was fundamental to this project, not only for the reasons already mentioned but also for their assistance in monitoring the prototypes and financing them (through the parents association). The community was involved in nearly every step of this study, also participating through a survey to investigate material preferences for construction and the availability of those materials in their area of residence. These are some of the positive aspects that citizen science offers to this type of study, contributing not only with data but also with essential information that helps optimize the solution obtained.

However, in this project, it was possible to observe some of the inherent difficulties of citizen science as a data collection method. This was evident in the collection of weights for the wet and dry substrates, where there were failures in the data collected, which prevented a quantitative discussion of results. This was primarily due to initially granting students full autonomy in the early monitoring sessions. After teachers began assisting students in the monitoring, this issue was largely addressed.

Another aspect to highlight is the use of local materials, many of which were reused and sourced from the local economy. As mentioned, in this specific context of the Azores, being an archipelago with limited access to materials, the contribution of local businesses was crucial for the project's realization. This constraint ultimately turned into a positive aspect, demonstrating that using local materials is feasible and benefits not only the environment but also the local economy.

The results obtained from the conducted monitoring sessions allowed us to conclude that the prototype with pumice in the drainage layer is a viable solution for implementing a green roof on a wooden structure. This prototype demonstrated adequate drainage capacity and the substitution of traditional materials with local ones.

The soil from the Azores used in the substrate layer stood out positively in this study, as the clogging of the prototypes was not due to the use of natural soils but rather to the geotextile.

The type of green roof to be used at the eco-school will be extensive, which is typically non-accessible for walking but should be accessible for maintenance purposes. According to technical recommendations, it will require the following maintenance actions: irrigation, substrate fertilization, planting/replanting of vegetation, removal of unwanted vegetation, introduction of filling substrate in case of erosion, pest control, vegetation control in substrate-free areas, cleaning of the rainwater drainage system and technical installations, and vegetation pruning.

For the future, the costs associated with sustainable construction can be reduced, with an increase in specialized companies focusing on these systems. Therefore, it is suggested to continue developing this solution in Portugal to establish credibility regarding the execution and maintenance of green roofs on wooden structures. This would be an opportunity for development that connects sustainable systems with durability and quality.

It is also proposed to carry out more on-site prototypes of the chosen solution to further refine the installation process in detail and optimize it up to the construction phase, considering it is still in the design phase. This was not possible during this study but was essential for identifying available solutions.

Further study of the prototypes through laboratory tests would also be beneficial to analyze runoff water and potential additions to the soil from the Azores, promoting improvements in drainage. Regarding the substrate layer, it would be advantageous to determine the amount of substrate that ensures thermal comfort and supports the development of various vegetation types.

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