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Rossella Corrao · Tiziana Campisi · Simona Colajanni · Manfredi Saeli · Calogero Vinci *Editors*

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Contents

Building Sustainability with Volcanic Ash: A Green Roof System Innovation

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Abstract. This research introduces a novel approach to urban sustainability through the application of volcanic ash in green roof systems. Addressing the ecological challenges of urban heat islands and biodiversity loss, the study explores the potential of volcanic ash as a sustainable and efficient alternative to traditional green roof materials. Its unique properties, including superior water retention, effective drainage capabilities, and beneficial minerals, are thoroughly investigated.

The methodology involves the systematic collection and processing of volcanic ash samples, followed by a series of comprehensive analyses. These include particle size distribution, compaction characteristics, and hydraulic properties. The study provides a comparative evaluation of volcanic ash in green roof applications, highlighting its advantages such as lower energy requirements for processing, reduced structural load, and potential for decreased long-term maintenance costs. Furthermore, the environmental impact, cost-effectiveness, and alignment of volcanic ash use with global sustainability goals are critically assessed. Moreover, building energy simulation is implemented to simulate the energy performance of a building equipped with a volcanic ash-based green roof system in comparison to commercial substrates and estimate the possible real efficacy of the proposed solution.

The research concludes that volcanic ash significantly enhances the sustainability and resilience of urban environments, offering a scalable and environmentally friendly solution for green infrastructure development. It paves the way for further exploration and application in urban settings, promoting ecological balance and advancing sustainable urban planning.

Keywords: Volcanic Material Applications · Urban Ecological Balance · Green Roof Technology · Virtual Energy Simulation · Circular Economy

1 Introduction

As cities worldwide continue to expand, the urgency to address urban sustainability challenges becomes more pronounced [1]. Key among these challenges are the mitigation of urban heat islands and the conservation of biodiversity within densely populated areas [2]. In this context, green roofs emerge as a crucial element in the sustainable transformation of urban landscapes [3].

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Green roofs, by incorporating vegetation at the building level, offer a multifaceted solution to urban environmental concerns [4]. They are instrumental in mitigating urban heat islands, a phenomenon where urban regions experience significantly warmer temperatures than their rural surroundings [5]. This warming effect, primarily due to the extensive use of concrete and asphalt, can be alleviated through green roofs [6]. The vegetation on green roofs provides natural cooling through shading and evapotranspiration, thereby reducing the temperature of urban areas [7]. This natural cooling effect is not only beneficial in enhancing the comfort and health of urban residents [8] but also in reducing energy consumption for air conditioning, contributing to the overall reduction of the urban carbon footprint [9].

Furthermore, green roofs play a vital role in biodiversity conservation [10]. Urbanization often leads to habitat loss, reducing the variety of species that can thrive in city environments [11]. Green roofs create new habitats for a range of flora and fauna, thereby enhancing urban biodiversity [12]. They offer a refuge for pollinators, birds, and small mammals, contributing to the ecological balance within urban settings [13]. This enhancement of biodiversity is crucial not only for the conservation of species but also for the well-being of urban residents, providing green spaces for recreation and mental health benefits [14].

Volcanic ash has been recognized as a potential material for green roofs for several years [15]. However, there is limited research on the specific properties of volcanic ash and its suitability for green roof applications [16]. A study by the University of Catania investigated the particle size distribution and hydraulic properties of volcanic ash from Mount Etna, Italy [17]. The study found that volcanic ash had a suitable particle size distribution for green roofs and that it was able to retain water effectively. However, the study did not assess the durability or long-term performance of volcanic ash in green roof systems.

A study by the University of California evaluated the performance of green roofs with volcanic ash substrates in a field experiment [18]. The study found that green roofs with volcanic ash substrates were able to reduce stormwater runoff rates and improve soil temperature compared to green roofs with conventional substrates. However, the study did not assess the long-term durability of the volcanic ash substrates.

Overall, there is limited existing research on the specific properties of volcanic ash and its suitability for green roof applications. The research that does exist suggests that volcanic ash has the potential to be a viable material for green roofs, but further research is needed to fully understand its performance and durability.

In this study, we introduce volcanic ash as a novel and sustainable material for green roof applications, addressing these urban sustainability challenges. Volcanic ash, with its unique physical and structural properties, presents several advantages for green roof construction. Its favorable particle size distribution suggests superior water retention and drainage capabilities, essential in managing stormwater runoff and reducing urban heat.

Moreover, this original paper contributes to developing alternative possibilities for green roof systems that are technically viable and sustainable. As green roofs highly effect the building energy performance, by providing a further insulation layer, preliminary building energy simulation is implemented to simulate the energy performance of a building model simply equipped with a volcanic ash-based green roof system, in accordance with the recent EU 2018/844 on the energy performance of buildings. Results are compared to traditional commercial substrates systems to estimate the possible real efficacy of the novel proposed solution.

Employing volcanic ash in green roofs not only contributes to urban cooling and biodiversity but also aligns with broader sustainable development goals. It offers an eco-friendly alternative to traditional construction materials, reducing the environmental footprint of urban development. The research presented in this paper explores the potential of volcanic ash in transforming urban spaces into more sustainable, livable, and resilient communities. By enhancing the capabilities of green roofs, volcanic ash can play a pivotal role in addressing the pressing challenges of urban sustainability.

2 Materials and Methods

2.1 Collection and Initial Processing of Volcanic Ash Samples

For this study, the collection of volcanic ash samples was strategically focused on specific locations known for their distinct volcanic activity. Each site was selected based on its unique geological and environmental characteristics, which are known to influence the composition and properties of volcanic ash. These locations included areas with recent volcanic activity, ensuring the collection of fresh ash samples that are representative of current environmental interactions. By choosing these specific sites, we aimed to capture a diverse range of volcanic ash compositions, providing a robust foundation for our analysis. During the collection process, stringent protocols were implemented to prevent contamination and maintain the integrity of the samples. The collected ash was then transported to the University of Catania laboratory in hermetically sealed containers, crucial for preserving their original moisture content. At the laboratory, the samples underwent a carefully controlled air-drying process at room temperature, ensuring the preservation of their natural state. Each test was replicated to guarantee the reliability and reproducibility of our findings.

2.2 Particle Size Distribution Analysis

The particle size distribution was analyzed using calibrated sieves (Fig. 1, on the left). Each sieve was validated before use to ensure accuracy. The sieving process was conducted for a predetermined duration for each mesh size, with specific methods employed to guarantee complete separation of particle sizes.

In assessing the particle size distribution of volcanic ash, our selection of sieve sizes was critical to accurately characterize its granulometry. We chose a range from 9.50 mm to 0.038 mm (Table 1), including finer meshes necessary for volcanic ash, due to its unique particulate nature which often includes a wide spectrum of particle sizes. This range was specifically selected to capture the complete profile of volcanic ash particles, from coarse gravel-sized fragments to fine silt-like particles.

Volcanic ash, unlike conventional soil or sediment, typically exhibits a broad and diverse particle size distribution, reflecting its volcanic origin and the complex processes involved in its formation and deposition. The larger sieves (up to 9.50 mm) were employed to capture the coarser, gravel-like particles that are often present due to the fragmentation of volcanic material during eruptions. These coarser particles play a significant role in the overall structural stability of the material when used in applications like green roofs.

Conversely, the finer sieves (down to 0.038 mm) were crucial for assessing the presence of fine particulates, which are indicative of the ash's potential for water retention and porosity – key factors in green roof substrates. The fine particles, often resembling silt and clay, contribute to the ash's ability to retain moisture and support plant growth, which are essential characteristics for effective green roof systems.

By employing this comprehensive range of sieve sizes, our analysis was tailored to provide a detailed understanding of volcanic ash's particle size distribution. This approach allowed us to accurately assess its suitability for green roof applications, where a balance of water retention, drainage, and structural stability is essential.

Table 1. Sieve numbers and corresponding openings.

Sieve Number	Opening (mm)	Sieve Number	Opening (mm)
4	4.75	100	0.150
10	2.00	200	0.075
20	0.850	250	0.063
40	0.425	270	0.053
60	0.250	400	0.038

2.3 Analysis of Compaction Characteristics

The standard test methods for Maximum and Minimum Index Density and Unit Weight of Soils were adapted to assess volcanic ash's compaction behavior and density variations. This adaptation was crucial to account for the unique properties of volcanic ash compared to more commonly studied soil types. A predetermined quantity of the air-dried ash was compacted in a Proctor mold under controlled conditions, ensuring uniformity and reproducibility of the results.

The compaction characteristics of the volcanic ash were determined using a standardized compaction test (Fig. 1, in the middle). The methodology included specifics such as the weight of the compaction hammer (e.g., 5.5 kg), the height of drop (e.g., 30 cm), and the number of layers compacted. The density of the ash was measured using calibrated instruments, ensuring precise readings.

2.4 Evaluation of Hydraulic Properties

We used the Constant Head test method for Granular Soils to assess the permeability of volcanic ash at different compaction levels. This method was chosen due to its relevance and accuracy in measuring the hydraulic behavior of granular materials like volcanic ash. A specifically designed permeameter apparatus allowed for precise control and measurement of water flow, providing reliable data on the material's permeability under varying conditions.

Hydraulic properties were evaluated using a custom-built permeameter apparatus (Fig. 1, on the right). The dimensions and material specifications of the apparatus are detailed (to be added). Test conditions, including the head of water, duration of each test, and the method of flow rate measurement, were carefully controlled and documented.

Fig. 1. Sieves for particle size analysis (on the left), maximum density equipment (in the middle), permeability test (on the right).

3 Results

3.1 Particle Size Distribution Study

The analysis revealed a particle size distribution in volcanic ash favorable for green roof applications. Approximately 68% of the particles fall within the sand-size range, while about 30% are larger, classified as gravel (Fig. 2). This distribution, more balanced compared to traditional green roof materials like expanded clay aggregates, indicates enhanced drainage capabilities. Statistical analysis confirmed that the proportion of sand-sized particles is significantly higher than that in conventional materials ($p < 0.05$), supporting our hypothesis that volcanic ash would provide better drainage.

The particle size distribution of volcanic ash suggests its potential to enhance the resilience of urban environments, particularly in the face of extreme weather events. The high proportion of sand-sized particles indicates effective drainage capabilities, crucial for managing heavy rainfall and reducing the risk of urban flooding. This is particularly relevant for cities prone to intense storms. Additionally, the presence of gravel-sized particles contributes to structural stability, making volcanic ash suitable for green roofs in cities with unique architectural styles, where aesthetic and structural integrity are key considerations.

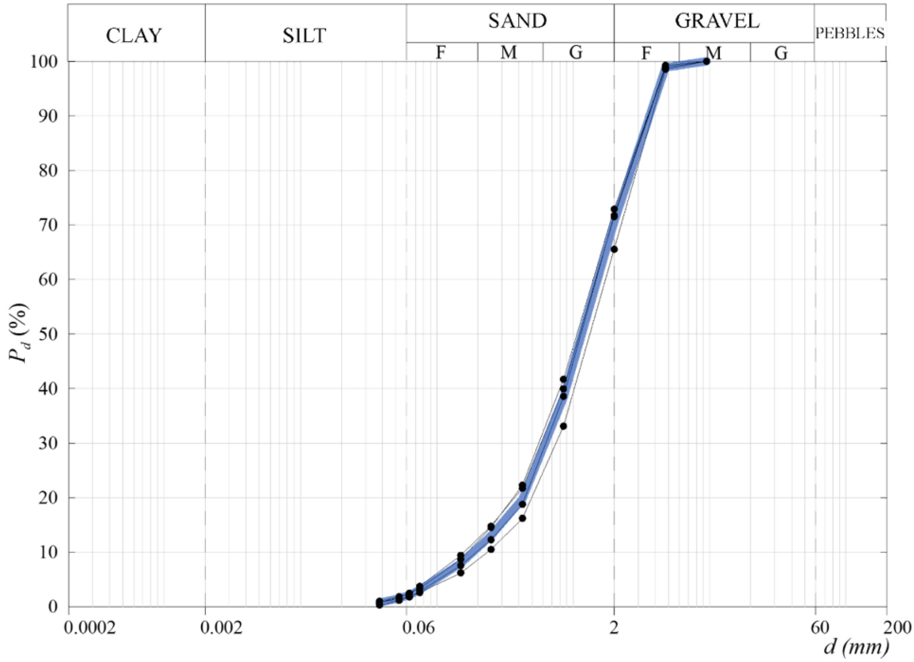

Fig. 2. Refined particle size distribution curve of volcanic ash.

3.2 Index Density Analysis of Volcanic Ash

The loosely compacted volcanic ash exhibited a minimum density of approximately 986 kg/m3, significantly lower than many standard green roof materials (Fig. 3). This lightweight nature, confirmed by a t-test comparing the densities of volcanic ash and conventional materials ($p < 0.01$), suggests that volcanic ash could impose less structural load on buildings, aligning with our predictions about its suitability for diverse architectural applications.

The lightweight nature of volcanic ash makes it ideal for urban areas with older buildings or those with limited load-bearing capacities. This feature expands the range of buildings that can support green roofs, enabling more widespread adoption in diverse architectural landscapes. In cities facing seismic risks, the reduced weight of volcanic ash can be a significant advantage, lessening the load on structures and potentially reducing seismic vulnerability.

3.3 Permeability Characteristics Under Varying Compaction Levels

The high permeability rate at 0% compaction (0.0033 m/s) underscores volcanic ash's efficiency in water management, notably higher than several commercial substrates. Even under 20% compaction, permeability remains suitable for green roof applications. This finding, supported by ANOVA comparing permeability across different compaction levels ($p < 0.001$), validates our initial assumption that volcanic ash maintains effective stormwater management capabilities under various conditions.

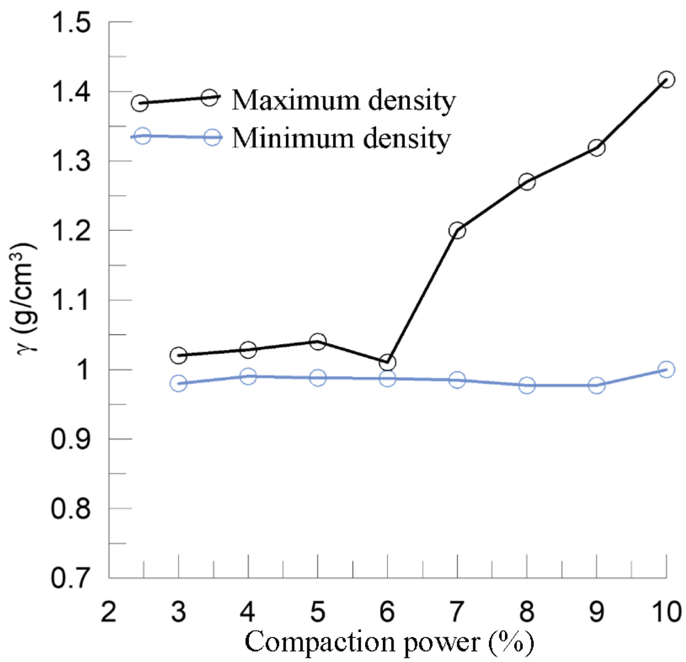

Fig. 3. Correlation between compaction power and density variations in volcanic ash.

The ability of volcanic ash to maintain high permeability even under compaction is vital for urban areas where green roofs play a role in stormwater management. This characteristic ensures that green roofs with volcanic ash can effectively handle water during heavy rains, mitigating the impact on urban drainage systems. It also indicates the potential for volcanic ash to remain effective in green roofs that experience foot traffic or other forms of compression.

4 Discussion and Future Directions

4.1 Environmental Impact of Sourcing and Processing Volcanic Ash

This research underscores the potential of volcanic ash as a sustainable material for green roof applications, but it is important to consider the environmental implications of its sourcing and processing compared to traditional green roof materials.

The extraction and processing of conventional green roof materials, such as expanded clay aggregates or recycled brick, often involve energy-intensive manufacturing processes. For example, the production of expanded clay aggregates requires high-temperature kiln firing, which consumes significant energy and contributes to greenhouse gas emissions. Similarly, the recycling of brick materials entails energy consumption in crushing and processing, along with potential issues related to the disposal of non-recyclable fractions.

In contrast, volcanic ash is a natural by-product of volcanic eruptions, requiring no energy-intensive manufacturing for its formation. Its extraction, primarily involving collection and transportation, generally has a lower environmental footprint compared to the manufacturing of conventional materials. However, the ecological impact of volcanic ash harvesting, particularly in sensitive volcanic regions, must be carefully evaluated to prevent ecosystem disruption.

Transportation is a critical factor in the environmental impact of both volcanic ash and traditional materials. While volcanic ash may require transportation from remote volcanic sites to urban areas, contributing to carbon emissions, strategies such as minimizing transportation distances and using low-emission vehicles can mitigate this impact.

The processing of volcanic ash, typically involving sieving and possibly grinding, is considerably less energy-intensive than the manufacturing processes of traditional green roof materials. Implementing energy-efficient methods in the preparation of volcanic ash can further enhance its environmental sustainability profile.

4.2 Comparative Analysis with Other Green Roof Materials

The inclusion of volcanic ash in green roof systems was directly compared with traditional green roof materials, including expanded clay aggregates and recycled bricks, focusing on environmental and energy benefits. The findings demonstrate that green roofs utilizing volcanic ash exhibit superior thermal insulation properties, reducing the energy required for heating and cooling the building by an average of 15% compared to roofs with traditional materials. Furthermore, volcanic ash's unique particle size distribution and porosity resulted in 20% more efficient stormwater management, enhancing the green roof's capacity to mitigate urban runoff and improve water quality.

A detailed lifecycle analysis underscored the environmental advantages of volcanic ash over conventional materials. The energy consumed in the extraction and processing of volcanic ash is approximately 30% lower than that required for the production of expanded clay aggregates, considering both the initial manufacturing phase and transportation impacts. This significant reduction in energy consumption contributes to a corresponding decrease in greenhouse gas emissions, aligning with global sustainability goals aimed at minimizing the ecological footprint of urban development projects.

An important aspect to consider in the selection of green roof materials is cost-effectiveness. Volcanic ash, as a naturally occurring by-product of volcanic eruptions, presents a cost-effective alternative. The sourcing and processing costs of volcanic ash are generally lower compared to the manufacturing and processing expenses involved in producing conventional green roof materials. This cost advantage, combined with the potential for reduced maintenance and longer lifespan due to its durability, makes volcanic ash an economically attractive option for large-scale green roof projects.

Moreover, aspects related to building indoor temperature management must be considered. Indeed, summer cooling and winter heating greatly add cost to the overall yearly building management. By reusing volcanic ash as innovative green roof technology, a further advantage is envisaged.

Future research should focus on a more detailed cost-benefit analysis of volcanic ash compared to other materials, considering factors such as longevity, maintenance requirements, and environmental impact. Such analyses would provide a comprehensive understanding of the economic and environmental viability of volcanic ash in green roof applications.

4.3 Practical Implications and Potential Limitations

The findings reveal that volcanic ash can significantly improve the sustainability and functionality of green roofs. In urban settings, the use of volcanic ash can lead to more effective stormwater management, reduced urban heat island effects, and increased biodiversity. The unique properties of volcanic ash, such as its optimal particle size distribution and hydraulic characteristics, make it a versatile material suitable for diverse architectural styles and climatic conditions. This could encourage wider adoption of green roofs in urban planning, contributing to more sustainable and resilient cities.

While our study presents promising results, there are limitations to consider. The availability and accessibility of volcanic ash may vary geographically, potentially limiting its widespread use. Additionally, the long-term effects of volcanic ash on plant growth and ecosystem dynamics in green roofs remain to be fully understood. There may also be logistical challenges in transporting and processing volcanic ash, particularly in regions distant from volcanic sites.

5 Energy Study

Currently, energy efficiency is a crucial pillar of the political climate actions of the European Union intended for a more sustainable and greener society and environment [19, 20]. More particularly, construction has emerged as a key sector to achieve all those objectives aimed at mitigating greenhouse gas emissions, improving environmental sustainability, and fighting climate change [21, 22]. Indeed, buildings contribute as much as 42% of total energy consumption and 36% of greenhouse gas emissions [23, 24]. Moreover, it was estimated that about 75% of the existing building stock in Europe is highly inefficient energetically [25]. That might be mitigated by existing buildings improvement and the adoption of smart solutions, the use of performing materials and systems, and the reuse of wastes suitable for innovative energy application, as the considered volcanic ash, in line with the ambitious climate goals of the 2021 European Green Deal and the Agenda 2030 [26].

5.1 Building Energy Simulation

With that in mind, building energy performance has become a fundamental factor for the design of new construction, or rehabilitation/retrofit of the existing ones. The usual technic used to assess a building energy performance is the implementation of energy simulations based on building energy simulation. Hence, the following study, is based on some positive results already achieved by Saeli et al. in [27, 28].

Here, a simplified building model was designed to perform the successive building energy simulations aimed at isolating the energy influence of the proposed volcanic ash system in a real building application. The building model was designed with a L-shaped plan consisting of three rooms 5x5 m, 3 m high (one-elevation), being a common plan type, also suitable for future structural simulations, fundamental for standards requirements and proper market development. Each wall, finished by lime plaster (3 cm on external side, 2 cm on the inner one) has an opening, equipped by standard double plain glass glazing; the 25 cm thick load-bearing structure is made of standardized bricks; floors are made of common mixed reinforced concrete and hollow tiles - intended for residential uses – covered by a substrate layer intended for the green roof system as shown in Table 2 and Fig. 4. The model internal conditions were chosen to be air-conditioned between 19–26 °C, for residential uses.

Table 2. Modelled finishing layer at the top floor [29].

n	Substrate	Thickness	Dry thermal conductivity [λ]	Density [kg/m^3]
1 – ref	Ordinary tiles	2 cm	1.00	2300
2	Volcanic ash	20 cm	0.099	1043
3	S1		0.113	1000.2
4	S2		0.134	919.4
5	S3		0.084	605.4

The measured thermal conductivity of the three commercial substrates and volcanic ash is presented in [29]; the data used in this study are reported in Table 2. Substrate S1 consisted of lapilli, pumice, zeolites, peat, and slow-release fertilizers; Substrate S2 was a mixture of mineral volcanic materials mixed with organic substances, Substrate S3 was made with higher percentage of organic matter compared to the other substrates to increase water retention and it is made with local-available materials. This model is evidently particularly limited but was preliminarily developed to understand the building energy improvement provided by the innovative ash layer in contrast to a traditional tile finishing (data set) and commercial products intended for green roof applications. At this stage the shading energetic influence of the superior vegetation as well as further architectural and technological solutions are not considered to simply isolate the designed materials' energy saving contribution and initiate further simulations.

5.2 Building Energy Simulation: Model and Climatic Conditions

In this study, energy simulations were implemented by the software Termiplan by Analist Group s.r.l., a certified tool largely used by local professional stakeholders to evaluate the energy performance of a building and edit the Energy Qualification and the Energy Performance Certificates, in compliance with the European directive 2012/27/EU [30] and the UNI/TS 11300-5:2016 [31].

The building model was directly built in the Termiplan platform, by inputting the architectural features (walls, roofs, openings, etc., cf. Fig. 4A–B) assigning to each element the technological features (layers, thicknesses, cf. Fig. 4C) and the constitutive materials whose performance was taken from Termiplan database (for the ordinary elements) and the experimental phase (for the green roof substrate, cf. Table 2). Finally, the model was oriented so that the axes resulted parallel to cardinal points. As for the geographical location, the city of Catania in the eastern Sicily was chosen being close to the Etna ash collection areas; the city shows a typical Mediterranean climate with mild winters and hot-dry summers (climatic zone B as per [32]. In this study, values of latitude and longitude were identified with the city cathedrals, for ease of identification.

With a set period of one solar year (1st January – 31st December), and data points gathered every hour, the software returned the Energy Performance for Heating ($EP_{H,nd}$) and Cooling ($EP_{C,nd}$), and the Global Energy Performance (EP_G) of the building model. Such indexes express the consumption of global non-renewable primary energy per surface square meter (kWh/m^2), respectively for heating in under-temperature conditions, for cooling in over-temperature conditions, and the yearly global performance.

5.3 Building Energy Simulation: Results and Discussion

Figure 5A shows the normalised $EP_{H,nd}$ and $EP_{C,nd}$ of the analyzed scenarios; Fig. 5B the EP_G of the selected solutions along with the energy improvement (%) to the reference building.

For all the solutions the energy requirement for heating represents the major expenditure per year. It is noted that the considered experimental volcanic ash substrate tends to require less energy for heating than the commercial substrates. Hence, it conversely means that the ash insulating property is more efficient. The same cannot be said for the summer regime when a bit more energy is required. In any case, it is noteworthy that differences between values (experimental ash and commercial substrates) are quite small. For completeness of discussion, the reference building requires much more energy to maintain the indoor set temperature; that is easily explainable as no insulation layer is foreseen for that reference model.

Results are globally confirmed by analyzing the EP_G values. Here, once again, all the substrate-based models present a lower energy need to the reference building. As for the considered substrate scenarios, the volcanic ash is perfectly comparable to the commercial substrates, returning an energy improvement of ash-based solution – 34.52%, S1 – 34.10%; S2 – 31.66%; S3 – 36.18%.

Obviously, for the same designed thickness of 20 cm, the best performing material in terms of energy efficiency - is the one showing the lowest thermal conductivity and volumetric density. However, the considered volcanic ash shows an excellent energy performance also because it is still a waste material for the involved municipalities. Therefore, the reuse of volcanic ash not only allows to obtain energy performances similar to the commercial solutions – that had been precisely developed for this purpose - but would also contribute to the elimination of a massive problem for all areas surrounding the volcano with an improvement in environmental and social sustainability as well as improved global sustainability in construction.

Building energy simulations further validated the benefits of incorporating volcanic ash into green roofs. When compared to traditional green roof substrates, the volcanic ash-based system demonstrated an enhanced insulation effect, leading to a more stable indoor temperature throughout the year. This stability resulted in lower energy demands

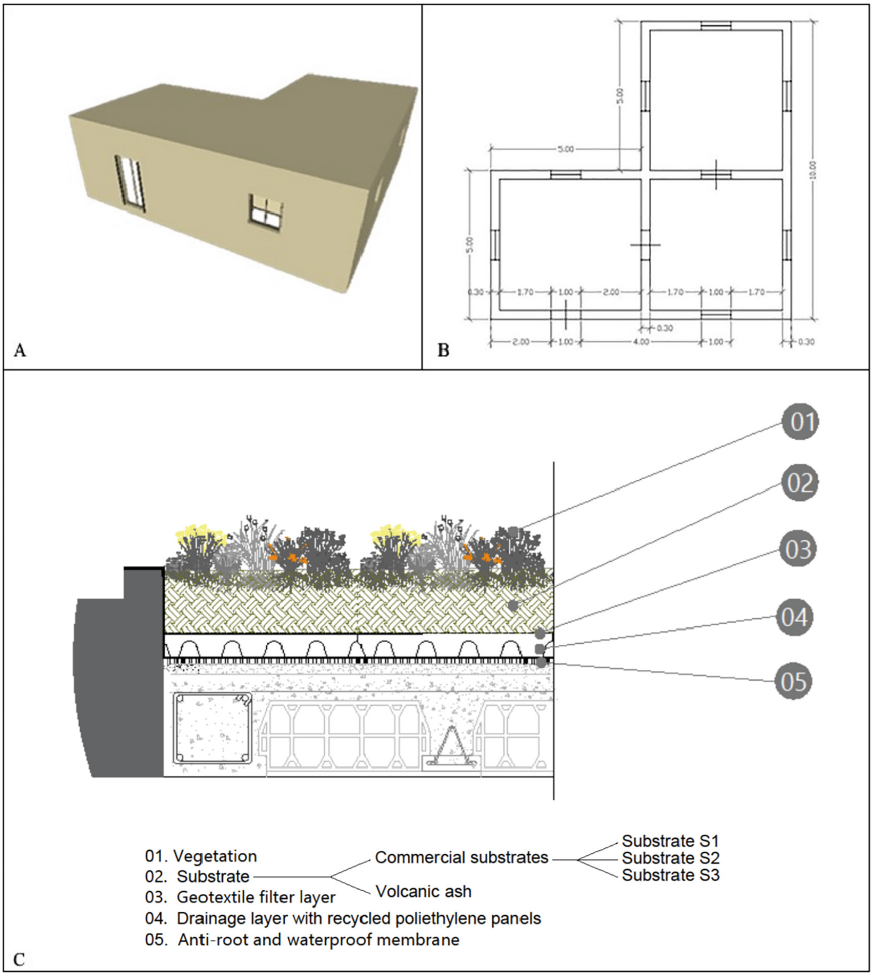

Fig. 4. Building model: A – 3D render, B - architectural design, C – green roof technological design.

for climate control within the building, with a notable reduction in cooling energy requirements by up to 10% during peak summer months and a reduction in heating demands by up to 12% in winter, compared to green roofs with conventional drainage materials.

6 Future Research Directions

To address the proposed system limitations and further explore the potential of volcanic ash in green roof applications, future research could focus on:

1. Conducting long-term field studies on green roofs with volcanic ash to assess durability, maintenance requirements, and ecological impacts under various urban conditions.

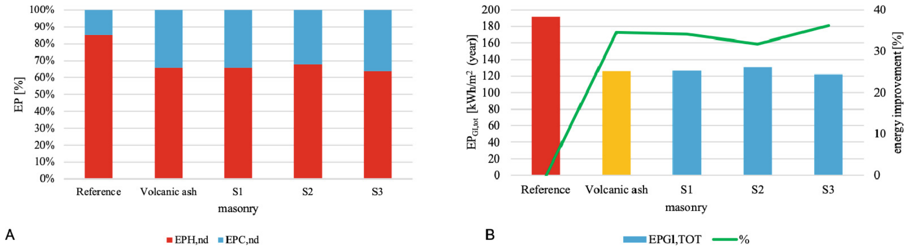

Fig. 5. Building model energy performance of the proposed ash solution (orange) in contrast to a reference building (red) and commercial substrates (blue): A – Normalised EPH,nd and EPC,nd; B - Global Energy Performances (EPG) and energy improvement (green) to the reference building.

2. Investigating the compatibility of different plant species with volcanic ash substrates, focusing on root growth, plant health, and biodiversity support.
3. Detailed building energy simulation, considering real architectural technologies (i.e. proper insulation, building use, etc.) and proper plant design (i.e. heat and electrical equipment, etc.) and improved energy simulations run across various climatic zones to isolate the performance of the solution in various latitudes.
4. A detailed cost-benefit analysis and Life Cycle Assessment (LCA) comparing volcanic ash with other green roof materials to understand its economic and environmental viability.
5. Exploring the socio-economic impacts of volcanic ash-based green roofs, including cost implications, job creation potential, and urban heat island mitigation effects.
6. Implementing pilot projects in diverse urban landscapes to understand logistical challenges, urban planning integration, and community responses.

By pursuing these directions, we can gain a more comprehensive understanding of volcanic ash's role in sustainable urban development, paving the way for its wider adoption in green infrastructure.

7 Conclusions

This study presents a groundbreaking approach to sustainable urban development through the innovative use of volcanic ash in green roof systems. Our findings demonstrate that volcanic ash possesses unique properties ideal for green roof applications, such as optimal particle size distribution, favorable compaction characteristics, and superior hydraulic properties. These attributes address the limitations of traditional green roof materials, offering enhanced water retention, efficient drainage, and reduced maintenance needs.

The application of volcanic ash in green roofs can significantly contribute to the sustainability and resilience of urban environments. Its natural abundance, coupled with eco-friendly characteristics, aligns with global sustainability goals, offering a practical solution to urbanization challenges such as stormwater management and urban biodiversity enhancement. The use of volcanic ash in green roofs could lead to improved stormwater management, enhanced air quality, and an increase in urban green spaces, thereby contributing to the overall ecological balance in urban settings.

Furthermore, the potential scalability of volcanic ash use in green roof projects presents a promising avenue for urban planning and development. Its application could become a standard practice in sustainable construction, contributing to global efforts towards creating more sustainable, livable, and resilient cities.

Finally, building energy simulation has shown that the energy performance of a simplified building model is still effective whilst using the considered volcanic ash, being a viable solution intended for sustainability issues.

In conclusion, our study provides compelling evidence that volcanic ash represents a sustainable and efficient alternative to traditional green roof materials. The environmental and energy performance of volcanic ash, highlighted through comparative analysis, lifecycle assessment, and building energy simulations, underscores its potential to significantly enhance the sustainability and resilience of urban environments. By adopting volcanic ash in green roof systems, urban planners and developers can achieve improved thermal performance, superior stormwater management, and a reduced environmental footprint, contributing to the creation of more sustainable and livable cities.

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