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Research of gas exchange and air purification processes by plants of the common privet (*Ligustrum vulgare* L.) species

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Abstract. Growing urbanization creates air pollution problems, which is becoming dangerous for human health and unsuitable for indoor ventilation. An effective solution is the combination of green structures with engineering systems, which requires the development of new methods and quantitative laboratory studies of gas and mass exchange processes of plants. The purpose of the study was to quantify the ability of plants of the common privet (*Ligustrum vulgare* L.) to release and absorb oxygen and CO_2, as well as to study the effectiveness of air purification from particulate matter in order to properly take into account the impact of plants in the process of their selection for greening urban landscapes. The research was carried out according to the methodology developed by the authors in a gas exchange chamber, which was upgraded to model external conditions and study plants with small leaf area and developed stems. The results of the experiment showed that *Ligustrum vulgare* L. bushes with a small total photosynthetic leaf surface area are inefficient for carbon dioxide absorption in an urbanized environment, so plants with a significant proportion of photosynthetically active biomass and fast-growing plants should be preferred. It was determined that at maximum illumination, the degree of absorption of PM2.5 and PM10 by *Ligustrum vulgare* L. bushes was $8.84 \cdot 10^{-5}...1.5 \cdot 10^{-4}$ μg/s, which confirms the effective absorption of particulate matter with a diameter of up to 2.5 and up to 10 μm from the air by the studied plants. The results obtained indicate an increase in the concentration of total volatile organic compounds in the outlet compartment, which indicates the active release of volatile phyto-organic substances by plants in the amount of 2.442...2.973 μg/s. The results of the study can be used for effective taxonomic selection of woody plants during the design and creation of urban green spaces that are resistant to the conditions of the urban environment

Keywords: green structures; sponge agents; solid particles absorption; PM2.5; PM10; CO_2 absorption

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Introduction

Air pollution has become a serious environmental problem in urban areas of developing countries. The main cause of this problem is urbanization, which has led to an increase in construction sites, vehicles, high energy consumption and industrialization. In this regard, the impact of vegetation on mitigating these negative effects is of considerable interest to scientists and urban planners. For example, urban vegetation is believed to provide a variety of social and environmental benefits to society, collectively referred to as cultural ecosystem services, thereby increasing the resilience of cities. Urban green infrastructure is represented by trees, hedges, and various types of vegetation that can act as a porous barrier to pollutants, changing their dispersion patterns and providing additional surface for deposition.

However, according to the literature review, there is a growing interest in the topic of green structures in the world due to the combination of various effects in one solution. Green structures are biotechnical systems in which the construction of buildings and structures and individual elements are combined with living plants, forming a single system of living and non-living components of biogeocenoses of modern cities in the concept of sustainable development. Green structures include vertical greening systems (green walls, facades); horizontal greening systems (green coatings, green balconies and terraces); kinetic (mobile) greening; greening with the use of algae, as described by such scientists as M. Kravchenko & T. Tkachenko (2023). Green structures provide solutions to a number of important environmental problems, increasing the energy efficiency of indoor climate formation and improving the microclimate of territories through additional thermal insulation of buildings, providing a cooling effect (evapotranspiration) and reflection of solar radiation, and also allow rainwater retention, which leads to a reduction in the load on stormwater drainage systems within the concept of a sponge city (Tkachenko *et al*., 2023).

A separate important environmental function of green structures is their impact on the sanation and improvement of indoor and outdoor air quality due to the phytoncidal properties of plants and the purification of air from various pollutants and dust. The removal of air pollutants by trees and other vegetation, called phytoremediation, is of particular interest because poor air quality in urban areas is one of the main environmental problems that have a direct impact on public health on a global scale. The paper by S. Bandehali *et al.* (2021) provides comprehensive information on plant species that can remove pollutants such as volatile organic compounds (TVOC) and particulate matter (PM), describes the sources of indoor air pollutants, and their impact on human health. In addition, the authors investigated the potential role of green walls and potted plants in improving indoor air quality, proving the effectiveness of this process and suggesting a list of plant species suitable for phytoremediation of indoor air. According to N.J. Paull *et al.* (2020), PM removal and relative frequencies of particle size fractions were found to be statistically different between species, locations, and seasons. It was shown that green wall plants are effective in accumulating PM of different fractions, as all plant species studied had the same efficiency in PM removal with minimal influence of leaf characteristics.

An equally important function of the vegetation of green structures is the absorption of carbon dioxide. M. Lalošević *et al.* (2018) studied green roofs in a densely populated urban area in the centre of Belgrade (Serbia). To analyse the impact of residential urban neighbourhoods on CO_2 concentrations, they developed a baseline model (fully consistent with the actual state and real conditions in the area), as well as modernization models (which include the baseline model with added elements of extensive and intensive green roofs) and conducted numerical simulations of CO_2 concentrations for all presented models. The results of the numerical modelling showed that the use of green roofs instead of classical flat roofs in the Belgrade climate zone can reduce the CO_2 concentration in the atmosphere around the building by up to 11%, on average by 2.3%. It was also found that the greatest impact on reducing CO_2 concentration is felt in the immediate vicinity of plants.

A separate type of green structures intended for engineering and technical structures are rain gardens, which are installed along the road near the roadway and are intended primarily to capture water from both sides. However, no less important benefits for the urban environment from this type of structure as sponge agents are the accompanying effects, namely noise reduction, air purification, CO_2 absorption, O_2 release, increase of the video-ecological aspect and maximum approximation of the urban environment to the natural one. Vegetation of sponge agents can be represented by trees, shrubs, bushes and grasses, occupying a certain part of the land area in cities and improving air quality. According to the analysis of O. Lukash & A. Kushnir (2023), the leader among the taxons used in the construction of hedges within large cities of Ukraine is common privet (*Ligustrum vulgare* L.), which accounts for more than 85% of all plants planted in green areas. In addition, this type of hedges is known for its ability to absorb harmful substances and produce a significant percentage of oxygen in the atmosphere. The purpose of the study was to investigate gas exchange in plants of the *Ligustrum vulgare* L. species, which involves quantifying its ability to release and absorb oxygen and carbon dioxide, as well as to purify the air from harmful substances and release volatile phytobiological substances in order to properly account for the impact of plants on the ecological situation in urbanized cities. In the presented work, it is hypothesized that green structures, as sponge agents representing the urbanized environment, improve air quality compared to areas without them; the degree of removal of pollutants from the air is directly related to the volume and structure of vegetation representing green structures.

Materials and Methods

The material for the research was *Ligustrum vulgare* L., a tall, upright shrub with a dense crown up to 4-5 m in height, which is easy to form and resistant to growing conditions in urban environments. It is widely used in urban greening as plantings for city parks,gardens, squares, residential areas, industrial areas, and motor transport systems. Two mature bushes without pest damage were selected for the study (Fig. 1). The Convention on Biological Diversity (1992) was followed during the study. The study was conducted in 2023.

Figure 1. Specimens of *Ligustrum vulgare* L. bushes that were the objects of the study
Source: created by the authors

The dimensions of bushes I and II of *Ligustrum vulgare* L. were, respectively: height – 67 and 72 cm, width – 85 and 93 cm, depth – 56 and 58 cm. The volumes of the bushes, respectively, were: $V_1 = 0.32$ m^2 and $V_2 = 0.39$ m^2. The plant care regimen before the study was in line with the recommendations for this species and was as close as possible to the operating conditions of green structures. The experiment was carried out in a gas exchange chamber adapted to reproduce the external conditions of the urbanized environment and study plants with a small photosynthetic mass, according to the methodology developed by the authors (Fig. 2).

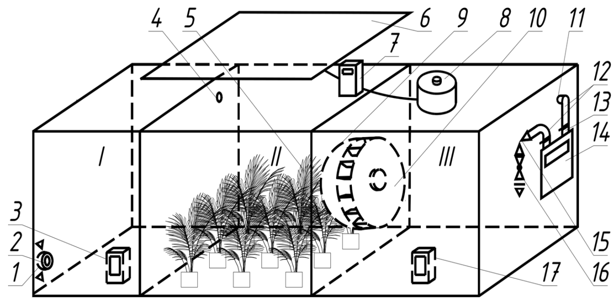

Figure 2. Gas exchange chamber

Notes: I – intake chamber (300×1000×1000(h)); II – gas exchange chamber (1000×1000×1000(h)); III – outlet chamber (1000×1000×1000(h)); 1 – protective grid at the inlet; 2 – inlet (ø 15); 3 – gas analyser; 4 – overflow hole (ø 15); 5 – plants; 6 – lighting panel with full-spectrum LED (light-emitting diode) phytolamps; 7 – voltage relay with a voltmeter; 8 – lighting regulator; 9 – protective grid at the entrance to the fan; 10 – mixing fan; 11 – air outlet; 12 – pipelines; 13 – filter; 14 – gas meter; 15 – control valve; 16 – ball valve (authors' original scheme); 17 – gas analyser
Source: created by the authors

The chamber operates as follows: air enters through the protective grid 1 and the inlet 2 into the intake chamber I with a gas analyser 3. Through the flow hole, it passes to the gas exchange chamber II with experimental plants 5. The chamber is illuminated by a lighting panel with LED phytolamps 6, the actual voltage on which is controlled by a voltage relay with a voltmeter 7, and the brightness of which is set by the regulator 8. After gas exchange, the air is forced through the protective grid 9 by the mixing fan 10 to the outlet chamber III. The mixing fan 10 provides intensive mixing of air in this chamber to avoid the influence of uneven distribution of gases in chamber II. From this chamber, the air exits through an outlet 11 to the pipeline system 12, which contains a filter 13, a gas meter 14, a control 15 and a shut-off 16 valve. The latter is used to prevent dust from entering when the plant is not in operation and can be closed without changing the position of the control valve 15. The gas concentration at the outlet is controlled by a gas analyser 17 in chamber III.

To measure the illumination, a Mustech (China) luxmeter is used, which is introduced after the experiments and slowly moved evenly to cover the entire area of the chamber at the plant level and to average the illumination. The flow orifices are designed to provide a meaningful velocity to avoid back-diffusion of gases. Since the mixing fan 10 performs the mixing function, its speed was not regulated. The lighting regulator 8 should not create electromagnetic interference that could be induced on the gas analysers or the luxmeter. Therefore, in this work, a laboratory autotransformer (LATR) (Megommeter, Ukraine) was used. Voltage relays with a voltmeter were installed to record the current voltage for the possibility of setting the same illumination, as well as to protect the lamp from accidental overvoltage. The air density was calculated using the following formula:

$$\rho = \frac{P_b}{286.9 \cdot T} \cdot \frac{1+d}{1+1.6085744 \cdot d} = \\ = \frac{P_b}{286.9 \cdot (273.15+t)} \cdot \frac{1+d}{1+1.6085744 \cdot d}, \quad (1)$$

where P_b is barometric pressure, Pa; T is air temperature, K; d is air moisture content, g/(kg of dry air); t is air temperature, °C. The saturated vapour pressure was determined by the modified Buck's formula, Pa, after basic simplifications without loss of accuracy:

$$Psat = EF \cdot \begin{cases} 611.15 \cdot e^{\left(23.85455 - \frac{T}{333.7}\right) \cdot \left(1 - \frac{279.82}{T+6.67}\right)} = 611.15 \cdot e^{\left(23.036 - \frac{t}{333.7}\right) \cdot \frac{t}{t+279.82}}, & T < 273.15\text{K}, t < 0°C \\ 611.21 \cdot e^{\left(19.84282 - \frac{T}{234.5}\right) \cdot \left(1 - \frac{257.14}{T-16.01}\right)} = 611.21 \cdot e^{\left(18.678 - \frac{t}{234.5}\right) \cdot \frac{t}{t+257.14}}, & T \geq 273.15\text{K}, t \geq 0°C \end{cases} \quad (2)$$

where EF is the correction for the influence of air molecules (enhancement factor), which is the ratio of the saturated vapour pressure in air to this pressure in a "vapour-liquid-only" system:

$$EF = 1 + 10 - 4 \cdot EF = \begin{cases} 1.00022 + P_b \cdot (6.4 \cdot 10^{-10} \cdot (T - 546.3) \cdot T + 5.1581 \cdot 10^{-5}), & T < 273.15; \\ 1.00072 + P_b \cdot (5.9 \cdot 10^{-10} \cdot (T - 546.3) \cdot T + 4.7220 \cdot 10^{-5}), & T \geq 273.15, \end{cases} = \\ = \begin{cases} 1.00022 + 6.4 \cdot 10^{-10} \cdot P_b \cdot (5{,}984.375 + t^2), & t < 0; \\ 1.00072 + 5.9 \cdot 10^{-10} \cdot P_b \cdot (5{,}423.7288 + t^2), & t \geq 0. \end{cases} \quad (3)$$

The moisture content of the air was determined by temperature and hygrometer readings – relative humidity φ, %, or dew point temperature T_d, K, or T_d, °C, according to equation:

$$d = \frac{0.623 \cdot P_{sat} \cdot \varphi}{P_b - P_{sat} \cdot \varphi} = \frac{0.623 \cdot P_{sat,d}}{P_b - P_{sat,d}}, \quad (4)$$

where P_{sat} is the pressure of saturated vapour at a given air temperature, Pa; φ is the relative humidity (dimensionless); $P_{sat,d}$ is the pressure of saturated vapour at the dew point temperature, Pa. The calculation of the carbon dioxide absorption rate ΔG_{CO_2}, g/s, was carried out according to formula:

$$\Delta G_{CO_2} = 0.0015197 \cdot (Y_{in} - Y_{out}) \cdot G, \quad (5)$$

where Y_{in} is the mole fraction of carbon dioxide in the inlet zone, ppm; Y_{out} is the mole fraction of carbon dioxide in the outlet zone, ppm; G is the mass flow rate of air, kg/s. Oxygen release was estimated according to the gross photosynthesis reaction $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2\uparrow$, g/s, using formula:

$$\Delta G_{CO_2} = 0.72709 \cdot \Delta G_{CO_2}. \quad (6)$$

The absorption of harmful impurities s or particles of a certain size, µg/s, mg/s, was calculated using formula:

$$\Delta Gs = (q_{in}/\rho_{in} - q_{out}/\rho_{out}) \cdot G = (q'_{in} - q''_{in}) \cdot G, \quad (7)$$

where q_{in} is the concentration of an impurity or particles of a certain size, respectively, µg/m³, mg/m³; q_{out} is the concentration of an impurity or particles of a certain size, respectively, µg/m³, mg/m³; q'_{in} is the concentration of an impurity or particles of a certain size, respectively, µg/kg, mg/kg; q''_{in} is the concentration of an impurity or particles of a certain size, respectively, µg/kg, mg/kg; G is the mass flow rate of air, kg/s.

Results

A general view of the gas exchange chamber with *Ligustrum vulgare* L. plants is shown in Figure 3. The studies were conducted at an atmospheric pressure of 1000 hPa and at CO_2 concentrations of 400 ppm and 1025 ppm in the room. The rates of air density, saturated vapour pressure, and air moisture content at the chamber inlet, outlet, and in the meter, respectively, are presented in Table 1.

Figure 3. General view of the gas exchange chamber during the day and at night with plants of *Ligustrum vulgare* L.
Source: created by the authors

Table 1. Calculated rates of air density, saturated vapour pressure and air moisture content at the chamber inlet, outlet and in the meter

Air density ρ, kg/m³			Saturated vapour pressure P_{sat}, hPa			Air moisture content, d		
inlet	outlet	in the meter	inlet	outlet	in the meter	inlet	outlet	in the meter
1.166	1.152	1.120	29.972	35.820	56.216	0.009	0.012	0.017
1.156	1.143	1.107	35.820	40.251	63.095	0.007	0.015	0.024

Source: created by the authors

The rates of air flow and carbon dioxide concentration in plants are presented in Table 2. The readings of the gas analyser in the inlet compartment, in the gas exchange compartment, and in the outlet compartment are presented in Table 3.

Table 2. Air flow rate and carbon dioxide concentration in plants

Air flow rate		Carbon dioxide concentration in plants, g/kg
kg/s	kg/h	
2.668E-05	0.096	0.992
2.513E-05	0.090	1.589

Source: created by the authors

Table 3. Gas analyser readings in the inlet compartment, in the gas exchange compartment and in the outlet compartment

Gas analyser readings	PM2.5, µg/m³	PM10, µg/m³	HCHO, mg/m³	TVOC, mg/m³	CO_2, ppm	Temperature, °C	Relative humidity, %
In the inlet compartment	14	15	0.115	0.4915	400	24	48
	19	21	0.089	0.461	1,025	27	33
In the gas exchange compartment	-	-	-	-	653	28.5	68.4
	-	-	-	-	1,046	37	80
In the outlet compartment	10	11	0.599	0.591	678	27	56
	12	14	0.065	0.591	1,048	29	60

Note: HCHO – formaldehyde
Source: created by the authors

The air parameters at the meter inlet, such as temperature and relative humidity, were 34.9°C and 37.0°C and 47.4% and 60.3%, respectively. The elevated temperature level in the gas exchange compartment can be explained by the presence of LED phytolamps, which release energy in the form of light and heat during operation. This effect is especially important when growing plants in conditions where lighting and temperature conditions are important for their growth and development. Calculations of the degree of carbon dioxide absorption and oxygen release were carried out using formulas (5; 6), the results of which are presented in Table 4.

Table 4. The degree of carbon dioxide absorption and oxygen release by plants of the *Ligustrum vulgare* L. species

Carbon dioxide absorption		Oxygen release	
g/s	g/h	g/s	g/h
-1.127E-05	-0.040	-8.196E-06	-0.029
-8.785E-07	-0.003	-6.388E-07	-0.002

Source: created by the authors

Plants purify the air around the clock. However, during active photosynthesis, the plants saturate the air with oxygen, and during respiration only, they secondary pollute it with carbon dioxide. The photosynthetically active biomass of *Ligustrum vulgare* L. is rather small leaves around the perimeter of the bush. The inner part of the bush consists of a dense stem system that does not photosynthesize. The results of the study allow us to conclude that the process of carbon dioxide emission by *Ligustrum vulgare* L. plants prevails instead of its absorption. With a mole fraction of carbon dioxide in the air near the plants of 653 ppm, a mole fraction of 678 ppm was recorded at the output. The total carbon dioxide emission was 11.27 μg/s. With a mole fraction of carbon dioxide in the plant zone of 1,046 ppm, the outlet was 1,048 ppm, i.e. almost the same mole fraction. Carbon dioxide emission dropped to an unreliable, close to zero rate of 0.8785 μg/s. Calculations of the degree of absorption of PM2.5, fine dust (PM10), HCHO and total TVOC were carried out according to formula (7), the results of which are presented in Table 5.

Table 5. The degree of absorption of impurities and particles of a certain size by plants of the *Ligustrum vulgare* L. species

Absorption of PM2.5		Absorption of PM10		Absorption of HCHO		Absorption of TVOC	
μg/s	μg/h	μg/s	μg/h	g/s	g/h	g/s	g/h
8.868E-05	0.319	8.840E-05	0.318	-1.125E-05	-0.040	-2.442E-06	-0.008
1.5 E-04	0.537	1.4 E-04	0.535	5.057E-07	0.002	-2.973E-06	-0.010

Source: created by the authors

The most harmful PM is PM2.5. They can penetrate deeply into the lungs and cause irritation of the alveolar walls, their damage, and respiratory distress (Li & Liu, 2021). PM2.5 enters the bloodstream through the alveolar-capillary barrier, causing cardiovascular and respiratory diseases, as well as cancer. Moreover, it is now known to cross the blood-retinal barrier, the epithelial barrier in human nasal epithelial cells, and the skin barrier (Xian *et al.*, 2020). PM10 can also penetrate deeply into the lungs and cause health problems, but they are not as harmfuL. The results of the study under maximum illumination showed the degree of absorption of PM2.5 and PM10 by *Ligustrum vulgare* L. bushes to be $8.84 \cdot 10^{-5}$... $1.5 \cdot 10^{-4}$ μg/s, which suggests that the plants under study effectively absorb PM with a diameter of up to 2.5 and up to 10 μm from the air.

Firstly, plants adsorb PM, when in contact with the microstructure of the leaf surface or when immersed in the cuticle layer. Secondly, PM around the leaf surface is absorbed by the plant through stomata in the process of photosynthesis and transpiration. Thirdly, when the air saturated with PM reaches the crown layer of the plant, the flow rate decreases, which leads to a blocking effect. In the case of the study with *Ligustrum vulgare* L. bushes, which have a voluminous stem part but a small leaf area, it is likely that PM absorption occurred around the leaf surface through stomata during photosynthesis and transpiration.

An interesting result is the increase in the concentration of total TVOC in the outlet compartment, which indicates not the degree of absorption, but the active release of volatile phyto-organic substances by plants in the amount of 2.442...2.973 μg/s. No stable absorption of HCHO was detected, the results were unreliable as they had a very small order and the opposite sign. It is important to note that an increase in TVOC concentration is not always a negative phenomenon. The release of TVOC by plants is an important means of communication and self-defense. In nature, the behaviour of plants that emit TVOC is often considered a defence mechanism. It can be interpreted as an induced resistance, i.e., the release of volatile compounds by plants after mechanical damage, stressful situations, or insect feeding (McCormick *et al.*, 2019). Understanding the mechanisms and types of TVOC released by plants, as well as the biological information conveyed by the released TVOC, can help improve the quality of the urban environment and individual biogeocenoses (Kim *et al.*, 2020).

A comprehensive quantitative study of green structures as sponge agents, taking into account the concomitant positive effects on the air environment, is a fundamentally new approach to the effective development of cities affected by military operations, as well as to improving the quality of the urban environment in generaL. There is a need to grow air-purifying plants in all unused areas of urban and rural areas, namely along roads, in adjacent areas, between fields, gardens, etc. Fast-growing ornamental phytoncidal shrubs, such as *Berberis*, *Cotoneaster lucidus*, *Cornus alba*, *Ligustrum vulgare* L., *Physocarpus opulifolius*, *Philadelphus coronaries*, *Spiraea*, various shrub forms of *Cupressáceae*, including *Juníperus*, are usually recommended for greening. In this study, *Ligustrum vulgare* L. was considered in detaiL.

Whenever possible, hedges should be preferred to construction fences. If a hedge is not possible, most fences can be easily vertically landscaped with climbing plants (various species of *Parthenocissus, Hedera, Clematis*, etc.). Similar vertical (on the facades) and vertical-horizontal (covering the walls and roof) greening can also provide passive air conditioning and thermal insulation. And for very intensive land use, where there is not enough soil for planting, green roofs and terraces on buildings should be used, which also provide thermal and solar radiation improvements. The study confirmed the hypothesis that green structures, as sponge agents, can improve air quality compared to areas without them, and the degree of removal of pollutants from the air is directly related to the morphological characteristics of the vegetation that represents green structures.

Discussion

The results of studies presented in the scientific literature allow to draw a number of valuable conclusions about the impact of vegetation on changes in air quality, but often limit the determination of quantitative indicators of the absorption of certain types of pollutants by specific plants. In addition, research is hampered by the lack of rapid methods to determine the uptake process that need to be developed, and most conclusions that suggest that urban vegetation is an effective means of removing air pollutants are based on modelling results in which pollutant removal is a simple function of deposition rate, pollutant concentration, and some parameters describing vegetation structure (such as biomass index and leaf area).

According to a recent study by J. Linden *et al.* (2023), it was determined that the inclusion of detailed vegetation characteristics in urban air quality modelling would significantly improve the ability to quantify the pollution removal potential of different vegetation types. However, these models often use data from a limited number of sites within a city, making them unlikely to capture changes in canopy structure and urban microclimate conditions. In addition, such models are based on data from chamber studies of plants conducted in the field or in greenhouses, where factors affecting plant physiology and physicochemical processes are studied, as well as studies that measure fluxes of air pollutants, often, for example, over tree crowns. There are only a few studies in which pollutant fluxes have been quantified within vegetation or directly in the crowns of tree and shrub species where pollutant absorption occurs, such as the study by M. Steinparzer *et al.* (2023).

According to the analysis of literature sources, the leaves of trees and grasses allow the removal of PM, gaseous pollutants such as NO_2 (Gong *et al.*, 2022) and CO_2 (Wang *et al.*, 2021), O_3 (Grulke & Heath, 2020) by dry deposition. The removal of organic pollutants by plants has been confirmed by Z. Wei *et al.* (2021). In addition, plants are often used as bioindicators to monitor air pollution by heavy metals. However, the ability of plants to accumulate heavy metals can vary significantly depending on the plant species and its morphology. The authors N. Sevik *et al.* (2020) studied the peculiarities of heavy metal accumulation by some landscape plants growing in the city centre of Kastamonu (Turkey), taking into account plant species and traffic density. For this purpose, samples of leaves and branches were collected from various woody plants commonly used in urban landscape design, including the *Ligustrum vulgare* L. species. It was found that the concentration of Pb in branches was higher than in leaves for all species and depended on traffic density.

Another study conducted by D. Bidolakh & O. Kolesnichenko (2023) helped to study certain ecosystem functions of green spaces (reduction of pollutants, carbon absorption and sequestration, amount of oxygen released). As part of this work, the annual ecosystem function was calculated to absorb 770 kg of harmful compounds (ozone, carbon monoxide, nitrogen dioxide, and PM of various sizes), reduce air pollution by 7.43 metric tons of gross carbon sequestration (19 kg per plant), and reduce water runoff by 684.9 cubic meters. In addition, it was concluded that the highest indicators of ecosystem efficiency belong to park plantings, while trees and shrubs in the central part of the city are more efficient at absorbing pollutants.

However, urban vegetation can also have a negative impact on air quality, in particular through allergenic effects (Poncet *et al.*, 2020), as well as through the emission of TVOC that can form ozone over time (Koppmann, 2020). The results of the experiment in this paper show an increase in the concentration of total TVOC in the outlet compartment of the gas exchange chamber, which indicates not the degree of absorption, but the active release of volatile phyto-organic substances by plants, the impact of which on the air needs to be investigated in future experiments.

The study helped to obtain significant results regarding the peculiarities of the photosynthesis process. The predominance of the process of carbon dioxide emission by *Ligustrum vulgare* L. plants, instead of its absorption, indicates an increase in the photosynthetic mechanism with an increase in carbon dioxide content. But even at this mole fraction, the photosynthetic activity of leaves cannot outweigh the respiration of the entire biomass. The complex and interconnected reactions of photosynthesis are often limited to two more fundamental processes, which are the conversion of solar energy into chemical energy or the diffusion of CO_2 from the atmosphere through stomata and, ultimately, into the chloroplast. The authors E.L. Harrison *et al.* (2020) investigated the effect of plant stomatal morphology (shape, size, pattern) and distribution on photosynthesis through changes in gas exchange, concluding that stomata are an integral part of the photosynthetic mechanism that regulates the amount and rate of O_2 release and CO_2 uptake. It would be interesting to evaluate this in further experiments on the plant species under study.

The results obtained allow us to conclude that the bushes of *Ligustrum vulgare* L., which are characterized by a significant density of sprouts with no leaf mass inside the bush and the presence of leaf mass only on the outer sprouts, have a small total area of photosynthetic leaf surface, are inefficient for carbon dioxide absorption in an urbanized environment. Thus, for efficient carbon dioxide sequestration, plants with a significant proportion of photosynthetically active biomass and fast-growing plants should be preferred. This conclusion is in line with the results of a systematic sampling study of the dependence of CO_2 uptake on the productive photosynthetic area of roadside trees in Bilaspur (India), conducted by A. Ragula & K.K. Chandra (2020). The tree species with the highest CO_2 absorption potential in this study were *Delonix regia, Tamarindus indica,* and *Ficus religiosa*. These were the tree species with the largest crowns, which led to an increase in photosynthetic rate and, ultimately, to carbon dioxide absorption and increased biomass.

Similar to the results of this study, the reduction of PM2.5 and PM10 in the air has been confirmed by numerous studies, indicating a negative correlation between total green area and PM concentrations. However, most of them emphasize the role of trees in this phenomenon, although bushes and herbaceous plants significantly support this potentiaL. In a neighbourhood with high pollution levels and 26% vegetation cover, which is typically inhabited by low-income citizens, K. Wróblewska & B.R. Jeong (2021) conducted an experiment that revealed a 1.6% reduction in PM levels due to trees and another 1.1% due to shrubs and bushes. Similar results were obtained by Z. Cimburova & M. Berghauser Pont (2021), whose research showed that the leaves of woody plants provide an effective large contact area for dry deposition of PM particles, while requiring a relatively small area of land, unlike herbaceous plant species. Another study by D.P.M. Junior *et al.* (2022) compared PM2.5 concentrations in two locations (with and without vegetation cover) in Rio de Janeiro to test how green spaces can actually affect air quality. The results show that the PM2.5 concentrations in the areas with existing tree and shrub vegetation is 33% lower than in other areas. This confirms the possibility of reducing PM2.5 levels through urban green spaces, contributing to the important environmental issue of improving air quality.

Despite the large number of scientific papers on the impact of plants on air quality, the issue of gas exchange in the plant layer plays a key role in ensuring effective air purification, and without a proper understanding of this process, it is difficult to draw valid conclusions. The method and experimental setup for laboratory research of gas exchange in plants shown in this paper allow us to determine the exchange of carbon dioxide and other gases. Tests of the installation confirmed the correctness of the method. The research will contribute to the active implementation of green structures in Ukraine and increase the environmental awareness of residents of modern cities, which are key aspects on the way to implementing the concept of sustainable development of the urban environment.

Conclusions

The results of the study allow to confirm the hypotheses put forward in the work and conclude that the frequency and efficiency of photosynthesis and respiration of *Ligustrum vulgare* L. are closely related to the size of the stems and the leaf surface area, which is small in this plant species, which explains the negative rates of carbon dioxide uptake and oxygen release. *Ligustrum vulgare* L. bushes, which are characterized by a significant density of sprouts with no leaf mass inside the bush and the presence of leaf mass only on the outer sprouts, have a small total area of photosynthetic leaf surface, are inefficient for carbon dioxide absorption in an urbanized environment. They can be recommended as green barriers in urban environments for noise insulation.

The ability to effectively capture PM is an important factor in the selection of optimal plant species for use in urban greening, so it was important to investigate the ability to adsorb PM2.5 and PM10 by *Ligustrum vulgare* L. plants to optimize their use in green urban environments. As can be seen from the results, PM2.5 was adsorbed more than PM10 in terms of the amount of PM absorption, but this is more significant, since PM2.5 poses the greatest threat to human health. It should be concluded that even with a small leaf mass of the studied bushes of the *Ligustrum vulgare* L. species, the amount of adsorbed PM2.5 and PM10 particles is significant for air purification, especially in an urbanized environment, where PM can be toxic and destroy leaf cell tissue, as well as contain heavy metal particles.

By removing pollutants from the air with the help of sponge agents as a special type of green structures, it is possible to improve the quality of the urban environment by reducing the impact of various pollutants. Even if the percentage of air quality improvement due to this type of structure is small, it can be increased by expanding urban vegetation. The methods, techniques, and results obtained correspond to the current level of scientific and technical knowledge, have no global analogues, are unique, and allow for the systematic implementation of green structures with maximum positive effects, engineering calculations, and certification of plant layers.

An increase in the concentration of TVOC in the outlet compartment of the gas exchange chamber may indicate a defence mechanism of *Ligustrum vulgare* L. plants due to stressful situations. However, there is still a lack of reliable and relevant data to understand the true mechanisms of pollutant removal and factors in these systems (plant species, microorganism species, pollutant composition, light source, number of plants), which may be the direction of further research and development of appropriate methods.

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Conflict of Interest

None.

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Дослідження процесів газообміну та очищення повітря рослинами виду бирючини звичайної (*Ligustrum vulgare* L.)

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Анотація. Зростаюча урбанізація створює проблеми забруднення повітря, яке стає небезпечним для здоров'я людей та непридатним для вентилювання приміщень. Ефективне рішення – поєднання зелених конструкцій з інженерними системами, що вимагає створення нових методів і виконання кількісних лабораторних досліджень газомасообмінних процесів рослин. Метою дослідження було кількісне визначення здатності рослин виду бирючини звичайної (*Ligustrum vulgare* L.) виділяти та поглинати кисень і CO_2, а також вивчення ефективності очищення повітря від твердих частинок задля правильного врахування впливу рослин у процесі їх добору для озеленення урбанізованих ландшафтів. Дослідження проводилися за розробленою авторами методикою в газообмінній камері, яка була модернізована для моделювання зовнішніх умов та дослідження рослин із малою площею листя й розвиненими стеблами. За результатами експерименту встановлено, що кущі *Ligustrum vulgare* L., які мають малу загальну площу фотосинтетичної поверхні листя, є неефективними для поглинання вуглекислого газу в урбанізованому середовищі, тому слід віддавати перевагу рослинам зі значною часткою фотосинтетично активної біомаси, і таким, що швидко ростуть. Визначено, що при максимальному освітленні ступінь поглинання PM2,5 та PM10 кущами *Ligustrum vulgare* L. склав $8{,}84 \cdot 10^{-5}...1{,}5 \cdot 10^{-4}$ мкг/с, що підтверджує ефективне поглинання досліджуваними рослинами твердих частинок діаметром до 2,5 та до 10 мкм із повітря. Отримано результати, які свідчать про збільшення концентрації загальних летких органічних сполук у вихідному відсіку, що вказує на активне виділення рослинами летких фітоорганічних речовин обсягом 2,442...2,973 мкг/с. Результати дослідження можуть бути використані для ефективного таксономічного підбору деревних рослин під час проектування і створення міських зелених насаджень, стійких до умов урбанізованого середовища

Ключові слова: зелені конструкції; засоби-губки; поглинання твердих частинок; PM2,5; PM10; поглинання CO_2