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RESEARCH ARTICLE

The effect of nighttime lighting on the anatomical and physiological features of the leaves of linden, horse chestnut, and plane trees in garden-park and street plantings of Kyiv

Natalia Zaimenko [1], **Dmytro Klymchuk** [2], **Yuri Akimov** [2], **Tetyana Kuchma** [3,4], **Nataliya Didyk** [1,*], **Olena Chudovska** [1], **Bogdana Ivanytska** [1]

[1] M.M. Gryshko National Botanical Garden, National Academy of Sciences of Ukraine, Sadovo-Botanichna str. 1, 01014 Kyiv, Ukraine; * nataliya_didyk@ukr.net

[2] M.G. Kholodny Institute of Botany, National Academy of Sciences of Ukraine, Tereshchenkivska str. 2, 01601 Kyiv, Ukraine

[3] Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine, Metrologichna str. 12, 03143 Kyiv, Ukraine

[4] National University of Kyiv-Mohyla Academy, G. Skovorody str. 2, 04070 Kyiv, Ukraine

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Abstract

The effect of nighttime lighting on the anatomical and morphological structure and the content of photosynthetic pigments in the leaves of *Tilia cordata, Aesculus hippocastanum,* and *Platanus acerifolia* was estimated on the example of garden-park and street plantings of Kyiv. At the experimental sites, the level of illumination and the soil surface temperature during the day and night periods were examined. The anatomical and morphological structure of the leaves was studied using transmission electron microscopy. The content of photosynthetic pigments (chlorophylls and carotenoids) in tree leaves was determined spectrophotometrically.

The analysis of variance revealed that nighttime lighting significantly affected the anatomical structure and the content of photosynthetic pigments in the leaves of *T. cordata* and *P. acerifolia*. In *A. hippocastanum*, only parameters of stomata and palisade parenchyma showed a significant reaction to this stress factor.

Keywords: *Tilia cordata, Aesculus hippocastanum, Platanus acerifolia*, nighttime lighting, photosynthetic pigments, stomata area, palisade mesophyll

Authors' contributions: Conceived and designed the experiments: Zaimenko N.V. Performed the experiments: Kuchma T. analyzed light intensity within the experimental areas; Ivanytska B.O. collected leaf and soil samples, measured content of photosynthetic pigments in leaves and chemical soil characteristics; microscopic studies were carried out by Klymchuk D.O., Akimov Y.M. and Chudovska O.O. Wrote the paper: Didyk N.P. Critically revised the manuscript: Zaimenko N.V.

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Introduction

Urban greenings are important for revitalizing the living environment for the human population and fauna. In large, densely populated cities, such as Kyiv, green plantations of perennial plants are exposed to significant anthropogenic load, which disrupts natural coenotic and trophic relationships and reduces the resistance of plantations to abiotic and biotic stressors. Artificial illumination of inhabited areas is considered a major disturbing factor of natural light regimes and anthropogenic pollution (Meravi & Prajapati, 2018). Effect of artificial illumination on natural and urban ecosystems has been intensively studied during recent decades and was shown to have both beneficial and harmful consequences (Sodani et al., 2022). Recent studies demonstrated that the ecological effects of artificial illumination are not limited to the irradiated area but also affect pollination, net primary productivity, flowering and nutrient recycling, ecosystem services, and biodiversity far beyond (Sodani et al., 2022).

It has been proved that intermittent light at night, even of short duration or at low intensities, can have marked physiological effects on vegetation (Meravi & Prajapati, 2018). The photosynthetically active radiation (wavelengths between 400 and 700 nm) associated with nighttime light pollution (<0.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$) is much lower than the one during the day (100–2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and therefore the effect of light pollution on photosynthetic processes is negligible (Raven & Cockell, 2006). On the other hand, steady light of a given red and far-red ratio could regulate specific physiological reactions associated with photomorphogenesis, phototropism, and circadian rhythm (Briggs, 2016). Artificial illumination mainly affects plant phenology, viz. seed germination, dormancy breaking, blooming time, defoliation time, etc. (Kwak et al., 2018; Sodani et al., 2022). The phenological phases could be reduced or increased by nighttime illumination depending upon the type of plant species with their genetic constituents. There is evidence in the literature that duration of phenological phases such as flowering, seed ripping, leaf senescence in trees are more susceptible to night illumination than shrub species, and deciduous species are more susceptible than evergreen ones (Yang & Duan, 2019).

Despite the world scientific community's considerable attention to the ecological consequences of light pollution, such studies have been practically absent in Ukraine until recently. According to a recent assessment, the current level of light pollution in large cities of Ukraine causes concern, while the annual growth of light pollution over the past ten years is about 2.5% annually (Zhuk & Zarochentseva, 2021).

The study aimed to evaluate the effect of nighttime illumination on the morpho-anatomical structure and the content of photosynthetic pigments in the leaves of *Tilia cordata* Mill., *Aesculus hippocastanum* L. and *Platanus acerifolia* Willd. trees grown in the streets and Garden park plantings of Kyiv. The wide distribution of the above-mentioned species in the green zones of Kyiv and other urbanized regions of Ukraine caused this choice. In particular, nearly 90% of the modern green areas of Kyiv contain *Populus* sp., *Tilia* sp., and *A. hippocastanum* (Levon, 1999). Recent studies showed that most street plantings of *T. cordata* and *A. hippocastanum* in Kyiv are severely weakened (Miroshnyk et al., 2019). These trees significantly suffer from the deterioration of environmental conditions caused by intensive urbanization and aerotechnogenic and light pollution. *Platanus acerifolia* rarely occurs in the Kyiv green areas. However, this species is typical for many other urban green spaces of Ukraine.

Material and methods

Experimental sites

The studies were conducted on two selected experimental sites in Kyiv with artificial plantings of *Tilia cordata*, *Aesculus hippocastanum*, and *Platanus acerifolia* – on the territory of the M.M. Gryshko National Botanical Garden (Site 1), which is not exposed to nighttime artificial lighting and on the street plantings of Lesia Ukrainka blvd. (Site 2) exposed to significant artificial lighting (Fig. 1). Both experimental sites are located in the central part of Kyiv. The distance between them makes up 2.6 km. Stationary test plots (five test plots for each tree species) were established in each studied site. The illumination and temperature on the soil surface were measured during the day (9:00–12:00) and at night (21:00–00:00) periods. The illumination level was determined using a UT-383 luxmeter (UNI-T, China) at the height of 1.5 m above the ground. In addition, an LI-250A analyzer (LI-COR, USA) equipped with a high-precision PAR sensor was also applied. Soil temperature was determined with a Check Temp portable

Figure 1. Location of the experimental sites: **1** – M.M. Gryshko National Botanical Garden (Site 1); **2** – Lesia Ukrainka blvd. (Site 2).

thermometer (Hanna Instruments, USA). The research was conducted over a period from May to September 2021.

Light intensity within the study plots was also analyzed using Visible Infrared Imaging Radiometer Suite (NASA/NOAA Suomi National Polar-orbiting Partnership, 2022) satellite imagery – the monthly averaged composites of satellite image data obtained using a 500 m spatial resolution night sensor. The data were obtained using the Google Earth Engine platform (Gorelick et al., 2017) and averaged over a month within the test sites. To analyze the dynamics of air pollution by traffic emissions, the index of NO_2 concentration in the atmospheric column (i.e., in the entire layer from the satellite to the earth's surface) was applied using Sentinel-5P imagery of the Google Earth Engine platform with a spatial resolution of 3 × 7 km.

The soil samples for agrochemical analysis were collected from the rhizosphere layer (0–30 cm depth) simultaneously with plant material sampling. The macro- and microelements in soil samples were determined using inductively coupled plasma spectrometer iCAP 6300 DUO from Thermo Fisher Scientific (USA). They were extracted with 1N HCl (Rinkis & Nollendorff, 1982). The contents of nitrates, ammonia, and organic carbon were determined spectrophotometrically using a qualitative reaction with diphenylamine (Rinkis & Nollendorff, 1982). Soil moisture was determined by gravimetric technique (Papish, 2001).

Quantification of photosynthetic pigments

Healthy mature leaves exposed to sunlight were collected (ten leaves from each sample site, 50 leaf samples for each tree species) on 18 May, 13 July, and 16 September 2021. Freshly collected leaves were chopped with scissors and mixed. To analyze the content of photosynthetic pigments, averaged samples of this mixture were used. Photosynthetic pigments (chlorophylls *a* and *b* and carotenoids) were extracted from freshly collected leaves with dimethylsulfoxide (Hiscox & Israelstam, 1979). Quantitative content was determined

Table 1. Illumination values on the experimental sites.

Sampling site	Illumination, μmol photons · m^{-2} · s^{-1}		
	Soil surface	1.5 m above the ground	4 m above the ground
Site 1	0.02–0.15	0.02–0.15	0.02–0.15
Site 2	0.15–0.35	0.15–0.65	0.40– 0.75

using a spectrophotometer SPECORD 200 (Analytik Jena), according to Wellburn (1994).

Electron microscopic studies

For electron microscopic examination, cuttings were taken from the leaves fixed with 3% solution of glutaraldehyde in a 0.1 M cacodylate buffer (pH 7.2) for 3 h applying vacuum infiltration and further fixation with 1% osmium tetroxide in the same buffer for 1 h at room temperature and 12 h at 4 °C. The samples were dehydrated in series of ethanols of increasing concentration and polymerized in a mixture of epoxy resins (Epon 812-Araldite). Transverse silver-gold sections (60 ± 10 nm) were Reynolds stained with lead citrate and examined in a JEM-I230 transmission electron microscope (JEOL) at an accelerating voltage of 80 kV.

Statistics

Statistical processing of the results of the experiments was carried out by the method of ANOVA with the help of Statistica 10.0 software (Stat Soft. Inc., USA). P values of less than 0.05 were considered statistically significant.

Results and discussion

Comparative analysis of daytime illumination indices within the study areas of Site 1 and Site 2 revealed no significant difference. During the period of observations, the illumination values ranged from 74–93 μmol photons · m^{-2} · s^{-1} in the shade to 870–963 μmol photons · m^{-2} · s^{-1} in the sun. At night, the illumination values in Site 2 were 2.3–7.5 times higher than in Site 1 (Table 1).

The temperature of the near-surface layer of the soil (0–5 cm) during the night period has not differed significantly between the studied areas. However, in the afternoon, in Site 1, the temperature of the near-surface layer of the soil was 1–1.3 °C lower than in Site 2.

The analysis of satellite data on the intensity of nighttime illumination (i.e., the intensity of electromagnetic radiation, nanoWatts/cm^2/sr) showed that their values were 1.9–2.4 times higher in Site 2 compared to Site 1. While the average monthly values of the NO_2 pollution index almost did not differ due to small distance between the studied areas (Table 2).

The content of nutrients (i.e., nitrogen, sulfur, sodium, iron, and silicon) in Site 2 was significantly higher as compared to Site 1 (Table 3). The bioavailability of toxic metals (i.e., zink and lead) was also significantly higher in the soil samples collected in Site 2 than in Site 1. However, in both sampling sites, the concentrations of the mentioned toxic metals were far below the threshold level necessary for physiological reactions in higher plants (Dijkshoorn et al., 1979). The concentration of humus (organic carbon) and soil solution pH did not differ significantly between the two sampling sites. To sum up, the edaphic conditions on Site 2 seem more favorable for trees growing than on Site 1.

Morpho-anatomical studies of the tree leaves revealed significant differences in the structural organization of their stomatal apparatus and the palisade cells of the mesophyll (Tables 4 & 5, Figs 2–4). The detected changes were specific for each of the analyzed tree species. In particular, *T. cordata* growing in Site 2 demonstrated a decrease in the number of stomata by 13% compared to plants growing in Site 1. In *A. hippocastanum* exposed to nighttime lighting, the number of stomata on the adaxial surface of the leaves of horse chestnut increased by 26%, but their size decreased by 19–23% compared to the plants growing in Site 1. A similar but less pronounced trend was observed for *P. acerifolia* – a slight increase in the stomata number (8%) and an insignificant reduction in their size. Thus, significant differences in stomata anatomical characteristics between trees growing in Site 1 and Site 2 were detected only for *T. cordata*.

Table 2. Dynamics of illumination indices (nanoWatts / cm^2 / sr) and NO_2 indices (mmol / m^2) during 2021 on the territory of M.M. Gryshko National Botanical Garden (Site 1) and Lesia Ukrainka blvd. (Site 2) according to VIIRS/NOAA data and Sentinel-5P satellite data

Month	Site 1		Site 2	
	Illumination	NO_2	Illumination	NO_2
January	50.83	0.21	113.24	0.20
February	49.77	0.25	105.35	0.25
March	22.21	0.14	43.71	0.13
April	19.81	0.14	42.15	0.14
May	18.08	0.10	42.93	0.11
June	18.47	0.11	38.23	0.11
July	18.60	0.12	36.76	0.13
August	19.04	0.11	37.40	0.11
September	20.54	0.13	38.37	0.12
October	20.80	0.13	40.82	0.13
November	19.15	0.12	44.29	0.12
December	21.94	0.08	51.95	0.08

Table 3. Content of nutrients (mg / kg), humus (Corg, %), pH, and soil moisture (%) on experimental plots.

Soil characteristics	*Tilia cordata*		*Aesculus hippocastanum*		*Platanus acerifolia*	
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
NH_4	18.7±2.2	33.5±3.4	10.3±2.1	24.8±2.4	9.8±2.3	32.9±1.8
NO_3	17.6±1.9	25.6±1.2	24.8±3.3	29.3±2.8	21.4±1.4	32.5±1.1
Fe	1375.4±4.8	1882±5.4	2190.2±6.5	2842±4.1	2163.5±5.4	2685±2.9
Ca	935.6±7.8	899±9.1	1089.2±8.3	1074.2±9.9	1004.9±3.3	979.4±4.7
K	234.6±8.5	255.3±10.4	379.5±12.5	355.6±8.3	328.5±8.3	319.2±14.3
Cd	0.2±0.1	0.2±0.1	0.2±0.1	0.3±0.1	0.2±0.1	0.3±0.1
Cr	2.7±0.3	3.32±0.3	6.7±0.5	7.5±0.4	3.9±0.6	5.7±0.9
Cu	3.4±0.8	5.1±0.9	5.4±0.5	6.5±0.5	5.3±0.3	6.1±0.9
P	5.8±0.8	6.5±0.49	3.1±1.2	5.1±0.9	4.1±0.8	5.9±0.9
Pb	4.6±0.7	9.3±2.2	3.8±0.8	8.5±0.9	21.6 ±4.3	27.4±3.9
S	488.6±2.4	984.1±3.8	386.2±3.7	132.4±2.5	430.2±1.6	660.5±4.3
Si	950.6±4.5	2019.3±8.7	1429.1±3.2	1482.4±5.7	1656.0±5.9	1753.4±9.8
Sr	1.4±0.3	6.7±0.5	3.7±0.8	5.8±0.9	4.4±0.7	5.1±0.4
Ti	422.1±4.4	813.5±6.3	568.5±2.6	690.8±8.2	677.8±6.4	869.8±4.6
V	16.1±1.7	24.4±2.3	21.5±1.5	23.2±1.7	26.9±1.3	28.1±1.9
Zn	17.2±3.7	25.2±3.3	29.7±2.6	33.1±2.5	24.9±10.7	30.4±9.9
Na	228.3±2.5	257.8±8.9	253.4±3.8	266.2±4.4	221.2±8.4	234.4±9.2
Al	1657±15.6	1545±24.8	1972.2±35.5	2017.0±29.8	1983.2±43.9	2048.8±36.3
pH	6.7±0.1	6.5±0.1	6.6±0.1	6.9±0.1	6.4±0.1	6.7±0.1
Corg	4.2±0.2	3.8±0.3	5.2±0.1	5.1±0.2	6.6±0.3	6.2±0.2
Soil moisture	44.6±2.4	50.2±3.7	46.3±4.2	45.6±3.3	43.8±2.7	48.2±4.6

Table 4. Changes in stomata characteristics in the leaves of tree species growing in M.M. Gryshko National Botanical Garden (Site 1) and Lesia Ukrainka blvd. (Site 2), mean ± standard error.

Location	Species	Stomata density per cm^2	Stomata length, nm	Stomata width, nm
Site 1	*Tilia cordata*	15.0 ± 0.2	24.8 ± 0.6	17.2 ± 0.4
	Aesculus hippocastanum	14.4 ± 0.3	24.4 ± 0.8	12.5 ± 0.4
	Platanus acerifolia	13.0 ± 0.4	32.2 ± 0.7	24.8 ± 0.5
Site 2	*Tilia cordata*	13.0 ± 0.2	27.5 ± 0.7	15.2 ± 0.4
	Aesculus hippocastanum	18.2 ± 0.3	18.8 ± 0.8	10.1 ± 0.5
	Platanus acerifolia	14.0 ± 0.3	31.2 ± 0.7	24.3 ± 0.4

Table 5. Anatomical peculiarities of palisade parenchyma in the leaves of tree species growing in M.M. Gryshko National Botanical Garden (Site 1) and Lesia Ukrainka blvd. (Site 2), mean ± standard error.

Location	Species	Cell length, nm	Cell width, nm	Parenchyma layer thickness, nm
Site 1	*Tilia cordata*	17.9 ± 0.2	7.8 ± 0.1	35.9 ± 0.2
	Aesculus hippocastanum	49.8 ± 0.3	9.7 ± 0.1	99.9 ± 0.3
	Platanus acerifolia	32.5 ± 0.3	9.3 ± 0.1	66.5 ± 0.2
Site 2	*Tilia cordata*	14.3 ± 0.2	5.2 ± 0.1	29.1 ± 0.2
	Aesculus hippocastanum	42.3 ± 0.3	6.8 ± 0.1	85.2 ± 0.3
	Platanus acerifolia	29.54 ± 0.3	9.4 ± 0.2	61.6 ± 0.3

For *T. cordata*, the most pronounced anatomical changes in the palisade parenchyma were found in trees exposed to nighttime lighting (Table 5). In particular, cell sizes decreased by 19–31%, and the integrity of cell walls and endoplasmic reticulum was disturbed. Similar but less pronounced trends were observed for *A. hippocastanum*. The foliar anatomy of *P. acerifolia* showed no correlation with the nighttime lighting effect.

The analysis of the content of photosynthetic pigments in the leaves revealed significant differences between trees growing in Site 1 and Site 2 (Table 6). In particular, the leaves of *T. cordata* and *A. hippocastanum* exposed to artificial nighttime lighting (Site 2) had lower chlorophyll *a* content during summer and spring than plants growing without nighttime lighting (Site 1). The content of chlorophyll *b* was higher in trees exposed to artificial nighttime lighting in all trees studied.

Chlorophyll *b* expands the range of wavelengths absorbed by chloroplasts, and the increase in its concentration indicates unfavorable illumination conditions (Yue et al., 2021). Whereas in autumn, on the contrary, trees exposed to nighttime lighting had a slightly higher chlorophyll *a* content than the control. This increase may be related to the shifts of natural phenological rhythms, particularly the delay of autumn leaf senescence. Trees growing near artificial lighting react late to autumn cooling and low temperatures – their leaves do not change color and often freeze completely green (Briggs, 2006; Gaston et al., 2013; Škvareninová et al., 2017).

The results of the analysis of variance are represented in Table 7. It was established that artificial nighttime illumination significantly affected the anatomical features and content of photosynthetic pigments in the leaves of *T. cordata* and *P. acerifolia* at $p < 0.05$. In the case of *A. hippocastanum*, only foliar anatomical features demonstrated significant dependence on nighttime illumination. It is known that the concentration of certain nutrients, such as nitrogen, iron, silicon, and sulfur, could influence leaf photosynthetic rate, gas exchange, and leaf anatomy (Li et al., 2021; Zaimenko et al., 2021). The supply of these nutrients has a different influence on

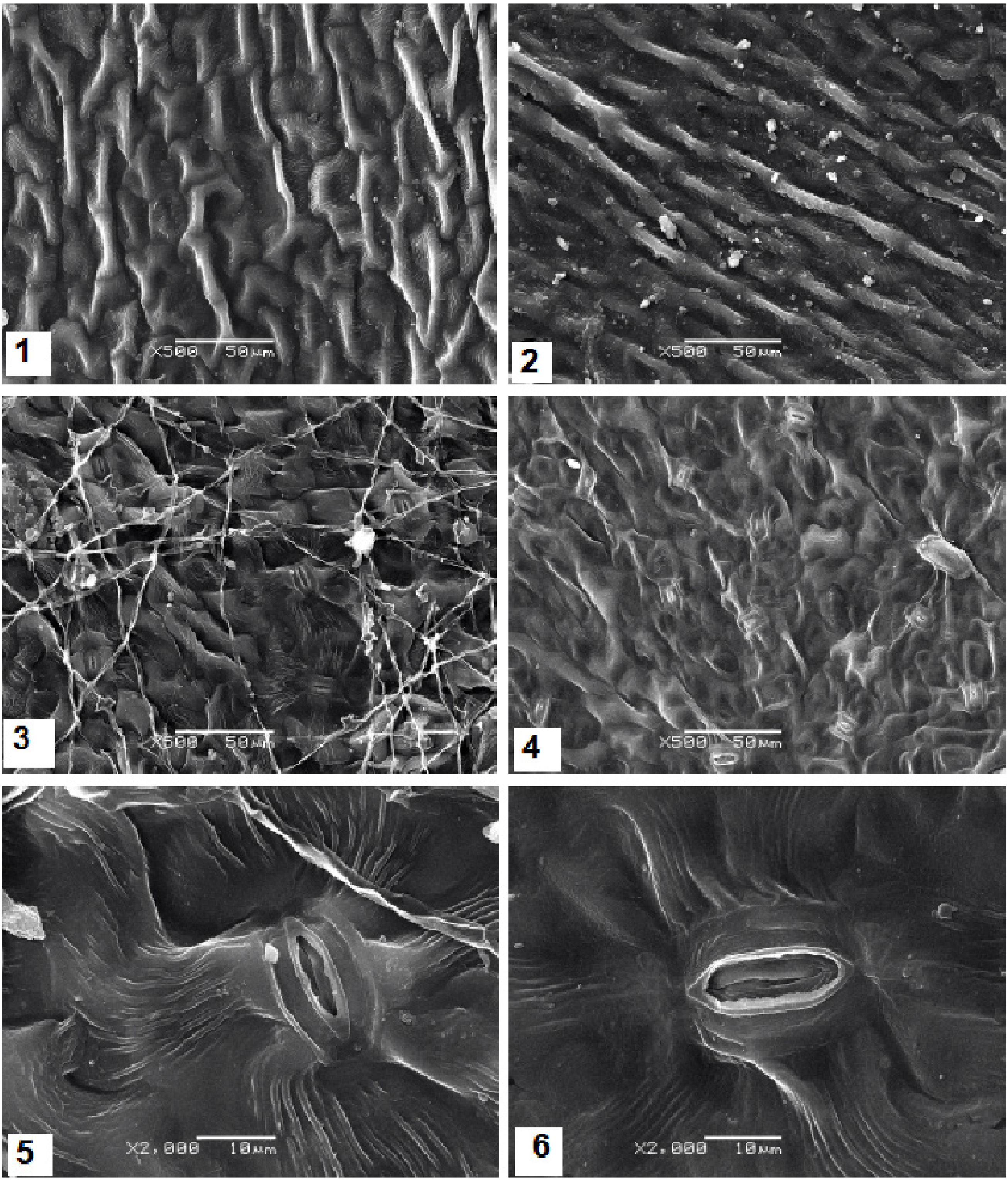

Figure 2. SEM images of *Aesculus hippocastanum* leaves fragments: **1, 3, 5** – M.M. Gryshko National Botanical Garden (Site 1); **2, 4, 6** – Lesia Ukrainka blvd. (Site 2); **1, 2** – the abaxial surface of the leaf; **3–6** – the adaxial surface of the leaf.

leaf anatomy, resulting in varying conclusions (Conley et al., 2002; Fernández et al., 2008; Liu & Li, 2016). Positive correlation between nitrogen, iron, silicon, and sulfur with photosynthetic rate and chlorophyll content has been established (Kumawat et al., 2006; Liu & Li, 2016; Li et al., 2021; Zaimenko et al., 2021). Though Site 2, compared to Site 1, showed a much higher concentration of macro- and micronutrients, the observed decrease in foliar chlorophyll *a* content in *T. cordata* proves that inhibiting effects of

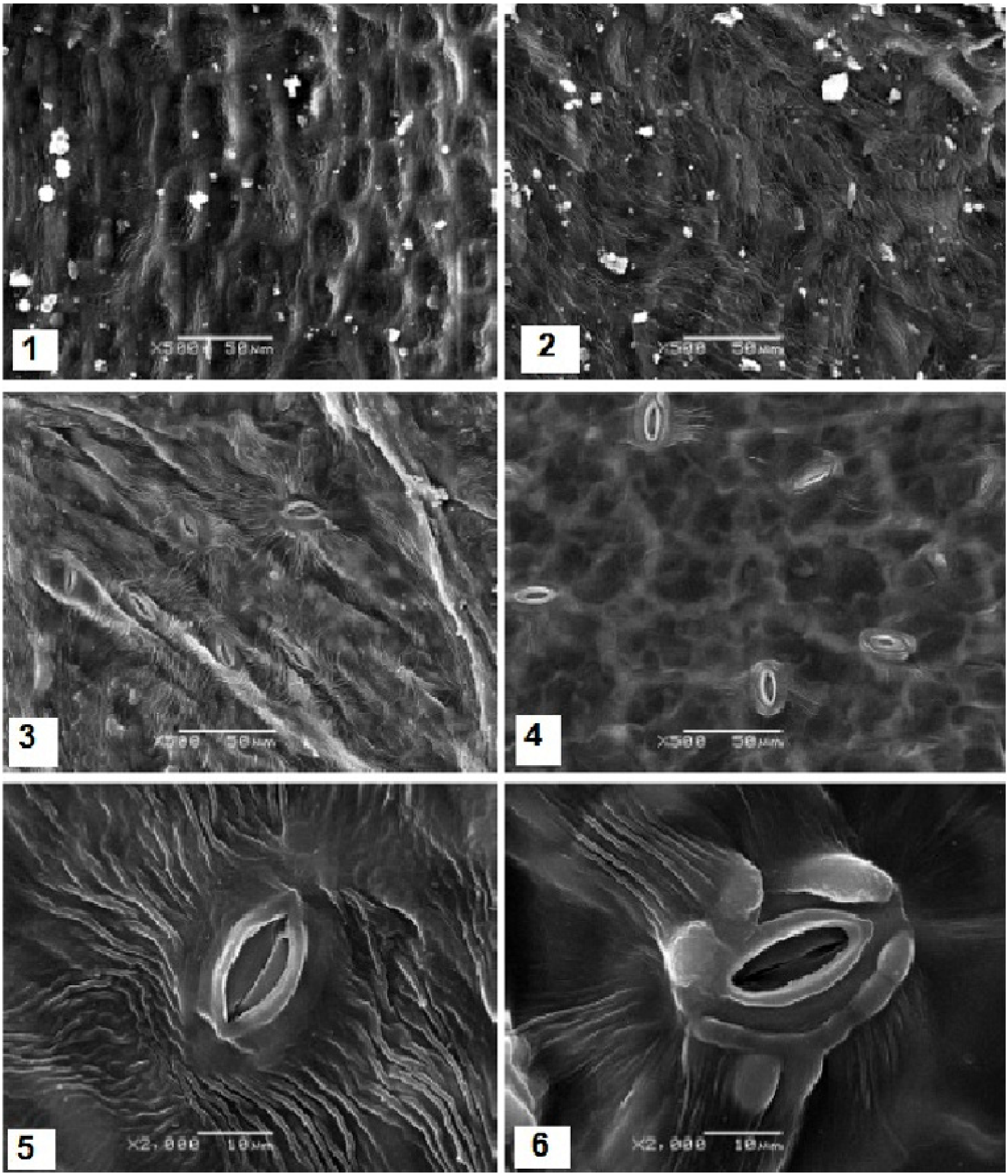

Figure 3. SEM images of *Tilia cordata* leaves fragments: **1, 3, 5** – M.M. Gryshko National Botanical Garden (Site 1); **2, 4, 6** – Lesia Ukrainka blvd. (Site 2); **1, 2** – the abaxial surface of the leaf; **3–6** – the adaxial surface of the leaf.

artificial nighttime light pollution exceeded the positive impact of better nutrient supply. At the same time, the observed increase in the content of chlorophyll *b* and carotenoids in the linden leaves could indicate both adaptive reaction to illumination stress and better nitrogen supply. On the other hand, the increase in the content of chlorophyll *a* and *b* in the leaves of *P. acerifolia* growing on Site 2 could be due to better nutrition, though the stimulative effect of nighttime lighting should not be excluded.

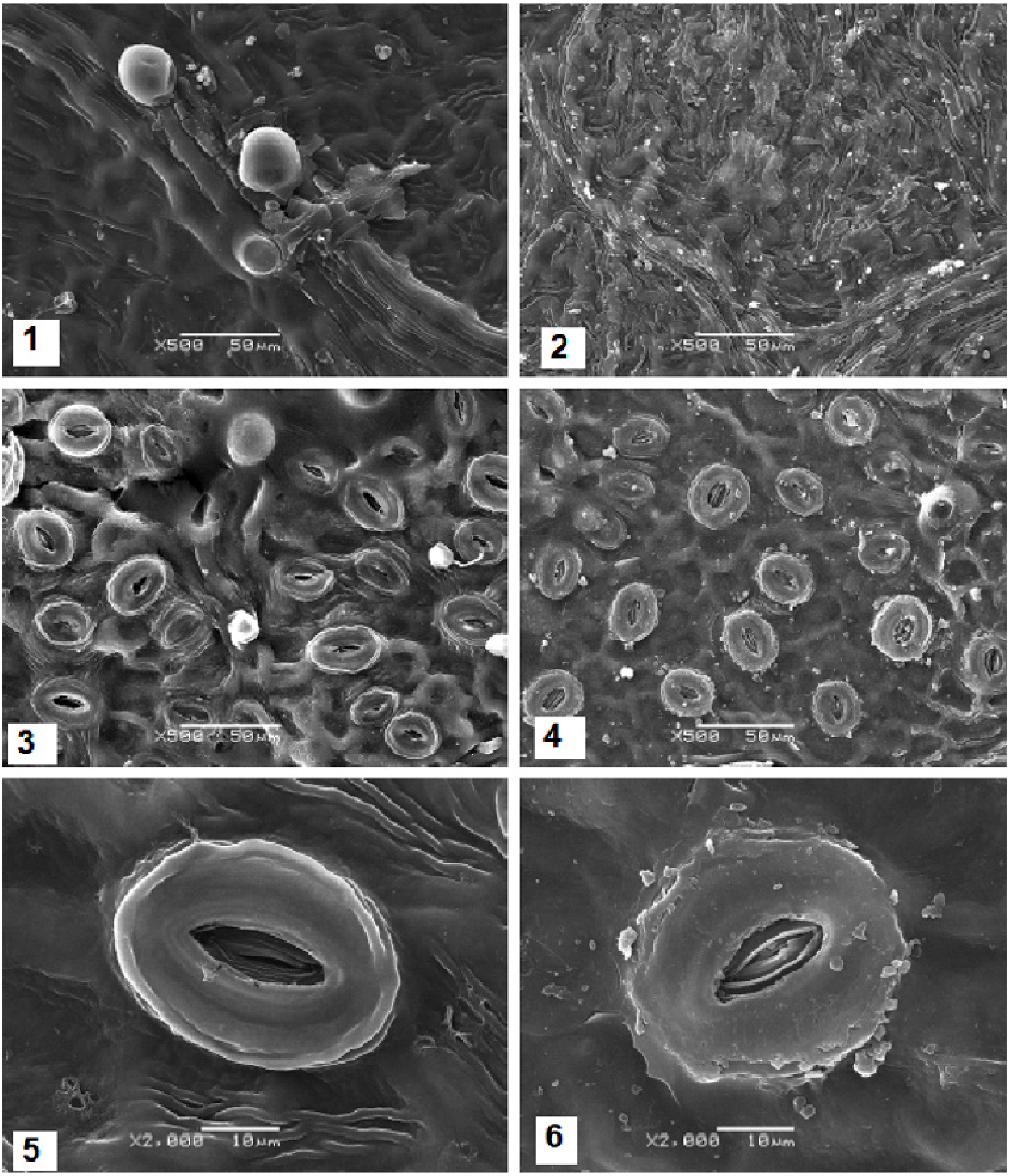

Figure 4. SEM images of *Platanus acerifolia* leaves fragments: **1, 3, 5** – M.M. Gryshko National Botanical Garden (Site 1); **2, 4, 6** – Lesia Ukrainka blvd. (Site 2); **1, 2** – the abaxial surface of the leaf; **3–6** – the adaxial surface of the leaf.

Photosynthesis is a dynamic process fluctuating in response to environmental factors, especially light. Additional artificial illumination could stimulate photosynthesis (Tewolde et al., 2016; Bian et al., 2018). On the other hand, absorption of excessive light lead to light-induced production of reactive oxygen species (ROS), photooxidative damage, lipid peroxidation, and PSII photoinhibition in higher plants (Ksas et al., 2015). Apart from this, altering circadian rhythms could cause an imbalance in carbon metabolism leading to the

Table 6. The content of photosynthetic pigments in the leaves of tree species growing in M.M. Gryshko National Botanical Garden (Site 1) and Lesia Ukrainka blvd. (Site 2), mean ± standard error.

Location	Species	Sampling date	Chlorophylls		Carotenoids
			a	*b*	
Site 1	*Tilia cordata*	18.05.2021	13.84 ± 0.11	3.52 ± 0.04	3.11 ± 0.03
		13.07.2021	12.96 ± 0.18	4.12 ± 0.02	3.42 ± 0.02
		16.09.2021	11.85 ± 0.13	4.65 ± 0.02	3.58 ± 0.02
	Aesculus hippocastanum	18.05.2021	12.22 ± 0.12	4.33 ± 0.03	4.7 ± 0.02
		13.07.2021	13.28 ± 0.17	4.87 ± 0.04	4.4 ± 0.03
		16.09.2021	9.87 ± 0.14	4.12 ± 0.04	4.9 ± 0.04
	Platanus acerifolia	18.05.2021	12.07 ± 0.10	6.39 ± 0.03	2.15 ± 0.01
		13.07.2021	12.35 ± 0.15	6.42 ± 0.04	2.94 ± 0.02
		16.09.2021	11.91 ± 0.12	5.87 ± 0.04	3.10 ± 0.02
Site 2	*Tilia cordata*	18.05.2021	11.88 ± 0.17	5.65 ± 0.02	3.35 ± 0.02
		13.07.2021	12.76 ± 0.15	6.34 ± 0.03	3.56 ± 0.03
		16.09.2021	11.87 ± 0.11	5.87 ± 0.03	3.85 ± 0.03
	Aesculus hippocastanum	18.05.2021	11.94 ± 0.17	4.75 ± 0.04	5.19 ± 0.04
		13.07.2021	12.68 ± 0.14	5.93 ± 0.04	5.75 ± 0.03
		16.09.2021	12.73 ± 0.16	5.88 ± 0.03	5.98 ± 0.04
	Platanus acerifolia	18.05.2021	12.02 ± 0.13	6.97 ± 0.04	2.53 ± 0.03
		13.07.2021	12.55 ± 0.14	6.34 ± 0.02	2.78 ± 0.03
		16.09.2021	12.92 ± 0.12	6.62 ± 0.03	3.64 ± 0.03

Table 7. The analysis of variance of the effect of artificial nighttime illumination on anatomical and biochemical characteristics of tree species growing in M.M. Gryshko National Botanical Garden (Site 1) and Lesia Ukrainka blvd. (Site 2). **F** – Fisher's criterion; **P** – level of significance; **r** – Pearson correlation coefficient.

Characteristics	*Tilia cordata*			*Aesculus hippocastanum*			*Platanus acerifolia*		
	F	P	r	F	P	r	F	P	r
Stomata density	347.16	<0.01	−0.85	2850.97	<0.01	0.89	69.53	<0.01	0.85
Stomata length	1498.26	<0.01	0.83	6230.47	<0.01	−0.88	253.85	<0.01	−0.88
Stomata width	836.71	<0.01	−0.84	852.19	<0.01	−0.91	75.75	<0.01	−0.84
Palisade parenchyma length	1656.59	<0.01	−0.87	1700.94	<0.01	−0.86	287.15	<0.01	−0.88
Palisade parenchyma width	1325.88	<0.01	−0.76	1782.48	<0.01	−0.84	7.08	0.022	0.53
Chlorophyll *a*	147.54	<0.01	−0.77	9.03	0.012	−0.67	1891.09	<0.01	−0.90
Chlorophyll *b*	121.495	<0.01	−0.74	4.09	0.068	−0.52	2481.22	<0.01	−0.80
Carotenoids	10.154	<0.01	−0.49	0.489	0.499	−0.21	27.73	<0.01	−0.65

down-regulation of photosynthetic processes due to high accumulation of starch and sugar (Demers et al., 1998; Van Gestel et al., 2005).

Yellow-poplar (*Liriodendron tulipifera* L.) seedlings exposed to nighttime artificial high-pressure sodium (HPS) lighting exhibited the enhancement of accessory pigments, the reduction of photosystem II, increased stomatal limitation, downregulation of photosynthesis, and the decreased respiration rate as well as aboveground and belowground biomass (Kwak et al., 2018).

While other studies showed positive effects of continuous light and supplemental lighting on plant growth and development. In particular, Tewolde et al. (2016) documented that nighttime lighting can stimulate physiological functions such as photosynthesis and yield. Bian et al. (2018) established the positive effects of supplemental green light on lettuce plants by enhancing the activity of antioxidative enzymes and promoting LHCb and PsbA expression to maintain higher photosynthetic capacity.

Thus, the results of our research demonstrated that anatomical features and content of photosynthetic pigments in the leaves of *T. cordata* and *P. acerifolia* significantly depend on nighttime lighting. The inhibiting effect of artificial nighttime lighting on the content of chlorophyll *a* in the leaves of *T. cordata* has been proved. While in *A. hippocastanum* only stomata and palisade parenchyma characteristics changed in response to this stress factor.

Conclusions

Artificial illumination today is recognized as an important factor of anthropogenic pollution. Although the world scientific community has been concerned with the problem of ecological consequences of light pollution far ago, in Ukraine, such studies were almost totally absent until yet. Present comparative study of the anatomical and morphological structure and content of photosynthetic pigments in the leaves of the most common tree species used in the street and park plantings of Kyiv showed that these species reacted differently to nighttime lighting. Nighttime lighting significantly affected the anatomical features of stomata and palisade parenchyma, chlorophyll *a* and *b* contents in the leaves of *T. cordata* and *P. acerifolia*. For *A. hippocastanum*, significant dependence of stomata and palisade parenchyma features on this stress factor was revealed.

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Вплив нічного освітлення на анатомічні і фізіологічні властивості листків липи, гіркокаштана і платана у садово-паркових і вуличних насадженнях Києва

Наталія Заіменко [1], Дмитро Клімчук [2], Юрій Акімов [2], Тетяна Кучма [3, 4], Наталія Дідик [1, *], Олена Чудовська [1], Богдана Іваницька [1]

[1] Національний ботанічний сад ім. М.М. Гришка НАН України, вул. Садово-Ботанічна, 1, Київ, 01014, Україна; * nataliya_didyk@ukr.net

[2] Інститут ботаніки ім. М.Г. Холодного НАН України, вул. Терещенківська, 2, Київ, 01601, Україна

[3] Інститут агроекології і природокористування НААН України, вул. Метрологічна, 12, Київ, 03143, Україна

[4] Національний університет “Києво-Могилянська академія”, вул. Г. Сковороди, 2, Київ, 04070, Україна

Досліджено вплив штучного нічного освітлення на анатомо-морфологічну структуру та вміст фотосинтетичних пігментів в листках насаджень *Tilia cordata, Aesculus hippocastanum* і *Platanus acerifolia* на прикладі садово-паркових і вуличних насаджень Києва. На дослідних ділянках реєстрували рівень освітленості, температуру на поверхні ґрунту в денний та нічний періоди. Анатомо-морфологічну структуру листків досліджували за допомогою трансмісійного електронного мікроскопу. Вміст фотосинтетичних пігментів (хлорофілів і каротиноїдів) у листках дерев визначали спектрофотометрично.

Результати дисперсійного аналізу показали, що нічне освітлення суттєво впливає на анатомо-морфологічну структуру, а також вміст фотосинтетичних пігментів у листках *T. cordata* і *P. acerifolia*. Водночас, в *A. hippocastanum* лише морфологічні показники продихів і палісадної паренхіми виявили істотну залежність від цього стресового фактору.

Ключові слова: *Tilia cordata, Aesculus hippocastanum, Platanus acerifolia*, нічне освітлення, фотосинтетичні пігменти, продихи, палісадний мезофіл