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Moss as a Multifunctional Material for Technological Greenery Systems

Valeria Marsaglia, Guido Brusa, Ingrid Paoletti

TECTONICS

ABSTRACT - *Nature-based solutions can help mitigate the heat island phenomenon in densely populated urban areas. As far as building envelopes are concerned, both green roofs and walls provide multiple benefits to the surrounding areas and to the buildings where they have been installed by using plants that act as building materials with specific attributes and performances. In detail, living wall systems are particularly sensitive to the vegetal choice due to their sophisticated technology and to the artificial vertical layer where plants are forced to live. The purpose of this paper is to investigate the characteristics of mosses in relation to their potential use in technological greenery systems. In this regard, the most recent and innovative application examples in buildings and design are presented and discussed.*

Keywords: bryophytes; green envelopes; moss; nature-based solutions; technological greenery

NbS	Nature-based Solutions
TG	Technological Greenery
GR	Green Roofs
VGS	Vertical Greening Systems
LWS	Living Wall Systems

The world's cities are growing both in size and number. In 2018, an estimated 55.3% of the world's population lived in urban areas. By 2030, this proportion will rise to 60% globally and one in every three people will live in cities with at least half a million inhabitants.[1] At the same time, urbanized areas are experiencing higher temperatures than outlying areas because of the “heat island effect” and critical levels of air pollution. In 2019, the World Health Organization estimated that 4.2 million people per year died from ambient air pollution in urban areas due to stroke, heart disease, lung cancer, and chronic respiratory diseases.[2] Nature-based solutions (NbS) can improve quality of life for people in urban areas, mitigating the heat island effect.[3] NbS “are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience. Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services.” [4] Unfortunately, in vast urban areas, it is difficult to find spaces for plants and greenery because of economic issue and construction density. For these reasons, much effort has recently been spent on technological greenery, which are systems applied to the envelope of buildings both horizontally and vertically.[5]

TECHNOLOGICAL GREENERY

Green Roofs

There are two main families of technological greenery systems (TG): green roofs (GR) and vertical greening systems (VGS). Referred to as roof gardens, horizontal systems have historically been the first form of integration of vegetation into the built environment. They are vegetated surfaces (green canopy) endowed with a substrate of organic material (soil). From a technological point of view, GR are divided into intensive and extensive, according to the depth of the substrate (which feeds the vegetation) and the use of the roof. Some authors add a semi-intensive category, with characteristics in between the two main ones.[6]

Intensive GR generally have a considerable substrate depth (more than 15–20 cm [5.91–7.87 in.]), a wide variety of plants (similar to ground-level landscapes), high water retention capacity (over 50%), high capital costs ($25/sq. ft. [0.09 m^2]), and heavy weight (180-500 kg/m^2 [37-102.5 lb./sq. ft.]).[7] Depending on the soil depth, the plant selection is wider and can include small trees, shrubs, and bushes.[8,9] However, the greater weight of the roof can require additional structural reinforcement, and the richness of the vegetation requires a higher level of maintenance, with drainage and irrigation systems that increase the technical complexity and associated costs.[10] Typically intensive GR are designed for human recreation purposes and, thanks to plant variety, can improve biodiversity.[11]

Extensive green roofs are characterized by a thinner depth of substrate layer (less than 15 cm [5.91 in.]), thus only limited types of plants, including grasses, mosses, herbs, and a few succulents can be used and irrigation is not required unless periodically. As a consequence, they are more economic, very lightweight, and the construction process is technically simple. Generally, they are not accessible. In comparison with intensive green roofs, they perform worse in terms of energy savings and storm water management. On the contrary, intensive ones can decrease runoff by 85% when compared to traditional roofs.[12]

In highly urbanized areas, apart from improving stormwater management, GR provide different ecosystem services: they increase regulation of building temperature, sound insulation,[13] heat island control,[14] and restoration of biodiversity.[15] In particular, energy saving is due to different mechanisms [16]:

- shading: vegetation provides an additional layer that shades the roof, blocking part of the incoming solar radiation;
- evapotranspiration: plant transpiration and soil evaporation cool the surface of the plants;
- decreased heat flux toward the interior of the building and the urban heat island, etc.;
- thermal inertia: the substrate increases the roof thermal mass, delaying and reducing incoming heat fluxes;
- thermal insulation: the substrate and drainage layers increase the heat resistance of the roof by providing an additional layer.

Despite its high initial cost, in the long term, green roofs are an economical option considering their energy savings, but they are often chosen by developers purely for aesthetic reasons. This is generally due to a lack of research on different aspects of vegetative roofs and the premature introduction of products into the market.[17]

Vertical Greening Systems

Vertical Greening Systems (VGS) refer to all forms of vegetated wall surfaces, though a standard classification is still missing.[18] They can be classified by their growing method into green façade and living wall systems, basically divided between systems rooted into the ground or based on hydroponic. Green façades are simple systems in which climbing plants or hanging shrubs grow using special support structures to cover a desired area. The plants can be placed directly on the ground, at the base of the building, or in pots at different levels of the façade.

Living Wall Systems (LWS) are made of pre-vegetated panels, vertical modules, or planted blankets that are fixed vertically to a structural wall or frame. The panels (or boxes) and geotextile felts provide support to the plants. These panels are generally made out of plastic, expanded polystyrene, synthetic fabric, clay, metal, or concrete. The ecological benefits are more pronounced compared to green façades. The multiple beneficial effects of VGS on dense urban areas have already been demonstrated in the literature.

At the building and urban scale, the main ability of VGS is to work as a passive tool for energy saving obtained by negative heat transfer, especially in Mediterranean areas, which balances the cost for installation on the building's envelope.[19] Since they diminish heat flux into the indoor space, they lower air conditioning necessities, thus cutting down electricity consumption in summer. In a Mediterranean climate, when compared to a conventional/reference wall, green façades can have an energy efficiency of 34% [20] and living walls from 59% [21] to 66% [22] during the cooling season. Vertical greening systems are even able to improve air quality through absorption of fine dust particles like PMx and the uptake of gaseous pollutants, such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2).[23] This performance depends on many factors: foliage density,[24] measurable trough leaf area index (LAI, leaf area per m^2 of wall surface), the ability of plants to live in certain environments, plant species, leaf macro, and micromorphology.[25]

Acoustic isolation of interior spaces [26] and water management can benefit from VGS. Finally, social benefits like urban heat island mitigation, urban hydrology, and biodiversity enhancement [27] must be listed, although they cannot be quantified in an economical way due to a lack of reliable data from literature or difficulty in estimating their effect directly attributed to a single VGS. From an economic point of view, the living wall system is the most expensive: panels and plant species cost from a minimum of €185 to a maximum of €500/m^2 [€0.09 sq. ft.]. Additionally, the cost of irrigation systems is much higher: about €30/m^2 [€2.8 sq. ft.].[28]

In terms of Life Cycle Assessment (LCA) of VGS, scientific papers show diverse results. The choice of materials plays a fundamental role, especially in indirect greening systems that are based on metallic mesh since stainless steel has a high contribution to the profile.[29] In general, materials selection should be based on using raw materials from local sources, materials with low carbon emissions and low embodied energy, or materials that can be recycled or reused.[30] The more durable the construction, the less the environmental impact [31]: thus, the service life is determinant on understanding the real environmental impact of the system.

The second voice of expenses is maintenance, which consists mainly of pruning and replanting greenery and maintenance of the fertilization and irrigation system. These operations are directly related to the system's features, climate, and plant species, which may have a strong impact, especially in eutrophication potential and freshwater aquatic ecotoxicity.[32] Therefore, it is essential to use species that need low maintenance and caring, live locally, and are able to survive in stressful environments such as urban settlements with high pollution, solar radiation, wind, etc. The weight of the panels should not be too high in order to avoid stability problems and system flexibility. The consumption of water and nutrients (fertilizers) is one of the main issues of these systems in relation to their environmental impact and should be minimized.

Finally, greenery systems have a strong sensitivity to local conditions. Dealing with living nature, they are dynamic, and their performance may vary considerably depending on biogeographic regions, climatic zones, and human factors. Providing general results for decision-making is possible only by collecting a large number of local empirical studies (laboratory-scale experiments, pilot projects, and large-scale projects on state-of-the-art buildings). Taking into consideration all these issues, mosses are among the plants that possess very suitable features in relation to living wall systems (reduced weight, low cost, low maintenance, high water absorption, minor sensitivity to pollutants). An interdisciplinary approach is needed to deal with these topics as, from the above-mentioned, specific knowledge of living materials (i.e. plants) is fundamental.

MOSSES

Biology of Mosses

Among the world of plants, bryophytes are the second largest group, exceeded only by the *Magnoliophyta*– the flowering plants (350,000 species). There are between 18,000 and 23,000 species of bryophytes worldwide [33] where they occur in every location that is habitable by photosynthetic plants. However, bryophytes cover three systematic phyla: hornworts (*Anthocerotophyta)*, liverworts (*Marchantiophyta*) and mosses (*Bryophyta*).[34] The last group includes the most part of bryophytes suitable for applications. For this reason, mosses are the sole bryophytes treated in this review. (Fig. 1.)

Mosses are small (rarely larger than a few centimeters) and unable to produce lignin (they cannot become woody). The most important ability of mosses is that when they are completely hydrated after dry periods, they quickly resume their metabolism after rewetting. This peculiarity, named poikilohydry, makes them particularly resilient and is in part the result of totipotency – the ability of any cell of an organism to dedifferentiate and then differentiate into a new plant.[35] All bryophytes are to some extent totipotent: they can regenerate from fragments, or even single cells, making them great survivors. Peat moss (genus *Sphagnum*) is one of the most important genus of plants, and certainly the most important peat producer in the world, locking away an enormous amount of carbon and holding vast quantities of water [36]: peat moss is essentially a huge sponge. Mosses growing on trees (i.e., epiphytes) have been known as great indicators of air pollution for a long time.[37] Mosses show a vast range of specific sensitivity and visible symptoms to pollutants greatly exceeding that of higher plants.[38]

What distinguishes mosses collectively from all other land plants (ferns, conifers, and flowering plants) is that their life cycle is dominated by gametophyte generation rather than sporophyte generation; that is, by

Figure 1. There are between 18,000 and 23,000 species of bryophytes worldwide and they cover three systematic phyla: (a) hornworts (*Anthocerotophyta*), (b) liverworts (*Marchantiophyta*), and (c) mosses (*Bryophyta*). Despite their small size, the role of mosses in the ecosystem may be significant. Peat-moss (d) alone may be the genus that sequesters the most carbon of any other on Earth.

the haploid or sexual phase (when gametes are produced), as opposed to the diploid, spore-producing phase.[39] In contrast, all other land plants are dominated by the sporophyte generation, with the gametophyte much reduced, often to just a few cells. In other words, the leafy green part that one sees in the main plant, which is mainly photosynthetic, is the gametophyte in bryophytes, whereas it is the sporophyte in all other land plants. The bryophyte sporophyte is usually reduced to a spore-producing, stalked capsule that remains attached to the gametophyte, and is dependent on it for sustenance. In addition, many mosses produce specialized asexual reproductive organs, such as gemmae, which circumvent the sporophyte generation entirely, simply replicating the gametophyte parent.

Distribution, Habitats, and Ecology

Mosses occur on all continents and in many different habitats except in the sea. They are almost ubiquitous, growing even in very dry semi-deserts, but require some moisture, at least at some stages of their life cycle.[40] Unlike other land plants (i.e., vascular plants), most species are poorly equipped to regulate their water content internally. This means that they are often luxuriant in moist forests and in high rainfall areas. Water absorption, along with the minimal amounts of nutrients they require, occurs over their entire surface from the surrounding environment, rather than taking it up through roots and a vascular system.

Central Europe, specifically, mountainous areas in the Alps and, to some degree, Scandinavia, Scotland, Wales, Pyrenees, and Eastern Europe, including the Carpathians, are the areas with the highest number of bryophyte species. Species richness gradually declines toward the south and the east of Europe.[41]
In Europe, 22.5% of existing bryophyte species are considered to be under threat. Natural system modifications (i.e., dam construction, increases in fire frequency/intensity, and water management/use), climate change (mainly increasing frequency of droughts and temperature extremes), agriculture (including pollution from agricultural effluents), and aquaculture are the main threats that have been identified.

Ecosystem Services

From an ecological point of view, mosses are important because with limited needs, they manage to settle in environments where most land plants are unable to survive (for example, mosses colonize stones and trunks).[42] The most interesting aspect is that mosses are also common in a city in the joints of floors, on roofs, and on walls; in short, mosses are easily adaptable organisms in urban habitats. Aside from the extreme case of peat moss, most moss species act to some extent as sponges, taking up water rapidly, holding it, and releasing it only slowly. They are efficient colonizers and stabilizers of bare substrates (e.g., soils) and they can serve as hosts for blue-green algae (cyanobacteria), which have an important role in nitrogen (N) fixation.[43] A spore less than 100 µm [1/250 in.] in diameter can provide sufficient energy for a new moss to get started. Water is clearly needed by mosses, but rather than maintaining hydration, they are able to become metabolically inactive, exercising an ectohydric strategy that holds water in capillary spaces while they dry slowly. Being small itself seems to be a strategy to conserve water.[44]

Additionally, they provide habitats for other organisms: seedbeds for vascular plants, shelter and food for small invertebrates, nesting material for birds and small mammals, etc. A type of mire (i.e., bogs) in particular, forms entire ecosystems fundamentally dependent on mosses (peat moss). Despite their small size, the role of mosses in the ecosystem may be significant: even though it is a largely overlooked field of study, recently ecologists are increasingly recognizing that mosses can no longer be ignored. For example, peat moss alone may be the genus that sequesters more carbon than any other on Earth, and the role of mosses in housing small organisms that ultimately increase the diversity of their predators could be vital.

Cultivation

Mosses are often considered weeds in grass lawns, but they are deliberately encouraged to grow under aesthetic principles exemplified by Japanese gardening.[45] In old temple gardens, moss can carpet a forest scene, and is thought to add a sense of calm, age, and stillness. Moss is also used in bonsai to cover the soil and enhance the impression of age. The rules of cultivation are not widely established, thus enthusiasts (e.g., Michael Fletcher) [46] and specialists (e.g., Sean Haughian and Jeremy Lundholm) [47] have developed their own methods. Moss collections are quite often begun using samples transplanted from the wild in a water-retaining bag. However, specific species of moss can be extremely difficult to maintain away from their natural sites with their unique requirements of combinations of light, humidity, substrate chemistry, shelter from wind, etc.

Growing moss from spores is even less controlled. Moss spores fall spontaneously in a constant rain on exposed surfaces; those surfaces which are hospitable to a certain species of moss will typically be colonized by that moss within a few years of exposure to wind and rain. Materials which are porous and moisture retentive, such as brick, wood, and certain coarse concrete mixtures, are hospitable to moss. Surfaces can also be prepared with particular substances (acids, buttermilk, yogurt, urine, etc.), thus creating a gently purified mixture of moss samples, water, and sometimes of an ericaceous compost; however, the use of the former substances is controversial.

Functional Characteristics of Mosses

Since ancient times, mosses have been used as insulation both for dwellings (Fig. 2) and in clothing. Because it is so dense and has a tight root system, moss acts as an excellent insulator. Traditionally, dried moss was used in some Nordic countries and Russia as an insulator between logs in log cabins, and tribes of the northeastern United States and southeastern Canada used moss to fill chinks in wooden longhouses. Circumpolar and alpine people have used mosses for insulation in boots and mittens. Ötzi the Iceman had moss-packed boots.

The capacity of dried mosses to absorb fluids has made their use practical in both medicinal and culinary uses. Peat moss, and many other mosses for that matter, are extremely spongy and hold large amounts of water. In the case of peat moss, it can be literally squeezed, drinking the water that comes from it. Since it is acidic, bacteria do not tend to grow in it. Finally, dried moss is extremely flammable, whereas when it is alive, it is waterproof.

Figure 2. The characteristic turf houses of Iceland as a pioneer application of moss on buildings.

MOSSES' EXPERIMENTAL APPLICATIONS IN ARCHITECTURE

Methodology

The aim of this research is to select scientific papers containing innovative uses and experimental solutions even in different fields for possible application in green building systems. The present research adopts a qualitative systematic review approach,[48] where scientific literature relevant to the use of mosses is reviewed and case studies across different disciplines are analyzed in order to evaluate possible future applications in building technology. Data were collected from online libraries and databases (Scopus and Web of Science) using theme-related keywords such as "Nature-based solutions," "living wall systems," "moss," "bryophytes," "green wall," and their mutual combinations. The literature review resulted in three main areas of experimentation that imply mosses being identified in contemporary research. They may be referred to as follows:

(1) moss and building materials [49]
(2) moss and biofiltration [50]
(3) moss and electric generation. [51]

Moss and Building Materials

This first line of research concerns the use of moss in the specific field of building technology, in particular the envelope. Two main themes are identified. The first has a specific name, "bioreceptive design," which consists of designing building components and materials that are able to host biological plant life such as mosses, lichens, etc. directly thanks to their chemical and physical properties. The second item concerns the use of moss grown on substrates used for the building envelope in technological greenery, such as green roofs or living wall systems.

Bioreceptive Design

In relation to buildings, mosses have always been seen as enemies to be eradicated in monument conservation and restoration projects. On this topic, there is an important established research area on biodeterioration, which tries to define the negative effects of biological growth on building materials and mechanisms to prevent biofouling. An innovative approach toward mosses and building materials was introduced in 1995, when Guillitte defined bioreceptivity as "the aptitude of a material (or any other inanimate object) to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration." [52] He claimed that bioreceptive concretes can be colonized by micro-organisms, macro-organisms, and plants.

In 2014 the Spanish biologist Sandra Manso Blanco tested and developed a new type of concrete that provides a biological substratum for the growth of photosynthetic systems to proliferate without affecting structural concrete.[53] Manso stated that undesirable biological colonization on cementitious materials such as monuments, historical buildings, or merely old constructions is a consequence of three interconnected factors, which are the presence of pioneer living organisms in the environment, the environmental conditions, and the properties of a material. Thus, she decided to work mainly on the material scale and she tested two types of cement: one was conventional carbonated concrete (based on Portland cement), which possesses a pH of around 8. The second material was manufactured with a magnesium phosphate cement (MPC), a hydraulic conglomerate slightly acidic and thus more appropriate to host biological growth. Besides the pH, other parameters that influence the bioreceptivity of the material were modified, such as porosity and surface roughness.

The investigation resulted in an international patent concerning an application for the construction of multi-layered panels (PCT/ES2013/070438). The invention relates to a cement-based multilayer assembly that can be used as a biological support for building façades or other structures. The structure of the panel comprises a first layer which consists of conventional concrete and is responsible for the structural function of the panel, dependent on project requirements. Subsequently, there is a second layer with the main function of protecting the first. This has a waterproofing capability and could also improve adhesion between the first and the third layers. Then, the third layer is that with an enlarged bioreceptivity which would be discontinuous in order to allow different designs of the surface. Areas without this layer would allow organisms to colonize the surface and the retained water would maintain local humidity. Water egress is then redirected to these holes promoting better local conditions for colonizing organisms.

The invention introduces a new green wall concept that can be used for new constructions as well as for the renovation of existing buildings. In contrast to existing vertical greening systems, no complex support structures are required and it is possible to choose the area of the façade on which the biological cladding is to be applied. This pivotal research has led to several experimental projects. In the BiotA Lab at the Bartlett School of Architecture, University College London, the impact of biocolonization on façades, from the small-scale design of the surface geometry to its application on building panels, is explored. They call it "Bioreceptive Design," which means to work across micro (material), meso (surface) and macro (tectonic) scales.[54]

The design of the texture of a tectonic surface, with its recesses and protrusions, allows to intensify water catchment on the façades and consequently helps plants stay attached to the substrate when dry or stirred by the wind. Thus, the cementitious panel is milled to produce fissures and depressions in geometries that are optimized to be bioreceptive for the growth of mosses, lichens, and algae. Then the panel is sown, creating a favorable environment for biocolonization when it is installed as architectural façade. Marcos Cruz in collaboration with Richard Beckett, within the EPSRC-funded grant "Computational Seeding of Bioreceptive Materials" concluded in April 2017, developed a cladding able to support this biological strategy. The team included Sandra Manso, Chris Leung, and Bill Watts, in partnership with Laing O'Rourke and Pennine Stone Limited with a series of three pilot projects.

The first prototype of poikilohydric wall was exhibited at the Centre Pompidou (Paris) in February 2019. Following this, thirty-two concrete panels were installed in September 2020 at the St Anne's Catholic Primary School in South London (Fig. 3) and a second realization was made of 20 concrete panels at East Putney Station in London. All the panels used in the *in situ* installations were made of glass fiber reinforced concrete (GRC) according to a recipe by Pennine Stone Ltd composed of cement, sand, lime dust, water, admixtures, yellow dye, and glass fibers, calibrated for increased porosity and a high level of water-absorption capability. State-of the-art CNC milling of moulds and industrial casting systems were employed. Different types of moss were considered for transplantation onto the St Anne's and East Putney projects. Finally, Bryum Capillare, Tortula Muralis, Grimmia Pulvinata were selected according to their resilience during the grafting process, speed of establishment, occurrence on vertical and concrete surfaces, dehydration tolerance, and aesthetic qualities.[55]

Figure 3. Poikilohydric Living Walls, installed at the St Anne's Catholic Primary School in London. Moss transplanted onto 8 bioreceptive porous TecCast panels.

This research revealed that MPC panels, even though very porous, had good structural integrity during structural tests but they did not perform well when exposed to the action of freeze-thaw, thus inappropriate for long-term outdoor exposure in continental climate. Moreover, after one year, there was no sign of biological growth of mosses on MPC panels, and all tests confirmed that both residual chemical surface properties and porosity created an unexpected inhibitor for growth in a single annual cycle on the MPC panels. Further test demonstrated that more time (2 years) was necessary for these panels to become bioreceptive, possibly to allow uncured chemicals in the material to be washed out.
On the contrary, the behavior of the OPC (Ordinary Portland Cement) panels in urban environments demonstrated that certain moss types are capable of growing on them because, despite initial high alkalinity, OPC has a gradual decrease of pH when carbonized over time, which makes it gradually more bioreceptive. Thus the goal turned out to be the offset of the carbon footprint of OPC, which is the cheapest and most available material in the construction industry.
The tests revealed that algae and moss growth occurred in specific areas of OPC panels that had no porosity and, therefore, offered water catchment areas in horizontal crevices. As a consequence, surface morphology plays a vital role in creating bioreceptivity on concrete panels.[56]

A third installation in December 2020 was a smaller wall made of 10 GRC limestone corkcrete panels made of a mix of OPC and cork aggregates, and integrated in a building extension at Merchiston Park in Edinburgh. The underpinning research was underway with the University of Coimbra

(Prof Fernando Branco) and the Technical Institute of Tomar (Dr Lurdes Belgas) as well industrial partners Amorim (ACC) in Portugal, where additional mixes of natural and expanded cork were investigated as an alternative aggregate. The aim was to promote the growth of lichens along with mosses and test the long-term carbon offset by the photosynthetic activity of the plants. When compared with the slow growth on MPC panels, Corkcrete samples proved to be more bioresponsive, even hosting moss and lichen after a single winter cycle.[57]

Following the same principles, other researchers worked to develop bio-integrated systems using surface geometry in an ordered and systematic manner as a design variable to facilitate moss growth on concrete panels.[58] The research followed a top-down approach where, first, designs were developed based on a literature review and field surveys, then the fabricated panels were validated through practical experimentations and finally, a general design guideline was provided. The resulting guideline indicates the macrogeometries that performed best and allows countless options of surface morphology that can be used to create a self-sustaining bioreceptive concrete façade panel. In 2022, Marc Ottelé, who is among the authors in this paper, launched a TU Delft spin-off called “Respyre” and has developed an innovative – patent pending – bioreceptive concrete solution. After hardening, the bioreceptive concrete’s surface accommodates the growth of moss thanks to its porosity and water retainment, micropore texture, acidity, and nutrients that are included in the mixture.

Moss in Technological Greenery

In Mediterranean areas, mosses are among the plants with high potential for green roof use, because they are adapted to survive in climate conditions with low and variable water availability and high radiation. Climate change will lead to more extreme weather events, such as increased drought and decreased precipitation with intense flash rain events. Increased desertification is expected, especially in the Mediterranean Basin, where in summer, radiation and temperatures are high and water is scarce. Therefore, while vascular plants boost water consumption in green roofs during warmer periods, mosses present themselves as potential candidates due to their poikilohydric nature, responding to the environmental availability of water, completely drying out, and recovering upon rehydration.

The compensation for the ability of moss species to survive such extreme conditions is a slow growth rate, which probably accounts for the few studies regarding their use in green infrastructures in the Mediterranean Basin. Among these, Anderson [59] shows how mosses used on green roofs can significantly enhance stormwater management performance and thermal environment. Even if the most used plants on green roofs in hot and dry climates are succulents, especially Sedum species,[60] Brandão shows that the combination of plant species and moss improves green roofs' hydrological performance.[61] M. Amir A.K.[62] established the thermal performance of Sunagoke (*Racomitrium canescens*) moss green roofs in addressing the UHI effect. Despite the absence of soil, both Sunagoke moss green roofs showed a decent insulation effect and provided thermal relaxation comparable to grass. Cruz de Carvalho [63] has identified a selection list of the ten most widely distributed species of mosses in the thirty-four countries of the Mediterranean Basin that are all acrocarpous and with a tuft life form and a colonist strategy: *Bryum argenteum*, *Tortella nitida*, and T*richostomum crispulum*; *Tortula muralis*; *Didymodon fallax*; *Grimmia lisae* and *Syntrichia laevipila*; *Ceratodon purpureus*, *Pleurochaete squarrosa*, and *Tortula inermis*. These studies demonstrate the potential for mosses to be valuable components of green roofs, either in combination with vascular plants or planted exclusively within moss species selection.

Moss can also be used for façade coatings because of its lightness and poor maintenance and many commercial solutions can be found already on the market but the claimed characteristics are not proven and lack a scientific background. In general, these solutions differ in the supporting system which can be a rigid panel or a mat, and in the use of the most suitable essence for the geographic location of the final user. Several systems are not marketed anymore, probably due to limited market success. Moss is a very traditional and valuable plant in oriental countries: in Japan, a garden is not complete if moss is missing. For this reason, moss modules there have already been used since the beginning of this century and various patents are related to moss cladding.[64] For example, in Japan, in 2003, Yamagata Co., a company highly specialized in moss greening, marketed a system that uses "moss mats." With the use of rice cultivation techniques, moss is cultivated on a mat made of tightly entangled rice roots and the modules can be used both vertically and horizontally.

Since 2006, Green Alliance, a non-profit organization, has been promoting moss greening by utilizing an exterior insulation greenery panel called "Woolly Moss." It is a panel using Sunagoke moss (*Rhacomitrium canescens*) and Haigoke moss *(Hypnum plumaeforme*), as well as insulation materials made of carbonized corks and mudstones. In Korea, the environmental remediation company Ilsong has developed the Moss Catch system which consists of substrate sheets and rolls, in which two moss species are disposed in the early stage of development. This system is designed to generate the first stage of an ecosystem that facilitates the implementation of other species. Panels will be used as horizontal and vertical covering of walls, façades, roofs, etc., and rolls mainly to create gardens or green roofs. The species used is not specified.[65]

In Western countries, a recent (2021) invention is the "moss machine" developed by Günter Haese, chief executive of Wohnungsgenossenschaft Gartenheim, a Hannover-based housing association. This vertical greening

Figure 4. MosSkin panel.

system is innovative because it allows uniform frontal irrigation of large surfaces and thus provides mosses with optimal living conditions even on an artificial vertical plane. In Italy, Katia Perini [66] patented a modular multilayer panel, with a built-in irrigation system, called MosSkin (Fig. 4). It is a low-cost, low-maintenance, versatile, and lightweight system, with interesting performance in terms of water management and surface temperature reduction (up to 14 °C [57.2 °F]). Several moss species, that is, *Homalothecium sericeum*, *Barbula unguiculata*, *Pseudoleskea incurvata*, *Grimmia pulvinate*, and *Hypnum cupressiforme*, were selected, based on their ability to tolerate the abiotic stresses of urban environments, as the most suitable for the development of the greening system. Four different configurations of the panel were designed, with dimensions of 80 × 80 cm [31.50 × 31.50 in.], and all consisting in:

- an elastic belt, supporting and anchoring to the building surface;
- a layer of the selected material, comprising a thin waterproof membrane with the function of isolating the wet panel from the building surface;
- a micro-perforated channel, inserted in a slot obtained by stitching between Layers 2 and 4;
- one or two layers of the selected material depending on the configuration.

Figure 5. Expansion of the Fine Art Museum, Aarau, Switzerland (1998-2003), by Herzog & de Meuron, with moss cultivated directly on the tuff-like limestones of the roof.

The advantages of these solutions are the reduced cost of the panels compared to the systems on the market and the no need for pruning, which could allow a wide integration in densely urbanized areas.

The most famous application of mosses in façade is the City Hall in Reykjavík (1987-92). A scientific paper is deserving of this since it has worked well for thirty years.

> "The wall was constructed from reinforced precast concrete elements with a lava finish. The lava was laid in a flat bed and concrete (with a retarder) poured over. The careful selection of the lava is important to ensure porosity, frost resistance, and appearance (somewhere between natural and artificial). Before the concrete hardened completely the elements were raised and the cement slurry washed from the lava. Carbon dioxide was blown over the surface to balance the ph of the elements. The moss was harvested locally to ensure that it would flourish in the climate of application. Our tests took two years." (Studio Granda.[67]) (Fig. 6.)

Another example of application is visible in the Prada building in Tokyo by Herzog & de Meuron (2000-2003). The external access and plaza are covered by moss wall on oblique surfaces like a vegetal carpet that covers the anteroom of the building (Fig. 7). In this case, the moss was treated like a textile and sewn directly onto the stone surface. This realization is an ideal continuation of an earlier (1998-2003) moss application by Herzog & de Meuron in the extension project of Aarau Fine Art Museum (Switzerland) where, on the contrary, the architects used a different technique for cultivating mosses (see Fig. 5). Spores were injected directly into tuff-like limestones, following the French biologist Michel Chiaffredo who developed this technique as an ecological means of cleaning and rehabilitating beaches that had been polluted by oil spills.

Figure 6. Reykjavík City Hall, by Studio Granda (1992). The moss wall surrounded by the pond: green and soft in summer, it freezes in the winter and glows behind a protective shield of ice.

Figure 7. 178 Prada Aoyama, in Tokyo, by Herzog & de Meuron (2003). The moss cladding covers the external entrance and the plaza around the lantern like building. Moss was treated like a textile and sewn directly on the stone surface.

Today companies that sell lightweight and easy to install exterior live moss wall panels are active also in the USA. For example, in Pennsylvania, Moss Acres (https://mossacres.com/) and Moss Walls (https://mosswalls.com/), which refer to the same owners. They produce and sell a low-maintenance living exterior rain screen system that features moss grown on a capillary water retention mat. It is backed with a masonry backer panel, available in around 1.2 m [3.94 ft.] wide rolls, and has an installed cost of around a quarter of the price of traditional living plant walls. A third company in North Carolina is called Mountain Moss (https://www.mountainmoss.com/). Held by bryophytic botanic Annie Martin, they sell moss wall mats based on flexible material in sizes of approximately 1×1 m [3.28×3.28 ft.] or 1×2 m [3.28×6.56 ft.]. This last company seems to be very active in publications, seminars, and specialistic courses.

Moss and Biofiltration

Two Swedish scientists discovered that mosses are a good bioindicator of heavy metals pollution in the atmosphere.[68] Since this finding, mosses have been commonly used as bioaccumulators in environmental research, that is, as organisms resistant to contamination and capable of concentrating pollutants internally.[69] This allows to establish a relationship between the concentration of pollutants in mosses and the level of environmental alteration integrated into a given area.[70] The use of mosses is possible to assess the concentrations of the following contaminants: heavy metals and metalloids, macro-elements, radioisotopes, dioxins, and furans, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs).[71]

There are several design projects that exploit the ability of moss to absorb pollutants. One of the first design firms to address this issue in 2016 was the Dutch duo Klarenbeek & Dros, who are specialized in biomaterials experimentation. They developed a sort of "absorbent" architecture which is made up of panels and frames with a porous structure through which light and air can pass. The whole acts as a filter and is the visual basis for the growth of moss. The innovative and green structure can form multifunctional places such as a span for a traffic artery or a bus stop along the roads, or as shelter from fine dust. Unfortunately, the models tested to date appear to have little effect, but they have contributed to experimenting with alternative approaches and methods (Fig. 8).

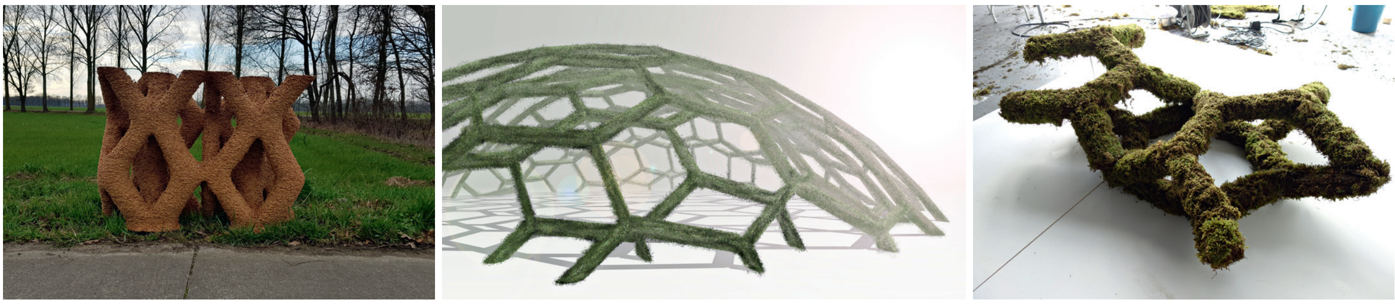

Figure 8. Living printed moss structures: from left, first pilot setup along N65 in Holland, the concept and the prototype.

CityTree

In the same years, a more holistic approach has been followed by Green City Solutions GmbH, a German start-up founded by P. Sänger and Zhengliang Wu, in collaboration with Splittgerber V., Alfred Wiedensohler (Head of the Department of Experimental Aerosol and Cloud Microphysics, Leibniz Institute for Tropospheric Research, Leipzig), the Institute of Air Handling and Refrigeration Dresden (University of Dresden), the University of Leipzig and the University of Applied Science in Dresden. The team developed a self-supporting biofilter called CityTree that has been adopted in more than twenty cities in Europe in central areas as street furniture and has been supported by the EUHorizon2020 funding for its research and development. CityTree is a 3 m × 0.6 m x 4 m [9.84 × 1.97 × 13.12 ft.] (length x width x height) urban infrastructure, with the two largest vertical sides covered with combi-hydroponic cultures of mosses, predominantly of *Amblystegium varium* and *Leucobryum glaucum* types. The second species was located toward the outer surface of the panel because of its hardiness and ability to withstand sunlight, whereas the first was toward the inner side as it thrives on reduced direct sunlight.[72] The planting concept consists of variously structured plants with smooth and raw surfaces, needles and hair, tall and small leaves. Moss is used as an optimal substrate in which vascular plants flourish. The chosen structures of the vascular plants are able to reduce wind speed and PM 10 particles.

Irrigation is provided by a fully automated self-regulated system, according to temperature and relative humidity measurements, to ensure the highest efficiency for moss cultures. CityTree collects atmospheric pollutants through two distinct mechanisms: via spontaneous deposition of particles and gases onto the moss surfaces (passive mode) and via impaction and interception of aerosols when the air is forced to flow across the panel using a ventilation system (filtration mode or active mode). Panels are specifically designed to force airflow (in active ventilation mode) through the layers of moss, ruling out airflow leaks through the metal joints of the structure. Being permeable to air and with their mesh-like texture, mosses can capture atmospheric particulate matter by impaction and deposition when flowed with ambient air. Air flow is forced into CityTree by an internal venting system. Consequently, the particles of the fraction PM 5.5 and PM 0.1 are attracted, bounded, and converted into phytomass by the moss. Thus, all fractions of fine dust are fixed and unable to get back into the air. The systems' living components lead to an excellent fixing of nitrogen oxide compounds because of their better quality and vitality.

The energy for Internet of Things (IoT) technology and automatic irrigation systems is supplied by photovoltaic panels and only a few hours per year are required for maintenance. Since ground anchoring is not required, CityTree can be placed anywhere, especially in city centers where there are no possibilities for planting new trees and consequently there is a high concentration of air pollutants (Fig. 9). CityTree is aligned and planted depending on the prevailing wind direction, the exposure to pollutant emitters, and the sun. Therefore, an algorithmic analysis is carried out to achieve excellent effectiveness.

By courtesy of intelligent selection and positioning of the used plant matter, the so-created planting concept leads to a nitrogen oxide reduction up to 10/15% and a fine dust reduction up to 20/25%. Thanks to IoT technology, CityTree performance in terms of pollution reduction is fully traceable. Anyway, the results are strongly affected by the actual urban context, where a detailed survey is necessary to map the PM and NOx concentration at street scale.[73] Finally, in terms of circular economy, due to the growth of the plants and the possible pyrolysis of the clippings within five years the CityTree binds more carbon dioxide than it requires for production. Pyrolysis converts the cutting waste and thus prevents the carbon dioxide from re-entering the atmosphere.

Figure 9. CityTree is a movable biofilter for urban areas. It has been experimented in many European cities like Bruxelles (seen in photo), London, Berlin, Modena. Plants are specifically chosen to work in a symbiosis between moss and vascular ones. *Leucobryum glaucum* type was located toward the outer surface of the panel because of its hardiness and ability to withstand sunlight, whereas *Amblystegium varium* was toward the inner side as it thrives with reduced direct sunlight.

Moss and Energy Generation

Among other plants, mosses have been used in biochemistry for the construction of plant microbial fuel cells (PMFC), a recently developed technology that exploits photosynthesis in vascular plants by harnessing solar energy and generating electrical power. In this process, carbon dioxide is fixed by plant leaves using solar energy. Part of the fixed carbon is transported to the roots and released as small molecular weight components. These so-called exudates are partly utilized by electrochemically active micro-organisms yielding carbon dioxide, protons, and electrons. Carbon dioxide is returned to the atmosphere. Electrons are transferred by electrochemically active micro-organisms to the anode to gain metabolic energy. The anode is coupled to a cathode and, owing to a potential difference between the two poles, the electrons flow from the anode through an electrical circuit with a load to the cathode. To retain electro-neutrality a proton is transported through the membrane from the anode to the cathode. In the cathode, oxygen is reduced with protons and electrons to water. [74]

In their experiment, Paolo Bombelli [75] used *Physcomitrella patens*, and other environmental samples of mosses, to develop a non-vascular bryophyte microbial fuel cell (bryoMFC) and demonstrated that ten pots of moss samples are able to power a commercial radio receiver or an environmental sensor (LCD desktop weather station) (Fig. 10). A novel three-dimensional anodic matrix was successfully created and characterized and was further tested to determine the capacity of mosses to generate electrical power. The peak power output reached 6.7±0.6mWm−2. Notwithstanding the low amount of energy harvested, compared with silicon-based photovoltaic cells, a solar cell that uses biological material to capture light energy would be cheaper to produce, self-repairing, self-replicating, biodegradable, and much more sustainable.

Figure 10. Experimental test set up for turning on a radio through a moss MFC by Paolo Bombelli et al.

SYNOPTIC TABLE AND FUTURE WORKS

The following synoptic table synthesizes the projects presented here, which are supported by scientific papers, and clarifies the interdisciplinarity of contemporary experimental applications of mosses with the potential advantages of each implementation.

Despite these few promising applications, use of mosses in technological greenery is only at the beginning.
Further research is urgently needed and should be addressed on the following three main topics:

(1) market research should be applied for designing new modules of systems that integrate mosses and provide a more appealing aesthetics; indeed mosses are proven to be plants well suitable for LWS due to their lightness, low cost, and low maintenance, and for green roofs too;
(2) appearance modification and durability of plants during the seasons years should be tested in accordance with user expectations;
(3) research species which are more suitable for specific functions, in combination with local geographic and climatic conditions, in order to protect biodiversity.

Among a high diversity of species, only a few mosses have been used in technological greenery. This is a clear limitation, especially if the use is intended outside under different climatic conditions. Indeed, research should be addressed to explore more suitable species to a specific regional climate (or even better, to the near future change of regional climate), but an assessment of species ranges is strictly recommended to avoid the risk of introducing a possible invasive alien plant (i.e., a moss outside its natural range and harmful to the local biodiversity). The selection of moss species is therefore a crucial way for developing technological greenery that is efficient and attractive to the market, but scientific research is currently on potential candidates [76] and few studies are directly based on comparative experiments among moss species.[77] Species selection is linked to develop and test cultivation methods on a broad-scale for moss.[78]

However, harvesting from the wild appears to be the most widely used method of commercially offering mosses, but this repeated practice may adversely affect rare species and deplete ecosystems in the long term. For the latter reasons, limitations for the harvesting of moss in nature was introduced by international (e.g., Habitats Directive, 92/43/EEC: species in Annex V, i.e. *Leucobryum glaucum* and *Sphagnum* spp.) or national laws (e.g., Lombardy Region in Italy: “the harvesting of lichens, mosses and *sphagnum* for commercial purposes is prohibited”).

Name of the project	Reference	Sectors/ Skills	Main function	Physical composition	Graphical scheme of the project	Main advantages due to moss usage	Used moss species
Bioreceptive concrete	Manso 2014; Cruz and Beckett 2016; Mustafa et al. 2021	Design Chemistry Biology	Building envelope	Vegetated surface on a GRC cladding panel		Integration of greenery without substructures (moss doesn't need earth as a substrate)	Bryum capillare, Tortula muralis, Grimmia pulvinate
MosSkin	Perini et al. 2022	Design Biology	Building envelope	Living Wall System (Greenery grown on a felt for cladding)		Lightness, low maintenance and low cost (moss very suitable for LWS)	Homalothecium sericeum, Barbula unguiculata, Pseudoleskea incurvata, Grimmia pulvinata and Hypnum cupressiforme
CityTree	Spittbeger and Saenger 2015	Design Biology Informatics	Urban furniture	Living Wall System combined with fans and electronic devices (sensors, photovoltaic panels)		Active airfiltering (moss is an airpurifier)	Amblystegium varium, Leucobryum glaucum
BryoMFC	Bombelli et al. 2016	Design Biochemistry	Indoor/Outdoor Furniture	Greenery in pots		Electric power production	Physcomitrella patens

Table 1. Synoptic table of moss experimental applications supported by a scientific paper.

CONCLUSIONS

The study highlighted that moss is a material that can be used in various integrated green systems and has the characteristic of being multifunctional as a plant (dynamic system) and as a functional layer of building systems, such as green roofs and façades. In particular, mosses possess very interesting features related to living wall systems (lightness, low cost, low maintenance, high water absorption) and, in combination with other systems, they can offer additional performances like electricity production or air pollution biofiltration. Recent experiments carried out in other research fields such as biochemistry or environmental engineering open up new horizons of use that could also be replicated in the construction sector. For example, the CityTree biofilter, based on the ability of mosses to filter pollutants in our cities, represents a first step toward the integration of NbS and IoT. Aiming at an ever-increasing integration of greenery in cities, this material is a candidate to become a protagonist even if there is still some difficulty in transplanting and cultivation due to a lack of scientific knowledge. This review has in fact revealed that although there are various products on the market, only a few are supported by scientific biological studies that substantiate the claimed properties and motivate the choice of moss species. A more interdisciplinary approach for the building sector with biologists and agronomists would surely bring advantages in the implementation of multifunctional and biobased materials like mosses.

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Credits

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Team: Prof. Marcos Cruz (PI, concept and lead design) with Dr. Brenda Parker (biochemical Engineering), Javier Ruiz (computation), Richard Beckett (concept)
Manufacturing: Pennine Stone Limited (as part of Haddonstone)
Moss transplant: Alexandra Lacatusu
Collaboration: Rushi Mehta and Giovanna Lanius-Pascuzzi
Mould manufacturing: UCL B-Made / Alex McCann, William Victor Camilleri, Richard Beckett
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Valeria Marsaglia is an experienced architect and currently a Ph.D. candidate in Architecture, Built Environment, and Construction Engineering at the Politecnico di Milano. Since graduating in architecture *cum laude*, she has been working in private companies while collaborating in parallel as a freelance with Italian architectural magazines (*Progettare*, *Recupero e Conservazione*) and technical publishers (UTET Scienze Tecniche, Zanichelli, Tecniche Nuove, and Silvana Editoriale). Her interests are focused on building integrated greenery systems and the technological implementation of nature-based solutions in urban environments. E-mail: valeria.marsaglia@polimi.it

Guido Brusa is a freelance biologist and an independent researcher. He mainly deals with applied botany and the conservation of plants and habitats. He has worked for institutions (protected areas, regional administrations, universities, etc.) and private companies (for environmental impact assessments, monitoring plans, etc.). He is the author of many publications, including scientific articles in both national and international journals. Since the beginning of his university career, he has been dealing with bryophytes of which he is a specialist. E-mail: guidobrusa72@gmail.com

Ingrid Paoletti is a Full Professor in Architectural Technology at the Politecnico di Milano. She holds a Ph.D. in Construction Technology from the Politecnico di Milano and has been a Research Associate at the Massachusetts Institute of Technology. She is the founder of the research group in theoretical and design experimentation Material Balance, where she deals with innovative building technologies and materials to develop new and responsible material culture. She has authored more than a hundred publications in international and national journals. E-mail: ingrid.paoletti@polimi.it