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PHYTOREMEDIATION POTENTIAL OF SELECTED HERBACEOUS SPECIES IN VERTICAL GARDENS FOR URBAN AIR POLLUTION MITIGATION AND INTEGRATION WITH THE EU EMISSIONS TRADING SYSTEM

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ABSTRACT: The cognitive objective was to prove the thesis that vertical gardens based on the proper selection of plant species are capable of purposefully and efficiently reducing air pollution in the urban environment. Simultaneously, the practical purpose is to propose a response of the construction industry with an original method to the European Emissions Trading System to reach the Zero-Emission objective. The research applies the analysis of the most common pollutions in metropolitan areas, using the example of Cracow, field experimentation methods, biochemical and laboratory studies, statistical analysis, and quantitative techniques. The relevant qualities and adequacy of the chosen species with valued medicinal and health-promoting properties were tested. The plant species used included fennel spike (*Agastache Foeniculum*), lemon balm (*Melissa officinalis*), thyme (*Thymus vulgaris*), chives (Allium schoenoprasum), dill (*Anethum graveolens*) and common ivy (*Hedera helix*). The analysis proved that a significant level of phytoremediation of air pollutants can be achieved with vertical gardens. The technology offers a promising nature-based solution concerning its combined innovation responding to the new trend in food production – urban farming and effective greenhouse gas reduction.

KEYWORDS: Loreair pollutants, European Emissions Trading System, ETS, green infrastructure, nature-based solutions, phytoremediation

DOI: 10.34659/eis.2026.97.2.1129

Introduction and an overview of the literature

The space of agglomerations and larger cities is subject to both adverse and beneficial change. High concentrations of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), freons (CFC), nitrous oxide (N_2O), halon, and industrial gases (e.g. HFC, PFC, SF), in addition to the presence of tropospheric ozone (O_3), and water vapour, belong to the darker side of the urbanisation (Cao et al., 2025; Flatabø et al., 2023; Jain & Hayhoe, 2003). In addition to gases that cause the "greenhouse effect", other undesirable gases in the urban air include sulphur oxides (SO_x) and nitrogen oxides (Nox) (Tang et al., 2009). So-called "ballast elements" such as cadmium (Cd)[1] or lead (Pb)[2], classified as dangerous carcinogens, may also be present in the urban air (Ercilla-Montserrat et al., 2018). In addition, aerosols, i.e. substances in the liquid and solid phase suspended in the air, which cause various cardiovascular, respiratory or nervous system diseases, are also undesirable (Ezzati et al., 2004). They usually come from the combustion of solid fuels used for heating, cooking or transportation. A high concentration of dust means a threat both inside buildings and in the external space (Tran & Lee, 2020; Wang et al., 2022).

One of the main factors affecting air purification from the above-mentioned substances is the presence or introduction of specially selected plant species for this purpose. Phytoremediation, as the biological method of air purification, relies on appropriately selected plants for cleaning polluted urbanised environments. As the awareness of environmental pollution has been improving, phytoremediation has gained increasing importance (Kennen & Kirkwood, 2015; Royer et al., 2023). It represents significant and up-to-date technology ensuring cities' sustainable and green transformation. The phytoremediation approach makes it even possible to restore brownfield sites to a condition in which they can be developed for agricultural cultivation (Tan et al., 2023).

Interestingly, scientific studies have proved that plants can remove some of the most toxic substances found in our environment, e.g. benzene – up to 90%, and trichloroethylene (TCE) – up to 23%, present even in indoor air (Wolverton et.al., 1989). In addition, plants reduce the local air temperature through transpiration and significantly decrease the level of toxic ground-level ozone while simultaneously enabling the creation of urban shade zones. Some species that release volatile substances can improve the efficiency of the human respiratory system and circulation, thereby relieving stress considerably. Certain volatile substances of plants exhibit bacteriostatic properties as well (Dzierżanowski et al., 2011; Hewitt et al., 2020).

The formulation of the research concept by the author relied on the insights gained from more than 20 years of vast international experiences obtained while working on green-innovation developments in roles like an independent expert of the European Innovation Council's (EIC) Accelerator and evaluator of startups' applications to the Green Deal pilot via the EIC and SMEs Executive Agency (EISMEA). The author's experiences also include an accelerator programme launch – the Circular ClimAccelerator Poland. The programme was established in cooperation with Climate-Knowledge and Innovation Community (Climate-KIC) – the biggest international private-public organisation supporting the development of solutions against climate and environmental challenges. The author's engagements also include mentoring and coaching in the sustainability programmes of the EC's European Institute of Innovation and Technology (EIT) via the EIT Food, the New European Bauhaus of the EIT Strategic Synergies Cluster, the EIT Urban Mobility, the EIT Manufacturing, in addition to the Climate-KIC. The collaboration with the Climate-KIC included a professional engagement on green-innovation developments with Warwick Business School, Wrocław University of Environmental and Life Sciences, Imperial College London, Denmark Technical University, Munich Technical University and others (Hancox et al., 2015).

Direct inspiration for this research came from the pioneering research by NASA that identified 18 effective plants for air purification and oxygen production (Wolverton et al., 1989). That research aimed to select the best-suited plants that could be taken into space to create atmospheric effective atmosphere. Of course, more plants are particularly well suited to air-filtering and oxygen-produc-

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[1] Cadmium results in human kidney stones, so cadmium poisoning leads to kidney failure, but at the same time to respiratory failure, which causes severe circulatory disorders.

[2] Lead contamination causes a disease entity known as lead poisoning, which puts a significant strain on the immune and circulatory systems of people exposed to this element or its compounds.

tion functions; however, their effectiveness has not been well characterised in the context of vertical gardens in European metropolises. Urban areas are not cosmic space, but they also need clean air from substances harmful to human health and life, especially in the urbanised polluted areas.

A radical increase in green areas, which would perform filtration functions by removing hazardous substances from the air and turning them into oxygen, had been considered the solution against high levels of those components. Air-filtration process is performed as the essential function of plants, mainly when concentrated, e.g. in vertical gardens (VGs). In addition to cleaning the air, VGs can bring added value to production-related activities, i.a., to the agri-food production (Russo et al., 2017). It can be realised by utilising:

- Reduction in energy consumption of buildings, due to the beneficial natural properties of the extensive presence of plants on the buildings' surface, offering shade and insulation (Janiak, 2019);
- Positive impact through increased quality and value of real estates as VGs improve not only the builings' aesthetics but, in consequence, also increase their market valuation, that is, their price (Jim & Chen, 2010; Krellenberg et.al., 2014; Conedera et al., 2015);
- The introduction of VGs can also achieve improvement in corporate/enterprise image by serving as a visible sign of firms' environmentally conscious approach to the immediate surroundings and also their contribution to a greener urban landscape;
- The offer of modest but gratifying opportunities to increase food variety and security as demonstrated, e.g. during the Covid-19 pandemic, with the reassuring possibility of self-reliance in the context of food supplies and access to locally grown fresh fruits and vegetables even in small urban spaces (Carvalho et al., 2022; Ed-Tanboury et al., 2021; Russo & Cirella, 2020);
- Given the presence of nectar-producing plants in the VGs, like in the studied set of species, plant location and growth conditions can influence insect composition and activity (Moniuszko et al., 2025).

Current examples of VG implementation in European cities include, among others, Milan's famous "Bosco Verticale" (Kalogeropoulos et al., 2024) or realisations of Patric Blanc at the Museum of Science and Technology in Paris (Blanc, 2015). These examples emphasise a certain type of nature-based solutions (NbS), namely façade greening, to improve local living and environmental conditions as well as aesthetics (Gantar et al., 2022).

Based on the desk and laboratory research, the following general conclusions have been drawn: currently, vertical gardens are offered as purely decorative or utilitarian, as in the case of VGs in the more significant form of the vertical farms (Sharma et al., 2023). Although the production of VGs often emphasises the air-filtration property of plants, oftentimes it is a marketing campaign element rather than a reality as the products currently offered on the market actually contribute to the deepening of environmental problems as the vast majority of the construction of VGs uses materials harmful to the environment (e.g. in the forms of plastic pots and plant fixing structures) and electricity from traditional sources (for the irrigation and fertilisation system propulsion). In addition, VGs currently offered on the market, especially those containing mosses, are artificially coloured in the production process with, e.g. glycerine, thus providing a wide range of attractive colours. That allows for maintaining a more prolonged fresh-look effect for the visual attractiveness of such products. However, it has nothing to do with genuine care for the natural environment, and plants treated with glycerine collect dust, dirt and harmful substances instead of purifying the air from pollutants.

Considering the benefits of vertical gardens, the primary aim of the study was to identify a set of effective seed plant species suitable for the construction of VGs to 1) reduce the most common polluting substances from the air and absorb CO_2 and other GHGs, and 2) intensify the production of oxygen.

The following research questions were identified: Will the cleaner production of VGs based on the appropriate selection of plants to combat air pollutants achieve quantifiable positive effects on converting CO_2 into oxygen and filtering air from substances detrimental to human health? As a preliminary question, whether these effects can be precisely quantified at an acceptable and reliable significance level should be examined.

If the answers to these questions are positive, the industrial consequences can be profound. For example, the VGs could be included in the calculation of ETS quotas for the construction industry within the European Union (Directive, 2003).

Research methods

Based on desk research, laboratory analysis and the demand reported by the Norwegian Fund, the research problem was formulated as an impartial identification of the proper selection of plant species capable of efficiently reducing air pollution in the urban environment.

The practical purpose is to propose an original method for responding to the European Emissions Trading System, which will help the construction industry achieve its Zero-emission objective.

The research method included qualitative research, i.e. a detailed analysis of plants' efficiency: 1) in converting CO_2 into oxygen and 2) in filtering air from substances harmful to human health. Among the applied methods were the following:

- Analysis of the most common pollutants in the air of the metropolitan areas through the example of Cracow Metropolitan Area;
- Field experimentation method (plant cultivation): during the greenhouse experiments, the plants' essential physical factors – such as temperature, humidity, irradiance and also light exposure- were monitored to ensure appropriate conditions for their growth;
- Biochemical analyses included:
    - measurements of the growth parameters of plants and the biometric analyses of primary shoots growth, length and width of fully developed leaf blade,
    - determination of the Relative Water Content (RWC) index,
    - analysis of the number of plant hairs per unit area,
    - analysis of epidermal surface characteristics,
    - filtering and measuring the leaf areas;
- Quantitative methods of Folin-Ciocâlteu and Fukumoto-Mazza for measurements of chloroplast pigments and phenolic compounds;
- Laboratory analyses of:
    - the micropollutant content,
    - the epicuticular waxes of leaves;
- Statistical analysis.

In the experimentation phase of the research, two different drought-stress treatments were applied (Ghorchiani et al., 2018), taken as a specific level of soil water deficiency of 70% and 30% concerning the proper water capacity of the substrate used during the cultivation of plants carried out in pots of about 2.2 dm^3 (control treatment). The control treatment included plants grown in optimum substrate moisture, defined as their total water-holding capacity. The substrate in which the plants grew during the experimental cultivation was a mixture of sand, perlite and all-purpose soil in a ratio of 1:1:3, respectively. After the rooted plants were planted in pots, their stabilisation lasted 7 days. During the experiment, industrial-type lighting with high-pressure sodium (HPS) bulbs was used to periodically compensate for the short time of daylight and ensure an adequate plant growth rate.

During the cultivation experiment, 30 individual plants per experimental treatment were used. The drought-stress treatment was maintained for 56 days, with the material evaluated on the 42nd day (6 weeks in term I) and on the 56th day (8 weeks in term II) after establishing the cultivation experiment.

Growth parameters and biometric analyses were conducted for each species tested and included the height of the primary and lateral shoots. The plant material was collected and preserved in liquid nitrogen for biochemical analyses. Leaf weights were 5 g by 8 replicates for each treatment and species. The fresh and dry weights of shoots and roots were measured based on additional weightings taken from the rest of the material to calculate the RWC index. Microscopic observations were carried out to assess the number of hairs per unit area [p] and further analysed as the more hairy the plant, the potentially better air retrofitting quality of the plant. Five leaves per cultivated plant were taken. Out of those leaves, small samples of 1cm x 1cm were cut. Laboratory analyses included chloroplast pigment content measured in total phenolic compound content using the Folin's reagent according to the Folin-Ciocâlteu method (Raposo et al., 2024) and the determination of phenolic profile in line with the Fukumoto-Mazza method (Fukumoto & Mazza, 2000).

The plant tissue (0.25 g) was grated with pure sand in 80% acetone (5 ml). The resulting extract was centrifuged at 4°C for 15 min. with a relative centrifugal force of 5800 g. Then, the supernatant (1 ml) was taken from the extract for dilution and made up to 5 ml with 80% acetone. Afterwards, the absorbance of the samples was measured at λ=470 nanometres (nm), 646 nm and 663 nm using a spectrophotometer. The content of chlorophyll A, chlorophyll B and carotenoids was calculated by application of the Lichtenthaler-Wellburn formula (Lichtenthaler & Wellburn, 1983):

$$C_a = 12.21A_{663} - 2.81A_{646}, \tag{1}$$

$$C_b = 20.13A_{646} - 5.03A_{663}, \tag{2}$$

$$C_{x+c} = 1000A_{470} - 3.27C_a - 104C_b, \tag{3}$$

where:
C_a – the function of Chlorophylls A,
C_b – the function of Chlorophylls B,
C_{x+c} – the function of Carotenoids.

The determination of total phenolic compounds was carried out by spectrophotometry. Plant tissue of 0.25 g was grated in 5 ml of 80% methanol with sand and then centrifuged at 4°C for 15 min. with a relative centrifugal force of 5800 g. Then, 0.25 ml of supernatant was mixed with 0.25 ml of 0.1% ethanolic HCl and 4.5 ml of 2% HCl. After 15 min., the absorbance of the samples was measured at λ=280 nm, 320 nm, 360 nm, and 520 nm using a spectrophotometer.

For the statistical analysis of the collected data, the normality of the data was checked (standard Shapiro-Wilk test) together with the homogeneity of variance (Levene test) before proceeding with the analysis of variance. One-way ANOVA analysis of variance at a 95% confidence level was used to test the significance of differences between individual treatments within one variety (1), as well as between individual treatments (drought levels) within one variety (2), as well as between the same treatments within the two varieties tested (3). Post-hoc comparisons were made using the Tukey test. Mean values from all analyses include standard deviation (±SD).

Results of the research

The first necessary step in the selection of the plants for pollution-filtering VGs was the identification of types of most common pollutants appearing in the selected localisation – Cracow Metropolitan Area. Apart from a whole range of volatile organic compounds released during the combustion of petroleum products, ground-level ozone (O_3) is present in higher concentrations in the ambient air of the area.[3] Significant concentrations of NO_2 are also standard[4]. Elevated levels of CO, which is a colourless and odourless gas, can also sometimes be found[5]. Significant levels of SO_2 are repeatedly found in the air as well[6] (Baścik & Gegórska, 2015; Koźmińska & Hanus-Fajerska, 2015).

Particulate matter (PM) in the smog is equally dangerous as gaseous pollutants. Within the Cracow Metropolitan Area, the problem is most acute with regard to PM of the finest gradation, i.e. PM2.5 – inhalable solid particles with a diameter of less than 2.5 micrometres (μm)[7]. Elevated levels of particulate pollutants with a particle diameter of less than 10 μm can also be commonly detected.

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[3] O_3 can aggravate symptoms of respiratory diseases and lead to upper respiratory tract irritation, headaches and chest pain,

[4] Its inhalation increases the risk of coughing attacks and causes breathing difficulties, while chronic respiratory infections usually occur after prolonged exposure.

[5] When inhaled at very low concentrations, it causes dizziness, nausea, vomiting and repeated long-term exposure can lead to heart disease.

[6] Human exposure to this dangerous gaseous substance usually leads to irritation of the eyeballs, throat and exacerbation of asthmatic conditions, and ultimately to chronic bronchitis.

[7] These particles can quickly enter the lungs and bloodstream and cause serious health problems. Exposure to this component of smog can lead to permanent coughing or great difficulty in breathing, exacerbation of asthma, as well as generating chronic respiratory diseases, so they ultimately have a substantial impact on extensive myocardial indisposition.

The plant material selection was performed after the specification of the existing contamination in the study area. In order to verify the phytoremediation capacity of individual plant species, representative leaf samples of the tested species/varieties were collected into bags in four replicates from each species and variety with a single mixed sample comprising no fewer than 10 leaves. Epidermal surface characteristics were checked first, and the number of stomata per epidermal unit was assessed for the selected species/varieties. In appropriate cases, measurements were made of the content of micropollutants and epicuticular waxes in the leaves and the leaf sample was then placed in a desiccator. Filters with pore diameters corresponding to the individual particulate matter fractions (PMs) were used to measure the microdust content. Before proceeding to the filtration stage, the filters were incubated for 30 minutes in a heat chamber at 60°C. Then, after being left for 20 min. at room temperature to equilibrate humidity, they were weighed. A suitable sample of leaves taken from the desiccator was rinsed in 250 ml of deionised water to rinse the dust from their surface. The water, together with the rinsed surface dust (i.e. with the impurities in it), was poured through a laboratory sieve with a mesh size of 100 µm in order not to measure the content of dust more significant than those that were the subject of the study, into a clean crystalliser. After rinsing a specific sample of leaves with distilled water, the same leaves were set aside in the glass crystalliser. The largest of the three filter sizes used, the one with an aperture diameter of 10 µm, was placed in the filter set. The filter set was fitted, and the pump was switched on. The water was filtered until it became utterly cleared of dust of the given diameter.

Meanwhile**,** after the first filtration, the water in the flask was successively filtered through filters of smaller mesh diameter. Leaves from the same sample, previously rinsed with water, were washed in a crystalliser with 150 ml of chloroform for 40 s. Filtering was carried out analogously to water filtering in the same order of filter insertion, except that the chloroform remaining after filtering was poured into a previously weighed, empty and clean beaker.

After the chloroform had evaporated, which took from several to up to 48 hours, the beakers were weighed on a laboratory microbalance. The difference in weights of the empty beakers and the beakers with wax indicated how much wax was present in 1 cm^3 of the leaf. After filtration was completed, the dirty filters were placed in a heat chamber at 60°C for 30 min. and then at room temperature for 30 min. After this time, the filters were weighed on a laboratory microbalance. Leaves from each sample after the final chloroform rinse were dried upright on paper sheets and on a countertop in the laboratory to dry and not get folded during filtration, so that their surface area could be measured. Leaf area was measured using SKY's Leaf Area, Root Length and Image Analysis Systems. The results obtained were subjected to statistical analysis – a one-way analysis of variance. The significance of differences was assessed with Tukey's honest significant difference (HSD) test at a significance level $\alpha = 0.05$.

Species for VGs production must be selected by considering several environmental factors, e.g. sun exposure, soil composition and quality, plants' tolerance to salinity stress (Rameshkumar, 2018; Sarkar, 2018)[8]. Consideration should also be given to the type of climbing, which determines the type of supporting infrastructure and its fixing. In the research, however, the selected plants have been examined concerning their ability and efficiency to absorb gaseous air molecules via the stomatal apparatus, cuticle and waxy layer of leaves and the epidermis or periderm of stems.

Within the range of numerous floral families, genera, and species representing angiosperms, a wide range of valuable crop species exist in the Lamiaceae plant family, which is helpful in absorbing nitrogen and carbon oxides. Numerous species of mint (*Mentha* sp.), mainly lemon mint, peppermint and round-leaved mint, may also be useful in this aspect. Classified species include thyme, lemon balm, and fennel spike. From other botanical families, chives (*Allium schoenoprasum* L.) or dill (*Anethum graveolens* L), the former from the celery family, while the latter from the amaryllis family, have proved useful. Those plants are also important because they provide valuable, healthy ingredients for human food and, at the same time, important nutrients for pollinating insects (Čepulienė et al., 2024). For this reason, the benefits of their use can be multifaceted, as their value is not limited to their utilitarian and health-promoting qualities for humans but also has important ecological benefits.

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[8] For example, climbers growing directly in the ground along roadways are exposed to sodium chloride (NaCl) and other salts used during winter snow removal from streets, which contributes to a lot of damage to buds, leaves and stems that can result in their dying.

DOI: 10.34659/eis.2026.97.2.1129

An interesting group of plants are climbers occupying small ground areas. A good example of this type of plant may be the common ivy of the Araliaceae family (Ackerfield & Wen, 2003). It belongs to the native species in the European continental climate zone, and it is helpful in cleaning the air of both particulate matter and the secondary deposition of heavy metals. The small substrate volume it occupies produces a large area of winter-hardy foliage that can be directed vertically with appropriate support structures. For this reason, these species were selected to be tested in relation to substances causing ambient air pollution in urban environments.

Moreover, native species, representing the flora that are part of the communities making up natural grassland vegetation or xerothermic grasslands, are significant, providing a surface for the deposition of particulate matter and efficient capture of other pollutants, including heavy metals and atmospheric gaseous pollutants. Some herbaceous plant species include hill smudge (*Alyssum montanum* L., Brassicaceae) and common scabious (*Berteroa incana* L.) DC., *Brassicaceae*), yarrow (*Achillea millefolium* L., Asteraceae), and bird's-foot trefoil (*Polygonum aviculare* L., Polygonaceae) show high efficiency in capturing particulate atmospheric pollutants as well (Weber et al., 2014).

The phytoremediation function of herbaceous species against air pollutants is performed by trapping dust particles in the wax covering the surface of leaves and young shoots and the surface of the numerous cuticular hairs covering the leaf. Herbaceous plants play a vital role in the phytoremediation of air pollutants because, once dust is deposited on their surface, they prevent dust from re-emerging into the environment (Gawronski et al., 2017). For this reason, an excellent solution is the use of sodding plants or plant mixtures to produce in VGs a plant blanket that dynamically covers the ground surface.

The selection of vegetation for production-related experimentation with VGs consists of herbaceous plant species of varying taxonomic positions and a permanent climbing plant. Since climbers can be herbaceous plants and plants with woody stems and perennial secondary growth, we chose the permanent climber to act as a so-called "groundcover plant" that would envelop the vertical structure. The climbers' elongated, relatively flexible stems show their ability, uncommon for other species, to cling or wrap themselves around natural or artificially constructed supports. They do not usually form rigid stems, so the biomass created is devoted to dynamic growth. As a result, the annual growth can reach up to several metres in a single growing season in the continental climate zone conditions, which can be desirable for VGs intended to cover more enormous structures quickly.

The pilot study investigated the suitability of a range of plants for reducing air pollution by components contributing to smog formation. In the course of the experiments, the suitability of herbaceous perennial species of the botanical family Liliaceae with valued medicinal and health-promoting properties, such as *thyme* (*Thymus vulgaris* L.), lemon balm (*Melissa officinalis* L.), and fennel spike (*Agastache foeniculum* (Pursch) Kuntze) was tested. In addition, garden dill (*Anethum graveolens* L), celery (Apiaceae) and chive garlic (*Allium schoenoprasum* L. f. *foliosum*, amaryllis (Amaryllidaceae) were considered as plants with post-health effects, often used as a spice. The ground cover plant was common ivy (*Hedera helix* L.) Araliaceae (Araliaceae).

In summary, we planned to use for production-related experimentation with VGs the *Agastache foeniculum* (Lamiaceae), *Melissa officinalis* (Lamiaceae), *Thymus vulgaris* (Lamiaceae), *Allium schoenoprasum* (Amaryllidaceae), *Anethum graveolens* (Apiaceae) and the long-lived vine species *Hedera helix* (Araliaceae) as a groundcover plant to improve the urban microclimate.

Two different drought-stress treatments were applied during the greenhouse experiments conducted at the specific levels of soil water deficiency of 70% and 30%, concerning the proper water capacity of the substrate used during plant cultivation. Herbaceous plants from the botanical family of buttercups, celery and amaryllis were tested during cultivation. Selected results of biometric and biochemical analyses are presented in Tables 1, 2 and 3. Those results were obtained in successive repetitions after the sixth and eighth weeks of the experiment, which were designated as terms I and II of the material evaluation, respectively, with the whole experimental block repeated.

Table 1 presents the results of biometric measurements and the tested plants' tissue hydration degree expressed by the RWC index.

The shoot growth index of the control tussock (*Agastache foeniculum,* Lamiaceae) was 1.04, while at the 70% level, it was just 0.64. Interestingly, drought stress (30% water capacity) did not reduce shoot growth, as it was similar to the control (with a value of 0.98).

In the case of lemon balm (*Melisa officinalis*, Lamiaceae), the shoot coefficient for the control group was 1.51, while for 70% – 1.01, and for 30% substrate water capacity – 0.99. Neither species reacted negatively to a prolonged lack of substrate water.

A third species representing the light-leaved family with very fine leaves, thyme (*Thymus vulgaris*), responded most mildly to drought stress: in the control group – 1.01, in 70% drought stress – 1.09, and in 30% water capacity, 0.99, so all growth rates were very similar despite significant differences in hydration conditions.

Table 1. Study of shoots growth and degree of hydration (RWC) for: *Agastache foeniculum* (Lamiaceae), *Melissa officinalis* (Lamiaceae), *Thymus vulgaris* (Lamiaceae), *Allium schoenoprasum* (Amaryllidaceae), *Anethum graveolens* (Apiaceae) and *Hedera helix* (Araliaceae) measured after 6. weeks of the cultivation experiment i.e. after four (I) and five (II) weeks from the experiment launch (control) or after four (I) and five (II) weeks of drought stress, respectively, representing 70% and 30% of the total soil water capacity, (± SE) standard error, α= 0.05

Assessed characteristics	control		70%		30%		control		70%		30%	
	I	II	I	II	I	II	I	II	I	II	I	II
	Agastache foeniculum						Melissa officinalis					
Stem length (mm)	27.24 ±1.15	28.25 ±1.22	25.05 ±1.02	16.54 ±1.45	15.25 ±1.09	15.02 ±1.04	22.55 ±1.25	24.25 ±1.02	25.70 ±1.52	26.04 ±1.40	21.20 ±1.10	21.07 ±1.06
Index RWC (%)	92.00 ±2.12	92.15 ±2.09	93.53 ±1.62	93.42 ±2.40	92.22 ±1.29	91.25 ±1.24	95.54 ±1.44	96.05 ±1.48	99.05 ±1.58	98.06 ±2.10	92.05 ±2.26	89.55 ±2.85
	Allium schoenoprasum						Anethum graveolens					
Stem length (mm)	9.55 ±1.05	10.14 ±1.08	11.02 ±1.04	14.08 ±1.10	12.03 ±1.02	12.28 ±1.04	21.05 ±1.15	20.21 ±1.20	22.75 ±1.25	24.06 ±1.10	20.23 ±1.12	21.87 ±1.06
Index RWC (%)	88.00 ±1.15	89.55 ±1.45	91.03 ±1.52	91.41 ±2.04	91.25 ±1.90	91.05 ±1.04	85.05 ±1.74	86.45 ±1.45	85.90 ±1.78	84.55 ±2.50	85.05 ±2.26	84.54 ±2.25
	Thymus vulgaris						Hedera helix					
Stem length (mm)	16.02 ±1.10	16.25 ±1.02	15.05 ±1.02	16.54 ±1.45	15.25 ±1.09	15.02 ±1.04	150.05 ±1.40	164.05 ±1.04	149.05 ±1.24	171.05 ±2.45	152.05 ±1.90	154.05 ±1.02
Index RWC (%)	96.00 ±2.12	96.15 ±1.95	95.05 ±1.62	96.054 ±2.04	91.55 ±1.99	91.05 ±1.44	95.05 ±1.44	96.45 ±1.04	89.95 ±1.28	88.65 ±2.05	89.05 ±2.06	88.055 ±2.25

Source: author's work based on laboratory examinations.

Macroscopic evaluation and biometric dimensions showed that the small plants of thyme *(Thymus vulgaris)* grew at a slower rate compared to fennel spike (*Agastache foeniculum*) and lemon balm (*Melissa officinalis*), but produced extensive clumps covering the ground relatively quickly, which is important for the phytoremediation of air pollution.

The plant growth strength of the Lamiaceae family under drought-stress conditions did not prove to be significantly different from that of other botanical families (Table 1). Chives (*Allium schoenoprasum,* Amaryllidaceae) responded as follows: the growth coefficient values of the control plants were 1.06, for 70% substrate moisture – 1.27, and for 30% – 1.02. For these species, the values of the growth coefficient under water stress are very similar to the control value.

The corresponding values for garden dill (*Anethum graveolens*, Apiaceae) were 0.96 for the control, 1.05 for 70% dehydration, and 1.08 for drought stress (30%). Temporary drying of the substrate tolerated and stimulated this species positively.

The same relationship applies to ivy (*Hedera helix*, Araliaceae), where the experiment results were: 1.09 in the control group, 1.14 in the group with 70% stress, and 1.13 in the 30% group. The hydration of organs above ground, as expressed by the RWC index (Table 1), differed significantly from that of the species in the control group.

Chlorophyll totals (Table 2) were another indicator of photosynthetic plant performance, demonstrating the ability to maintain an adequate growth rate under stress conditions. This biochemical trait is also species-dependent. Chlorophyll *a* was present in higher amounts (leaf content) on the second analysis data concerning the control of lemon balm (*Melisa officinalis*, Lamiaceae). Still, values fell below those of the control in plants exposed to drought stress.

Chlorophyll *b* was present in lower concentrations in the 30% drought treatment relative to the control group, while the other plants had higher values than the control. In the 30% drought, carotenoids were maintained at levels similar to the control at both drought-stress dates. Otherwise, the carotenoid was higher at the analysed term I but decreased at term II.

Among all the species tested (Table 2), the highest chlorophyll *a* content was found in *Hedera helix* plants in the first term in the 30% drought treatment, and the lowest content occurred in this species in the second analysis term.

Contrary to *Hedera helix* plants, *Agastache foeniculum* had the highest values of chlorophyll *b* in the first and second terms of the 30% drought treatment and the lowest in the second term of the 70% treatment.

The highest carotenoid content was recorded in *Agastache foeniculum* (*of the* Lamiaceae family) in the second term of the control treatment, and the lowest in plants of the same species under drought conditions in the second analysis term (Table 2).

The results of the microscopic analysis revealed that the reference plant, *Agastache foeniculum,* contains a significantly lower number of secretory hairs per unit leaf area (12.0) than *Melisa officinalis* (16.0). During the drought-stress generation experiment in the substrate, the following relationships could be observed:

- For the drought levels tested, the number of trichomes per unit leaf area of Agastache foeniculum in plants in which 70% drought was generated was 41.9% relative to the control treatment, and in the series with 30% drought, 67.7% relative to the control;
- Melissa officinalis in the experimental treatments did not differ from the control, confirming the tolerance of the tested chemotype of this species to the drought stress applied in the studied experimental setup;
- Weaker biomass growth correlated with a reduction in the number of trichomes per unit leaf area treated with drought stress;
- In this aspect, Agastache foeniculum was proven to exhibit drought-stress resistance, as it maintained harmonious biomass growth with an equal number of hairs per unit area in all experimental treatments.

The data collected in Table 2 also present the results for common ivy (*Hedera helix,* Araliaceae) to compare the chlorophyll content of the control treatment. Drought stress accounted for 70% or 30% of the value for the control plants, respectively.

The cultivar ‘Thorndale’ of common ivy with leaves analogous to wild plants was evaluated in terms of photosynthetic pigment content, and based on the biochemical analyses carried out, a discrepancy between the chlorophyll *a* to *b* ratio in the individual experimental treatments and the control was presented. In the case of the *H. helix* cultivar tested, 70% drought stress stimulated chlorophyll production. On the other hand, the carotenoid content was found to be equal in this species in the applied experimental setup (Table 2). For this reason, *the Hedera helix* ‘Thorndale’ was identified as a beneficial plant for covering the air-filtering VG structures.

Table 2. Chloroplast pigment content in the plants *Agastache foeniculum* (Lamiaceae), *Melissa officinalis* (Lamiaceae), *Thymus vulgaris* (Lamiaceae), *Allium schoenoprasum* (Amaryllidaceae), *Anethum graveolens* (Apiaceae) and *Hedera helix* (Araliaceae) measured after six weeks of the cultivation experiment, i.e. after four (I) and five (II) weeks from the establishment of the experiment (control) or after four (I) and five (II) weeks of drought stress, representing 70% and 30% of the total soil water capacity, (± SE) standard error, α= 0.05, d.m. – dry mass

Assessed biochemical trait	control		70%		30%		control		70%		30%	
	I	II	I	II	I	II		I	II	I	II	I
	Agastache Foeniculum						Melissa officinalis					
Chlorophyll a+b (µg/g d.m.)	350.15 ±4.94	402.26 ±3.54	345.32 ±4.07	268.21 ±7.07	250.23 ±2.75	300.26 ±9.40	Chlorophyll a+b (µg/g d.m.)	350.15 ±4.94	402.26 ±3.54	345.32 ±4.07	268.21 ±7.07	250.23 ±2.75
Carotenoids (µg/g)	111.03 ±5.94	99.50 ±7.94	101.02 ±8.22	98.12 ±2.45	98.12 ±2.78	97.60 ±5.45	Carotenoids (µg/g)	111.03 ±5.94	99.50 ±7.94	101.02 ±8.22	98.12 ±2.45	98.12 ±2.78
	Allium schoenoprasum						Anethum graveolens					
Chlorophyll a+b (µg/g d.m.)	451.26 ±5.02	463.36 ±5.08	425.52 ±4.99	440.64 ±2.66	351.42 ±6.05	335.16 ±5.45	Chlorophyll a+b (µg/g d.m.)	451.26 ±5.02	463.36 ±5.08	425.52 ±4.99	440.64 ±2.66	351.42 ±6.05
Carotenoids (µg/g)	102.65 ±5.45	110.9 ±4.66	99.24 ±3.01	125.02 ±4.33	98.11 ±3.85	102.23 ±3.78	Carotenoids (µg/g)	102.65 ±5.45	110.9 ±4.66	99.24 ±3.01	125.02 ±4.33	98.11 ±3.85
	Thymus vulgaris						Hedera helix					
Chlorophyll a+b (µg/g d.m.)	512.82 ±5.02	520.25 ±4.69	502.56 ±3.78	505.42 ±2.48	420.28 ±6.22	402.87 ±3.14	Chlorophyll a+b (µg/g d.m.)	512.82 ±5.02	520.25 ±4.69	502.56 ±3.78	505.42 ±2.48	420.28 ±6.22
Carotenoids (µg/g)	132.22 ±1.92	129.04 ±1.87	124.05 ±2.02	122.12 ±1.45	119.36 ±1.58	110.05 ±2.03	Carotenoids (µg/g)	132.22 ±1.92	129.04 ±1.87	124.05 ±2.02	122.12 ±1.45	119.36 ±1.58

Source: author's work based on laboratory examinations.

Plants of the experimental population of Agastache foeniculum (Lamiaceae) accumulated higher levels of phenolic compounds under the conditions of the applied drought stress. Thus, in this group of plants, the amount of bound phenolic compounds under 70% drought stress increased significantly at the II term of plant material collection for the analysis, 217.17 mg · 100 g^{-1} versus 252.12 mg · 100 g^{-1} of the herb.

Also, in the case of lemon balm (Melisa officinalis, Lamiaceae), the most phenolic compounds were found in plants growing at 70% of the water capacity of the substrate. Agastache foeniculum showed lower levels of phenolic compounds compared to Melisa officinalis plants. The content of phenylpropanoids, flavonols and anthocyanins in all the species tested appeared to vary (Table 3), but at the same time, high enough for plants with medicinal and health-promoting properties for the human body.

Table 3. Contents of phenolic compounds in the plants *Agastache foeniculum* (Lamiaceae)*, Melissa officinalis* (Lamiaceae)*, Thymus vulgaris* (Lamiaceae), *Allium schoenoprasum* (Amaryllidaceae), *Anethum graveolens* (Apiaceae), and *Hedera helix* (Araliaceae) measured after six weeks of the cultivation experiment, i.e. after four (I) and five (II) weeks from the establishment of the experiment (control) or after four (I) and five (II) weeks of drought stress, respectively, representing 70 and 30% of the total soil water capacity, (± SE) standard error, α= 0.05

Assessed biochemical trait	control		70%		30%		control		70%		30%	
	I	II	I	II	I	II		I	II	I	II	I
	Agastache foeniculum						**Melissa officinalis**					
Total phenols (mg-100g-1)	119.69 ±6.94	149.60 ±2.54	217.17 ± 9.06	252.12 ±4.17	191.41 ±30.62	162.7 ±1.05	Total phenols (mg-100g-1)	119.69 ±6.94	149.60 ±2.54	217.17 ± 9.06	252.12 ±4.17	191.41 ±30.62
Phenylpro-panoids (mg-100g-1)	115.65 ±3.15	205.55 ±7.50	194.95 ±10.31	222.22 ±24.16	175.25 ±16.90	183.33 ±5.46	Phenylpro-panoids (mg-100g-1)	115.65 ±3.15	205.55 ±7.50	194.95 ±10.31	222.22 ±24.16	175.25 ±16.90
Flavonols (mg-100g-1)	51.20 ±1,04	54.68 ±1.80	40.28 ±2.56	42.54 ±6.09	35.47 ±2.64	31.86 ±0.78	57.11 ±5.66	59.83 ±7.07	54.87 ±6.89	53.35 ±9.40	67.91 ±4.09	63.95 ±13.75
Anthocyanins (mg-100g-1)	10.75 ±1.89	15.71 ±0.94	16.12 ±1.64	19.43 ±6.45	15.92 ±3.06	20.05 ±1.79	16.12 ±4.96	11.99 ±3.41	11.37 ±4.13	13.43 ±4.13	36.38 ±11.75	15,09 ±2.18
	Allium schoenoprasum						**Anethum graveolens**					
Total phenols (mg-100g-1)	252.22 ±12.15	322 ±25.10	317.17 ± 11.02	352.12 ±5.17	260.20 ±12.64	262.72 ±11.05	327.27 ±9.12	340.91 ±2.07	333.84 ±3.46	125.05 ±15.89	109.6 ±14.8	161.92 ±9.16
Phenylpro-panoids (mg-100g-1)	89.65 ±2.12	92.60 ±5.10	94.95 ±4.31	92.22 ±4.16	75.55 ±3.50	83.33 ±2.46	368.18 ±68,95	314.65 ±103.15	263.13 ±25.64	415.66 ±46.46	453.03 ±140.01	531.31 ±88.69
Flavonols (mg-100g-1)	83.11± 1.80	88.11± 6.20	80.28± 2.52	42.54± 6.09	35.47± 2.64	51.86± 0.78	47.11± 2.66	52.83± 4.07	49.98± 3.07	53.35± 2.40	47.91± 3.09	43.95± 2.75
Anthocyanins (mg-100g-1)	15.71 ±1.94	16.12 ±1.64	16.12 ±1.24	19.43 ±1.45	11.92 ±1.3.6	18.05 ±1.29	16.12 ±4.96	11.99 ±3.41	11.37 ±4.13	13.43 ±4.13	36.38 ±21.75	15,09 ±2.18
	Thymus vulgaris						**Hedera helix**					
Total phenols (mg-100g-1)	217.27 ±9.12	290.80 ±8.03	233.84 ±9.46	225.05 ±11.09	269.60 ±8.80	169.02 ±3.16	352.22± 10.15	362.32± 9.10	357.17± 11.02	342.12± 5.17	269.25± 10.64	267.92± 8.05
Phenylpro-panoids (mg-100g-1)	162.18 ±4,05	114.65 ±3.15	163.13 ±2.04	115.66 ±4.06	153.03 ±40.01	131.31 ±8.09	289.65 ±2.12	292.25 ±5.10	294.95 ±4.31	292.22 ±4.16	195.55 ±3.50	183.33 ±2.49
Flavonols (mg·100g-1)	77.11± 14.66	59.83± 17.07	54.87± 6.89	73.35± 9.40	97.91± 34.09	93.95± 13.75	83.11± 1.80	92.11± 6.20	80.28± 2.52	82.54± 6.09	85.47± 2.64	71.86± 0.78
Anthocyanins (mg·100g-1)	16.12± 4.96	11.99± 3.41	11.37± 4.13	13.43± 4.13	36.38± 21.75	15,09± 2.18	35.71± 1.94	46.12± 1.64	36.12± 1.24	39.43± 1.45	41.92± 1.56	38.05± 1.29

Source: author's work based on laboratory examinations.

DOI: 10.34659/eis.2026.97.2.1129

Discussion/Limitation and future research

All of the species examined in the presented experimentation proved useful for the environmentally friendly innovative technology of air-filtering VGs. The VGs production-related experimentation included the plant's materials, such as the *Agastache foeniculum* (Lamiaceae), *Melissa officinalis* (Lamiaceae), *Thymus vulgaris* (Lamiaceae), *Allium schoenoprasum* (Amaryllidaceae), *Anethum graveolens* (Apiaceae) and the long-lived vine species *Hedera helix* (Araliaceae) as a groundcover plant to improve the urban microclimate. This species was tested with a variety of methods, and the *Hedera helix* 'Thorndale' was found to be the most useful in eliminating particulate matter and metal particles present on its surface as secondary pollutants. *Hedera helix* 'Thorndale' grows vigorously and shrubs well. Common ivy can also perform well as a ground cover plant for ceramic vertical elements, building walls, and tree trunks, as well as covering sunny or shady vertical areas where establishing a lawn is difficult. In addition, it will successfully create a shield against the ingress of dust and dirt and protect against secondary air pollution. Like other plants, it efficiently absorbs CO_2 and produces oxygen necessary for human life. Since ivy plants produce a vast surface area capable of accumulating pollutants quickly, this is an important reason why climbing plants should be widely used in producing VGs.

In the course of the experiments and experimental work described above, the usefulness of herbaceous perennial species from the Light-flowered (Lamiaceae) botanical families with valuable properties, such as thyme (*Thymus vulgaris* L.), lemon balm (*Melissa officinalis* L.), fennel tussock (*Agastache foeniculum* (Pursch) Kuntze), and common leek (*Origanum vulgare* L.) was proven. As a ground cover plant, we will use the common ivy (*Hedera helix* L.) of the Araliaceae (Araliaceae). This choice of species is optimal, as it will provide a permanent covering for the VGs, regardless of the raw material. No replenishment of seedlings will be required, and the plants can tolerate urban conditions, as demonstrated in the experimental work. Their growth vigour is optimal for a sustainable green mass for at least five years.

The presence of plants favours air purification, but a significant level of phytoremediation of air pollutants can be achieved with adequately planned green infrastructure. One of the design principles is that the applied technology should be cost-effective, which, in relation to the VGs, raises, among other things, the question of optimising the selection of plants. Suppose plant species or varieties are to be proposed for air pollution reduction efficiency. In that case, the presented analysis results will be helpful, especially for those producers offering the construction of VGs in the continental climate zone.

The practical implementation of this type of technology includes the necessity to consider the latest state-of-the-art knowledge in fields like: 1) precision agriculture, which uses technology to optimise yields and reduce waste, which can be done by collecting data on e.g. temperature, humidity of soil and air, and sunlight levels to suport decision-making processes, 2) relavant sensors and Internet-of-Things technologies (IoTs).

Technical barriers and challenges include also 1) verification of technology components, which differ from project to project, 2) development of prototypes and their demonstration, 3) testing and validation of VGs in real-world conditions, 4) adverse or upnormal weather conditions, 5) relatively high upfront costs comparing the traditional (horizontal) gardening, i.e. approximately 1.000 – 2.000 PLN per m^2 (compare with e.g. https://ogrodywertykalne.eu).

Possible financing sources include Horizon Europe's programmes and EU climate funds, such as:

- the European Innovation Council's (EIC) Accelerator and PreAccelerator;
- the sustainability programmes of the European Institute of Innovation and Technology (EIT) via:
  - the EIT Food,
  - the New European Bauhaus of the EIT Strategic Synergies Cluster,
  - the EIT Manufacturing,
  - the Climate-Knowledge and Innovation Community (Climate-KIC), e.g. ClimAccelerator programmes.

Future work should focus on optimising the density of plants for climate-focused vertical gardens and verifying the phytoremediation capacity of other plant species suitable for vertical garden production.

In addition, complex measures of vertical gardens' climate impacts would allow for their inclusion into the European Emissions Trading System (ETS). To the best of our knowledge, very few vertical garden solutions in the world are purposefully designed to filter the air in combination with measurements and report the results continuously to their users or to the services responsible for the compliance of companies with environmental standards as this is all highly important as the development of such impact measurement would allow the inclusion of the beneficial effects of the plants used for vertical garden production into the European ETS calculations. By doing so, the production costs could decrease in industries which the ETS will soon regulate, i.e. since 2027 – buildings, road transport and additional sectors of the economy (European Commission et al., 2024).

Conclusions

The essential aim of the work was to identify a unique set of seed plants suitable for reducing air pollution. All the species used in our set fulfilled this task perfectly. Their leaves were covered with a thick layer of wax or hairs, which, as shown above, fulfilled the requirements of phytoremediation plants. Even whole shoots, i.e. above-ground organs, perform this function to a great extent. At the same time, when used as a cover crop, herbaceous plants planted on shelves can act as a food base with medicinal, spice and melliferous properties. As a plant to cover VG structures and perennials, the common ivy (*Hedera helix* L. Araliaceae) can be proposed as an excellent phytoremediation plant.

All of the proposed species are melliferous. Therefore, tussocks in the production of the VGs can be planned to form the peripheral part of the shelves to attract honeybees and other pollinating insects, similar to a typical honey plant. Lemon balm can successfully perform a similar function (Table 3), so it will be planted alternately with tussock, while shrubs such as *thyme* (*Thymus vulgaris*) and oregano (*Origanum vulgare* L.) in their older growth stage could be planted in the inner part of the VGs.

The control treatment proved to be the best with regard to ivy growth strength. Interestingly, if periodic drying of the substrate occurred after a certain two-week period of growth destabilisation, the plants' adaptation process to the stress conditions took place, and the growth rate was levelled to the values found under control conditions.

Common ivy can be planted in boxes as a groundcover plant for VGs in free-standing racks. Such control plants help to clean the air from various dust pollutants and trace elements deposited on dust as secondary pollutants and from various types of gaseous pollutants, mainly carbon and nitrogen oxides, important components of smog.

The important characteristics of and results obtained with regard to perennials such as herbaceous angiosperms, thyme (*Thymus vulgaris* L., Buttercups – Lamiaceae), fennel spike (*Agastache foeniculum* (Pursch) Kuntze, Lamiaceae), common leek (*Origanum vulgare* L. Lamiaceae), lemon balm, (*Melissa officinalis* L., Lamiaceae) dill (*Anethum graveolens* L., Celery – Apiaceae), chive garlic (*Allium schoenoprasum* L., Amaryllidae – Amaryllidaceae) are summarised in Table 1. Dill is an annual but sprinkles its seeds directly into the ground to grow each season without re-sowing, while the other species are herbaceous perennials.

The research results presented in the article add value on a social level by positively contributing to the quality of societal life, increasing health, and slowing down climate change. The primary purpose of the analysed innovation is the foreseeable positive impact on these social aspects. The proposed approach will contribute to improved air quality through an increase in the amount of oxygen and a reduction in airborne materials harmful to human health.

When plant species are proposed for air pollution reduction, the presented analysis results will be helpful for producers specialising in vertical gardens. The study results include plant selection suitable for vertical gardening, aiming at pollution filtering and efficient oxygen production.

Acknowledgements

This research has been supported by the Norwegian Fund within the framework of project No. NORW.19.01.04-02-0046/20 *Entrepreneurship Development and Innovation*.

The publication has been supported by the Ignatianum University in Cracow.

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Agnieszka KLUCZNIK-TÖRŐ

POTENCJAŁ FITOREMEDIACYJNY WYBRANYCH GATUNKÓW ROŚLIN ZIELONYCH W OGRODACH WERTYKALNYCH W CELU OGRANICZENIA ZANIECZYSZCZENIA POWIETRZA W MIASTACH I INTEGRACJI Z UNIJNYM SYSTEMEM HANDLU EMISJAMI

STRESZCZENIE: Celem poznawczym było udowodnienie tezy, że ogrody wertykalne oparte na odpowiednim doborze gatunków roślin są w stanie celowo i skutecznie redukować zanieczyszczenie powietrza w środowisku miejskim, natomiast celem praktycznym jest zaproponowanie oryginalnej metody odpowiedzi na Europejski System Handlu Emisjami w celu osiągnięcia celu zerowej emisji w budownictwie. W badaniach zastosowano analizę najczęściej występujących zanieczyszczeń w obszarach metropolitalnych na przykładzie Krakowa, metody eksperymentów terenowych, badania biochemiczne i laboratoryjne, analizę statystyczną oraz techniki ilościowe. Sprawdzono odpowiednie właściwości i adekwatność wybranych gatunków o cenionych właściwościach leczniczych i prozdrowotnych. Wykorzystano następujące gatunki roślin: koper włoski, melisę lekarską, tymianek pospolity, szczypiorek, koper ogrodowy i bluszcz pospolity. Analiza dowiodła, że za pomocą ogrodów wertykalnych można osiągnąć znaczący poziom fitoremediacji zanieczyszczeń powietrza. Technologia ta oferuje obiecujące rozwiązanie oparte na naturze w zakresie połączonej innowacji odpowiadającej na nowy trend w produkcji żywności – rolnictwo miejskie i skuteczną redukcję gazów cieplarnianych.

SŁOWA KLUCZOWE: zanieczyszczenia powietrza, Europejski System Handlu Uprawnieniami do Emisji, ETS, zielona infrastruktura, rozwiązania oparte na przyrodzie, fitoremediacja

DOI: 10.34659/eis.2026.97.2.1129