https://doi.org/10.15407/scine22.01.012

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MANIFESTATION OF LABILE MECHANISMS OF STABILITY OF WOODY PLANTS IN AN URBANIZED ENVIRONMENT

Introduction. *The plasticity and diversity of plant adaptive strategies determine their ability to survive under extreme environmental conditions and ensure the overall stability of the biogeocenosis.*

Problem Statement. *Recent monitoring studies have shown that most urban street plantings experience significant anthropogenic stress caused by intensive urbanization, particularly due to air and light pollution.*

Purpose. *To determine the physiological and biochemical characteristics underlying the resistance of major tree species in the Kyiv metropolis to light and aerogenic pollution resulting from vehicular emissions.*

Materials and Methods. *The study has focused on street plantings of Tilia cordata Mill., Aesculus hippocastanum L., and Platanus acerifolia (Aiton) Willd. in Kyiv. Field observations have been carried out at two sites: the M.M. Gryshko National Botanical Garden of the NAS of Ukraine (Site 1) and the green zone along Lesia Ukrainka Boulevard (Site 2). Soil temperature and surface CO_2 emissions have been measured. The content of chemical elements in soil and plant samples has been analyzed using an*

Citation: Zaimenko, N. V., Didyk, N. P., Pavliuchenko, N. A., Kharytonova, I. P., Dziuba, O. I., Zakrasov, O. V., Yunosheva, O. P., Chernikova, N. S., and Slyusarenko, O. M. (2026). Manifestation of Labile Mechanisms of Stability of Woody Plants in an Urbanized Environment. *Sci. innov.*, 22(1), 12—23. https://doi.org/10.15407/scine22.01.012

iCAP 6300 DUO plasma emission spectrometer (Thermo Fisher Scientific, USA). The levels of photosynthetic pigments, tannins, and brassinosteroids in plant leaves have been determined. In a vegetation experiment, plants have been treated with a 1% aqueous solution of $Ti(SO_4)_2$*, titanium mefenaminate, and mefenamic acid. A microbiological analysis of the leaf phylloplane has also been conducted.*

Results. *A multivariate analytical approach has enabled the assessment of interactions within the plant–soil–plant system and the identification of the most stable and sensitive parameters for evaluating external stress. Under conditions of light and aerogenic pollution, the concentrations of titanium (1.2—4.4-fold), brassinosteroids (1.4—3.0-fold), tannins (1.2—4.1-fold), and silicon (1.1—2.3-fold) in plant tissues have increased, indicating the activation of labile mechanisms that enhance plant resistance.*

Conclusions. *The study has demonstrated that the use of titanium- and silicon-based compounds can increase the adaptive capacity of plants under stress conditions. This approach has shown promise for the development of effective protective formulations for urban green plantings.*

Keywords: Tilia cordata, Aesculus hippocastanum, Platanus acerifolia, secondary metabolites, titanium, brassinosteroids, tannins, silicon.

In addressing complex environmental challenges, green plants should be regarded as one of the most essential components of human existence, as they are capable of absorbing toxic substances, incorporating them into biogeochemical cycles, and neutralizing a wide range of environmental pollutants. The vital activity of plants under both optimal and extreme conditions largely depends on the characteristics of their regulatory systems [1].

Among the most informative parameters for identifying the functional state of plants under stress conditions are those directly related to the regulation of ecological, physiological, and biochemical processes. The plasticity and diversity of plant adaptive strategies determine their capacity to survive under extreme conditions and ensure the overall stability of the biogeocenosis.

The essence of adaptation lies in the internal processes occurring within a biosystem that maintain the stability of its external functions with respect to various environmental parameters [2]. Two main types of adaptation can be distinguished: (1) adaptation supported by all structural elements at a given systemic level, and (2) compensatory adaptation.

Genetic adaptation to geochemical and other environmental factors is based on the phenomenon of genetic polymorphism. Stable adaptive mechanisms ensure the adjustment of organisms to the average (typical) state of the environment, which remains relatively constant over long periods. Labile adaptive mechanisms, on the other hand, enable adjustment to irregular and relatively short-term fluctuations in environmental conditions [3].

The coordinated functioning of both groups of adaptive mechanisms ensures the highest efficiency of plant adjustment to specific environmental conditions with minimal energy expenditure for adaptation. Particularly significant in this context is the ability of plants to regulate the synthesis of secondary metabolites and to employ them in controlling metabolic processes and the synthesis of biologically active compounds.

A living cell simultaneously carries out an enormous number of processes, directly or indirectly interconnected with one another and with the external environment. The rate and direction of these processes in plant organisms must be precisely coordinated in time and space to ensure the characteristic balance between stability and plasticity typical of metabolism. Coordination of reactions in such a complex system is impossible without sophisticated control and regulatory mechanisms that maintain homeostasis within sufficiently narrow limits [4].

The key role in metabolic regulation belongs to mechanisms operating at the level of secondary metabolism. Certain properties of individual metabolites may be interrelated, which complicates the determination of the specific role of a given

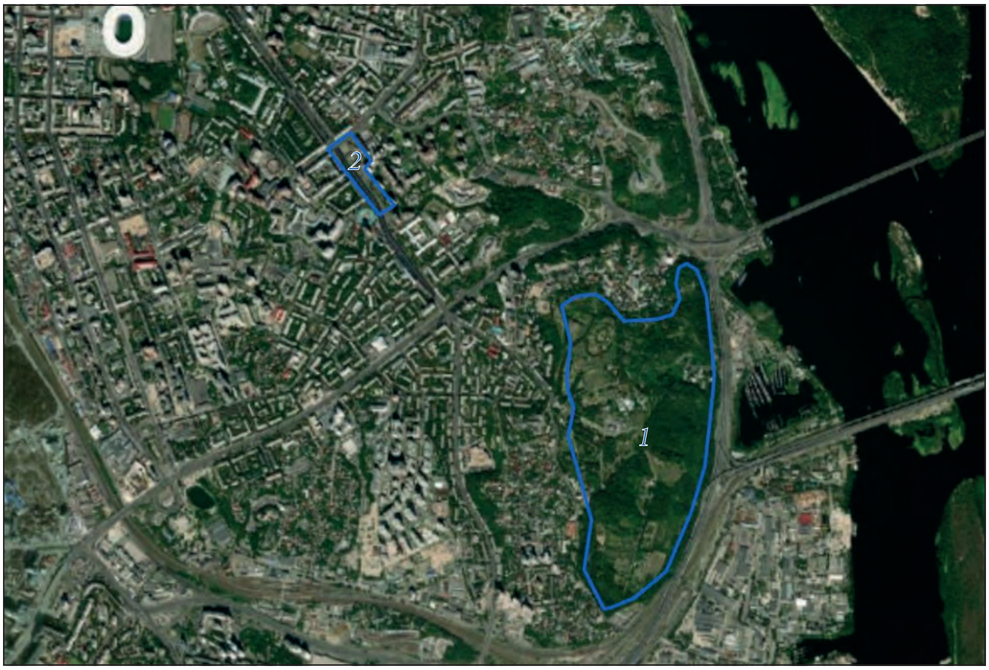

Fig. 1. Territory of the M.M. Gryshko National Botanical Garden of the NAS of Ukraine (NBG NAS of Ukraine); *2* — Lesia Ukrainka Boulevard
Source: Satellite map of Kyiv. URL: https://kv.2ua.org/kiev/karta/sat/

compound in metabolic processes. Therefore, the identification of these compounds requires the empirical combination of various analytical approaches and techniques [5].

In this context, the aim of our study is to determine the physiological and biochemical features of the resistance of the main tree species of the Kyiv metropolis to light and aerogenic pollution caused by motor vehicle emissions. The multivariate approach applied in assessing the contribution of light and aerogenic pollution to the regulatory mechanisms of plant stability formation has made it possible to analyze the interactions within the plant–soil–plant system and to identify the most stable and, at the same time, the most sensitive parameters for evaluating external impact.

The objects of our research have been street plantings of *Tilia cordata* Mill. (small-leaved linden), *Aesculus hippocastanum* L. (horse chestnut), and *Platanus acerifolia* (Aiton) Willd. (London planetree) within the Kyiv metropolis. These species currently suffer most from anthropogenic pressure resulting from intensive urbanization, particularly from aerogenic and light pollution. Modern monitoring studies have shown that most street plantings of *T. cordata* and *A. hippocastanum* have become severely weakened, while *P. acerifolia* occurs only sporadically in the city's green zones [6].

Field observations have been conducted at two sites located within the territory of the M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine (NBG NAS of Ukraine) and along Lesia Ukrainka Boulevard. Site 1, situated within the Botanical Garden, has been characterized by the absence of artificial lighting, a distance of approximately 500 m from low-traffic roads, and about 1200 m from major highways with intensive traffic. Site 2, located in the green zone along Lesia Ukrainka Boulevard, has been exposed to substantial artificial illumination and heavy four-lane traffic. This boulevard is regarded as one of the most polluted transport arteries of the Kyiv metropolis.

The monitoring sites have been located on the Pechersk Hills (approximately 180 m above sea level) and share similar exposure conditions and soil types (grey forest soil). The distance between the sites has been about 2.6 km (see Fig. 1).

At each study site, permanent sampling plots were established (five plots per tree species). The soil surface CO_2 emission rate was measured using a gas analyzer *EGM-5* (PP Systems, USA), and soil temperature was determined with a portable thermometer *Check Temp* (Hanna Instruments, USA). All measurements were performed in five replications.

No temperature differences have been recorded between the experimental sites during nighttime. During daytime, soil temperature within the NBG territory has been significantly lower, amounting to 13.9 ± 1.2 °C under *Platanus acerifolia*, 13.7 ± 1.3 °C under *Aesculus hippocastanum*, and 14.0 ± 1.5 °C under *Tilia cordata*. For the eco-units located along Lesia Ukrainka Boulevard, the respective values have been 15.0 ± 1.7 °C, 15.2 ± 1.0 °C, and 15.3 ± 1.1 °C under planetree, horse chestnut, and linden, respectively.

CO_2 emission from the soil surface has been higher for the eco-units situated along Lesia Ukrainka Boulevard — 2.3 ± 0.3, 2.6 ± 0.6, and 2.8 ± 0.8 μmol CO_2 m^{-2} s^{-1} for planetree, chestnut, and linden, respectively. Within the NBG territory, these values have amounted to 1.8 ± 0.3, 1.9 ± 0.4, and 2.2 ± 0.5 μmol CO_2 m^{-2} s^{-1} for the same species.

Soil samples for chemical analysis were prepared according to the method of G. Rinkis and V. Nollendorf [7]. Acid-soluble forms of chemical elements were extracted with a 1.0 N nitric acid (HNO_3) solution. Plant material preparation for analysis was carried out by wet ashing in a 1.0 N high-purity nitric acid solution using a Speed Wave Xpert DAP-60X microwave digestion system (Berghof Products GmbH, Germany).

The concentrations of chemical elements in the resulting solutions were measured with an iCAP 6300 DUO plasma emission spectrometer (Thermo Fisher Scientific, USA). Element content was calculated on a dry weight basis and expressed in mg/kg. The relative measurement uncertainty U ($k = 2$, $P = 0.95$) ranged from 7 % to 12 %, depending on the element. U represents the interval of measurement results encompassing the major portion of probabilities characterized by combined standard uncertainty, while P denotes the confidence level.

Internal laboratory quality control of measurement accuracy was conducted according to the compatibility criterion using the certified reference material of moss M2 (*Moss Reference Material M2, Pleurozium schreberi (Brid.) Mitt. — The Finnish Forest Research Institute*).

The abundance of bacteria utilizing predominantly mineral nitrogen compounds was determined on starch–ammonia agar (SAA), while heterotrophic bacteria utilizing organic nitrogen compounds were determined on meat–peptone agar (MPA). Micromycetes were cultured on Czapek medium, and actinomycetes on SAA [7].

Photosynthetic pigments (chlorophylls *a*, *b*, and carotenoids) were extracted from freshly collected leaves using dimethyl sulfoxide (DMSO) [8]. Their quantitative content was determined with a SPECORD 200 spectrophotometer (*Analytik Jena*, Germany) according to the method described in [9].

To determine the tannin content in leaves, plant tissues were extracted with boiling distilled water, followed by incubation in a water bath for one hour. Quantitative determination was performed by titration with a 0.1% potassium permanganate solution of the filtered extract mixed with indigo carmine indicator [10].

For the analysis of endogenous brassinosteroids under optimal and stress conditions, extraction was carried out in two stages. The first stage involved triple extraction (3 × 5 mL) of the aqueous tissue extract (1 g tissue + 5 mL extraction solution) with ethyl acetate. The ethyl acetate fraction was evaporated under vacuum, and the residue was extracted with 5 mL cyclohexane. The second extraction stage was conducted with a mixture of ethanol and water (4 : 1), again in three portions of 5 mL, from the cyclohexane phase. The ethanol extract was evaporated under vacuum, and the residue was dissolved in a small volume of ethyl acetate.

The brassinosteroid content was measured using a SPECORD 200 spectrophotometer (*Analytik Jena*, Germany, 2003) at a wavelength of 450 nm [11].

Statistical analysis of the experimental results has been performed using ANOVA with the Statistica 10.0 software package (*StatSoft Inc.*, Tulsa, USA, 2011). Differences were considered statistically significant at $P < 0.05$.

The analysis of the distribution of chemical elements in the leaves of the studied tree species growing under conditions of intensive vehicular emissions along Lesia Ukrainka Boulevard has shown an increase in titanium content during August–October, on average 1.2—4.4 times. The highest concentrations have been recorded in October, with the maximum values observed in horse chestnut leaves (Table 1).

Titanium is a valuable element with significant importance for various industrial sectors, including chemical, medical, and defense industries [12]. At the same time, titanium is a biogenic element involved in photosynthesis and chlorophyll biosynthesis, activation of redox enzymes such as catalase, nitrate- and nitrite-reductases, and phosphatases, as well as in enhancing the uptake of macro- and microelements. Increased titanium accumulation in leaves contributes to improved plant immunity against stress factors of various origins [13, 14]. This is confirmed by results from vegetation experiments on the biosynthesis of photosynthetic pigments and the population dynamics of key microbial groups in the phylloplane of horse chestnut seedlings.

The studies have demonstrated the effectiveness of using titanium(IV) coordination compounds with mefenamic acid as biologically active agents for enhancing plant resistance to pathogens. Titanium mefenamate is low in toxicity compared to titanium sulfate, exhibits a high adaptive potential against phytopathogens, stimulates the biosynthesis of photosynthetic pigments (particularly carotenoids), and has growth-promoting effects. Comparative evaluation of photosynthetic activity and growth-stimulating efficiency of simple titanium salts versus the titanium-mefenamate complex in vegetation experiments has demonstrated the superiority of titanium mefenamate. Specifically, the carotenoid content was on average 1.4—1.6 times higher compared to other experimental variants (Table 2). A similar trend was observed for chlorophyll content that increases 1.5—1.8 times.

The positive effect of titanium mefenamate is explained by its significant influence on the phylloplane mycocoenosis, primarily through the stabilization of fungal populations. Table 3 presents the quantitative composition of the main microbial groups in the phylloplane of horse chestnut seedlings.

Analysis of the microbial communities on horse chestnut leaves following treatment with a 1% aqueous solution of $Ti(SO_4)_2$, titanium mefenamate, and mefenamic acid showed that among the primary microbial groups studied, only the

Table 1. **Titanium Content in the Leaves of the Studied Plant Species under Different Growth Conditions, mg/kg**

Species	Month of the study					
	May	August	October	May	August	October
	NBG			Lesia Ukrainka Blvd.		
Planetree	10.2 ± 0.51	12.7 ± 0.59	11.24 ± 0.54	7.3 ± 0.33	21.1 ± 1.02	25.3 ± 1.19
Chestnut	13.1 ± 0.70	18.0 ± 0.87	12.10 ± 0.60	6.7 ± 0.29	48.4 ± 2.37	52.9 ± 2.56
Linden	9.1 ± 0.42	30.5 ± 1.48	19.46 ± 0.92	11.8 ± 0.55	35.5 ± 1.69	42.2 ± 2.07

fungal group responded markedly to treatment with the complex, with their overall abundance substantially reduced.

A comparative analysis of the distribution of chemical elements in the leaves of the studied plant species revealed notable differences (Table 4). Specifically, the contents of iron (Fe), potassium (K), and magnesium (Mg) in horse chestnut tissues reached their maximum values in October, regardless of the growth conditions.

For planetree and small-leaved linden, an increase in calcium (Ca), magnesium (Mg), and iron (Fe) was observed in August, while potassium (K) peaked in May. Across all experimental trees, the highest phosphorus (P) levels were recorded in May, silicon (Si) in August, and copper (Cu) in October.

Notably, horse chestnut leaves exhibited the highest silicon content as compared with the other species, which may indicate stress conditions and a corresponding activation of the plant's immune system against pathogens and pests [15, 16].

In addition to their role in metabolic processes, tannins perform a protective function in plants against harmful effects of ultraviolet radiation, damage caused by pests and phytopathogens, and also act as natural pesticides [17].

An increase in the tannin content in horse chestnut leaves (1.5 times, in May and August, and 4.1 times, in October) (Table 5) has indicated the activation of chemical defense mechanisms under stressful conditions. This is further supported by the observed increase (1.7—3.0 times) in the brassinosteroid concentration (Table 6).

As is well known, brassinosteroids induce plant resistance to abiotic stressors by modulating enzymatic and non-enzymatic antioxidant activity [18, 19]. Their role is equally important in mitigating stresses of various origins, including extreme temperatures, water and osmotic deficiency, contamination by organic and inorganic substances, and pathogen infection [20, 21].

Significant differences have also been identified in the soil samples. In particular, a sharp increase in the content of chemical elements has been observed in August in the soils of the monitoring sites along Lesia Ukrainka Boulevard. The most

Table 2. **Effect of Titanium Compounds on the Biosynthesis of Photosynthetic Pigments in Horse Chestnut Leaves, mg/100 g fresh weight**

Experiment option	Pigments		
	Chlorophyll		Carotenoids
	a	*b*	
$Ti(SO_4)_2$	22.4 ± 1.02	11.7 ± 0.56	32.8 ± 1.52
Titanium mefenamate	39.6 ± 1.87	21.4 ± 1.03	51.6 ± 2.43
Mefenamic acid	26.5 ± 1.28	12.8 ± 0.59	35.1 ± 1.68
Reference	2.83 ± 1.31	13.2 ± 0.62	37.8 ± 1.79

Table 3. **Abundance of Major Microbial Groups in the Phylloplane of Horse Chestnut Leaves after Treatment with Titanium Mefenamate**

Experiment option	Bacteria, CFU $\cdot 10^8$	Micromycetes, CFU $\cdot 10^6$	Actinomycetes, CFU $\cdot 10^6$
$Ti(SO_4)_2$	8.2 ± 0.41	48.9 ± 2.36	3.5 ± 0.16
Titanium mefenamate	7.5 ± 0.36	12.5 ± 0.59	1.2 ± 0.07
Mefenamic acid	8.4 ± 0.39	41.4 ± 2.01	3.1 ± 0.14
Reference (water)	8.9 ± 0.42	79.3 ± 3.57	4.7 ± 0.21

Table 4. **Content of Chemical Elements in Leaves of Studied Plant Species under Different Growth Conditions, mg/kg**

Element	NBG			Lesia Ukrainka Blvd.		
	Month					
	May	August	October	May	August	October
			Planetree			
Ca	5554 ± 223.7	12450 ± 596.3	5842 ± 255.4	5350 ± 247.9	15020 ± 721.7	14780 ± 711.8
Cu	9.7 ± 0.42	9.8 ± 0.45	10.3 ± 0.51	12.3 ± 0.57	18.8 ± 0.89	27.9 ± 1.31
Fe	231.5 ± 11.2	214.2 ± 10.5	293.0 ± 14.3	125.3 ± 6.07	492.3 ± 24.2	245.7 ± 12.14
K	14790 ± 728.3	63.42 ± 307.5	9556 ± 452.3	13465 ± 662.9	7460 ± 357.2	14230 ± 705.6
Mg	1547 ± 74.8	1864 ± 91.3	921 ± 44.8	1565 ± 77.1	2294 ± 107.6	1878 ± 89.9
P	3719 ± 182.6	1475 ± 72.1	971 ± 47.5	3045 ± 151.8	1703 ± 85.2	1086 ± 53.7
Si	1549 ± 76.3	1677 ± 81.7	1310 ± 62.9	655 ± 31.8	3906 ± 44.2	1210 ± 58.9
			Chestnut tree			
Ca	7350 ± 359.2	10990 ± 532.7	13050 ± 632.9	7314 ± 354.2	8266 ± 411.5	12190 ± 606.8
Cu	13.4 ± 0.61	11.5 ± 0.52	16.9 ± 0.78	15.5 ± 0.71	12.1 ± 0.58	28.9 ± 14.2
Fe	244.1 ± 11.8	195.6 ± 9.4	318.5 ± 15.6	175.2 ± 8.5	954.3 ± 45.7	1139.7 ± 55.8
K	9146 ± 432.4	8585 ± 423.7	9791 ± 489.0	10180 ± 506.3	5632 ± 276.4	12315 ± 611.3
Mg	1701 ± 84.3	2788 ± 138.6	2928 ± 144.7	1241 ± 61.2	1397 ± 68.1	2423 ± 120.5
P	2286 ± 113.2	2130 ± 104.7	1440 ± 71.6	2608 ± 130.2	1693 ± 84.0	2173 ± 107.4
Si	1725 ± 85.3	2961 ± 147.4	1508 ± 74.6	1116 ± 54.3	4326 ± 214.8	3118 ± 151.2
			Linden			
Ca	11196 ± 58.5	19950 ± 988.3	15210 ± 751.7	10427 ± 519.4	18380 ± 912.8	15530 ± 769.6
Cu	9.8 ± 0.45	8.6 ± 0.41	15.9 ± 0.77	12.3 ± 0.59	7.7 ± 0.37	16.0 ± 0.75
Fe	195.6 ± 9.2	607.5 ± 29.3	338.1 ± 16.4	332.5 ± 16.4	992.4 ± 48.7	347.2 ± 16.8
K	18505 ± 915.6	12680 ± 624.1	12990 ± 645.2	17100 ± 852.5	12380 ± 617.0	13991 ± 697.4
Mg	1775 ± 86.2	2129 ± 105.7	1497 ± 73.5	1723 ± 85.1	2304 ± 114.2	1505 ± 73.1
P	2404 ± 125.1	2129 ± 105.7	1315 ± 79.6	2909 ± 135.1	1808 ± 89.4	1 365 ± 66.3
Si	715.2 ± 34.8	2411 ± 134.6	2218 ± 110.2	711.6 ± 34.6	2672 ± 131.5	2536 ± 118.9

Table 5. **Tannin Content in Leaves of Studied Plant Species under Different Growth Conditions, % of Dry Leaf Weight**

Location	Species	Month		
		May	August	October
NBG	Planetree	11.2 ± 0.97	12.9 ± 0.91	5.8 ± 0.32
	Chestnut tree	8.3 ± 0.59	8.0 ± 0.61	3.5 ± 0.24
	Linden	9.1 ± 0.62	7.4 ± 0.48	3.3 ± 0.21
Lesia Ukrainka Blvd.	Planetree	11.6 ± 0.96	13.1 ± 1.02	6.0 ± 0.43
	Chestnut tree	12.7 ± 0.95	12.0 ± 0.98	14.5 ± 1.09
	Linden	9.6 ± 0.76	8.7 ± 0.79	4.1 ± 0.32

pronounced differences have concerned Na, Fe, Mn, and Cu. A marked increase in the content of iron and sodium in the soil beneath planetree, sodium beneath horse chestnuts, and sodium and manganese beneath lindens under polluted conditions has been established (Table 7). The copper content in the soil has increased by factors of 9.8, 5.3, and 4.3 beneath the planetree, horse chestnut, and linden, respectively.

A particular focus of these studies has been the role of titanium in plant physiology. It has been established that titanium and its chelate compounds, when absorbed by plants at low concentrations, have positively influenced plant growth and productivity, enhanced nutrient uptake by roots, stimulated the biosynthesis of photosynthetic pigments, and increased resistance to stress factors [14].

The observed increase in brassinosteroid content in leaves of the studied plant species under polluted conditions has indicated an enhancement of their immunity, which is associated with higher photosynthetic activity [22], accumulation of pro-

Table 6. **Content of Brassinosteroids in the Leaves of Studied Plant Species Under Different Growth Conditions, mg/kg**

Location	Species	Month		
		May	August	October
NBG	Planetree	1.2 ± 0.16	0.6 ± 0.11	3.3 ± 0.23
	Chestnut tree	7.5 ± 0.79	2.3 ± 0.21	10.3 ± 0.97
	Linden	6.2 ± 0.51	0.8 ± 0.14	5.4 ± 0.49
Lesia Ukrainka Blvd.	Planetree	0.1 ± 0.12	0.9 ± 0.15	6.6 ± 0.73
	Chestnut tree	4.1 ± 0.28	4.0 ± 0.31	30.8 ± 2.34
	Linden	5.5 ± 0.47	1.1 ± 0.19	7.6 ± 0.75

Table 7. **Content of Chemical Elements in the Soil Beneath the Studied Plant Species Under Different Growth Conditions, mg/kg**

Species	Element	NBG			Lesia Ukrainka Blvd.		
		Month					
		May	August	October	May	August	October
Planetree	Fe	5766 ± 279.2	7464 ± 361.5	4088 ± 197.2	10420 ± 506.4	22640 ± 109.7	10030 ± 498.2
	Na	113.8 ± 5.5	241.5 ± 11.3	234.6 ± 11.2	1068 ± 51.7	8400 ± 412.8	342.3 ± 16.5
	Mn	145.2 ± 6.8	201.0 ± 9.2	162.3 ± 7.9	171.5 ± 8.1	405.4 ± 18.3	265.1 ± 12.8
	Cu	15.4 ± 0.74	17.8 ± 0.80	17.7 ± 0.84	37.9 ± 1.82	174.8 ± 8.41	23.8 ± 1.14
Chestnut tree	Fe	9511 ± 442.6	8847 ± 440.9	8897 ± 432.7	8725 ± 429.5	10750 ± 527.4	9352 ± 452.8
	Na	151.6 ± 7.7	381.2 ± 16.4	477.5 ± 22.4	569.1 ± 27.5	4376 ± 215.8	632.8 ± 30.9
	Mn	166.1 ± 8.1	167.8 ± 7.9	159.3 ± 7.5	140.9 ± 7.1	137.2 ± 6.7	219.6 ± 10.4
	Cu	21.06 ± 0.92	21.5 ± 0.98	21.1 ± 1.02	26.8 ± 1.22	114.02 ± 5.5	49.50 ± 2.1
Linden	Fe	7546 ± 367.3	4683 ± 229.7	5731 ± 275.6	16437 ± 819.5	16060 ± 795.1	15540 ± 752.6
	Na	132.5 ± 6.2	271.8 ± 12.9	243.3 ± 12.4	676.1 ± 31.9	1614 ± 79.7	264.2 ± 12.8
	Mn	153.2 ± 7.3	125.9 ± 6.0	145.9 ± 7.1	883.8 ± 43.6	997.5 ± 49.3	821.3 ± 41.5
	Cu	14.5 ± 0.71	15.1 ± 0.69	18.2 ± 0.87	20.4 ± 0.92	65.2 ± 3.18	17.6 ± 0.85

line in tissues [23], increased content of N, P, and K [24], and greater resistance to dehydration [25, 26] and salinity [27]. Additionally, a reduction in the uptake of heavy metals by plant organs has been noted [28].

The active synthesis of brassinosteroids and the accumulation of titanium in leaves suggest a strengthening of plant stress tolerance [29], which can be explained by the efficient utilization of essential biogenic elements, particularly iron, magnesium, and manganese.

Moreover, silicon plays a crucial role in mitigating the negative effects of abiotic and biotic stresses on plants, as it is directly involved in metabolic processes and supports plant growth and development [30, 31].

The results obtained have demonstrated that under conditions of light and aerogenic pollution, plants activate a compensatory mechanism in response to stress factors, which manifests itself in the substitution of certain biochemical markers of resistance with others, since both brassinosteroids and tannins, as well as titanium and silicon, contribute to the adaptive capacity of the organisms. In particular, the increased uptake of titanium by plants mobilizes the synthesis of endogenous hormones, promoting disease resistance, while the elevated tannin concentration has confirmed the activation of chemical defenses against both phytopathogens and harmful radiation.

The higher content of brassinosteroids in leaves under polluted conditions has indicated modulation of enzymatic and non-enzymatic antioxidant activity. The increased silicon content in tissues under stress conditions testifies to the presence of light and aerogenic pollution and ensures the effective functioning of labile plant resistance mechanisms.

The use of titanium and silicon compounds appears promising for enhancing the adaptive capacity of plants under stressful conditions and for the development of effective formulations based on these elements.

Funding. This work has been carried out as part of the scientific project *Impact of Aerogenic and Light Pollution on the Structural and Functional Organization of Urban Phytocenoses* (No. DR 0120U100543) in accordance with the Targeted Program of Scholarly Research of the National Academy of Sciences of Ukraine *Aerospace Environmental Observations for Sustainable Development and Safety* (ERA-PLANET/UA).

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Received 30.01.2025
Revised 22.05.2025
Accepted 29.05.2025

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ПРОЯВ ЛАБІЛЬНИХ МЕХАНІЗМІВ СТІЙКОСТІ ДЕРЕВНИХ РОСЛИН В УРБАНІЗОВАНОМУ СЕРЕДОВИЩІ

Вступ. Пластичність та різноманіття адаптивних стратегій рослин визначають можливість їхнього існування за екстремальних умов і забезпечують стійкість біогеоценозу в цілому.

Проблематика. Сучасні моніторингові дослідження свідчать, що більшість вуличних насаджень потерпають від антропогенного навантаження через інтенсивну урбанізацію, зокрема значне аерогенне та світлове забруднення.

Мета. Встановити фізіолого-біохімічні особливості стійкості основних деревних порід насаджень Київського мегаполісу до світлового та аерогенного забруднення викидами автотраспорту.

Матеріали й методи. Об'єктами були вуличні насадження *Tilia cordata* Mill., *Aesculus hippocastanum* L. та *Platanus acerifolia* (Aiton) Willd. Київського мегаполісу. Польові спостереження проводили у НБС НАН України (ділянка 1) та зеленій зоні вздовж бульвару Лесі Українки (ділянка 2). Визначали температуру ґрунту дослідних ділянок, емісію CO_2 з його поверхні. Вміст хімічних елементів у ґрунтових та рослинних зразках досліджували за допомогою плазмового емісійного спектрометру iCAP 6300 DUO (*Thermo Fisher Scientific*, США). Аналізували вміст фотосинтетичних пігментів, танінів та брасиностероїдів у листках рослин. У вегетаційному досліді рослини обробляли 1%-м водним розчином $Ti(SO_4)_2$, мефенамінату титану та мефенамінової кислоти. Проводили мікробіологічний аналіз філоплани листків.

Результати. Мультиваріантний підхід дозволив проаналізувати взаємодію у системі «рослина-ґрунт-рослина» і відібрати найбільш стійкі та найчутливі параметри щодо оцінки зовнішнього впливу. За умов світлового і аерогенного забруднення спостерігалося підвищення вмісту титану в 1,2—4,4 рази, брасиностероїдів в 1,4—3,0 рази, танінів в 1,2—4,1 рази, кремнію в 1,1—2,3 рази в тканинах, що забезпечує ефективність функціонування лабільних механізмів стійкості рослин.

Висновки. Застосування сполук титану й кремнію є перспективним для підвищення адаптаційної здатності рослин до стресових умов, а також створення ефективних препаратів на їхній основі.

Ключові слова: Tilia cordata, Aesculus hippocastanum, Platanus acerifolia, вторинні метаболіти, титан, брасиностероїди, таніни, кремній.