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Comparative efficiency of roundwood processing into pallet lumber

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Abstract

The article is an attempt to determine the impact of market changes and sawnwood production on the utilisation of a limited supply of wood raw material, taking into account coniferous species and selected grades found on the market for the production of pallet lumber. The proposal to include the raw material value factor in the econometric model provides a measurable benchmark. Closed efficiency through the criterion of maximising the added value of wood in industrial processing takes into account the parameters that shape the impact of the value of the product and wood raw material. This criterion is derived from the supply of roundwood and customer demand for particular species and grades. The efficiency index is a reference to the price factors of market change over a variable period of time with the ability to forecast the direction of change.

Key words

lumber, technology, efficiency, added value

Introduction

The efficiency of rational processing of wood into materials and products depends on complex production, technological and market factors. In the market conditions of European Union countries, there are for lumber products in, significant differences in terms of resulting from the volume of wood processing for wood plants, as well as production methods resulting from the efficiency of technological equipment. The situation of the sawmill industry in Poland is associated with the emergence of many new variables for lumber producers and operators with very different technical and technological levels. The dynamic development of sawmills is the result of the favourable market situation in 2019–2022 and the policy of timber sales by the State Forests. Changes in market policy have led to a significant shift in the cost intensity of production. As indicated by data from the Central Statistical Office (GUS 2023) according to the Polish Classification of Activities (PKD), the production of wood and wood products, including sawmill products, boards, plywood, veneers, carpentry, furniture, cork and wicker products (excluding furniture), stabilised at 37–42 million m^3 of roundwood. According to an ongo-

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ing analysis (Jablonski 2000), and taking into account the amount of raw materials purchased from the State Forests, plants with a capacity of 50,000–400,000 m³/year play a dominant role in the Polish lumber industry. The group of small- (up to 5000 cubic meters/year) and medium-sized (from 5000 to 50,000 cubic metres/year) enterprises accounts for the dominant share of the number of Polish wood product-manufacturing plants, employing and presenting the highest growth dynamics (Mydlarz and Wieruszewski 2022).

The concentration of labour potential and its specialisation is due to the reduction in cost-intensive production processes. Examples include German, Austrian and Swedish sawmills that are oriented to the production of large-sized lumber mainly for construction (Krzosek 2003; Lis et al. 2000).

Material and methods

Woodworking technologies

Technological factors, especially the productivity of raw materials obtained in medium-sized plants in Poland, particularly affect the efficiency of this production. The processes of roundwood processing for the production of lumber and sawmill products are related, on the one hand, to the diverse quality of the roundwood raw material and, on the other hand, depend on the range of products obtained (Kupčák 2015). Traditional processing processes are dominated by various products, enabling the realisation of the requirements of local markets. Examples of harvesting levels and management directions for large-sized round pine timber with a thickness at the thinner end of more than 14 cm (W0 So), large-sized logs up to 6 m (WK So) and medium-sized logs with a thickness at the thinner end without bark up to 5 cm (S2B So) processed at sawmills are shown in Figure 1.

The technologies and equipment used are closely related to the product mix. It is possible to separate the following groups: small plants (employment up to 50 people – income up to € 7 million), producing commodity lumber for various purposes; groups of small- and medium-sized sawmills (income up to € 40 million – employment up to 250 people) specialising in the production of lumber and general-purpose products for the construction industry (including factories producing roof trusses) using frame, circular and band saws, and performing pre-fabrication operations; groups of small- and medium-sized plants dominated by the production of products and elements of the so-called ‘garden and pallet programme’, which has developed in Poland in recent years and has great dynamism. It should be added that traditional sawing machines and tools, frame saws, and a set of multi-saw equipment are used. These factories use large-scale automation of the process and deep processing of components into final products.

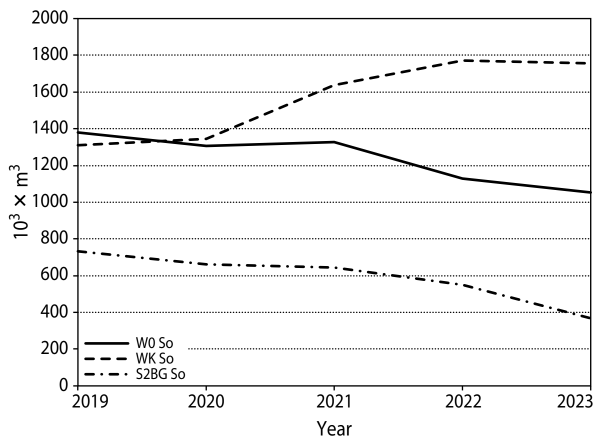

Figure 1. Level of use of softwood processed into lumber (www.e-drewno.pl, GUS 2023)

Crisis processes in Europe have resulted in a variable dynamisation of production concentration processes in large wood processing plants (Bidzińska and Ratajczak 2003; Krzosek 2003). The specialisation of production is inextricably linked to the introduction of systemic principles of production quality assurance. This is served by standards that optimise technological processes, which, unlike subject and production standards, are organisational standards and principles of systemic assurance of high, site-independent quality (Cholewa 2000; Jabłoński 2000). Systemic assurance of product quality and guarantee of repeatability of products from certified raw material are implemented by many factories in Poland that use standards: ISO 9001 and PEFC (Programme for Endorsement of Forest Certification) and FSC (Forest Stewardship Council®) certificates. This standardisation of products and production allows for the standardisation of product quality and the effective competition of wood products not only in the domestic market but also in European mar-

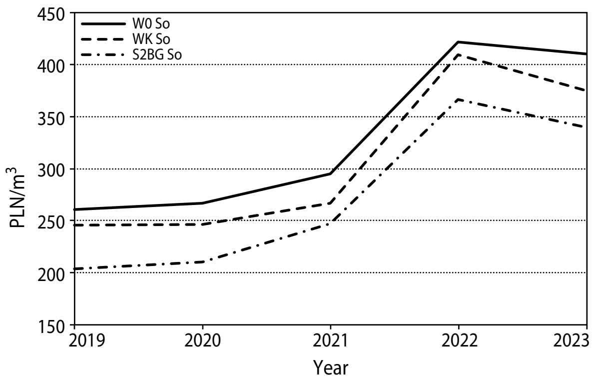

Figure 2. Price level of softwood processed into lumber (www.e-drewno.pl, GUS 2023)

kets (https://www.drewno.pl/, https://www.e-drewno.pl/stock/). The main products of roundwood processing with variable price ranges (Fig. 2) are sawn materials with varying market values (Tab. 1). By-products such as wood chips or sawdust and bark are also obtained as a result of sawmilling (Tab. 2). The share of these products is closely dependent on the processing technology used and the form of the main products (lumber). Both main products and by-products influence the efficiency index of the production process. Previous studies have confirmed a definite increase in the share of the production of chunk by-products (wood chips – up to 20–30%) with a significant share of sawdust, as a result of sawing (sawdust – 10–15%). In the overall structure, it is acceptable to take the economic effect obtained from the bark (up to 8%) as an additional group of by-products, called 'waste' of the process of preparation for sawing (Mydlarz and Wieruszewski 2022). Significant variability in the value of the product is due to local and global market changes. However, the main product, i.e. lumber and its semi-finished products, is the main indicator of the impact on the legitimacy of roundwood processing.

Table 1. Summary of averaged prices for pine pallet lumber (https://www.drewno.pl/, https://www.e-drewno.pl/stock/, Górna et al. 2023)

Period	Price of pine lumber (PLN/m^3)				
	2019	2020	2021	2022	2023
I quarter	440	450	480	1100	1000.0
II quarter	440	450	600	1300	800
III quarter	440	450	850	1400	700
IV quarter	450	460	1100	1100	600
Mean	442.5	452.5	757.5	1225.0	775.0

Table 2. Summary of averaged prices of pine by-products in 2019–2023 (https://www.drewno.pl/, https://www.e-drewno.pl/stock/, Górna et al. 2023)

Year	The by-product 'falls off' (PLN/m^3)			
	paper chips	lumber chips	pine bark	sawdust
2019	218	163	116	149
2020	192	140	117	135
2021	187	146	121	155
2022	330	329	238	370
2023	288	288	307	318
Participation in the process (%)	20–30		8	10–15

Influence of technological processes on the efficiency of woodworking

The technological processes of processing wood into lumber and sawmill products depend, in particular, on the conditions for the purchase of raw materials by various business entities. The analysis of the problem of cost and quality of wood raw material procurement in relation to the industry (Bidzińska and Ratajczak 2003; Jabłoński 2000; Krzosek 2003; Lis et al. 2000) cannot abstract from the current structure and size of sawmills in Poland.

Using the universal macro-indicator of technological efficiency of the processing of round raw material into lumber and sawmill products (Ep) formulated in natural units or as a percentage defined as the sum of the conformity of the value of the lumber raw material (main, accompanying or sawmill products) obtained from the lumber raw material, taking into account the cost of purchasing the raw material, which is necessary for its production, we describe formulas 1 and 2 (Hruzik et al. 2000):

$$Ep = \frac{\Sigma V_w^q \times C_w^q}{\Sigma V_s^q \times (Tr + C_s^q)} \times 100\% \quad (1)$$

where:

Ep – technological efficiency of raw material processing,

V_w^q – volume ‘q’ class sawnwood,
V_s^q – volume ‘q’ class raw materials,
C_w^q – prices of sawnwood,
C_s^q – prices of raw materials,
T_r – prices of transport.

$$Epc = \frac{\Sigma V_w^q \times C_w^q + V_{pt} \times C_{pt} + + V_k \times C_k}{\Sigma V_s^q \times (Tr + C_s^q)} \times 100\% \qquad (2)$$

were:
Epc – full technological efficiency of raw material processing.
V_{pt} – volume ‘q’ class sawnwood,
V_k – volume ‘q’ class raw materials,
V_w^q – volume ‘q’ class sawnwood,
V_s^q – volume ‘q’ class raw materials,
C_w^q – prices of sawnwood,
C_s^q – prices of raw materials,
C_{pt} – prices of wood waste and sawdust,
C_k – prices of bark,
T_r – prices of transport.

Results and discussion

Taking into account technological conditions and canons of work, as well as the fact of dimensional and quality variation of roundwood and current price reports (https://www.drewno.pl/, https://www.e-drewno.pl/stock/), the average productivity (W) of processing pine wood (Fig. 3) into pallet lumber in small- and medium-sized general-purpose lumber plants was determined, and production efficiency was analysed based on the formulas presented (Fig. 4). The average volume of efficiency adopted for further analysis is 60% where the changes in the price of wood transportation determined, in 2019–2023 oscillated on average at 28, 30, 33, 38 and 35 PLN/m^3 (own market research).

It can be concluded that comparing the processing of timber in sawmills in plants that used log quality sorting (O – lower, S – medium and W – upper) with that in plants that used only log diameter category, regardless of the type of plant, the best productivity can be obtained processing lower logs with larger diameters (68–72%), but the lowest productivity was confirmed when processing upper logs with small diameters (50–55%). In general, this regularity shaped the price relations for raw material and lumber in the domestic market, but this is mainly what the source material (EN 1611-1:1999/A1:2002) is limited to.

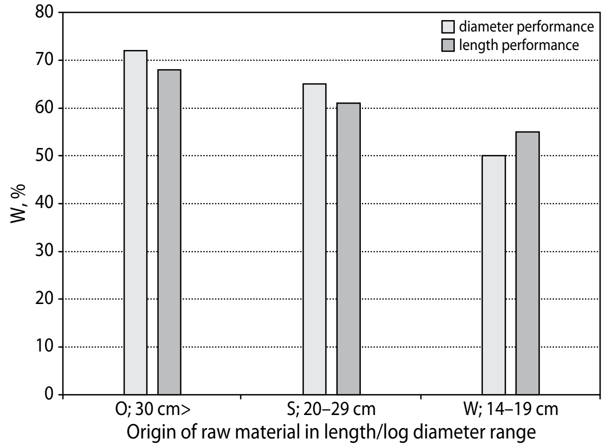

Figure 3. Technological efficiency of processing coniferous wood into semi-finished lumber in sawmills (own elaboration, Hruzik et al. 2000, 2005; Mydlarz and Wieruszewski 2022; Wieruszewski et al. 2020, 2023)

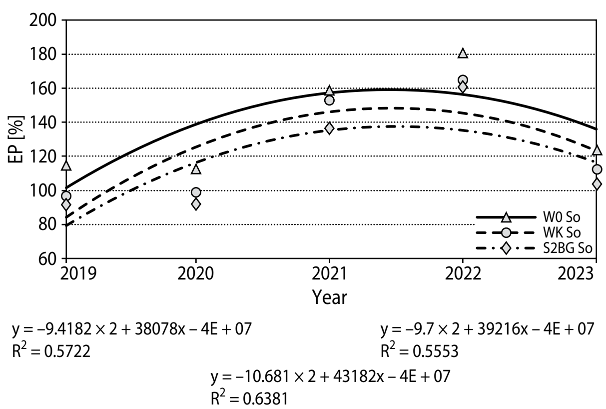

Figure 4. Ep processing efficiency of selected grades for pallet lumber production (own elaboration)

The efficiency of wood processing (Fig. 4) can also be considered in the example of specific grades (elements) of finished pallet products. Examples of the production efficiency of selected pine elements for pallet products made in 2022 (Fig. 3) indicate that these assortments allow for achieving an average efficiency of Ep=101–168% with similar material and sawing efficiency in the range of W = 50–72% (assumed average 60%) (Hruzik et al. 2000, 2005).

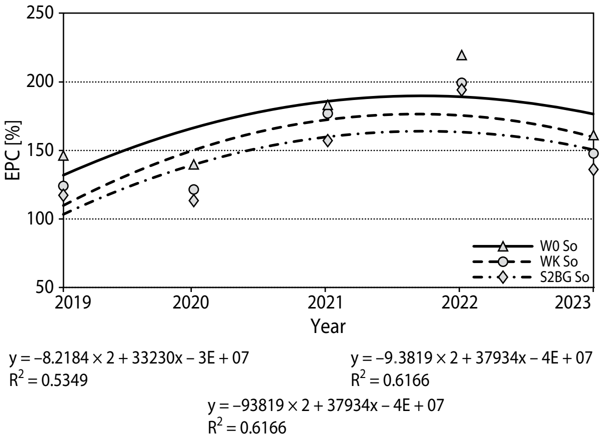

Figure 5. Total Epc efficiency including by-products in pallet lumber production (own elaboration)

The Ep variability curves show a good fit with the coefficient of determination $R^2>0.5$. At the same time, there are no significant differences in the effect of the type of pine raw material on the change in Ep ($p = 0.5$).

It is worth noting the impact of market prices associated with by-products. They have recently gained in value due to the possibility of obtaining energy biomass from them. This is particularly true for chunk products (wood chips) and sawdust. This translates into an additional component of the economic impact indicator, as presented in Figure 5 in the form of the Epc total efficiency indicator. The ANOVA statistical test showed no significant statistical difference in the effect of the tested by-product forms on Epc (p=0.7). At the same time, the functions describing the variability of Epc have a good coefficient of determination $R^2>0.5$ of matching results.

Plants producing components and pallet products are companies associated in a sphere dominated by production for the European market. Comparative spheres of sawmill production efficiency are supplemented by a potential indicator for large factories (using mainly compact technologies), but products and lumber are currently received by different technologies in sawmills. The potential range of average material efficiency in sawmilling, aligned with the economic indicator formed by the price relationship of raw materials and products, will not be different from the level of efficiency obtained in factories using traditional technologies because the relationship is not shaped by the local market but by the global market. The values of Ep production efficiency of selected pallet assortments in recent years gradually increased from a level of about 91% to 180% in 2022 to begin a sharp decline with the downturn in 2023. The added value of the process is the Epc efficiency effect of the use of by-products. As for lumber, it depends on market price fluctuations. In the structure of reference to the price of raw material, the highest increases in the indicator are obtained by S2BG wood processing where it fell from 31% to 25% in 2019–2021. An additional increase in the by-product efficiency ratio increased significantly in 2022 to a level of 33–38% to remain at a similar level in 2023. In sum, this allowed the efficiency of total Epc processing of pine raw material into pallet lumber to reach 194–220% in 2022 with a decrease in 2023 to 135–161%. This indicates how significant the rational management of by-products in the sawmilling process is.

The wood raw material offered by forest farms can be used in industrial processing for various wood materials and semi-finished products, leading to the manufacture of finished products. This depends mainly on the dimensional and quality structure of the roundwood of a given species. Different will be the shares of the various destiny grades of raw material from the division of arrows of higher classes of thickness and quality, while others from thinner arrows harvested during silvicultural operations in the forest. However, from a given arrow in a certain size group and height of trees, it is possible to manipulate different sorts according to demand, which is currently a topic of discussion among specialists. The direction of wood utilisation depends on a number of more or less important factors. The decisive one is the profitability of wood processing that can be quantified and analysed. It can be expected that, over time, the wood market will move towards the most efficient structure of its utilisation through the demand relations of individual wood industries determined by this profitability. The levels of customer demand exert an influence on the price levels of individual wood grades. They follow the individually shaped timber values accepted by individual entrepreneurs assuming expected levels of operational profitability of processing. Also important is the impact of the current market situation in a given phase of the economic cycle, as well as the technical and organisational levels of a particular wood-processing plant and the activities of sales and procurement services (Stanula et al. 2023a).

An attempt can be made to determine the structure of timber management, to which the market-shaped levels of demand from the wood processing industry for particular grades will follow over time. The most important of the expectations of entrepreneurs is the level of operational profitability in its technical and market conditions. The cost of bringing raw materials from forestry depots to the plant weighs significantly, especially in the recent period, on production costs (Stanula et al. 2023b). With their relatively high level, the value of timber in this case may be lower according to calculations based on the proposed formula. Recovery values from the sale or on-site processing of wood chips and sawdust are also noticeable (Hruzik et al. 2005). The calculated value of wood significantly determines the optimum management of the raw material.

The value added in economic activity achieved in wood processing is determined by subtracting the value of sales revenues from the value transferred, earned in other, preceding processes of processing raw materials and materials. The added values achieved in the considered phase of wood processing can also form the basis for determining the structure of roundwood utilisation, since in macro-scale analyses, these values make up this basic measure of the level of economic development. The high added value generated in the enterprise is distributed among employees, the budget, the financing of contributions charged to personnel costs, various mandatory benefits and, most importantly from the point of view of the economic entity, net profit. However, the inclusion of added value in the timber management account will not provide a fully accurate determination of the structure of the demand for particular grades, as opposed to the value of timber. The value of timber will certainly be influenced by the future structure of raw material prices, which, of course, would have to be determined in further work on the model.

Measures of roundwood value, value added in processing and efficiency indicators can therefore be used in the proposed method of raw material management account acting as functions of the econometric criterion.

Thus, it can be concluded that the timber value criterion will be the main factor shaping changes in demand for roundwood of various qualitative-dimensional grades and species limiting their growth. However, the maximisation of the objective function is limited by a number of more or less important conditions that can be described by relevant equations. Among the most important are:

- supply of individual wood grades and species,
- demand for wood.

The supply of roundwood is determined by the forest farms offering it, and in the case of Poland, mainly the State Forests, while demand is driven by the needs of the market for materials and semi-finished products and wood products. It is also related to the technological level and processing capacity of particular industries and enterprises.

The need for rational management of timber, also in terms of volume with forecasts, is indicated as the most important element of forest-timber cooperation by the timber circles, as well as central authorities. This implies the need for strict control of flows within the national economy.

It can be expected that the timber market will, to some extent, shape the profitable structure of timber utilisation, although the significant influence of the policy of the State Forests pursuing multiple objectives of maintaining stands cannot be overlooked.

Conclusions

Wood processing technology and the structure and size of sawmills at the current stage in Poland have little impact on the efficiency of lumber and wood product production.

Technological processes in the wood industry are directly related to the production mix, but the efficiency of its production, due to the dominant share of raw material costs, depends critically on the price relationship between raw material and products, as in between raw material and products, both in the local market and in the European market.

The efficiency of wood processing for lumber and sample lumber products is currently at about 60%. The efficiency of production of selected elements and sets (products) of pine pallet type is at Epc=135–161% in 2023, thanks to the added value of by-products.

Timber value accounting from the point of view of profitability of processing can be applied to determine the direction of changes in the demand structure for roundwood.

The criterion of added value in processing, as well as the efficiency relationship, can be used in the study of the management structure of a limited supply of wood, for example in multi-plant enterprises.

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ORIGINAL ARTICLE

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Variability of secondary metabolism and morphogenesis of *Ligustrum vulgare* L. under different growing conditions in an urban environment

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Abstract

Assessing the condition of plants in an urban landscaping is a necessary component of monitoring urban ecosystems. Studying how the sensitivity of plants to stressful conditions and the influence of many factors on their growth and development is important for determining the suitability of using plants for urban improvement.

The purpose of this study was to identify the impact of stress factors on the growth and development of *Ligustrum vulgare* L. (commonly called privet). The research was conducted in the city of Kyiv, where the plants are affected by significant vehicle traffic, intense insolation or excessive shade, and mechanical traumatization of plants due to plant trimming. Shoots of *Ligustrum vulgare* L. of different ages and under different growing conditions were used for the analysis.

The research used methods of morphometry, chromatographic profiling of secondary metabolites, and statistical data processing. To analyze the morphogenesis of annual shoots, the Gaussian model was used, which accurately (R2 > 0.90) describes their growth processes. The model coefficients were used for a comparative assessment of the growth dynamics of *Ligustrum vulgare* L. shoots depending on the growing conditions and plant care. Correlation analysis also allowed for the identification of potential connections between the growth model coefficients and certain phenolic synthesis products. It was found that the plant trimming leads to an increase in the length of the shoots and accelerated growth of the side shoots. The obtained results may indicate that phenolic compounds, in particular chlorogenic acid, directly or indirectly affect the regulation of growth and development of shoots of *Ligustrum vulgare* L. in response to stress factors, such as mechanical injury. The content of chlorogenic acid positively correlates with the increase in the length of internodes, which indicates its possible role in morphogenesis. It has been established that the profiles of phenolic substances allow identification of *Ligustrum* plants at the species level. Principal component analysis (PCA) and cluster analyses showed that the phenolic profiles of plants depend on their growing conditions and the urban environment. The study confirms the importance of plant trimming for stimulating plant growth. The significant adaptation potential of *Ligustrum vulgare* L. plants confirmed the suitability of their use in urban environments.

Key words

stability, internodes, shoot growth, urban environment, phenolic compounds

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Introduction

Studying the state of plants in urban landscaping is an important component of monitoring urban ecosystems. Determining the stability and prospects of using new types of plants for the improvement of urban areas, as well as improving the quality of life of citizens, requires a scientific basis. For this, it is important to understand the sensitivity of plants to stressful conditions, taking into account the influence of a complex of environmental factors on their general condition, growth, and development.

Ligustrum vulgare L. and its cultivars are one of the promising plants for urban landscaping. This semi-evergreen shrub belongs to the family *Oleaceae* Hoffmanns. & Link and has an attractive appearance and broad environmental tolerance (Zayachuk 2014). The expediency of using *Ligustrum vulgare* L. in landscaping is based on a complex of its beneficial morpho-physiological features.

Ligustrum vulgare L. is a semi-evergreen shrub or small tree that has a spreading crown and reaches 3 to 6 m in height. The oval leaves are elongated, dark green in color, and often glossy with a wax coating. Flowering typically begins from the end of May to the beginning of June. Cream-white flowers are collected in a pyramidal panicle and have a strong aroma. Stone fruits, green in color, acquire a dark purple color at the time of ripening. The plant tends to remain evergreen in warmer climates (Zayachuk 2014).

Ligustrum vulgare L. has a simple and at the same time beautiful appearance, which makes it attractive for urban landscapes (Turgunboevna 2022), domestic areas, gardens, parks, squares, alleys and streets (Kuznetsov et al. 2020), highways, and industrial zones (Yukhimenko et al. 2017). This bush is grown individually or as part of hedges (Dzyba 2020), creating harmonious, esthetically attractive landscape compositions (Shamray et al. 2021; Dudin and Levus 2022). Currently, the rather popular *Ligustrum vulgare* L. is an alternative to *Buxus sempervirens* L. in landscaped bridges (Lukash et al. 2023).

The use of *Ligustrum vulgare* L. in landscaping contributes to the preservation and increase of biodiversity in urban ecosystems (Stratu et al. 2016). White flowers gathered in dense pyramidal panicles attract insects (bees and butterflies), which play an important role in pollination of plants and maintenance of ecological balance (Zayachuk 2014). In turn, its fruits [rounded or ovoid drupes (Zayachuk 2014), which ripen in August–September] are a fodder base for birds (Enescu et al. 2015).

Ligustrum vulgare L. is a relatively undemanding plant to grow. It can grow in both sunny and shaded places and on fairly dry (Toscano et al. 2018) and poor soils. This allows it to be used in landscape conditions that are quite difficult for other plants (Kuznetsov et al. 2020).

Ligustrum vulgare L. exhibits high resistance to toxic substances, elevated temperatures (Beikircher et al. 2009), and other stress factors inherent in the urban environment (Strashok 2022). This shrub is able to successfully grow and develop in conditions of high concentrations of harmful gases (Hasanovic et al. 2022; Zhang et al. 2016) and high vehicle traffic (Shamray et al. 2021).

Phenolic compounds play an exclusive role in ensuring the viability of the plant organism. The phenolic complex of *Ligustrum vulgare* L. is quite unique. The presence of secoiridoid glucosides, (200R)- and (200S)-10-hydroxy-200-methoxyoleuropein (1 and 2), and secoiridoid aglycones, ligustrogemiacetals A (3) and B (4) was confirmed in the leaves and stems of this species (Tanahashi et al. 2009). Secoiridoids (oleuropein, ligustaloside A, ligustaloside B, and ligstroside), four kaempferol glycosides (kaempferol 3-O-glucoside 7-O-rhamnoside, kaempferol 3,7-O-dirhamnoside, kaempferol 3-O-rhamnoside, and kaempferol 3-O-glucoside), and two quercetin glycosides (quercetin 3-O-glucoside 7-O-rhamnoside and quercetin 3,7-O-dirhamnoside) (Romani et al. 2000). The presence of oleacein, oleuropein, and echinacoside has been established (Czerwińska et al. 2015).

Abiotic factors of the environment, such as lighting, temperature, and humidity individually and in combination, affect the biochemical composition and contents of compounds of secondary synthesis in the plant organism (Novosad 2014). An increase in light intensity promotes the accumulation of flavonoids and other photoactive molecules in the assimilation organs (Agati et al. 2009; Agati et al. 2020). Phenolic acids in plant cells play the role of nonspecific regulators in physiological processes (Huang et al. 2019; Likhanov et al. 2019). Gallic and ellagic acids, their derivatives, and other polyphenols, which have significant antioxidant activity, contribute to the protection of cells from damage in stressful conditions (Romani et al. 2000). Flavonoids, which are one of the most common classes of phenolic compounds, play a variety of physiological functions (Voytsehivska et al. 2015). They are involved in the regulation of cell division and differentiation and in the processes of formation of plant tissues and organs (Agati et al. 2012). Some flavonoids (quercetin, kaempferol) can affect auxin transport (Tanahashi et al. 2009) and regulate the growth and development of the root system (Agati et al. 2012). These flavonols reduce the negative effects of stress, particularly under conditions of soil salinity and excessive ultraviolet radiation (Falcone Ferreyra et al. 2021; Czerwińska et al. 2015).

The qualitative and quantitative composition of secondary metabolites characterizes the general state of the plant. Individual phenolic compounds and the quantitative ratio of individual classes of these substances are potential markers of stress. However, the importance of these substances for the plant organism and their physiological functions and synthesis depending on the conditions of local growth remain poorly researched.

In this regard, the purpose of this work is to perform phytochemical profiling of *Ligustrum vulgare* L. and to study the peculiarities of the morphogenesis of annual shoots depending on the conditions of plant growth.

Material and methods

Research conditions

The research was done in the city of Kyiv in 2021–2023. The climate of the city is moderately continental, with temperate winters and warm summers. Average monthly temperatures in January are –3.5°C and in July +20.5°C.

The studied plants are located on the streets of Kyiv, in public squares, as well as in park areas (Fig. 1). The exact location of plant growth is shown in Table 1.

Figure 1. Map of location of studied *Ligustrum vulgare* L. in green areas of Kyiv

In the city of Kyiv, *Ligustrum vulgare* L. is mainly used to create hedges. There are examples of its combination with other types of plants in the form of three-dimensional flat figures or in photocompositions with flower beds, as well as single free-growing specimens.

Table 1. Location coordinates and origin of the initial planting material of *Ligustrum vulgare* L. in the city of Kyiv, Ukraine

No.	Coordinates	The origin of the original planting material	Code	Location
1	2	3	4	5
1	50°21’55.0”N 30°27’52.0”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.1	Akademika Zabolotnoho Street, Kyiv, Ukraine
2	50°22’04.4”N 30°27’39.1”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.2	Heavenly Hundred Square, Akademika Zabolotnoho Street, Kyiv, Ukraine
3	50°22’12.4”N 30°27’27.3”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.3	Akademika Hlushkova Avenue, Kyiv, Ukraine
4	50°22’13.9”N 30°27’16.4”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.4	Teremkivska Street, Kyiv, Ukraine
5	50°22’27.4”N 30°27’04.2”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.5	Tadeia Rylskoho Boulevard, Kyiv, Ukraine
6	50°22’36.2”N 30°30’21.1”E	Nursery Department of Forest Reproduction and Forest Reclamation, National University of Life and Environmental Sciences of Ukraine	L.v.6	Henerala Rodymtseva Street, Kyiv, Ukraine

1	2	3	4	5
7	50°22’54.3”N 30°28’40.8”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.7	Vasylkivska Street, Kyiv, Ukraine
8	50°22’51.1”N 30°28’37.5”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.8	Akademika Hlushkova Avenue, Kyiv, Ukraine
9	50°22’51.3”N 30°28’50.9”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.9	Expo Center of Ukraine, M01, Kyiv, Ukraine
10	50°22’57.1”N 30°28’54.3”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.10	Holosiivskyi Prospekt, Kyiv, Ukraine
11	50°22’43.6”N 30°28’55.6”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.11	Expo Center of Ukraine, M01, Kyiv, Ukraine
12	50°22’37.2”N 30°28’42.1”E	Municipal enterprise for the maintenance of green spaces of the Holosiivskyi district of Kyiv	L.v.12	Expo Center of Ukraine, M01, Kyiv, Ukraine
13	50°23’01.0”N 30°29’48.2”E	National University of Life and Environmental Sciences of Ukraine	L.v.13	Heroiv Oborony Street, Kyiv, Ukraine
14	50°27’46.3”N 30°24’40.0”E	Municipal enterprise for the maintenance of green spaces of the Shevchenkivskyi district of Kyiv	L.v.14	Kyrponosa Street, Kyiv, Ukraine

These plantations are located at different distances from roads (main roads, transport interchanges, and avenues). Plantation of *Ligustrum vulgare* L. on Akademika Hlushkova Avenue, Kyiv, Ukraine (Fig. 2C); Akademika Zabolotnoho Street, Nebesnaya Hundred Square, Tadeia Rylskoho Boulevard, Vasylkivska Street, Kyiv, Ukraine, grows at a distance of 5–10 m from roads (Tab. 2).

Table 2. Characteristics of growing conditions

No.	Code	Age of plants, years	Plant condition	Lighting at the place of growth	Distance from highways, m
1	L.v.1	3	untrimmed	full sun	5–10
2	L.v.2	8	trimmed	full sun	1–2
3	L.v.3	6	trimmed	full sun	5–10
4	L.v.4	4	untrimmed	shade	45
5	L.v.5	4	untrimmed	full sun	2–3
6	L.v.6	15	untrimmed	shade	500
7	L.v.7	8	trimmed	full sun	25
8	L.v.8	12	trimmed	full sun	1–2
9	L.v.9	8	trimmed	partial shade	150
10	L.v.10	9	trimmed	partial shade	1–40
11	L.v.11	7	trimmed	partial shade	450
12	L.v.12	13	trimmed	partial shade	400
13	L.v.13	5	trimmed	partial shade	25–30
14	L.v.14	7	trimmed	full sun	1

These places are characterized by significant vehicle traffic. Plantation of *Ligustrum vulgare* L. at Expo Center of Ukraine, M01, Kyiv, Ukraine, and Henerala Rodymtseva Street, Kyiv, Ukraine (Fig. 2A), are not directly affected by vehicle emissions because they are located far from roads (<500 m) (Tab. 2).

Soils in the vast majority of locations where *Ligustrum vulgare* L. grow are sandy. The amount of sunlight in the areas where the studied plants grow also differ. Conventionally, they can be divided into three classes: full sun (duration of exposure to direct solar radiation is 10–12 hours per day), partial shade (3–9 hours per day), and shade (0–2 hours per day) (Tab. 2). Plantation of *Ligustrum vulgare* L. on full sun areas: Akademika Zabolotnoho Street, Nebesnaya Hundred Square, Akademika Hlushkova Avenue, Kyiv, Ukraine; partial shade: Expo Center of Ukraine, Teremkivska Street, Kyiv, Ukraine (Fig. 2B); and shade: Henerala Rodymtseva Street, Kyiv, Ukraine.

Plantations of *Ligustrum vulgare* L. also differ in appearance. Most of them are shaped in the form of hedges or massifs. Such plants are formed by pruning 2–3 times during the growing season, but there are also free-growing plants that do not undergo cutting at all.

Morphometric studies. The analysis of the morphometric parameters of the shoots was carried out to evaluate the determination of the features of the growth processes of plants depending on the conditions of their cultivation. Sampling was carried out in 14 localities

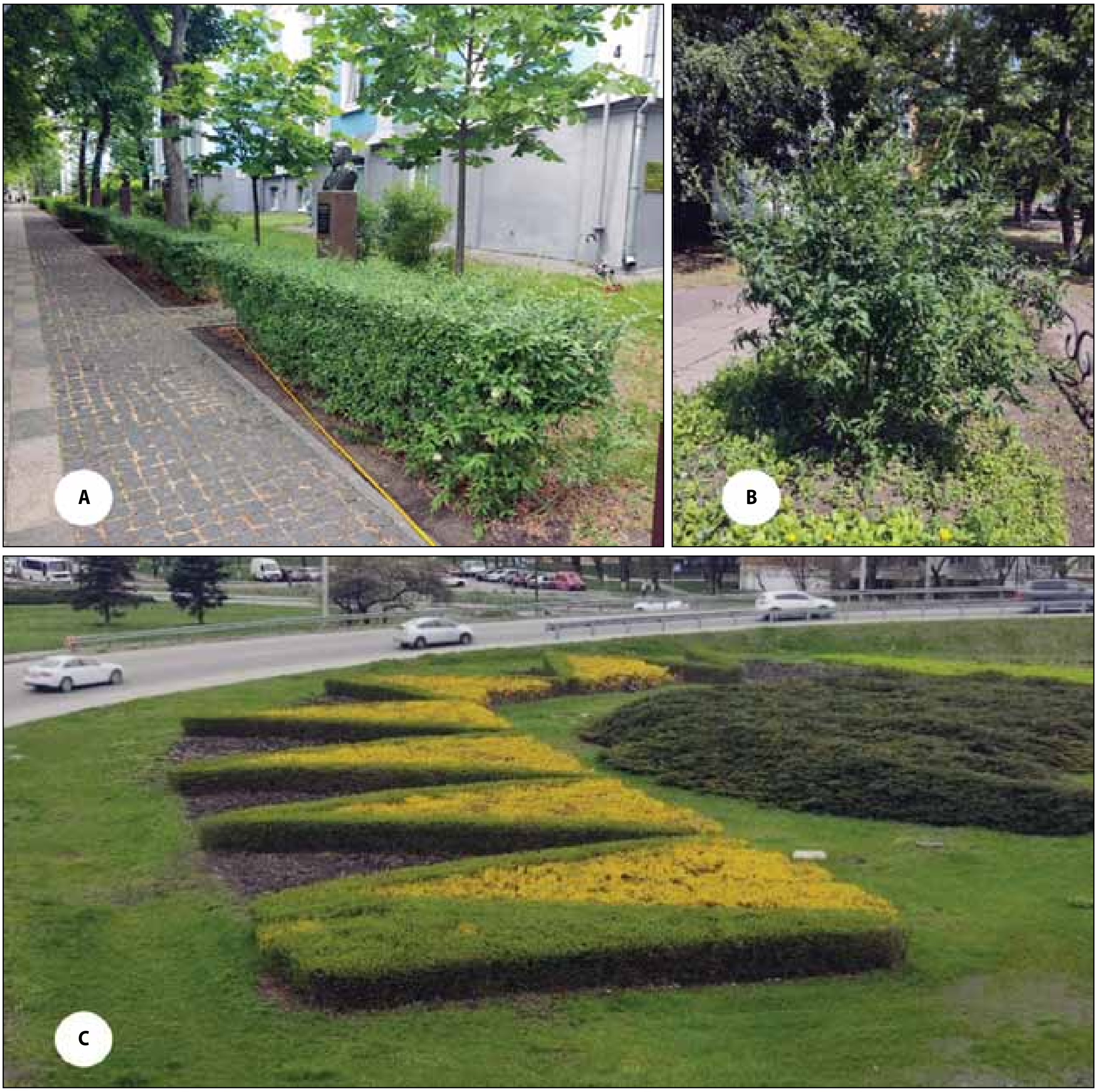

Figure 2. Examples of the use of *Ligustrum vulgare* L. in the green areas of Kyiv: A – living fence with *Ligustrum vulgare* L. on the territory of National University of Life and Environmental Sciences of Ukraine; B – *Ligustrum vulgare* L. free-growing plant, Teremkivska Street, Kyiv, Ukraine; C – composition on Akademika Hlushkova Avenue, Kyiv, Ukraine with a combination of *Ligustrum vulgare* L. and *Forsythia europaea* Degen & Bald

(Tab. 1). A total of 26 plants were used in the experiment. The length and diameter of internodes of one-year shoots of *Ligustrum vulgare* L. (n = 156) were measured.

To describe the dynamics of internode length changes in one-year-old shoots during the growing season, we used the Gaussian model, which accurately described the morphogenesis features of plants with clearly defined peaks and declines in the growth activity (1).

$$f = a \cdot \exp^{\left(-0{,}5 \cdot \left(\frac{(x - x^0)}{b}\right)^2\right)} \qquad (1)$$

To identify the relationship between the overall plant condition assessments and the coefficients (a, b) in the Gaussian model, we employed multiple Spearman rank correlation analysis.

Secondary metabolite profiling method. Separation of substances was carried out by the method of high-performance thin-layer chromatography (HPTLC) on Silicagel G 60 plates (Merck) in the solvent system: ethyl acetate – formic acid – acetic acid – water (v/v/v/v – 100 : 11 : 11 : 25). The obtained chromatograms were treated with a 0.5% NP reagent in ethyl acetate followed by treatment with 1.0% PEG and heating at 90ºC for 1 min. Flavonoids and other polyphenols were detected in the chromatogram in ultraviolet light (λ_{max} = 365 nm). Rf indicators (retention index) of individual compounds were determined photodensitometrically using the Sorbfil TLC Videodensitometer computer program.

Autofluorescence of shoot tissues was studied on an inverted microscope with a multichannel fluorescence imaging system (EVOS FL System, ThermoFisher Scientific, USA).

Method of statistical data processing. Measurement results are presented as mean ± standard error (x±SE). The significance of the difference ($p<0.05$) between the obtained data was determined by the method of variance analysis (one-way ANOVA) using Tukey's a posteriori test in the XLSTAT program (Addinsoft Inc., USA, 2010). Thus, we compared the total length of shoots between pruned and unpruned plants (the total number of shoots in the samples was n=140). Principal component analysis (PCA) and cluster analysis were performed in the XLSTAT program. The Sigma Plot 12.0 program (Systat Software, Inc., 2011) was used for regression analysis.

Results

Ligustrum vulgare L. bushes are usually cut when the shoot forms on average 5–7 internodes. The formation of lateral shoots occurs due to the stimulation of lateral buds during decapitation of the shoot, which in turn form 5–6 internodes within 1 month after cutting (Fig. 3). The length of the internodes of such shoots is usually 1.2–1.3 times greater than a normal shoot. The degree of lignification (maturation) of stem tissues slows down. The leaves on the lateral shoots in the lower internodes have an elliptical, ovoid shape and only at 3 nodes do they acquire the elongated-elliptical shape typical of *Ligustrum vulgare* L. Two shoots can form at the node at the same time, which creates a falsely dichotomous branching, or there may be only one shoot. In the first case, the growth of lateral shoots was almost uniform, and the first leaves in the node are small, almost round in shape and leathery.

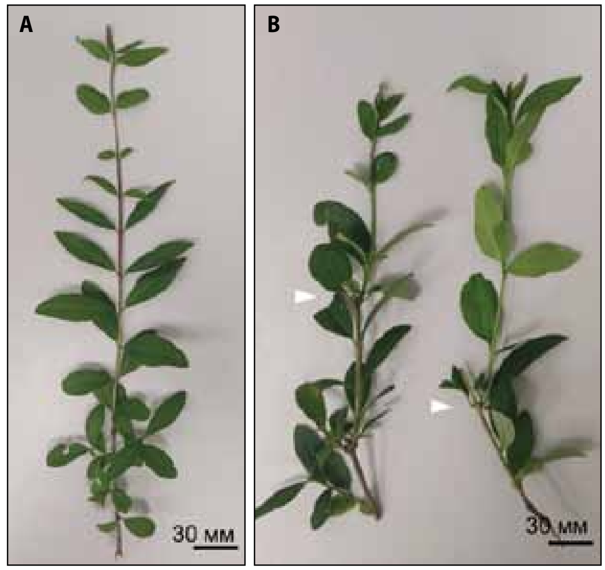

Figure 3. Formation of shoots of *Ligustrum vulgare* L. in normal condition (A) and after cutting (B). Note: The arrow indicates the cut stem; scale bar – 30 mm

The following leaves are elliptical, the internodes are elongated, slightly woody, and slightly pubescent, and the number of lenticels is reduced. In the case of drying of one shoot, which can occur as a result of cutting or natural injury, the growth of the side shoot slowed down somewhat, and the internodes had the typical length of *Ligustrum vulgare* L. (Fig. 4).

The average length of shoots formed during the season differs between pruned and unpruned *Ligustrum vulgare* L. plants. The length of shoots in unpruned plants is 1.6 times greater than that of pruned plants.

The structure of the tissues of the stems of the privet, which were cut, is significantly different from uncut plants (Fig. 5). First of all, this is due to the slowing down of the formation of periderm and xylem. Normally, in shoots of the current year, periderm formation occurs in the zones 1–5 of internodes (Fig. 5 A–J). As

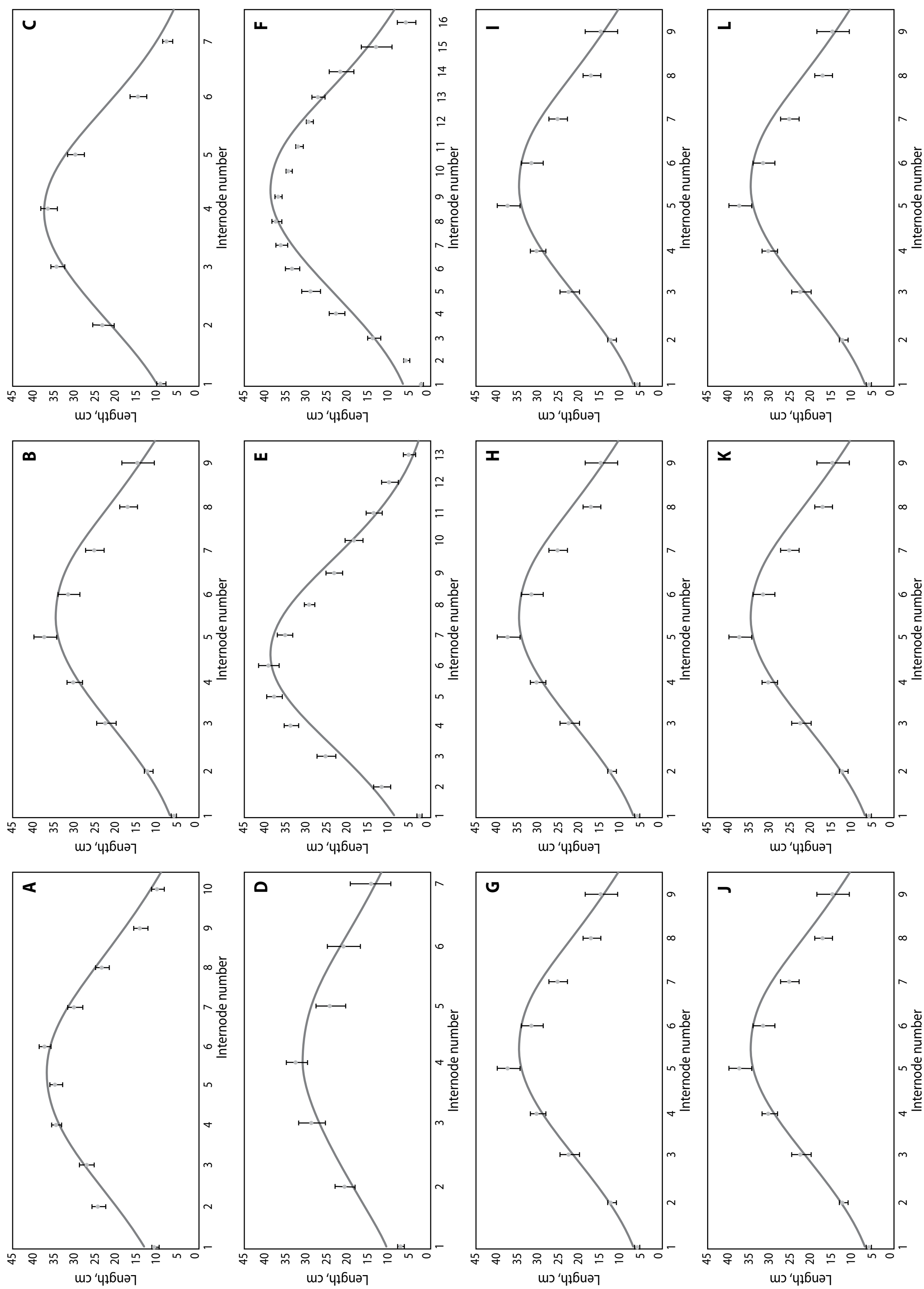

Figure 4. Dependencies of the length of internodes on the order of their location on a single growth cycle of the shoots under different growing conditions of *Ligustrum vulgare* L.

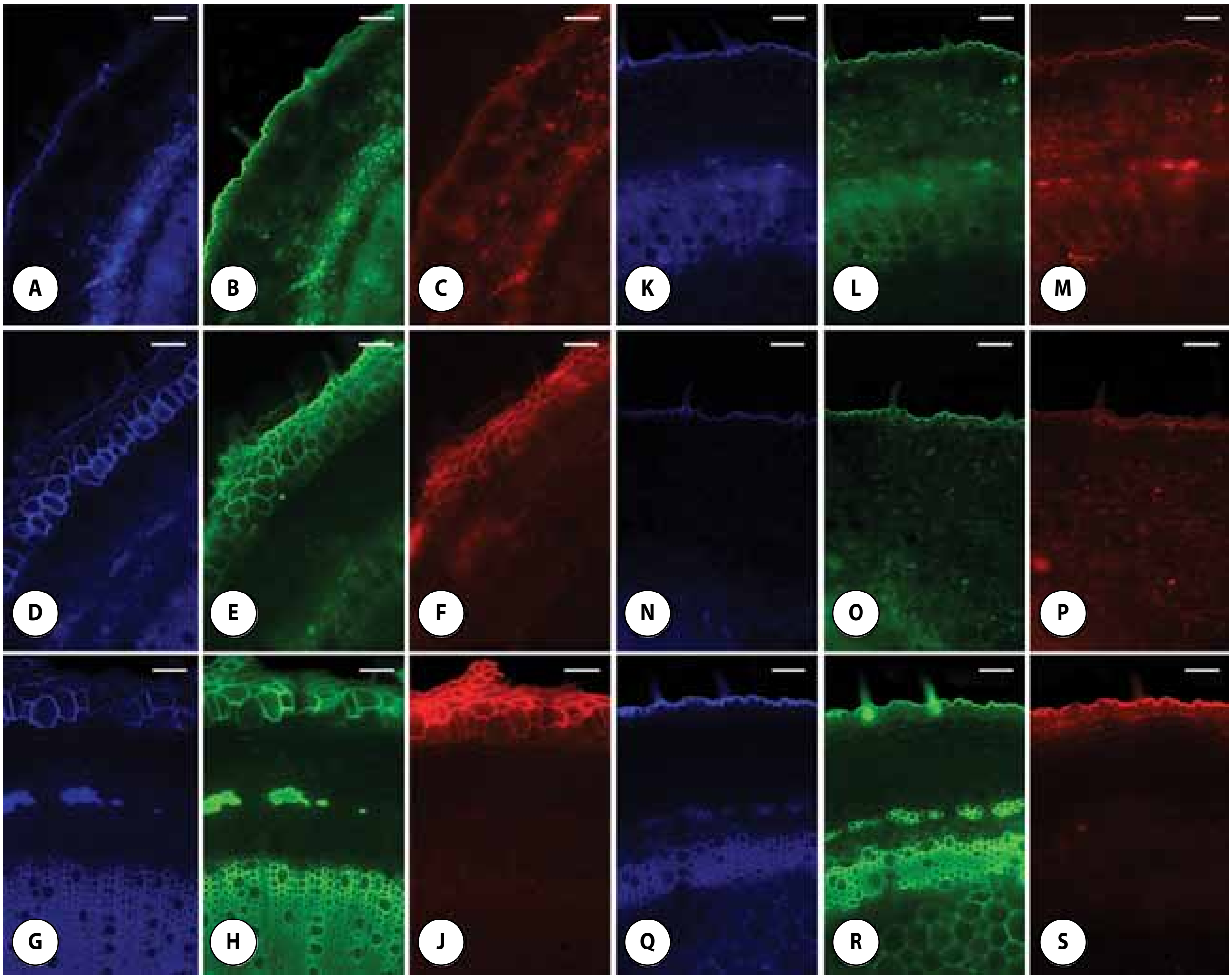

Figure 5. Autofluorescence of tissues of stems of *Ligustrum vulgare* L., which were not exposed (A–J) and were subjected to shearing (K–S): A–C – 9 internodes, D–F – 5 internodes; K–M – 5 internodes, N–P – 2 internodes; G–J and Q–S – 5 internodes after treating tissues with a NP reagent; ruler – 50 µm

a result of the decapitation of the main shoot, the lateral buds begin to grow much later. Because of this, the periderm does not have time to fully form. Epidermis with simple trichomes on such shoots is found even on the first internodes (Fig. 5 K–S).

Phellem cells become woody and are permeated with compounds of secondary synthesis. Accumulation of phenolic compounds and presumably proteins is found in the narrow zone of the secondary cortex of young metamers (Fig. 5 A–C K–M), where bast fibers are formed during the maturation of mechanical tissues. These fibers are laid in small bundles without forming a continuous mechanical ring. The autofluorescence of their cell walls in the blue, green, and red spectra is insignificant, but after treating the tissues with the NP reagent, it is enhanced and stands out against the background of the cortex parenchyma (Fig. 5 G–J, Q–S). This may indicate that the cell walls of the fibers contain products of phenolic synthesis (oxycinnamic acids and flavonoids), which are specifically detected in this way. In lateral shoots formed after cutting, the distribution of assimilates in the cells of the parenchyma of the secondary cortex is more evenly distributed and does not reveal a zone of concentration (Fig. 5 K–M). Xylogenesis, lignification of vessels, and formation of secondary cell walls in wood fibers also slow down. The width of the xylem ring in such stems is 2.5–3.0 times smaller than that in the corresponding internodes of

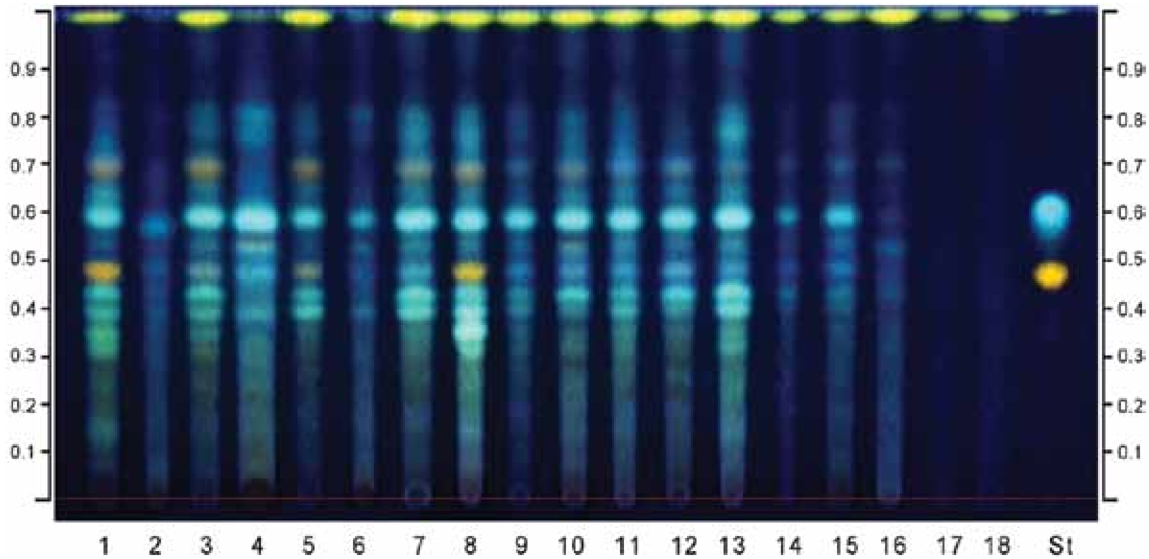

Figure 6. Chromatogram of bark and periderm extracts of annual shoots of *Ligustrum vulgare* L.: 1 – Akademika Zabolotnoho Street; 2 – Heavenly Hundred Square, Akademika Zabolotnoho Street; 3 – Akademika Hlushkova Avenue; 4 – Teremkivska Street; 5 – Tadeia Rylskoho Boulevard; 6 – Henerala Rodymtseva Street; 7 – Vasylkivska Street; 8 – Akademika Hlushkova Avenue; 9 – Expo Center of Ukraine, M01; 10 – Holosiivskyi Prospekt; 11 – Expo Center of Ukraine, M01; 12 – Expo Center of Ukraine, M01; 13 – Heroiv Oborony Street; 14 – Kyrponosa Street; 15 – Expo Center of Ukraine, M01; 16 – Expo Center of Ukraine, M01; 17 – Expo Center of Ukraine, M01; 18 – Expo Center of Ukraine, M01; St – rutin (Rf ~ 0.48), chlorogenic acid (Rf ~ 0.62)

uncut plants. The rapid growth of shoots with delayed lignification is compensated at the end of the growing season, and therefore, the last cutting of *Ligustrum vulgare* L. should take into account its growth and development characteristics.

Biochemical profiling of phenolic compounds in one-year stems of *Ligustrum vulgare* L. made it possible to identify 20 individual compounds that according to the retention coefficients and specificities of autofluorescence in the UV (λ = 365 nm) belong to phenolcarboxylic acids, their conjugates, and flavonoids (Fig. 6). In general, 2 main groups of plants are distinguished according to phytochemical profiles.

Rutin (quercetin-3-O-rutinoside) (Rf ~ 0.48) was detected only in samples from 4 localities (Akademika Zabolotnoho Street; Akademika Hlushkova Avenue; Tadeia Rylskoho Boulevard). Chlorogenic acid (conjugate of caffeic acid and quinic acid with Rf ~ 0.62) was detected in all samples.

The growth dynamics of shoots of *Ligustrum vulgare* L. is also related to the content in the cells of the parenchyma of a low polar flavonoid (Rf ~ 0.98) (Fig. 6). Its concentration in the bark parenchyma correlates with other phenolic compounds Rf ~ 0.41; 0.66; 0.73; 0.77. Elevated concentrations of this flavanol have been found in plants with uniformly rapid growth (without significant accelerations) between internodes, allowing the plant to achieve maximum growth in a short period of time. The importance of this metabolite and its close relationship with general phenolic synthesis indicates its integration into physiological processes related to the regulation of shoot growth and development. It is worth noting that the indicator of the coefficient b in the Gaussian model (Appendix), which characterizes the dynamics of stem growth, in the case of multiple correlation revealed a reliable connection with the substances Rf ~ 0.41; 0.98, and the "x_0" coefficient is associated with four substances (Rf ~ 0.51, 0.56, 0.73, 0.98). The coefficient a (upper asymptote) is positively correlated with the substance Rf ~ 0.61, which may indicate that this phenolic compound probably participates in the regulation of growth by stretching. As a result of this, the length of the internodes increases.

Based on the results of the cluster analysis, which took into account morphometric parameters of shoots

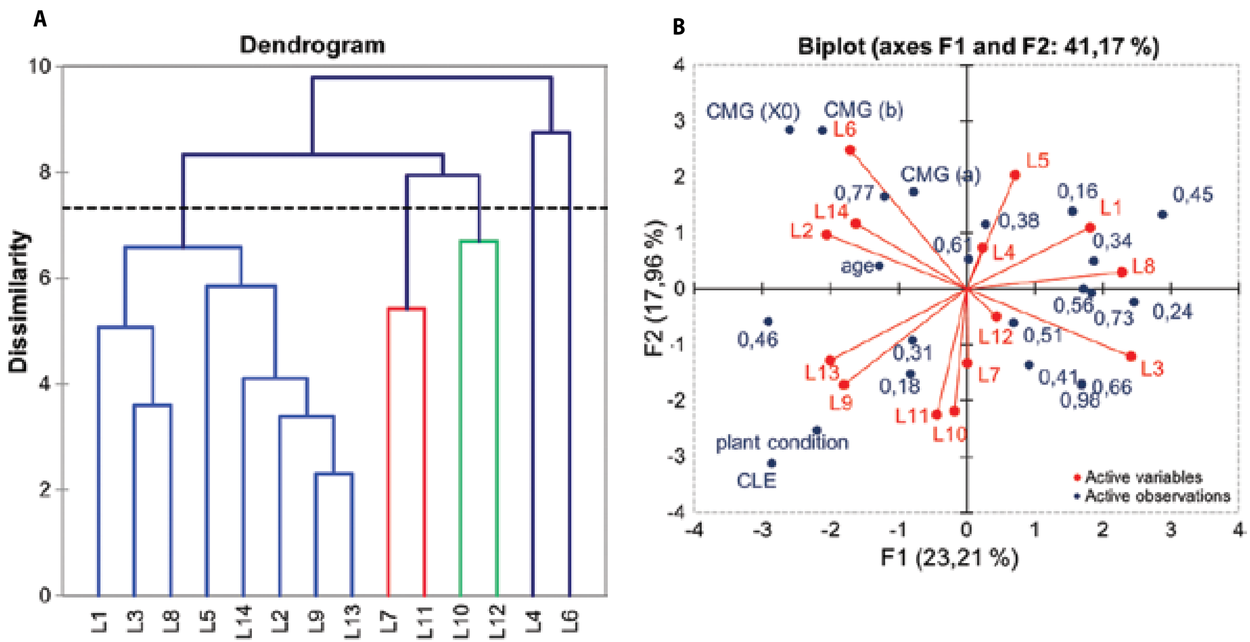

Figure 7. Cluster (A) and PCA (B) analysis taking into account urban conditions, the morphometry of shoots, and the qualitative composition of phenolic compounds in the tissues of shoots of *Ligustrum vulgare* L. Note: L1...14 – distribution of experimental plants by place of growth in the city of Kyiv, where: 1 – Akademika Zabolotnoho Street; 2 – Heavenly Hundred Square, Akademika Zabolotnoho Street; 3 – Akademika Hlushkova Avenue; 4 – Teremkivska Street; 5 – Tadeia Rylskoho Boulevard; 6 – Henerala Rodymtseva Street; 7 – Vasylkivska Street; 8 – Akademika Hlushkova Avenue; 9 – Expo Center of Ukraine, M01; 10 – Holosiivskyi Prospekt; 11 – Expo Center of Ukraine, M01; 12 – Expo Center of Ukraine, M01; 13 – Heroiv Oborony Street; 14 – Kyrponosa Street; 15 – Expo Center of Ukraine, M01; 16 – Expo Center of Ukraine, M01; 17 – Expo Center of Ukraine, M01; 18 – Expo Center of Ukraine, M01. Age – the age of the plant at the time of the study; Plant condition are clipped and unclipped plants; GMC – Gauss model coefficient; CLE is the coefficient of the linear equation (the ratio of the length to the thickness of the internodes).

and phenolic synthesis products, the plants were divided into three main groups (Fig. 7A). The first cluster (I) comprised plants that had never been pruned. The second cluster (II) grouped pruned plants from one location (VDNG) and accordingly had similar growth conditions, close origins, and age. The third cluster (III) was more heterogeneous in composition. As the similarity level increased, it split into two subclusters. Subcluster IIIa combined pruned plants growing near highways. In subcluster IIIb, pruned plants further away from the roadway were grouped.

Biplot principal component analysis (PCA) showed that the total variance of F1 and F2 components is 41.17% (Fig. 7B).

Principal component analysis methods emphasized the importance of the coefficients of the Gaussian model, which describe the dynamics of internode growth.

Discussion

The morphometric analysis of metamers of *Ligustrum vulgare* L. shoots showed that the parameters of the linear dimensions of internodes according to the sequence of their formation are quite accurately described by the Gaussian model (1). It takes into account the morphometric indicators of each internode (Appendix A). This model plays a key role in understanding the processes of growth and development of shoots and their adaptation to external conditions. Thus, the Gaussian model coefficients (KM (x_0) and KM (b)), which describe the dependence of the length of internodes on their spatial position on the stem, made the largest contribution to the total variance of the investigated traits (Fig. 8).

The increase in the concentration of chlorogenic acid in the bark and periderm of one-year shoots cor-

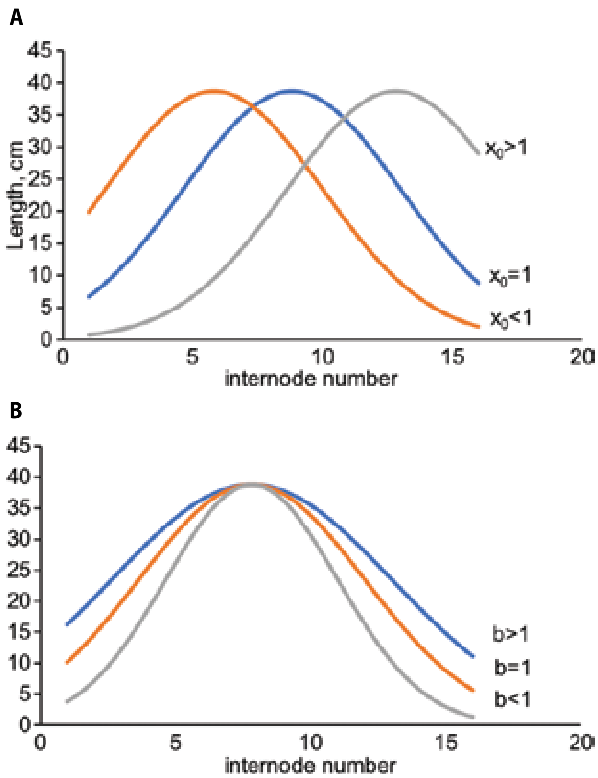

Figure 8. Curve dependence in the Gaussian model on the values of the coefficients x_0 and b

relates negatively (r = -0.635) with the coefficient "x_0" in the Gaussian model. A reliable relationship (r = –0.549) was established between the "b" coefficient of this model and the condition of the plants. By state, we understand the general appearance of the plant, in particular after an initial pruning. The negative correlation coefficient indicates that cutting plants leads to an increase in the size of the first internodes, which is caused by the awakening and accelerated growth of side shoots after decapitation of the main one. The indicator of the total length of the shoot is the result of the growth and formation of each internode during the entire growing season. There is a close correlation between the coefficient "a" and the total length of the shoot since the growth function of individual internodes determines the growth of the shoot as a whole. A reliable correlation was also determined between the coefficient "x_0", which determines the maximum growth rate of the shoot according to the number of the internode. During the formation of 7–8 internodes, they can stop growing in length and begin to become woody. Thus, as a result of ripening, they are fully adapted to the winter period during the growing season. At the same time, it is interesting that the apical bud of undamaged shoots sometimes initiates secondary growth. The reason for this phenomenon may be related to the systemic physiological restructuring of the plant, which is exposed to stress during cutting.

It has been established that against the background of the accumulation of individual phenolic substances, internodes quickly reach the maximum length. Because of this, it can be assumed that the increase in the content of chlorogenic acid is a compensatory mechanism in the process of adaptation of plants after injury. In turn, chlorogenic acid is known as a highly effective antioxidant. It effectively protects cell membranes from the negative effects of reactive oxygen species and free radicals, the concentration of which increases due to organ injury (Mei et al. 2020).

According to the result of multiple correlation analysis (according to Spearman), a close relationship between the degree of light regime and the vehicle traffic loads was established, which is explained by the fact that plants growing near highways are usually not shaded. According to G. Agati et al. (2009), quercetin and luteolin derivatives significantly accumulate in epidermal and mesophyll cells in response to intense sunlight. At the same time, monohydroxyflavone glycosides (luteolin 4-O-glucoside and two 7-O-glycosides of apigenin) did not respond to changes in solar radiation (Agati et al. 2009). In our studies, the autofluorescence intensity of tissues after their treatment with the NP reagent also increased in plants in open areas. This confirms the fact that flavonoids play a key role in the adaptation of plants to lighting conditions.

Summary and conclusions

The results of the research showed that the phytochemical profiles of phenolic compounds of *Ligustrum vulgare* L. depend on the growing conditions and the location of the plants. An increase in the content and qualitative composition of flavonoids is a reaction of plants to increased insolation and accordingly. There are close connections between the presence of certain individual compounds of secondary synthesis and shoot morphogenesis, which may indicate their role as non-specific regulators of growth processes.

The research results confirmed the high adaptability of *Ligustrum vulgare* L. plants to the urban environment. The complex nature of the relationships between plant growing conditions, secondary metabolism, and shoot growth in *Ligustrum vulgare* L. is shown.

Further, increasing the understanding of these interactions will contribute to the improvement in the methods of growing and caring for plants, as well as the use of *Ligustrum vulgare* L.in the landscaping of modern cities.

Acknowledgement

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Appendix

	Coefficient	Standards Error	t	P
1	2	3	4	5
Akademika Zabolotnoho Street, Kyiv, Ukraine				
a	35.351	1.1930	29.6317	<0.0001
b	2.9083	0.1364	21.3233	<0.0001
x0	5.1541	0.1152	44.7230	<0.0001
Heavenly Hundred Square. Akademika Zabolotnoho Street. Kyiv. Ukraine				
a	34.6465	1.5078	22.9778	<0.0001
b	2.4045	0.1365	17.6144	<0.0001
x0	5.2986	0.1215	43.6186	<0.0001
Akademika Hlushkova Avenue. Kyiv. Ukraine				
a	37.2528	0.9459	39.3817	<0.0001
b	1.7260	0.0545	31.6535	<0.0001
x0	3.7563	0.0506	74.2725	<0.0001
Teremkivska Street. Kyiv. Ukraine				
a	30.7231	2.1592	14.2289	0.0001
b	2.1289	0.2146	9.9227	0.0006
x0	4.0875	0.1754	23.3006	<0.0001
Tadeia Rylskoho Boulevard. Kyiv. Ukraine				
a	40.6227	1.9715	20.6055	<0.0001
b	3.0506	0.1833	16.6463	<0.0001
x0	6.1805	0.1715	36.033	<0.0001
Henerala Rodymtseva Street. Kyiv. Ukraine				
a	38.7128	1.4312	27.0493	<0.0001
b	4.1766	0.1984	21.0506	<0.0001
x0	8.8261	0.1788	49.3689	<0.0001
Vasylkivska Street. Kyiv. Ukraine				
a	43.7234	1.9391	22.5478	<0.0001
b	1.9210	0.1052	18.267	<0.0001
x0	4.1619	0.0984	42.3137	<0.0001
Akademika Hlushkova Avenue. Kyiv. Ukraine				
a	40.2798	0.9382	42.9345	<0.0001
b	1.9957	0.0579	34.4500	<0.0001
x0	4.5229	0.0536	84.4422	<0.0001

1	2	3	4	5
Expo Center of Ukraine. M01. Kyiv. Ukraine				
a	39.9353	1.7313	23.0661	<0.0001
b	2.1887	0.1265	17.3060	<0.0001
x0	4.8919	0.1109	44.1112	<0.0001
Holosiivskyi Prospekt. Kyiv. Ukraine				
a	28.7947	1.4152	20.3467	<0.0001
b	2.0946	0.1332	15.7255	<0.0001
x0	4.8765	0.1196	40.7621	<0.0001
Expo Center of Ukraine. M01. Kyiv. Ukraine				
a	29.302	2.7286	10.7388	0.0001
b	2.5388	0.3559	7.1337	0.0008
x0	4.1886	0.2826	14.8195	<0.0001

1	2	3	4	5
Expo Center of Ukraine. M01. Kyiv. Ukraine				
a	47.1108	1.6717	28.1816	<0.0001
b	1.8116	0.0774	23.4082	<0.0001
x0	4.7655	0.0741	64.3411	<0.0001
Heroiv Oborony Street. Kyiv. Ukraine				
a	29.8237	0.7349	40.5808	<0.0001
b	2.2400	0.0913	24.5212	<0.0001
x0	4.9506	0.0758	65.3288	<0.0001
Kyrponosa Street. Kyiv. Ukraine				
a	52.3945	1.8764	27.9227	<0.0001
b	2.9757	0.1550	19.1982	<0.0001
x0	6.3023	0.1297	48.6104	<0.0001