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BRYOPHYTES FOR THE LINEAR BARRIER AS A PM2.5 MITIGATION TECHNOLOGY IN THE URBAN LANDSCAPE

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Abstract. Air pollution has been recognized by the World Health Organization as a global problem, resulting in 9-12 million deaths annually, and particulate matter is the most severe threat to human health. Particulate matter can be distinguished by its size, as PM2.5 has a diameter of 2.5 µm or less, meaning that these tiny dust particles are invisible to the naked eye. Various solutions are being sought for the problem of air pollution, which resonate with landscape architecture solutions, such as Green Infrastructure and linear (vertical) barriers. They are being researched as an effective nature-based solution to the growing air pollution problem that organically blends into the urban landscape. Evaluations of various plants for their pollution abatement potential highlight bryophytes as particularly effective due to their high absorption capacity, and to ensure the sustainability of the linear barrier, cultivation under controlled conditions is recommended. This paper investigates the cultivation of bryophytes under controlled conditions and identifies the most effective moss species during a practical experiment. This experiment and paper are part of a larger, more extensive study on air pollution reduction using bryophytes, and the research described in this paper is instrumental in future research. The assessed bryophyte species will be further investigated for their ability to absorb air pollution PM2.5. This paper uses research methods such as literature analysis and a laboratory experiment conducted between January and April 2024.
Keywords: green infrastructure, urban landscape, air pollution, pollution mitigation, linear barriers

Introduction

Air pollution as a threat to human health [9] has been recognized since the time of Hippocrates around 400 BCE [11] and is currently a global issue [4,31], resulting in 9-12 million deaths per year [20,7]. Particulate matter (PM) is the primary source of air pollution [25,16] with PM 2.5, fine dust particles typically 2.5 µm in diameter or smaller, being especially hazardous as they are not visible to the naked eye [29] but are being absorbed deep into the human body, including the lungs and blood. PM has been recognized by the World Health Organization (WHO) as the most severe air pollutant for human health [14].

Air pollution has been studied for decades, and solutions are sought. One solution being used in landscape architecture worldwide is based on nature—using different plants for air purification with phytoremediation [24], green infrastructure (GI), and urban greening methods [17].

GI uses vegetation like grass, trees, shrubs, and other species for urban planning; GI is usually accessible for public use and mitigates the effects of vehicle-related environmental impacts like air pollution and urban heat islands [17]. As GI promotes public health and economic growth while emphasising the importance of environmental quality, social-environmental importance increases [28]. Natural conditions and elements of the environment are usually considered when forming the city's structure. Large greenery areas, street greenery, and other green structures must be connected to form the green network territory. Therefore, key GI elements are nodes or larger structures such as parks, squares, urban forests, and connecting linkages such as street greenery; these elements form a single green network. For these elements, the main targets are to ensure the sustainability and resilience of the overall ecosystem, as well as to ensure ecological and functional quality [17] and various ecosystem services like flood management, heat stress, water scarcity, carbon storage, energy use, groundwater recharge, erosion, wellbeing, ecological connectivity, environmental education, aesthetics, food production or green job opportunities [18]; additionally, GI can mitigate air pollution caused by traffic by absorbing gaseous pollutants and PM [28]. The walls of the buildings represent a large amount of the overall building surface, which is larger than the roof area. For high-rise buildings, this amount can be up to 20 times more than the surface of the roofs. Therefore, green walls can offer great potential. The effects of the green walls on air pollution depend on the climate, location, lightning, chosen vegetation species, and other factors [28]. To determine the most effective GI for air pollution mitigation, it is essential to understand how vegetation affects the movement of air pollutants on a global (entire city) and local scale. At the regional scale, a higher potential for air pollution mitigation indicates vegetation barriers to physically separate pollution sources from the receptors [2]. The introduction of linear barriers - such as hedges or fences - between source and receptor zones redirects the flow of air pollutants upwards, effectively extending the length of the air pathway from source to receptor and may also promote concentration reduction by increasing turbulence (Figure 1).

Thus, hedges and fences can decrease concentrations in sidewalks and other pedestrian areas adjacent to traffic by both pollutant flow movement upwards [27], and dry deposition, which is the process when the vegetation absorbs pollution; PM pollutants are at least temporarily removed from the atmosphere by interception, sedimentation, capture, and other sub-processes [2]. Nevertheless, currently, there is limited guidance on implementing GI, and as these systems are alive, it is challenging to provide standards [30].

In densely built-up urban areas, the widespread use of GI linear barriers can create an opportunity to improve environmental conditions, and one of the most promising plants that can grow anywhere in the world are bryophytes (more commonly called mosses) [5,26,21]. Recent studies have revealed the possibilities associated with using mosses with the impact of effective rainwater management, the ability to reduce surface temperature, and the ability to trap atmospheric pollutants. Properties of mosses, such as easy maintenance, lightweight, and durability compared to vascular plants, are advantages in reducing the heat island effect and contributing to the increase of urban biodiversity [26] as mosses are evergreen plants with whole-year photosynthesis [22].

There are studies on mosses' ability to reduce PM2.5 levels

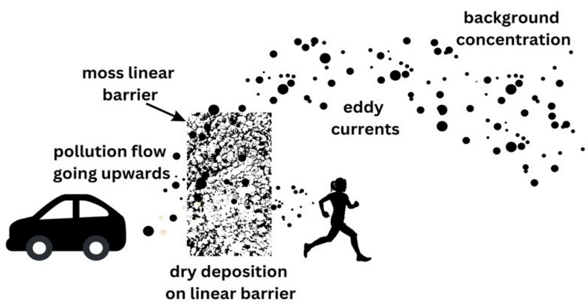

Fig. 1. Illustration of transport air pollution
[adapted by the authors from Sheikh et al., 2023]

in polluted environments, and these plants are already being used as a biomonitoring mechanism in many cases due to their ability to capture chemicals such as heavy metals and other types of particles [5,32]. This feature is facilitated by the fact that mosses, unlike vascular plants, do not have a cuticle layer to protect metals from entering cells through the single-cell layer of thick leaves, and it makes it possible to acquire nutrients from the air or surrounding water by absorbing particles onto their whole surface [13].

To ensure the sustainability of mosses as linear barriers, it is essential to transition from harvesting mosses from natural habitats to cultivating them in controlled environments.

Mosses need sunlight, carbon dioxide, minerals, and moisture to photosynthesize [23]. When growing mosses under controlled conditions, it must be considered that they can absorb water much faster than vascular plants [24]. Mosses are grown in natural environments such as Japanese gardens and used in bonsai to cover the soil and improve the impression of age. Cultivation protocols are not widely implemented. There are different methods. Cultivation of mosses under free conditions is often initiated using specimens transplanted from the wild. However, certain bryophyte species can be challenging to maintain away from their natural habitats due to their unique requirements for combinations of light, moisture, substrate chemistry, and wind shelter [22].

Under controlled conditions, mosses can be cultivated through various methods:

1. The cultivation of mosses from spores

This cultivation method involves a natural dispersal process wherein moss spores are released from sporangia and are carried by wind or rain to open surfaces. These spores adhere to surfaces conducive to the growth of specific bryophyte species, typically taking several years to establish and spread. Porous materials with moisture-retaining properties, such as brick, wood, and specific coarse concrete mixes, serve as ideal substrates for moss colonisation. Moreover, surfaces can be treated with particular substances, including acids, buttermilk, and yoghurt, to create an environment conducive to moss growth [22].

2. Vegetative propagation of mosses

When conditions are optimal, protonema and mature mosses regenerate well from cut fragments, making this method easy and fast. Trays with moss samples should be covered with foil or lid and watered with water to maintain optimal humidity. The first protonema appears after about 30 days, and the first adult moss gametophytes are obtained 60 days after propagation. If the weather allows (no minus degrees Celsius during the night), the trays can be moved outside in a shaded area. Finally, the moss colonies are exhibited 12 to 14 months after propagation. Various moss species (Hylocomium splendens, Rhytidiopsis robusta, Dicranum scoparium and Mnium lycopodioides) are successfully propagated by this method, but the first two show the most efficient growth [33].

3. In vitro propagation under controlled conditions

It is a technique in which moss tissue fragments are grown artificially under aseptic conditions. It involves culturing explants isolated from the mother plant in a sterile medium, resulting in cell proliferation and plant regeneration. In vitro plant propagation has contributed significantly to basic research knowledge and offers potential applications as it guarantees a sustainable industry based on the commercial production of plant compounds. Plant tissue culture effectively isolates and processes active compounds, including secondary substances and engineered molecules, from economically significant plants [19]. The advancement of modern technology has facilitated the development of numerous protocols for the large-scale production of various plant secondary metabolites.

The critical aspect of moss cultivation lies in achieving the right balance of soil composition and nutrient levels. Excessive nitrogen content, for instance, has been observed to decrease moss growth. Given that mosses thrive on dust accumulation, soil conditioners, while intended to enhance growth, can paradoxically hinder it. This phenomenon holds evidence for organic soil conditioners, which, if overly potent, can deter moss proliferation [23].

Results and Discussion

A research endeavour was conducted from January to April 2024 at RTU Liepaja Academy under the auspices of the Ecotechnology Master's program to assess various species of bryophytes as potential linear barriers.

Seven different bryophyte species (Table 1) were carefully selected, and small samples were taken from the forest in January 2024. These moss samples underwent further preparation, being carefully cut into smaller fragments using scissors. Subsequently, 65 g of moss biomass from each species was segregated into individual laboratory vessels. Each vessel was then repleted with 200 mL of a 2% agar solution prepared with spring water with a pH of 6.1.

The obtained moss-agar mixtures were blended to ensure homogeneity, creating a uniform application medium. These mixtures were applied to 10 x 10 cm tiles prepared in three layers: a veneer plate foundation overlaid with a hemp-growing mat and reinforced with a hardened metal mesh (Figure 2).

Following application, the samples were abundantly

Table 1. Visual evaluation of the results of the moss propagation experiment
[construction by the first author]

Species	Summary
Atrichum undulatum	Withered and didn't survive, probably due to the fragile habitus
Brachythecium albicans	Most promising species. Reached 0.8 mm height (height of the mature plant is 2 to 5 cm), bright green and thick surface structure
Brachythecium rutabulum	It started to grow after 2 months, 1 month, became 1 cm in height (2 cm medium height for mature plant), dark green and thick structure
Bryum argenteum	Good result, 0.3 mm in height (medium height for this species is around 1 cm), very thick and solid structure
Dicranum scoparium	Reached 1.2 mm in height (mature plant sized up to 5 cm), light green, not very thick surface, but solid and strong
The mix of different species	Shows excellent results with Brachythecium rutabulum, Brachythecium albicans, and Bryum argenteum as leaders in growth
Plagiomnium affine	Withered and didn't survive, probably due to the fragile habitus
Tortula muralis	It stopped growing after 2 months, at first, it was very promising

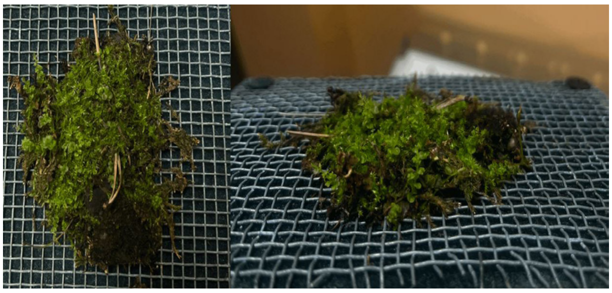

Fig. 2. Experimental tiles with cultivated moss sample after 2,5 months in an incubator [photo by the second author]

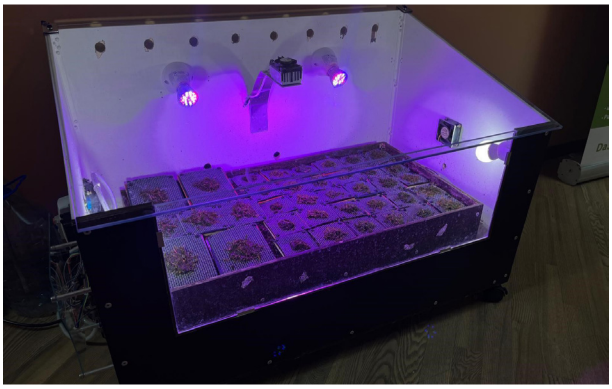

Fig. 3. Incubator for propagating vegetative mosses in the RTU Liepaja Academy building incubator [photo by the second author]

moistened with spring water and moved into an incubation chamber. Of seven moss species, 33 sample tiles were prepared in 10 x 10 cm tile size, and four extra 15 x 15 cm tile-sized samples were created. Each species was prepared on tiles in four replications (28 tiles in total), and additionally, five 10 x 10 cm and four 15 x 15 cm tile samples were created for a mix of all the species in one bowl.

A mix of different species has been showing promising results in various studies [23,32,33]. The incubator (Figure 3), measuring 100 x 60 cm with a height of 50 cm and featuring a glass cover, was equipped with red and white light sources (six lamps in total), emitting a luminance of 900 units, each rated at 60 W. A lighting regimen consisting of 16 hours of illumination followed by 8 hours of darkness was instituted throughout the cultivation period. Daily irrigation of the moss samples was meticulously carried out in the mornings over three months. Approximately 50 mL of spring water was applied daily to ensure the samples were fully humid, facilitating optimal growth conditions.

Weekly evaluations of the growing patterns were conducted, with results meticulously recorded and summarised at the end of the research.

The above research identified Brachythecium albicans, Brachythecium rutabulum, and Bryum argenteum as the most promising species, mainly when cultivated in combination (mix). The subsequent phase of experimentation necessitates the establishment of PM2.5

Fig. 4. Visualization of the placement of free-standing moss panels in a park in Riga [visualization by the authors]

Fig. 5. Visualization of the composition of moss panels with benches [visualization by the authors]

chambers within laboratory settings to assess the species' response to air pollution. Subsequent outdoor environment testing will be conducted in later stages.

This study aimed to define the results of the initial phase, which focused on the growing of mosses under controlled conditions. These findings are essential for the next step, the practical use of moss in urban landscape architecture, reducing air pollution, and creating an aesthetically pleasing environment.

Urban landscape architecture

Dynamic social, economic and ecological changes influence the modern urban landscape. The Most efficient hybrid solutions to these challenges are without fragmenting the space and urban fabric. With the awakening of global environmental consciousness and discussions of sustainability issues, the urban landscape is a challenging research field for various disciplines, even outside landscape architecture. These disciplines include planning, ecology, environment, and engineering, with the main focus on the synergy of these fields. **This article focuses on urban landscape architecture using nature-based solutions to reduce pollution.** The specific solutions form a representative design approach to the urban landscape.

Urban landscape architecture is a unique mix of theory and practice that has played a role in regenerating the urban environment. Landscape architecture, by definition, is a science, art, and technique that focuses on the study, design, and planning of natural or artificial landscapes or environments as perceived by humans [1]. Urban landscape architecture has a distinct role in restoring the urban landscape's spatial, ecological, and cultural continuity.

The authors' design for moss panels will harmoniously fit into the existing pilot research facility, a park in Riga, the capital of Latvia. It will be an inviting place for recreation and events, fully integrated into the surrounding urban landscape. Figure 4 shows free-standing moss panels, which also purify the air in autumn and winter and, with their green colour, make the environment more attractive. The planned dimensions of these panels are 2.3x2.5 m, 3.4x2.5m, and 4.9x2.5 m, with a height from the ground of 50 cm. According to the life cycle assessment, the materials of the panel's circular economy approach are planned using the most sustainable materials.

In the central part of the park, 2.5 to 6 m high moss panels, supplemented with benches, are planned to be installed. These panels will form the central composition and complement the park's landscape.

Conclusions

1. Air pollution poses a significant threat to human health, with staggering global implications. Statistics indicate that air pollution contributes to approximately 9 to 12 million deaths annually worldwide. Of particular concern is the presence of delicate particulate matter, PM2.5, which represents a primary contributor to air pollution and is a focal point of concern for the WHO.
2. Green infrastructure (GI), an incredibly linear barrier, has garnered attention as an effective technology for mitigating air pollution. Its mechanism involves creating a physical barrier between source and receptor zones. This barrier redirects the flow of air pollutants upwards, thereby elongating the air pathway from the emission source to the receptor area. Additionally, GI structures can reduce pollutant concentrations by enhancing turbulence within the airflow. These combined effects contribute to the overall efficacy of GI in combating air pollution.
3. More guidance on implementing GI is needed, and providing standards is challenging as these systems are alive.
4. Evergreen and primarily perennial plants, mosses distinguish themselves from vascular plants through their year-round photosynthetic activity. This perennial process enables mosses to exhibit a higher pollutant absorption capacity than their vascular counterparts. Furthermore, mosses have demonstrated resilience in inhabiting environments characterised by high toxicity levels, showcasing their adaptability to highly hazardous conditions.
5. A study conducted at RTU Liepaja Academy in Latvia from January to April 2024 has identified Brachythecium albicans, Brachythecium rutabulum, and Bryum argenteum as the most suitable species for cultivation in controlled environments. Following three months of controlled cultivation, these species have reached maturity levels conducive for deployment in urban environments.
6. Further research is required to assess the efficacy of identified species in mitigating air pollution, particularly PM2.5, both in laboratory settings and real-world environments. This research aims to elucidate the full potential of these moss species as an effective tool for air pollution mitigation.
7. For the designed moss panels, which are free-standing and combined with benches, use the most durable moss species or a mixture of moss species.

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Kopsavilkums
Pasaules Veselības organizācija ir atzinusi gaisa piesārņojumu par globālu problēmu, kā rezultātā ik gadu mirst 9–12 miljoni cilvēku, un cietās daļiņas ir vissmagākais drauds cilvēku veselībai. Cietās daļiņas var atšķirt pēc to lieluma, jo PM2,5 diametrs ir 2,5 µm vai mazāks, kas nozīmē, ka šīs sīkās putekļu daļiņas ir neredzamas ar neapbruņotu aci. Gaisa piesārņojuma problēmai tiek meklēti dažādi risinājumi, kas sasaucas ar ainavu arhitektūras risinājumiem, piemēram, Zaļā infrastruktūra un lineārās (vertikālās) barjeras. Tie tiek pētīti kā efektīvs uz dabu balstīts risinājums pieaugošajai gaisa piesārņojuma problēmai, kas organiski iekļaujas pilsētas ainavā. Dažādu augu novērtējumi attiecībā uz to piesārņojuma mazināšanas potenciālu izceļ bryofītus kā īpaši efektīvus to augstās absorbcijas spējas dēļ, un, lai nodrošinātu lineārās barjeras noturību, ir ieteicama audzēšana kontrolētos apstākļos. Šajā rakstā ir pētīta briofītu audzēšana kontrolētos apstākļos un praktiskā eksperimenta laikā noteiktas visefektīvākās sūnu sugas. Šis eksperiments un dokuments ir daļa no lielāka, plašāka pētījuma par gaisa piesārņojuma samazināšanu, izmantojot bryofītus, un šajā dokumentā aprakstītie pētījumi ir noderīgi turpmākajos pētījumos. Novērtētās bryofītu sugas turpmāk tiks pētītas attiecībā uz to spēju absorbēt gaisa piesārņojumu PM2,5. Šajā rakstā tiek izmantotas tādas pētniecības metodes kā literatūras analīze un laboratorijas eksperiments, kas veikts no 2024. gada janvāra līdz aprīlim.