Athens Journal of Architecture - Volume 12, Issue 2, April 2026 – Pages 171-194
(received: 8 June 2025, received in revised form: 11 October 2025, accepted: 30 November 2025)

The Green Wall: A Project and a Prototype of a Sustainable 3D Printed Bearing Wall with Integrated Vegetation

By Ilaria Cavaliere & Dario Costantino±*

In a context where the climate change topic is a primary matter of discussion, the use of vegetation to improve the thermal insulation of buildings and biodiversity while contributing to carbon sequestration has become a popular strategy to increase sustainability. This paper aims at presenting a model of a bearing wall made of 3D-printed stone ashlars with integrated greenery. This constructive system has been designed to merge a series of characteristics such as:

- *a simple and fast assembly process, that makes it suitable also for emergency contexts*
- *a good thermal performance due to the presence of the vegetation on the outer surface*
- *the possibility to customise the properties of the ashlars thanks to the use of 3D printing. Blocks can have different dimensions, different overhangs or can be customised to optimise their static behaviour, their thermal performance and their weight by changing their internal porosity*

the possibility to use recycled materials like waste stone powder or debris from demolition, keeping the entire construction process greener.

Introduction

In recent years, environmental sustainability has become a central theme in architectural research and practice, prompting a renewed focus on nature-based and resource-efficient design approaches.

The increasing awareness about the problems related to pollution, the global climate crisis and the waste of resources has pushed governments around the world to adopt strategic initiatives and action programs aimed at safeguarding the environment through more critical design strategies and projects more respectful towards nature. Important examples of this include the New European Bauhaus,[1] which encourages the realisation of increasingly sustainable buildings, the 2015 Paris Agreement,[2] which aims to decarbonise and maintain the planet's temperature increase below 1.5 °C, and the United Nations 2030 Agenda,[3] which aims to create resilient, inclusive and low-emission settlements.

In line with the objectives of these initiatives, the presented research investigates how digital fabrication, sustainable materials and vegetation can be combined in

*Researcher, Polytechnic University of Bari, Italy.
±Researcher, Polytechnic University of Bari, Italy.

1. European Union. *New European Bauhaus*. Retrieved from: www.new-european-bauhaus.europa.eu/index_en?prefLang=it. [Accessed 5 June 2025.]
2. United Nations Climate Change. *The Paris Agreement*. Retrieved from: www.unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [Accessed 5 June 2025.]
3. United Nations. *The 17 Goals*. Retrieved from: www.sdgs.un.org/goals. [Accessed 5 June 2025.]

https://doi.org/10.30958/aja.12-2-3 doi=10.30958/aja.12-2-3

architectural design. The aim is to develop a prototype of a load-bearing wall suitable for Mediterranean contexts, using 3D-printed stone ashlars to ensure thermal performance, recyclability and ease of assembly. Moreover, this study aims to merge Mediterranean tradition and contemporary digital tools while critically assessing the advantages and limitations of the proposed system.

The Relationship between Architecture and Nature

The relationship between architecture and nature is ancient, expressed in diverse places and forms as a symbolic link across cultures and times.

For example, since the first century BC, Vitruvius made this relationship explicit in his *De Architectura*, writing about the first human dwelling, which was a hut made of natural materials such as branches, mud and leaves.

Over time, the hut evolved from a simple shelter into a symbol of humanity's ability to shape nature for protection and survival.

In fact, based on the geographical area, the plant species and water resources available, people have always attempted to create habitats favourable to their lives, first in simple ways, gradually domesticating the vegetation, and then building increasingly complex architectures.

An interesting example is represented by the oasis systems in the Global South, which were real settlements centred on greenery, specifically on the date palm. As early as the first millennium BC, as demonstrated by the findings at Zinkekra, there were attempts made by mankind to domesticate the date palm,[4] starting a process that would then lead to the creation of extremely complex structures, in which they could produce and survive by exploiting the shade produced by these trees. Controlling vegetation meant fighting desertification, creating favourable microclimates and laying the foundations for the creation of durable settlements, made up of both open meeting places and homes made of local materials with a high thermal inertia (e.g., mud, earth, stone, leaves and palm bark). This led to a consistent expansion and to the creation of compact and densely built villages equipped with protective walls, agricultural systems distributed on multiple levels and underground systems for collecting and managing water.[5]

In Europe a similar phenomenon occurred thanks to the massive presence of olive trees. The cultivation of olive trees led to the creation of permanent rural settlements such as underground oil mills (Southern Italy, Greece, Spain),[6] fortified

---

4. Kaczmarek T, Van der Veen M, Ivorra S, Mattingly D, Terral J-F, Gros-Balthazard M (2024) Origins and evolution of oasis agriculture in the Sahara: Evidence from morphometric analyses of archaeological date palm seeds. *The Holocene, 3: 353–365.*

5. Neglia G A (2024) Il palmeto di AlDiriyah come esempio di vivibilità nei paesaggi delle aree desertiche. [The AlDiriyah Palm Grove as an Example of Livability in Desert Landscapes.] *RI-VISTA Research for landscape architecture* 22(1): 218-231.

6. Mazzotti M (2008) Enlightened mills: mechanizing olive oil production in Mediterranean Europe. *Technology and Culture* 45(2): 277-304.

farms and *trulli* (Sicily and Apulia),[7,8] Andalusian *cortijos* (Spain).[9] Therefore, exactly as in the Sahara Desert, the possibility of creating controlled microclimates by exploiting the properties of local vegetation has allowed the development of the aforementioned architecture-nature relationship in original and effective forms, of which we still have ample evidence today.

Nowadays, the reconnection with nature is central to renewed scientific and architectural interest, countering the effects of rapid urbanisation that have reshaped landscapes and lifestyles.

The governmental initiatives previously mentioned have been combined with an increasing understanding of the advantages of a strategic green approach, and urban vegetation has begun to be considered not only as a furnishing element but also as an active part of architecture, so as an element that works in synergy with design to go beyond the simple aesthetic question.

Combining greenery with buildings improves the microclimate, reduces urban heat islands and enhances citizens' psychological well-being. This approach has led to projects such as the *High Line Park* in New York and the *Bosco Verticale* in Milan.[10]

The path towards bioarchitecture and nature-based solutions has been opened, reviving the ancient tradition of combining anthropic and natural elements, but with a different, contemporary perspective, enhanced by the possibilities offered by new technological tools. These can give new lifeblood to the techniques used to design and realise architectures, and they allow the recovery and improvement of very ancient construction traditions, as dry construction. This, combined with the exponential evolution of three-dimensional modelling software and digital manufacturing tools, has allowed us to work on dry construction in new ways, significantly expanding the spectrum of formal possibilities and usable materials.

Therefore, it becomes possible to develop projects like the one described in this article, which leads to a virtuous combination of effects such as good thermal performance and greenery integration, obtaining a sustainable, adaptive and customisable construction system.

Today, several experiments related to the design of structures composed of interlocking ashlars or complex architectural patterns are underway, often involving the implementation of plant species to enhance their aesthetic and performance characteristics. These examples have been studied to face the design process with awareness.

---

7. Lombardo L, Luisi T (2024) Dry-stone architectural heritage in Madonie district.The rehabilitation of ancient rural complexes, as exemplary smart villages. *Sustainable Mediterranean Construction* 7: 15-22.

8. Ruggiero G, Dal Sasso S, Loisi R V, Verdiani G (2013) Characteristics and distribution of trulli constructions in the area of the site of community importance Murgia of Trulli. *Journal of Agricultural Engineering* XLIV: 87-94.

9. Palomares Alarcón S (2022) Olive grove landscape: the hydraulic pressing machine and its importance in the cultural heritage of Andalusia. *Revista de História da Sociedade e da Cultura* 22(1): 213-232.

10. Lehmann S (2021) Growing biodiverse urban futures: renaturalization and rewilding as strategies to strengthen urban resilience. *Sustainability 13(5): 2932.*

Literature Review

Even though the architectural practice of dry construction has aroused renewed and intense interest over the last twenty years– thanks to the advent of new technologies and the rediscovery of techniques –, the possibility of building architectural artefacts without the use of mortars or other adhesives has a long history behind it. Some significant examples are the Sardinian *nuraghi* (1800 BC), the Scottish *brochs* (1st millennium BC), the megalithic walls of the Mycenaean civilisation (3000 BC), the Apulian *trulli* (16th century) or the dry-stone walls widespread in Italy, Greece, Croatia, France, Spain and other regions.[11]

Dry construction has long been associated with sustainability, rapid assembly, microclimatic regulation, durability, and low cost. However, despite craftsmen's expertise, technological limitations confined this practice to the past, hindering modernisation. Today, by combining geometry, technology, and biology, new architectural projects are emerging that expand the boundaries of masonry construction.

Dry Construction Nowadays

A significant example of a contemporary construction system that does not involve the use of mortar or glue is represented by the Putra blocks made at the Universiti Putra Malaysia.[12] This is an innovative system of hollow blocks with interlocking joints that allow the creation of load-bearing and non-load-bearing walls, speeding up the construction process, improving efficiency and reducing costs. In fact, these blocks are modular concrete elements that implement a three-dimensional interlocking mechanism to eliminate the need for mortar, allow automatic alignment during assembly and, consequently, reduce the need for specialised labour and increase the precision of the work. 21 blocks were made, divided into three categories (stretcher, corner, half), each with standard dimensions and tested from different points of view: weight (about 12-14 kg per block), resistance, ease of production and ability to accommodate vertical and horizontal reinforcements. The system was put into practice by creating a 60 m^2 single-level house, and this operation allowed the project's potential to be verified, demonstrating a 30% reduction in construction times compared to traditional construction times.

Another project that follows the same logic was developed at the University of Innsbruck between 2022 and 2025.[13] In this case, too, interlocking ashlars were

---

11. UNESCO. *L'Arte della costruzione in pietra a secco: conoscenza e tecniche, elemento transnazionale (comprendente, oltre all'Italia, Croazia, Cipro, Francia, Grecia, Slovenia, Spagna, Svizzera, Andorra, Austria, Belgio, Irlanda e Lussemburgo)*. [The Art of Dry Stone Construction: Knowledge and Techniques, a Transnational Element (Including, in addition to Italy, Croatia, Cyprus, France, Greece, Slovenia, Spain, Switzerland, Andorra, Austria, Belgium, Ireland and Luxembourg).] Retrieved from: www.unesco.it/it/iniziative-dellunesco/patrimonio-culturale-immateriale/larte-della-costruzione-in-pietra-a-secco-conoscenza-e-tecniche-elemento-transnazionale-comprendente-oltre-allitalia-croazia-cipro-francia-grecia-slovenia-spagna-svizzera/. [Last accessed 5 June 2025.]

12. Thanoon W A, Jaafar M S, Abdul Kadir M R, Abang Ali A A, Trikha D N, Najm A M S (2004) Development of an innovative interlocking load bearing hollow block system in Malaysia. *Construction and Building Materials* 18(6): 445–454.

13. Hua H (2024) Porous interlocking assembly: performance-based dry masonry construction with digital stereotomy. *Architectural Intelligence*, 3: 55–72.

created through digital stereotomy and robotic cutting. Specifically, three types of ashlars were made, and each one was used to build a prototype. So, in the end, there were three architectural prototypes, each with a different level of porosity. The first prototype, called *G4*, was a room designed using G-shaped ashlars, which were interconnected with vertical and horizontal joints, taking advantage of the planar faces and ultimately obtaining an architecture with a porosity level of 61% (i.e., only 39% of the walls are actually full). This architecture was stable enough and easy to create, but at the same time it had a rigid shape, so it was not very interesting formally. Moreover, it was laterally weak. The second prototype, the *Abeille Crystal*, was built using blocks generated by complex diagonal cuts, which gave rise to asymmetric, sculptural and crystalline geometries with excellent thermal efficiency; however, they were fragile and required high precision in the cutting phase. Furthermore, the assembly process was difficult and required highly skilled workers. The third prototype, called *Woven Masonry*, was obtained from blocks cut in waves, which created a sort of adaptable and resistant wall fabric; nevertheless, it was geometrically very complex and therefore difficult to work with on-site due to the complexity of the alignments.

Despite their differences, these projects demonstrate the potential of customizable block systems to enable new architectural solutions that are efficient and, if carefully designed, practical to implement on site.

However, at the same time, they are bound to an approach that is too constrained by form and technological potential, and only partly it is based on the characteristics of the material. In particular, in the second case, expanded polystyrene was used, limiting the research to a formal test in view of future approaches with real building materials. Moreover, the relationship with greenery is totally absent in all the described case studies.

Integration of Greenery on Vertical Surfaces

Adding greenery to a façade is a practice commonly known as *vertical gardening* or *vertical greening,* and it is not only related to an aesthetic improvement. It is becoming a popular strategy to increase the thermal performance of buildings and outdoor comfort. As a matter of fact, vegetation on the outer side of a wall can help enhance thermal insulation – reducing the need for artificial cooling and heating systems –, it encourages biodiversity by creating habitats for birds and insects, and it helps reduce greenhouse gases.[14]

Nowadays, various vertical greening solutions are available on the market, but they mainly consist of coating systems that involve hanging vases or non-woven fabric pockets.

Some experimental tiling systems aimed at hosting greenery have also been developed thanks to the help of digital fabrication technologies. Two significant examples are the 3D printed hexagonal tiles developed by Emerging Objects for the pavilion called *Cabin of 3D Printed Curiosities*[15] (Figure 1a) and the 3D printed

14. Jain R (2016) Vertical Gardening: A New Concept of Modern Era. In N L Patel, S L Chawla, T R Ahlawa (eds), 527-536. *Commercial Horticulture*. New Delhi: New India Publishing Agency.

15. Rael R, Sanfratello V (2018) *Printing Architecture. Innovative Recipes for 3D Printing*. New York: Princeton Architectural Press.

cladding system *CO-mida*, designed and realised by the Advanced Architecture Group of the Institute for Advanced Architecture in Catalonia (IAAC)[16] (Figure 1b).

However, both these examples deal with a cladding system, which has no structural function.

Several projects consider the possibility of integrating vegetation with modular structural elements similar to those analysed in the previous paragraph and made with contemporary construction tools – such as 3D printers –, innovative materials and experimental techniques.

An example is an ashlar designed at the Polytechnic University of Bari,[17] which was conceived to be 3D printed using clay and to be completely hollow, allowing the insertion of insulation and metallic reinforcements. The problem is that vegetation is not designed together with the ashlars, but it is conceived as an additional element that improves their characteristics; therefore, the final result does not differ from those previously described in terms of green design.

16. Farinea C, Awad L, Dubor A, El Atab M (2020) Integrating biophotovoltaic and cyber-physical technologies into a 3D printed wall. Anthropologic: architecture and fabrication in the cognitive age. In *Proceedings of the 38th eCAADe Conference* Volume 2 (Berlin, Berlin, Germany, 16–18 September 2020). Berlin: eCAADe, 463–472.

17. Volpe S, Sangiorgio V, Petrella A, Coppola A, Notarnicola M, Fiorito F (2021) Building Envelope Prefabricated with 3D Printing Technology. *Sustainability*, 13(16): 8923.

Figure 1. a) *the 3D printed hexagonal tiles developed by Emerging Objects for the pavilion called Cabin of 3D Printed Curiosities; b) CO-mida, designed and realised by the Advanced Architecture Group of the Institute for Advanced Architecture in Catalonia (IAAC)*
Source: a) photo by Matthew Millman from www.emergingobjects.com; b) photo from https://advancedarchitecturegroup.net/projects/co-mida/.

Furthermore, adding greenery to a project and not planning it in the design phase means running into possible unforeseen events and damages due to the implementation of irrigation systems and the maintenance of the chosen species.[18]

Nevertheless, in some cases a design upgrade is made, attempting to overcome the simple juxtaposition and thinking of green walls that, in addition to possessing all the characteristics of previous projects – modularity, ease of production, speed of assembly – also present all the advantages of the superficial application of vegetation, such as the improvement of air quality, the improvement of physical and psychological well-being, the enhancement of architectural thermoregulation. Moreover, the shape

18. Zuniga-Teran A, Staddon C, de Vito L, Gerlak AK, Ward S, Schoeman Y, Mumme S (2020) Challenges of mainstreaming green infrastructure in built environment professions. *Journal of Environmental Planning and Management*, 63(4), 710–732.

is designed to accommodate different plant species. The project of a porous wall developed at the Beirut Arab University is emblematic, especially because it was applied to the theoretical case study of the Jarjouh Healing Resort in southern Lebanon.[19] A physical model on a small scale was built, and its ashlars were 3D printed with a self-compacting concrete. Their shape was organic, modular and vertically assembleable, and it was conceived as a pocket that could accommodate vegetation. Additionally, each block included internal channels to facilitate drainage and had a textured surface to allow vegetation attachment and drip irrigation. In this case, form and function were developed simultaneously and in the service of the vegetation. Moreover, this work was not limited to the laboratory, but the researchers attempted to contextualise it in Lebanon, even if only theoretically. This was an important step because it added a further degree of complexity, in terms of both design and social aspects. However, the formal complexity of the project brought with it problems even in the small-scale prototype: the project showed low structural resistance (with a deformation of 25 mm under simulated load) and, finally, the preparation of this type of model required advanced software and skills.

Another valuable example is represented by the *3D-VtGW* project, developed and realised in Nanjing (China).[20] This is a model of a wall composed of 3D-printed blocks shaped with a pocket to host vegetation and juxtaposed in staggered rows. An accurate simulation of the thermal performance has revealed a potentially good behaviour from the thermal point of view; however, the prototype has been realised with 3D printed concrete, which does not represent a sustainable solution due to its high value of embodied carbon. Moreover, the system does not integrate interlocking joints, which can help an easier and safer construction process.

The project Brick By Bit[21] by Victoria Roznowski (Figure 2) represents a significant solution for an interlocking self-bearing system. The geometry of the ashlars has been obtained through parametric modelling optimising the thermal performance. Some blocks have been shaped with a pocket to host vegetation, while others have been shaped to convey them water. The prototype has been 3D printed using clay. Even if this is a good example of interlocking system with the integration of greenery, information about more technical aspects (e.g., the optimisation and modelling process, the fabrication process, design criteria, etc.) are not available.

19. Chahin S, Afify A, Mohsen H, Youssef M (2022) Role of 3D Printed Green Walls in Healing Architecture. *BAU Journal – Health and Wellbeing* 5(1).

20. He Y, Zhang Y, Zhang C, Zhou H (2020) Energy-saving potential of 3D printed concrete building with integrated living wall. *Energy & Buildings* 222.

21. PA Editorial Team (2024) Victoria Roznowski's Brick By Bit redefines clay bricks with 3D printing. *Parametric Architecture*: https://parametric-architecture.com/brick-by-bit-redefines-clay-bricks-with-3d-printing/ [Accessed 11 October 2025].

Figure 2. *The prototype of the project Brick By Bit by Victoria Roznowski*
Source: Photo from https://parametric-architecture.com/brick-by-bit-redefines-clay-bricks-with-3d-printing/.

All these aspects, together with the pros and cons found in the analysed case studies, have been considered during the design process of the *Green Wall*.

Methodology: The Steps of the Design Process of the *Green Wall*

The *Green Wall* is a prototype of a self-bearing wall designed specifically for the Mediterranean context. This choice reflects the research focus of the Architecture Department at the Polytechnic University of Bari, which investigates stone in architecture and Mediterranean identity.

The design phase started from three main objectives:

1. the first objective was to design a constructive system suitable for the Mediterranean basin from various points of view, such as the formal language, the material used, and the thermal performance;
2. the second objective dealt with the ease of the construction process, in order to keep the final product suitable also for emergency contexts;
3. the third objective consisted in obtaining a sustainable architectural system, considering matters as recyclability, use of waste materials and adaptability to different contexts.

The Mediterranean Identity of the *Green Wall*

The Mediterranean area has a strong architectural tradition, based especially on the use of stone, which has been declined through the centuries in various ways: cities like Alberobello (Italy), Matera (Italy), Cyprus (Greece) or Mardin (Turkey) are very different from one another, but they are all expressions of the Mediterranean architectural language.

Stone is a material with high thermal inertia, and this characteristic helps obtain a good thermal performance. For this reason, stone is the material chosen for the *Green Wall*, even if in recomposed or 3D printed form.

Moreover, a particular language linked to stone architecture was chosen as an inspiration for this project: it is rustication, also known as *bugnato*. Rustication is a practice aimed at giving a stone surface a plastic appearance by protruding or tridimensionally finishing the front face of each ashlar.

Even if rustication was antiquely used by Greeks and Romans, it massively spread in Italy during the Renaissance period, when it was largely employed for private and public buildings, but it has also been used in other Mediterranean regions.[22]

There are different types of rustication: some of them have a rawer appearance (Figure 3a), while some of them have a more refined appearance (Figures 3b and 3c), but all of them give the façade strength and rhythm.

Figure 3. *Different typologies of rustication: a) the façade of the Medici-Riccardi palace in Florence (1444-1484, Italy); b) the southern façade of the Palace of Charles V in Granada (1527-1623, Spain); a detail of the House of the Beaks in Lisbon (Portugal, 1523)*
Source: a) photo by Sailko, Wikimedia Commons; b) photo by Rose Selavy from Wikimedia Commons; c) photo by Andreas Manessinger from Wikimedia Commons.

The inspiration to rusticated stone is linked not only to the will of respecting a Mediterranean aesthetic, but also to sustainability considerations. As a matter of fact, corrugations on a surface exposed to direct sunlight help produce shades on this surface, thus reducing the surface temperature and acting as a passive cooling strategy.[23]

The Constructive System

According to the choice of reinterpreting rusticated stone through the language of digital 3D modelling, a set of staggered blocks has been modelled to form a tridimensional pattern when put together.

The design process has followed these steps (Figure 4):

---

22. Acocella A (2004) *L'architettura di pietra. Antichi e nuovi magisteri costruttivi* [Stone architecture. Ancient and modern constructive skills]. Milan: Skira-Lucense.

23. Shahda M (2020) Self-Shading Walls to Improve Environmental Performance in Desert Buildings. *Architecture Research* 10(1): 1-14.

1. a set of cubic boxes has been made;
2. the front face of each block has been implemented with a volume shaped as a slightly twisted pyramid trunk;
3. the pyramid trunk has been excavated on the upper part to obtain a pocket for vegetation;

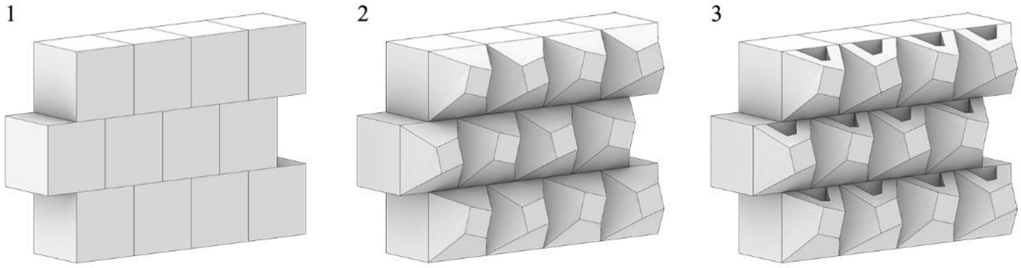

Figure 4. *Scheme of the modelling phases*
Source: drawings by the authors.

The interlocking system has been conceived to be as simple as possible and to guarantee that the ashlars could be reciprocally fixed without mortar or glue. Each ashlar was conceived with reciprocal male and female geometries: protrusions on the lower surface and corresponding cavities on the upper face of the block ensure that all the elements fit together in a self-aligning manner, guaranteeing both stability and ease of construction.

Four ashlar typologies are needed for a complete system: two for the planar part of the wall and two for the corners (Figure 5).

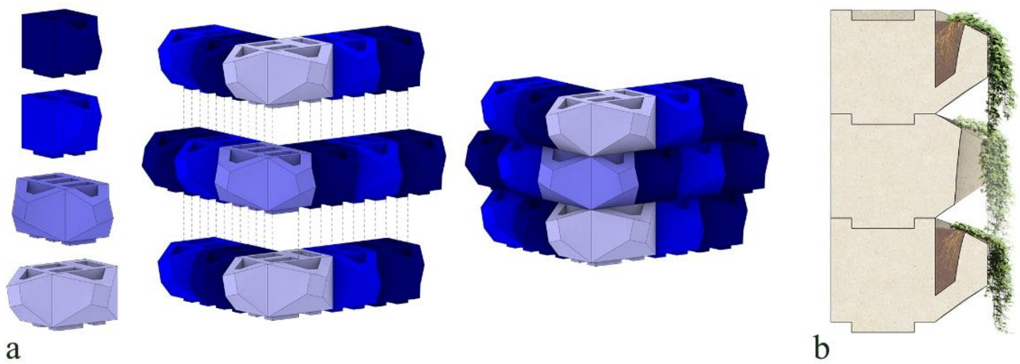

Figure 5. *Scheme of the constructive system: a) the four typologies of ashlars – marked by different colours – and an assembly scheme; b) a cross section showing the interlocking joint and the placement of vegetation.*
Source: drawings by the authors.

This basic pattern can be varied according to the design needs, thanks to the implementation of parametric modelling. For example, the ratio between length and height of the ashlars can be modified, the overhangs can vary to obtain wider holes for different vegetation species, or the pattern can be deformed to tessellate curved surfaces instead of planar ones (Figure 6).

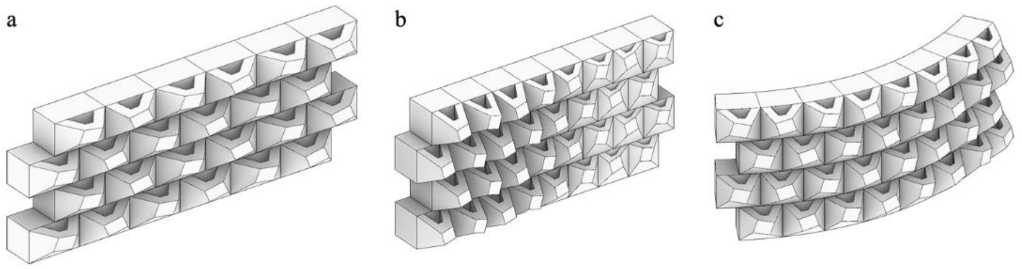

Figure 6. *Some possible variations of the pattern: a) variation of proportions; b) variation of overhangs; c) tessellation of a curved wall allowed by the deformation of the ashlars*
Source: drawings by the authors.

In the case of a real application, some precautions should be taken for the proper functioning of the *Green Wall*. Small holes at the bottom of the vases would prevent rotting by helping water in excess flow, for example in case of rain. This way, water would not be wasted, but it would be collected by the vases underneath. Moreover, a waterproof coating should be placed inside the cavities that host vegetation, in order to prevent stone imbibition.

The *Green Wall* can work exploiting passive irrigation: as a matter of fact, 3D printed stone is a porous material that favours moisture condensation. The collection of moisture condensation is a strategy commonly used especially in areas characterised by a very warm climate and by lack of water to favour cultivation. This is basically how dry stone walls work.[24]

However, the integration of an irrigation system could be investigated in order to make the system more flexible. A plausible hypothesis would involve external tubes for drip irrigation: this way, an easy application and maintenance would be guaranteed.

The Use of 3D Printed Stone

As noted earlier, the project aimed to explore an innovative use of stone to create a solution coherent with Mediterranean architectural traditions, while ensuring high thermal inertia suitable for warm climates without thick insulating layers.

However, traditional stone carving poses significant limitations in terms of precision, waste, and labour intensity, especially when producing complex geometries like those required for the *Green Wall*.

Given the modularity of the elements that compose this constructive system, a good fabrication solution could be the use of traditional recomposed stone through moulds, which would surely help reduce costs in case of mass production.

However, in this case stone 3D printing through binder jetting technology was investigated. Differently from the more common extrusion technology, the binder jetting process consists of depositing layers of binder on progressive layers of inert powder. The pile of powder that is generated during the printing process works as a

24. Laureano P (2007) Ancient water catchment techniques for proper management of Mediterranean ecosystems. *Water Supply* 7(1): 237-244.

support for the portions on which binder is sprayed, allowing the realisation of complex shapes and significant overhangs.

Additive manufacturing flexibility would allow for easy application of the previously mentioned variation of the system according to the project needs, without the necessity to produce specific moulds from time to time. Moreover, the shape complexity that can be obtained using the binder jetting technology allows for further customisation of the construction system by changing the porosity of the ashlars through lattice optimisation. This permits adjusting the weight of the ashlars, keeping their robustness optimal, or also obtaining internal cavities that can remain empty or filled with other materials, as specific insulants.

Binder jetting 3D printing technology applied to stone has already been experimented with, for example for some prototypes exposed at the international exhibition Marmomac Meets Academies in the 2023 and in the 2024 editions. The prototype *Technovauld* by Dustin White[25] and *Doppionodo* by Giuseppe Fallacara and Marco Massafra,[26] both realised using Lecce stone powder, demonstrate that the appearance of 3D printed stone is very similar to natural stone, keeping this technology very suitable for contemporary architectural applications (Figure 7).

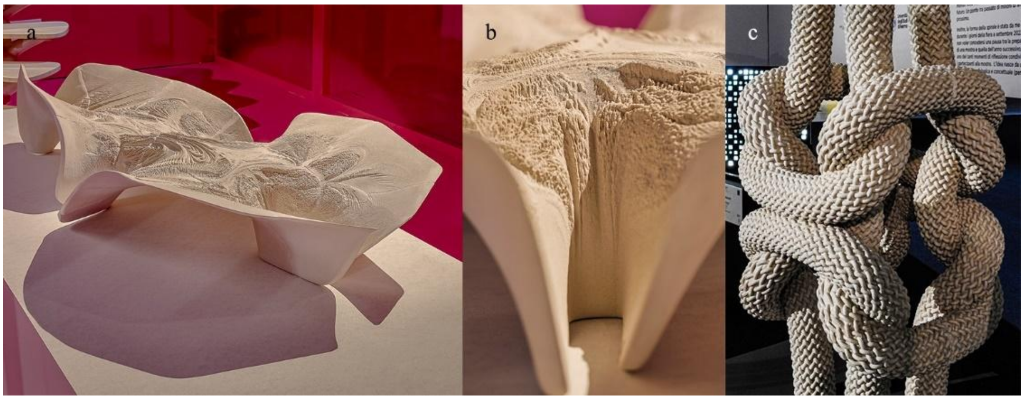

Figure 7. *Some prototypes realised through Lecce stone 3D printing with the binder jetting technology: a) Technovauld by Dustin White; b) a detail of Technovauld that shows the finishing of 3D printed stone; c) Doppionodo by Giuseppe Fallacara and Marco Massafra*

Source: a) and b) photos by Gaz Blanco; c) photo by the authors.

Additive manufacturing allows also for a greener fabrication process not only by reducing waste production, but also by giving the possibility of using waste powder from stone manufacturing or debris from demolition.

25. White D (2023) Technovauld. In G Fallacara (ed), 76-79. *Marmomac Meets Academies. Advanced research, lithic experimentation*. Ferrara: Media MD.

26. Fallacara G, Massafra M (2024) Doppionodo. In G Fallacara (ed), 62-63. *Ceci n'est pas un fossile. Marmomac Meets Academies 2024*. Ferrara: Media MD.

The 3D Printed Prototype

A physical prototype of the *Green Wall* was produced on the occasion of the exhibition Marmomac Meets Academies 2024, curated by prof. Giuseppe Fallacara and held in Verona from 24 to 27 September 2024. The prototype consisted of a fragment of a wall corner, which was placed on a podium with a surface of 60 cm × 60 cm.

The dimensions of the prototype and its components are shown in Figure 8. However, in the case of a real application, they can be scaled according to construction needs.

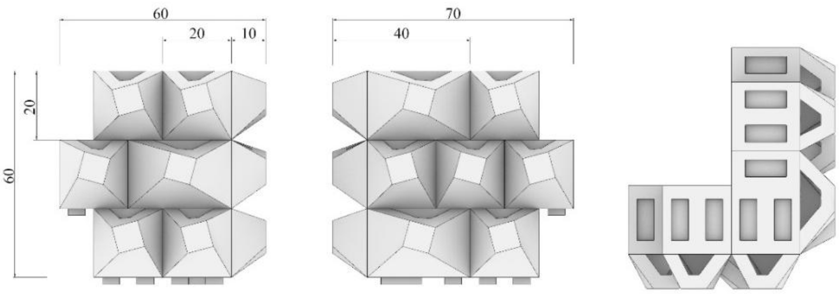

Figure 8. *A scheme of the prototype. All the measures are in cm.*
Source: photos by the authors.

The blocks were produced by the company D-Shape, a pioneer in large-scale binder jetting 3D printing. In this case, ashlars were fabricated using a standard 3D printed concrete. The machine used is meant for large-scale objects, so it has a low printing resolution, and, because of that, the tolerances of the interlocking systems had to be recalibrated, while the produced objects needed post-production to remove imperfections. Despite this, the ashlars resulted endowed with a rough superficial texture that gave them a strong resemblance to porous natural stone typical of the Mediterranean area (Figure 9). This phase represented a transition from speculation to physical experimentation, establishing a foundation for further development and deployment.

Figure 9. *The prototype of the Green Wall, exposed at Marmomac Meets Academies 2024*
Source: photos by the authors.

Possible Architectural Design Applications

The *Green Wall* offers a series of different architectural applications that span from the urban dimension to landscape applications. As a matter of fact, even if its initial formulation is suitable for self-bearing façades or boundary walls, the potential of the system extends far beyond these basic configurations.

The simplest application is the integration of portions made through the *Green Wall* system in private and public buildings, enriching cities with green areas that can improve the appearance and reduce heat islands.

Integrated cavities can host not only ornamental plants but also herbs and small-scale food crops, and the ashlars can be employed to create private and public hydroponic gardens. When equipped with passive or active hydroponic systems, these walls could contribute to urban food resilience and serve also educational or therapeutic functions in schools, healthcare facilities, or public housing. This way, the wall transforms into an infrastructure for urban agriculture, reconciling the built environment with the rhythms of plant growth and food production.

A more massive application of the *Green Wall* constructive system can lead to the realisation of urban micro-agglomerates composed of small, clustered units that can form the basis for sustainable settlements. These clusters could be deployed in peri-urban or rural areas to support agricultural communities, ecological resorts, or co-housing environments. In this case, the *Green Wall* can become a spatial device capable of organising and supporting social, productive, and ecological activities.

The ease of assembly, together with the capacity for bioclimatic adaptation, keeps the system highly suitable for incremental construction and self-built communities, also in emergency contexts.

At a landscape level, portions of the *Green Wall* could be used as a reinterpretation of ancient dry walls. Traditional dry walls, which are a distinctive trait of the Mediterranean landscape, are known to bring a series of environmental benefits, such as the creation of a local micro-climate, the creation of micro-habitats that enhance biodiversity, and the protection from wind and bad weather conditions[27].

In the Mediterranean context, the *Green Wall* system resonates deeply with regional architectural traditions while offering a path to future-oriented sustainability, and it can become a contemporary response to ancient environmental wisdom, and a tool for creating urban and architectural ecosystems that are resilient, expressive, and deeply rooted in the cultural identity of the Mediterranean basin.

---

27. Solomou A D, ProutsosN, Karetsos G, Tsagkari K (2020) Impact of Stone Terraces and Walls' Micro-environment on Biodiversity Conservation: A Case Study in the Mediterranean Island of Kythira-Greece. In *Proceedings of the 9th International Conference on Information and Communication Technologies in Agriculture, Food & Environment* (Tessaloniki, Greece, 24-27 September 2020). 549-547.

Figure 10. *Some examples of architectural applications of the* Green Wall
Source: a), b) and c): renderings by the authors; d): rendering by the authors edited on a photo by Fabio Boccuzzi, taken from Alamy Foto Stock.

An Evaluation of the Thermal Performance of the *Green Wall* System

During the description of this work, a great emphasis has been placed on the potentially good thermal performance of the *Green Wall* system. As a matter of fact, it is known that the high thermal inertia of massive materials like stone can help reduce the internal temperature of a building,[28] while the application of vegetation on roofs and façades helps improve both indoor and outdoor comfort due to shading combined with evapotranspiration.[29]

Therefore, some analyses have been run to evaluate the impact of the use of the *Green Wall* System, comparing it to more common construction systems: an external cavity wall with full-fill insulation and a simple stone wall, both 30 cm thick.

For this purpose, a small unit has been modelled in two versions: the first one as a simple square box with openings on the northern and southern sides, the second one with a simplified model of the *Green Wall* system placed on the outer faces (Figure 11a). This was obtained by considering the overhanging vases as a composition of stone faces 6 cm thick; to simulate vegetation, tridimensional shaders approximating the plants' volume were modelled (Figure 11b).

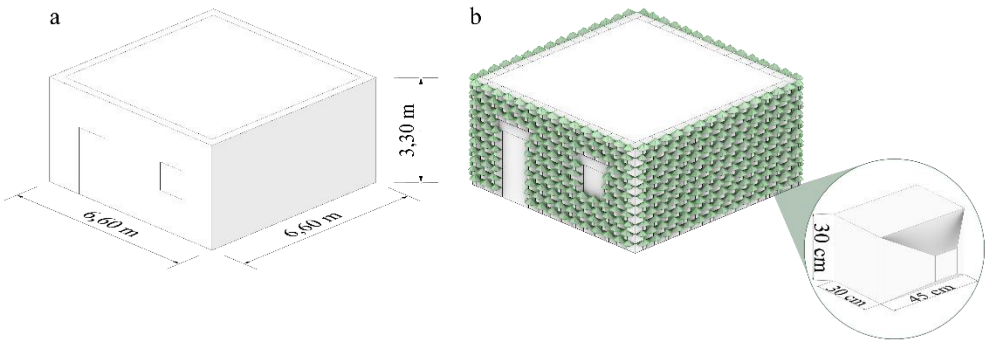

Figure 11. *3D model of the designed unit: a) unit with simple walls; b) unit with the Green Wall system applied*
Source: image by the authors.

All the analyses were performed using Honeybee, an add-on for the Rhinoceros plug-in Grasshopper.

The characteristics of the models were established by defining their materials and, consequently, their thermal parameters.

For the simple stone wall and the *Green Wall*, the thermal characteristics of an extra soft limestone were chosen, considering the UNI EN ISO 10456:2008 standards. Moreover, a solar absorptance value compatible with a light-coloured material has been chosen (Table 1).

28. Goussos J (2023) The Impact of Using Natural Stone on Thermal Performance of Building Envelopes in Hot Regions: Case of Al-Karama Town. *Civil Engineering and Architecture* 5A(11): 3125–3141.

29. Cascone S, Coma J, Gagliano A, Pérez G (2019) The evapotranspiration process in green roofs: A review. *Building and Environment* 147: 337–355.

Table 1. *The Thermal Characteristics of Extra Soft Limestone According to UNI EN ISO 10456:2008 Standards*

Material	Density [kg/m^3]	Conductivity [W/(m·K)]	Specific heat [J/(kg·K)	Solar absorptance
Extra soft limestone	1600	0.85	1000	0.4

The external cavity wall with full-fill insulation was characterised as described in Table 2. The thermal properties of each material were taken from technical sheets of products compliant to international standards, while the solar absorptance of the visible plastered surfaces has been chosen to be compatible with a very light colour.

Table 2. *The Characteristics of the Chosen External Cavity Wall with Full-Fill Insulation*

Material	Thickness [cm]	Density [kg/m^3]	Conductivity [W/(m·K)]	Specific heat [J/(kg·K)	Solar absorptance
External plaster[30]	1.5	1400	0.54	1000	0.3
External layer of semi-solid clay blocks[31]	12	889	0.25	840	-
Rockwool[32]	10	80	0.035	1030	-
Internal layer of hollow bricks[33]	8	600	0.23	840	-
Internal plaster	1.5	1400	0.54	1000	0.3

Analyses of the internal and external perceived temperature according to the Universal Thermal Climate Index (UTCI) were performed considering the city of Bari, in Southern Italy, as the construction site. The weather file referring to the 2020 meteorological data for this location was used to perform the analyses, which were run on 17 August, the first day of the hottest week of the year.

The analysis of the indoor comfort, which was run on the internal room with no ventilation or air conditioning, showed some promising results concerning the thermal performance of the *Green Wall*. Figure 12 displays through a colour gradient the mean temperature in the room taken from 6 A.M. to 8 P.M. (respectively dawn and sunset time in Bari on 17 August).[34] The external cavity wall with full-fill insulation resulted the worst system, with a mean temperature of about 36 °C. An envelope

30. Thermal parameters taken from: https://www.ferrimix.it/wp-content/uploads/2017/10/ST-FC19-INTONACO-TERMICO.pdf [Accessed 9 October 2025]

31. Thermal parameters taken from: https://www.stabila.it/wp-content/documentazione/Comune/Doppio%20Uni%2012%20VR/ST_R_DOPPIO_UNI_12.pdf [Accessed 9 October 2025].

32. Thermal parameters taken from: https://www.rockwool.com/siteassets/rw-it/documentazione-tecnica/schede-tecniche---gamma-edilizia/labelrock.pdf [Accessed 9 October 2025].

33. Thermal parameters taken from: https://www.stabila.it/wp-content/documentazione/Schede_Techiche_TRAMEZZE_ICMQ/ST_R_TRAMEZZA_8-25.pdf [Accessed 9 October 2025].

34. Data taken from: https://www.timeanddate.com/sun/italy/bari?month=8&year=2025 [Last accessed 9 October 2025].

made of a simple stone wall shows a better result, with a mean temperature of about 34.5 °C. As expected, the *Green Wall* is the most performing envelope, with a mean temperature of 32.5 °C. Figure 13 shows the variation of temperature during the entire day for the three envelopes.

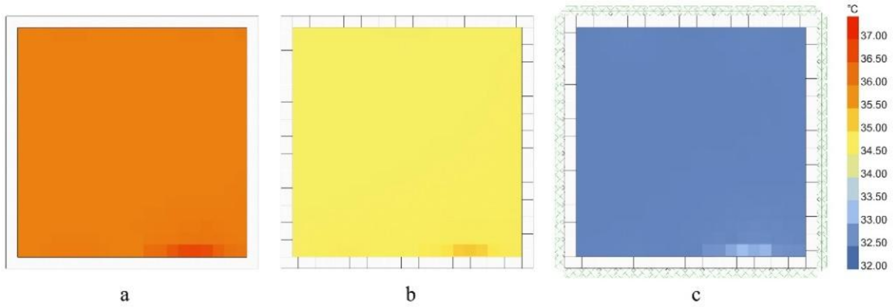

Figure 12. *Schemes showing the internal mean perceived temperature from 6 A.M. to 8 P.M. on 17 August in Bari: a) external cavity wall with full-fill insulation; b) simple stone wall; c)* Green Wall
Source: Schemes by the authors.

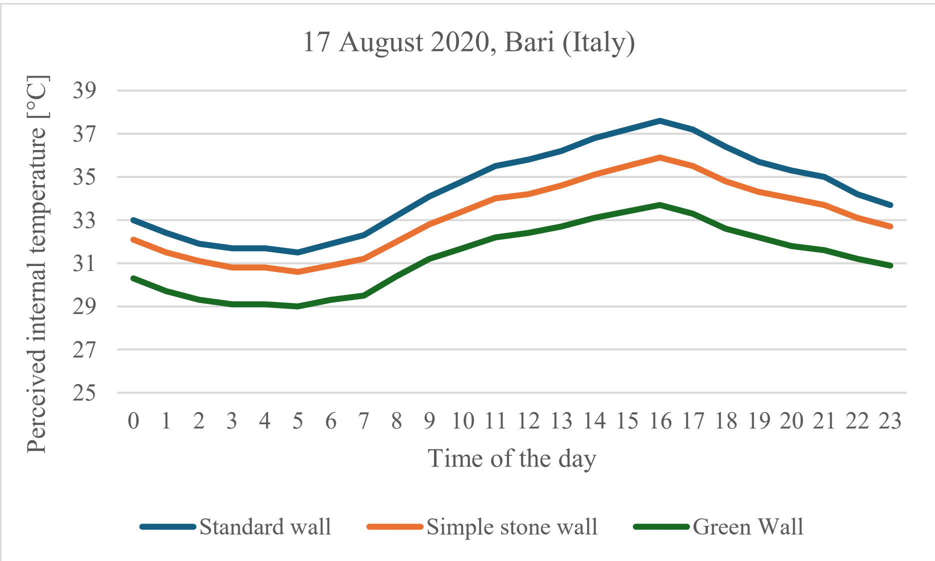

Figure 13. *Graph showing the variation of mean internal perceived temperature on 17 August in Bari: a) external cavity wall with full-fill insulation; b) simple stone wall; c)* Green Wall
Source: Graph by the authors.

It is essential to note that, although the lowest temperature reached using the *Green Wall* system (approximately 29 °C) is still too high to be considered comfortable, the analyses pertain to a room with no ventilation throughout the day. Air flow through the windows represents one of the primary passive cooling strategies and would improve the indoor comfort of the unit.

Moreover, Honeybee for Grasshopper does not allow the simulation of plants' evapotranspiration, whose effect can furtherly reduce internal temperature.[35]

The outputs of the analyses of outdoor comfort (Figure 14) revealed that the behaviours of the external cavity wall with full-fill insulation and the simple stone wall are similar, while the *Green Wall* shows a slightly better behaviour, by reducing the perceived temperature near the building of about 0.4 °C.

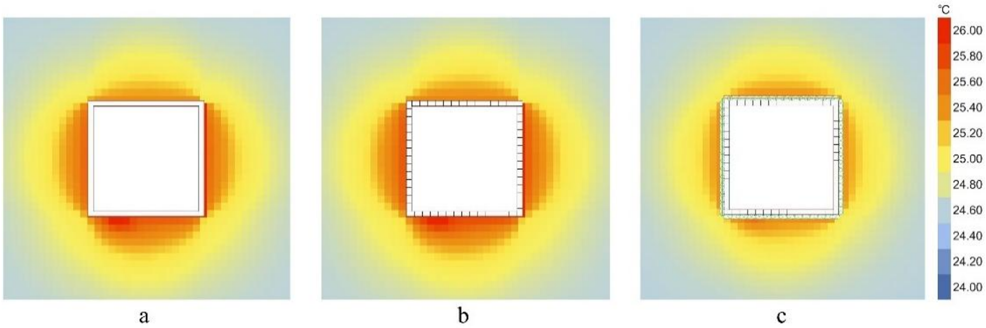

Figure 14. *Schemes showing the external mean perceived temperature from 6 A.M. to 8 P.M. on 17 August in Bari: a) external cavity wall with full-fill insulation; b) simple stone wall; c)* Green Wall
Source: Schemes by the authors.

Even if the benefit brought by the *Green Wall* system can seem irrelevant, once again we must underline that the evapotranspiration effect has not been considered: the slight cooling shown in the schemes is produced only by the shading of plants and by the self-shading of the pattern. Some studies show that evapotranspiration can impact on outdoor temperature,[36] therefore it is credible that the *Green Wall* would perform better than how the scheme shows.

Discussion and Conclusions

The *Green Wall* project is an example of how digital tools, traditional materials and ecological strategies can converge to produce a new Mediterranean architectural language. It takes inspiration from vernacular architecture built with stone and integrates it with contemporary parametric modelling and additive manufacturing, presenting a possibility for innovative buildings that are both structurally autonomous and environmentally integrated.

The *Green Wall* project addresses key challenges such as climate adaptation, urban resilience and biodiversity support, and it shows considerable potential from

35. Bagheri Moghaddam F, Fort Mir J M, Navarro Delgado I, Redondo Dominguez E (2021) Evaluation of Thermal Comfort Performance of a Vertical Garden on a Glazed Façade and Its Effect on Building and Urban Scale, Case Study: An Office Building in Barcelona. *Sustainability* 13(12): 6706.

36. Dehghan Lotfabad A, Hosseini S M, Dabove P, Heiranipour M, Sommese F (2025) Impacts of Vertical Greenery on Outdoor Thermal Comfort and Carbon Emission Reduction at the Urban Scale in Turin, Italy. *Buildings* 15(3): 450.

the point of view of thermal performance. As a matter of fact, digital simulations show it to be more efficient than more traditional systems, by reducing both internal and external perceived temperature on hot days.

At the same time, the project offers practical advantages, including ease of assembly, material reuse and adaptability to multiple contexts.

Nevertheless, several challenges remain to be addressed before the *Green Wall* system can evolve from a prototype to a widely applicable solution. Long-term durability could be a critical aspect, since the response of 3D-printed stone to weathering, vegetation growth and maintenance operations has not been investigated yet. Moreover, irrigation systems – both passive and active – require careful integration that must be deeply studied to avoid clogging, water leakage and expensive maintenance costs, especially when scaled up to large facades. Another important topic is the economic feasibility of binder jetting technology. While it offers great flexibility in form and material reuse, its current costs are still high compared to other contemporary technologies and methods. A preliminary assessment of cost scalability will be essential to determine whether this approach can really move from theory to practice in the near future.

Acknowledgments

The 3D printed prototype, designed by Ilaria Cavaliere and Dario Costantino, was realised and sponsored by the company D-Shape. Dario Costantino wrote the draft of the paragraphs: *Introduction, Literary Review* and *Discussion and Conclusions*. Ilaria Cavaliere wrote the draft of the paragraps: *Methodology: the steps of the design process of the Green Wall* and *An Evaluation of the Thermal Performance of the Green Wall System*. Both the author approved the final version of the article.

Bibliography

Acocella, A. *L'architettura di pietra. Antichi e nuovi magisteri costruttivi.* (Stone architecture. Ancient and modern constructive skills.) Milan: Skira-Lucense, 2004.

Bagheri Moghaddam, F., J. M. Fort Mir, I. Navarro Delgado, and E. Redondo Dominguez. Evaluation of Thermal Comfort Performance of a Vertical Garden on a Glazed Façade and Its Effect on Building and Urban Scale, Case Study: An Office Building in Barcelona. *Sustainability* 13, no. 12 (2021): 6706.

Cascone, S., J. Coma, A. Gagliano, and G. Pérez. The evapotranspiration process in green roofs: A review. *Building and Environment* 147 (2019): 337-355.

Chahin, S., A. Afify, H. Mohsen, and M. Youssef. Role of 3D Printed Green Walls in Healing Architecture. *BAU Journal – Health and Wellbeing* 5, no. 1 (2022).

Dehghan Lotfabad, A., S. M. Hosseini, P. Dabove, M. Heiranipour, and F. Sommese. Impacts of Vertical Greenery on Outdoor Thermal Comfort and Carbon Emission Reduction at the Urban Scale in Turin, Italy. *Buildings* 15, no. 3 (2025): 450.

Fallacara, G., and M. Massafra. Doppionodo. In G Fallacara (ed), 62-63. *Ceci n'est pas un fossile. Marmomac Meets Academies 2024*. Ferrara: Media MD, 2024.

Farinea, C., L. Awad, A. Dubor, and M. El Atab. Integrating biophotovoltaic and cyber-physical technologies into a 3D printed wall. Anthropologic: architecture and fabrication in the cognitive age. In *Proceedings of the 38th eCAADe Conference* Volume 2 (Berlin, Berlin, Germany, 16–18 September 2020). Berlin: eCAADe, 463–472.

Goussos, J. The Impact of Using Natural Stone on Thermal Performance of Building Envelopes in Hot Regions: Case of Al-Karama Town. *Civil Engineering and Architecture* 5A, no. 11 (2023): 3125-3141.

He, Y., Y. Zhang, C. Zhang, and H. Zhou. Energy-saving potential of 3D printed concrete building with integrated living wall. *Energy & Buildings* 222 (2020).

Hua, H. Porous interlocking assembly: performance-based dry masonry construction with digital stereotomy. *Architectural Intelligence* 3 (2024): 55-72.

Jain, R. Vertical Gardening: A New Concept of Modern Era. In N L Patel, S L Chawla, T R Ahlawa (eds), 527-536. *Commercial Horticulture*. New Delhi: New India Publishing Agency, 2016.

Kaczmarek, T., M. Van der Veen, S. Ivorra, D. Mattingly, J.-F.Terral, and M. Gros-Balthazard. Origins and evolution of oasis agriculture in the Sahara: Evidence from morphometric analyses of archaeological date palm seeds. *The Holocene* 3 (2024): 353-365.

Laureano, P. Ancient water catchment techniques for proper management of Mediterranean ecosystems. *Water Supply* 7, no. 1 (2007): 237-244.

Lehmann, S. Growing biodiverse urban futures: renaturalization and rewilding as strategies to strengthen urban resilience. *Sustainability* 13, no. 5 (2021): 2932.

Lombardo, L., and T. Luisi. Dry-stone architectural heritage in Madonie district.The rehabilitation of ancient rural complexes, as exemplary smart villages. *Sustainable Mediterranean Construction* 7 (2024): 15-22.

Mazzotti, M. Enlightened mills: mechanizing olive oil production in Mediterranean Europe. *Technology and Culture* 45, no. 2 (2008): 277-304.

Neglia, G. A. Il palmeto di AlDiriyah come esempio di vivibilità nei paesaggi delle aree desertiche. (The AlDiriyah Palm Grove as an Example of Livability in Desert Landscapes.) *RI-VISTA Research for landscape architecture* 22, no. 1 (2024): 218-231.

Rael, R., and V. Sanfratello. *Printing Architecture. Innovative Recipes for 3D Printing*. New York: Princeton Architectural Press, 2018.

PA Editorial Team. *Victoria Roznowski's Brick By Bit redefines clay bricks with 3D printing. Parametric Architecture (2024)*: https://parametric-architecture.com/brick-by-bit-redefines-clay-bricks-with-3d-printing/ [Accessed 11 October 2025].

Palomares Alarcón, S. Olive grove landscape: the hydraulic pressing machine and its importance in the cultural heritage of Andalusia. *Revista de História da Sociedade e da Cultura* 22, no. 1 (2022): 213-232.

Ruggiero, G., S. Dal Sasso, R. V. Loisi, and G. Verdiani. Characteristics and distribution of trulli constructions in the area of the site of community importance Murgia of Trulli. *Journal of Agricultural Engineering* XLIV (2013): 87-94.

Shahda, M. Self-Shading Walls to Improve Environmental Performance in Desert Buildings. *Architecture Research* 10, no. 1 (2020): 1-14.

Solomou, A. D., N. Proutsos, G. Karetsos, and K. Tsagkari. Impact of Stone Terraces and Walls' Micro-environment on Biodiversity Conservation: A Case Study in the Mediterranean Island of Kythira-Greece. In *Proceedings of the 9th International Conference on Information and Communication Technologies in Agriculture, Food & Environment* (Tessaloniki, Greece, 24-27 September 2020). 549-547.

Thanoon, W. A., M. S. Jaafar, M. R. Abdul Kadir, A. A. Abang Ali, D. N. Trikha, and A. M. S. Najm. Development of an innovative interlocking load bearing hollow block system in Malaysia. *Construction and Building Materials* 18, no. 6 (2004): 445-454.

UNESCO. *L'Arte della costruzione in pietra a secco: conoscenza e tecniche, elemento transnazionale (comprendente, oltre all'Italia, Croazia, Cipro, Francia, Grecia, Slovenia, Spagna, Svizzera, Andorra, Austria, Belgio, Irlanda e Lussemburgo)*. [The Art of Dry Stone Construction: Knowledge and Techniques, a Transnational Element (Including, in addition to Italy, Croatia, Cyprus, France, Greece, Slovenia, Spain, Switzerland, Andorra, Austria, Belgium, Ireland and Luxembourg).] Retrieved from: www.unesco.it/it/iniziative-dellunesco/patrimonio-culturale-immateriale/larte-della-costruzione-in-pietra-a-secco-conoscenza-e-tecniche-elemento-transnazionale-comprendente-oltre-allitalia-croazia-cipro-francia-grecia-slovenia-spagna-svizzera/. [Last accessed 5 June 2025.]

Volpe, S., V. Sangiorgio, A. Petrella, A. Coppola, M. Notarnicola, and F. Fiorito. Building Envelope Prefabricated with 3D Printing Technology. *Sustainability* 13, no. 16 (2021): 8923.

White, D. Technovauld. In G Fallacara (ed), 76-79. *Marmomac Meets Academies. Advanced research, lithic experimentation.* Ferrara: Media MD, 2023.