BIOLOGICAL AND ECOLOGICAL FEATURES OF THE FORMATION OF SEED PRODUCTIVITY OF LABURNUM ANAGYROIDES MEDIK. IN THE CONDITIONS OF THE LEFT-BANK FOREST-STEP OF UKRAINE

Sonora Yevhenii
Assistant, Sumy National Agricultural University, Ukraine
ORCID ID: 0009-0007-8116-2771

Tovstukha Oleksandr
Doctor of Philosophy, Sumy National Agricultural University, Ukraine
ORCID ID: 0000-0002-9925-3029

Introduction

Plant introduction is one of the leading approaches to enriching biodiversity and expanding the range of economically valuable, medicinal, and ornamental species. It plays an important role in the formation of stable and functionally complete phytocoenoses, contributing to increased ecological stability of urban and natural-anthropogenic landscapes. Introduction studies are aimed not only at incorporating new species into cultivation but also at assessing their adaptive potential, biological characteristics, reproductive capacity, and economic value under new environmental conditions.

Particular relevance is associated with the introduction of new tree and shrub species in temperate regions, where the assortment of ornamental introduced plants remains limited and is often represented by species with insufficient ecological plasticity. In this regard, there is a need to expand the species composition of plantings through the introduction of promising taxa capable of functioning effectively under changing climatic conditions. An important aspect is also the enhancement of biodiversity in urban ecosystems, which contributes to improving the microclimate, reducing air pollution levels, and increasing the aesthetic attractiveness of territories.

Under current climate change conditions, characterized by increasing aridity, more frequent extreme weather events, and rising temperature levels, special attention should be paid to the selection of species capable of combining high ornamental value, ecological plasticity, and resistance to abiotic stresses. Such stresses include moisture deficit, high temperatures, soil compaction, and increased anthropogenic pressure. In this context, the introduction of drought-tolerant and thermophilic species with a wide adaptive range is one of the key directions in modern ornamental horticulture and forestry.

A promising introduced species for landscaping and the establishment of plantings of various functional purposes is the golden chain tree (*Laburnum anagyroides* Medik., family Fabaceae). This species is widely used in ornamental horticulture across European countries due to its high aesthetic value, relative low maintenance requirements, and ability to form impressive compositions both in solitary and group plantings. The plant is characterized by outstanding декоративність, particularly during the flowering period, when long pendulous inflorescences with numerous yellow flowers create the distinctive visual effect known as the “golden rain” (Hartmann et al., 2010; POWO, 2021; FloraVeg/Euro+Med, 2025). This period is decisive in terms of the ornamental value of the species and determines its wide application in the landscaping of parks and gardens.

In addition to its декоративні properties, *Laburnum anagyroides* possesses a number of biological characteristics that enhance its value as an introduced species. As a member of the Fabaceae family, it is capable of forming symbiotic relationships with nitrogen-fixing bacteria, which contributes to the accumulation of biologically available nitrogen in the soil. This, in turn, positively affects soil fertility, increases its biological activity, and improves conditions for the growth of other plants within plant communities. This property is particularly valuable under conditions of degraded or low-fertility soils, where the introduction of leguminous species can perform a reclamation function.

At the same time, despite its considerable ornamental and ecological potential, the species requires comprehensive study under introduction conditions, particularly regarding its winter hardiness, drought tolerance, growth and development patterns, and reproductive biology. The assessment of these characteristics is a necessary prerequisite for substantiating the feasibility of its widespread use in landscaping and forestry practices.

The modern taxonomy of the species is characterized by a certain degree of synonymy, обусловлене its long history of description and refinement of its systematic position. In international botanical literature, *Laburnum anagyroides* is found under a number of synonymous names, including *L. anagyroides* subsp.

anagyroides, *L. platycarpum* Maire, *L. vulgare* J. Presl, *Cytisus laburnum* L., *C. alschingeri* (Vis.) C. Koch, as well as under the common English name "Golden Chain Tree" (Hartmann et al., 2010; Csurhes & Markula, 2016; POWO, 2021). Such diversity of nomenclatural variants requires unification in scientific research and practical applications to ensure accurate species identification and comparability of results.

In Ukrainian scientific and reference literature, the species is known under several common names, including *bobovnyk anahyrolystyi*, *bobovnyk zvychaynyi*, and occasionally "golden rain," the latter being directly associated with the characteristic morphology of its inflorescences and the abundant yellow flowering that creates a pronounced ornamental effect. This name is widely used in popular and landscape gardening practice; however, in scientific usage it has limited applicability due to its descriptive nature and lack of taxonomic specificity. At the same time, the term *bobovnyk* requires careful clarification in scientific contexts, as in some sources it may be applied to representatives of other genera within the Fabaceae family or even to species that do not belong to this family. In particular, it is sometimes erroneously used to refer to *Prunus tenella* L., which belongs to the Rosaceae family and is not taxonomically related to the genus *Laburnum* (Mamchur & Muskan, 2023; Pakhomov et al., 2023; Shlapak & Piskun, 2007). Such terminological ambiguity highlights the necessity of using Latin names in scientific research to ensure unambiguous and accurate species identification.

The etymology of the genus name *Laburnum* has ancient origins and is associated with the Etruscan linguistic tradition, where it referred to a "leguminous plant with trifoliate leaves." This reflects one of the characteristic morphological features of the genus – compound trifoliate leaves, typical of many legumes. The species epithet *anagyroides* is derived from the genus *Anagyris* and indicates the external similarity of the plant to the Mediterranean species *Anagyris foetida* L., which is also characterized by trifoliate leaves and yellow flowers. This similarity is primarily morphological and does not indicate close phylogenetic relatedness; rather, it reflects historical approaches to plant classification based on external traits.

The genus *Laburnum* was first described by P. C. Fabricius in 1759, and since then its systematic position has been repeatedly уточнювалося. According to modern taxonomic concepts, the genus comprises 3–4 species, among which the most well-known and widely distributed are *Laburnum anagyroides* Medik., *Laburnum alpinum* (Mill.) Bercht. & J. Presl, as well as their natural or artificially produced hybrid *Laburnum* × *watereri*. The latter occupies an intermediate position between the parental forms and is characterized by a combination of their ornamental and biological traits. In some taxonomic treatments, *Laburnum alschingeri* is also mentioned; some authors consider it a distinct species, while others treat it as a variation or form of related taxa. This reflects a certain degree of taxonomic ambiguity within the genus, обусловлену both morphological variability and the limited number of clearly defined diagnostic features.

In cultivation, numerous ornamental forms of *Laburnum anagyroides* have become widely распространені, differing in growth habit, crown shape, growth pattern, and leaf morphology. In particular, the form *f. pendula* is characterized by a weeping crown with pendulous branches, which enhances the ornamental effect during the flowering period. The form *f. aurea* is distinguished by its golden-colored foliage, which persists throughout the growing season and provides additional декоративність even outside the flowering phase. The form *f. quercifolia* has leaves resembling those of oak, which is a relatively rare feature among representatives of the Fabaceae family. A special place in ornamental horticulture is occupied by the hybrid *Laburnum* × *watereri* 'Sunspire', which combines abundant flowering with a more compact crown form and increased ornamental stability (Ferner, 1998). Owing to these characteristics, various forms and cultivars of golden chain tree are widely used in landscaping of urban and suburban areas.

Laburnum anagyroides is a deciduous woody plant of the Fabaceae family, naturally distributed mainly in Central and Southern Europe, particularly in mountainous and foothill regions, where it grows on well-drained, often calcareous soils. Under natural conditions, the species forms small trees or large shrubs 5–6 m in height, with a relatively narrow, sparsely branched crown and an upright or slightly curved trunk. The branches are typically thin and flexible, contributing to the characteristic openwork structure of the crown. Under favorable soil and climatic conditions, particularly with sufficient moisture and high soil fertility, plants may reach 9–10 m in height, with a crown diameter of 3–4 m (Shlapak & Piskun, 2007; Csurhes & Markula, 2016).

It should be noted that the morphometric parameters of the species may vary considerably depending on growing conditions, indicating its relative ecological plasticity. In cultivation, especially under urban conditions, plants often exhibit smaller dimensions due to limited soil volume, substrate compaction, and the influence of anthropogenic factors. Nevertheless, *Laburnum anagyroides* maintains a high level of ornamental value, making it a valuable component of modern green spaces.

In young plants, the crown is irregular, relatively narrow, and often asymmetric, which is обусловлено the intensive growth of apical shoots and the still insufficiently developed system of lateral branching. At this stage, it exhibits a somewhat open structure, with a predominance of vertically oriented branches. With age, the crown gradually expands, becomes denser, and acquires a more regular ovate or broadly ovate shape. In mature specimens, a more balanced architectural structure is formed; however, the crown generally retains a certain openness, which contributes to its ornamental appeal and its ability to transmit light.

The main shoots are upright, strong, light brown to brownish-grey in color, with a smooth or slightly fissured surface. Young branches are greenish-grey and covered with a characteristic silvery pubescence, which performs a protective function by reducing transpiration and protecting tissues from overheating. With age, the shoots become lignified, acquire a grey-brown coloration, and often become pendulous, which is one of the characteristic morphological features of the species and further enhances its decorative effect, particularly during the flowering period. The bark on older branches may become slightly fissured, forming longitudinal cracks.

The buds are arranged alternately, broadly ovate in shape, relatively small, and closely appressed to the shoots. They are covered with several light brown or brown scales that perform a protective function, safeguarding the primordial organs from unfavorable winter conditions. Generative buds are usually larger than vegetative ones and are formed on shortened shoots of the previous year.

The leaves are alternate, compound, trifoliate, with entire margins and a cuneate or slightly narrowed base. Each leaf consists of three leaflets, of which the central one is typically larger and borne on a longer petiolule. The leaf blade is elongated-elliptical or obovate, with a blunt or slightly pointed apex. The average leaf length is 7–8 cm and width 2.5–3.0 cm; however, these parameters may vary depending on growing conditions and plant age.

The petioles are 2–7 cm long, well developed, and covered with silvery-white pubescence, which is particularly pronounced on young organs. Young leaves are greyish-green in color and have a velvety surface due to dense pubescence composed of fine trichomes. This indumentum plays an important role in regulating the plant's water balance by reducing transpiration and protecting tissues from excessive solar radiation. During the period of full vegetation, the adaxial surface of the leaf blade becomes dark green, smooth, and glossy, whereas the abaxial surface remains lighter and often retains slight pubescence. Such differentiation of leaf surfaces contributes to efficient photosynthesis and regulation of gas exchange.

The flowers are bisexual, zygomorphic, and of the papilionaceous type, which is typical of representatives of the Fabaceae family. They consist of five free petals differentiated into a standard (banner), wings, and keel. The perianth is bright yellow, sometimes with brownish or reddish streaks that function as nectar guides for pollinators. The standard petal is significantly larger than the others, broadly ovate, with a characteristic notch at the apex, measuring 18–22 mm in length. The wings are elongated and partially enclose the keel, which is formed by two fused petals and protects the stamens and pistil.

The calyx is campanulate, approximately 5 mm long, with five unevenly developed teeth. Both the calyx and the pedicels (8–12 mm long) are covered with silvery pubescence, which is a characteristic feature of the species. The androecium consists of ten stamens, nine of which are fused into a tube while one remains free, corresponding to the diadelphous type. The gynoecium is represented by a single pistil with a superior ovary.

The flowers are arranged in multi-flowered pendulous inflorescences–racemes–measuring 20–30 cm in length, and under favorable conditions may reach even greater sizes. A considerable number of flowers can be formed within a single inflorescence, ensuring abundant and prolonged flowering. The pendulous nature of the inflorescences, combined with their substantial length, creates the characteristic ornamental effect that has given rise to the common name "golden rain." Flowering typically occurs in the spring–early summer period and is accompanied by high nectar production, which promotes active attraction of insect pollinators (Ferner, 1998; Stawiarz & Wróblewska, 2013).

In general, the morphological features of the aboveground organs of *Laburnum anagyroides* indicate its adaptation to conditions of sufficient light and moderate moisture, and also determine its high ornamental value, which is an important factor in its widespread use in landscaping.

The fruit is a dry, dehiscent, flattened, multi-seeded legume of linear-oblong shape, 2–8 cm long and approximately 0.5–1.5 cm wide. At early stages of development, the fruits are green and densely pubescent, with the indumentum gradually diminishing with age. At maturity, they acquire a light brown or brown coloration, become smooth, and sometimes slightly glossy. The surface of the pod may exhibit faint longitudinal veins. The fruit walls are relatively thin but sufficiently strong, ensuring seed preservation for an extended period after maturation.

The pods are generally straight or slightly curved, sometimes slightly constricted at the positions of the seeds. Fruit dehiscence occurs along two sutures; however, this process is not always complete, which results in partial seed retention within the pods during the winter period. Each pod contains from 1 to 9 seeds, dark brown to almost black in color, rounded or slightly reniform in shape, measuring 2–4 mm (Szentesi, 2006; Csurhes & Markula, 2016). The seeds are characterized by a dense, water-impermeable coat, which determines their state of physiological dormancy and necessitates pre-treatment (scarification) to improve germination.

An important biological feature of the fruits of *Laburnum anagyroides* is the presence of alkaloids, particularly cytisine, which confers toxicity to humans and animals. This is significant both from the perspective of safe use of the species in landscaping and in terms of natural protection of seeds against herbivory.

The vegetation of *Laburnum anagyroides* in its natural range begins in April, corresponding to the establishment of stable positive temperatures and the activation of physiological processes in the plant. In more northern regions, including the Forest-Steppe zone of Ukraine, the onset of vegetation shifts to later dates – usually to late April or early May – due to climatic conditions and a longer period of spring cooling. Bud break occurs relatively synchronously, ensuring coordinated development of the leaf apparatus.

Annual shoot growth is characterized as moderate and averages 2–4 cm; however, in young plants or under favorable growing conditions, this value may be higher. Growth intensity largely depends on moisture availability, soil fertility, and light conditions. Under limited moisture supply or in compacted soils, shoot growth may decrease significantly, reflecting the species' sensitivity to edaphic and hydrological conditions.

Flowering under natural conditions begins in the second decade of May and lasts on average 17–28 days. This period is characterized by high intensity of flower opening and pronounced ornamental expression. Under introduction conditions, the timing of flowering may vary depending on regional climatic factors, particularly the temperature regime in spring. In Central and Eastern Europe, including Ukraine, flowering typically occurs from May to early June and lasts 15–20 days. Under unfavorable weather conditions, such as late spring frosts, prolonged cool or rainy weather, disturbances in bud formation, irregular flowering, or even its complete absence in certain years may occur (Stawiarz & Wróblewska, 2013; Poçta & Florin, 2017). This is an important factor to consider when assessing the ornamental stability of the species.

Fruit maturation within the natural range occurs at the end of August, whereas under introduction conditions this process is usually shifted to September. The duration of fruit formation and maturation depends on the weather conditions of the growing season, particularly temperature and precipitation. Some pods dehisce already in autumn, ensuring natural seed dispersal; however, a considerable proportion remains on the plants until spring. This feature promotes gradual seed release and may be regarded as an adaptive mechanism that increases the likelihood of successful germination under varying environmental conditions.

The completion of the growing season largely depends on the temperature regime of the autumn period. Under conditions of an early decrease in temperature, leaf fall occurs rapidly and is often accompanied by the partial abscission of immature leaves. In contrast, during a prolonged warm autumn, vegetation may continue until the end of October or even the beginning of November. Under the conditions of the Forest-Steppe zone of Ukraine, the completion of vegetation typically occurs in mid to the second half of October, which is consistent with the general phenological patterns of development of woody introduced species in this region.Overall, the phenological characteristics of *Laburnum anagyroides* indicate its good adaptation to temperate climatic conditions; however, at the same time, they demonstrate a certain dependence on weather factors, which should be taken into account in the introduction assessment of the species as well as in planning its use in landscaping.

The natural range of *Laburnum anagyroides* encompasses the southern parts of Central Europe and Southeastern Europe, where the species occurs within the temperate biome with elements of sub-Mediterranean climatic influence (POWO, 2021). The main centers of its distribution are concentrated in mountainous and foothill regions, particularly in the Alps, the Carpathians, and the Balkan Peninsula, where it forms part of open deciduous forests, forest edges, shrub thickets, and petrophytic communities. Generalized floristic syntheses for Europe confirm the presence of the species in regional floras and indicate its affinity for warmer and relatively drier habitats compared to *Laburnum alpinum*, as well as its more frequent association with alkaline (calcareous) substrates (Trees and Shrubs Online, 2024; FloraVeg/Euro+Med, 2025).

Under natural conditions, *Laburnum anagyroides* predominantly grows on rocky slopes, screes, and in fissures and niches of limestone outcrops, where well-drained, shallow, and often skeletal soils with a high carbonate content and significant aeration are formed. Such ecotopes are characterized by limited water-holding capacity, pronounced temperature fluctuations, and a high level of solar radiation, which create specific conditions for the development of adaptive plant traits. These habitats correspond to the European typology of calciphilous rocky environments (limestone cliffs and chasmophytic communities), which are characterized by a deficit of soil moisture, shallow soil profiles, and low competition from other species (EUNIS, 2025). Under such conditions, *Laburnum anagyroides* acts as a competitive species due to the combination of drought tolerance, a light-demanding nature, and the ability to efficiently utilize limited resources.

Data on ecological and functional traits of the species in European plant trait databases further emphasize its adaptation to well-drained substrates, high insolation, and seasonally dry conditions (FloraVeg/Euro+Med, 2025). In particular, the presence of pubescence on young organs, relatively small leaf size, and their specific morphological structure contribute to a reduction in transpiration and an increase in water-use efficiency. In addition, the ability to form symbiotic associations with nitrogen-fixing bacteria provides an additional advantage under nutrient-poor soil conditions, where the availability of accessible nitrogen is limited.

In terms of ecological preferences, *Laburnum anagyroides* belongs to light-demanding species of the temperate zone, which most effectively realize their decorative and generative potential under conditions of full insolation. In open habitats, plants form a more compact, well-foliated crown and are characterized by intensive flowering and stable fruiting. Under the canopy or in partial shade conditions, plants are able to maintain viability; however, their growth becomes more elongated, the crown more sparse, and the intensity of flowering as well as the level of fruiting are significantly reduced, which is typical of light-demanding woody introduced species (FloraVeg/Euro+Med, 2025).

An important characteristic of the ecological amplitude of a species is its response to moisture conditions. *Laburnum anagyroides* exhibits xeromesophytic traits, that is, the ability to withstand periods of moderate drought provided that the soil is well-drained. Excessive moisture, especially in combination with heavy clay soils, negatively affects plant growth and development, causing suppression of the root system. This necessitates careful consideration of hydrological conditions when introducing the species.

The assessment of environmental gradients based on Ellenberg indicator values (light, moisture, soil reaction, nitrogen availability, etc.) is a widely accepted approach for interpreting plant ecological requirements and comparing species across different regions (Hill et al., 2000; FloraVeg/Euro+Med, 2025). The application of this approach makes it possible to quantitatively characterize the ecological niche of a species and to evaluate its acclimatization potential. For *Laburnum anagyroides*, typical indicator values include high light demand, preference for neutral to slightly alkaline soils, and moderate moisture conditions, which is consistent with its natural association with open calciphilous habitats.

The use of Ellenberg indicator values is also appropriate for introduction studies of *Laburnum anagyroides* in the Forest-Steppe zone of Ukraine, as it allows the formalization of the influence of key ecological factors – light, moisture, and soil reaction – on plant growth, development, and reproductive capacity. Such an approach contributes to substantiating optimal cultivation conditions, improving the efficiency of its use in landscaping, and predicting its performance under future climate change scenarios.

In general, the ecological characteristics of *Laburnum anagyroides* indicate that it belongs to a group of species with a relatively wide ecological amplitude, but with a clearly expressed preference for well-lit, well-drained, and calcareous habitats, which is of key importance when assessing its introduction potential.

The soil requirements of the species are associated with its natural affinity for calcareous substrates, which determines its preference for neutral or slightly alkaline soils with sufficient calcium content. The most favorable conditions for the growth and development of *Laburnum anagyroides* are light to medium loamy soils with good water and air permeability, as well as effective drainage that prevents moisture stagnation in the root zone. At the same time, the species is capable of growing on relatively poor and shallow soils, which indicates its adaptation to conditions of limited mineral nutrition.

The negative response of *Laburnum anagyroides* to excessive moisture, waterlogging, and soil compaction is primarily related to the functional characteristics of its root system, which requires a high level of aeration. Excessive moisture conditions lead to root hypoxia, resulting in the suppression of growth processes, reduced intensity of mineral nutrition, and, consequently, general weakening of the plants. Soil compaction, which is typical of urban environments, further restricts the penetration of air and water to the roots, thereby negatively affecting plant vitality and ornamental value (Trees and Shrubs Online, 2024; FloraVeg/Euro+Med, 2025).

From a practical perspective, this implies that under the conditions of the Forest-Steppe zone of Ukraine, proper site selection for planting is of critical importance. Preference should be given to well-drained sites, while low-lying areas prone to water stagnation should be avoided. In addition, irrigation intensity should be carefully regulated, especially on heavy soils. An important agrotechnical measure is also the prevention of soil compaction in the tree pit area, which can be achieved through mulching, limiting recreational pressure, and the use of soil-structuring materials.

Climatically, *Laburnum anagyroides* is associated with the temperate zone and is characterized by sufficient winter hardiness, allowing it to withstand seasonal decreases in temperature. However, the degree of resistance largely depends on the age of the plants and the nature of weather conditions during the winter period. The most vulnerable are young shoots, which may be damaged by prolonged extreme frosts or abrupt temperature fluctuations, especially in the absence of snow cover (Poçta & Florin, 2017). An additional negative factor is early spring thaws, which stimulate premature activation of growth processes, after which subsequent frosts may damage both generative and vegetative organs.

For the introduction assessment of the species, it is particularly important to consider the sensitivity of the generative sphere to abiotic stresses. The processes of flower bud formation, pollination, fruit set, and seed maturation represent the most vulnerable phases of ontogenesis and largely determine the reproductive success of the species. Late spring frosts may damage buds and flowers, leading to a reduction or complete loss of seed yield. Summer droughts limit water availability to plants, negatively affecting fruit development, whereas excessive soil moisture may cause ovary abscission and promote the development of pathogens (Poşta, 2018; FloraVeg/Euro+Med, 2025). Thus, the generative potential of *Laburnum anagyroides* serves as an integral indicator of its adaptation to specific environmental conditions.

Historically, *Laburnum anagyroides* has been widely cultivated as an ornamental woody plant far beyond its natural range, due to its high aesthetic value and relative ecological tolerance. In a number of regions worldwide, studies have been conducted to assess its capacity for naturalization, as well as to evaluate potential risks of invasiveness. Although in most cases the species does not exhibit aggressive invasive behavior, the existence of such studies indirectly indicates its ecological plasticity and its ability to adapt to new environments under favorable conditions (Csurhes & Markula, 2016).

An important direction in modern landscaping is the use of plants with phytoremediation potential, that is, species capable of improving the ecological condition of urbanized areas by reducing anthropogenic pressure, accumulating pollutants, and stabilizing the soil environment. In this context, increasing attention is being paid to ornamental species that combine high adaptability with the ability to function under conditions of air pollution, soil compaction, moisture deficiency, and other stress factors typical of urban environments.

Laburnum anagyroides is characterized by a sufficient level of tolerance to such conditions, including resistance to atmospheric pollution, temperature fluctuations, and periodic water deficit. This provides a basis for considering it as a promising component of urban green spaces, particularly in street plantings, parks, and recreational areas. An additional advantage of the species is its ability to form symbiotic associations with nitrogen-fixing bacteria of the genus *Bradyrhizobium*, which is accompanied by the formation of root nodules and ensures the biological fixation of atmospheric nitrogen (Sajnaga, Jach, 2020; Łotocka, 2024).

Biological nitrogen fixation in the "legume – rhizobia" system is considered one of the key mechanisms for increasing soil fertility, especially under conditions of soil degradation or anthropogenic disturbance. As a result, the content of available nitrogen forms increases, microbiological activity is enhanced, and the physicochemical properties of the soil are improved (Stępkowski et al., 2018; Jach et al., 2022). Thus, the use of *Laburnum anagyroides* in plantings may have not only decorative but also significant ecological importance.

The combination of high ornamental value, ecological plasticity, relative resistance to abiotic factors, and the ability for biological nitrogen fixation determines the feasibility of further comprehensive studies of this species. Of particular relevance are investigations of its reproductive biology, seed productivity, seed germination characteristics, and adaptive potential under urban conditions, which are essential for substantiating the effective use of *Laburnum anagyroides* in modern landscaping and phytomelioration.

Despite its considerable ornamental, ecological, and phytomeliorative potential, *Laburnum anagyroides* is still used to a limited extent in landscaping in Ukraine, particularly in the Left-Bank Forest-Steppe zone. Within the structure of urban and suburban plantings, the species is represented by individual specimens or small groups, which does not allow for the full realization of its aesthetic and ecological advantages. This situation is обусловлена a number of factors, among which insufficient knowledge of the species' biological characteristics under introduction conditions, a limited availability of adapted planting material, and the lack of established technologies for its mass propagation are of primary importance.

One of the main reasons for the limited introduction of *Laburnum anagyroides* into landscaping practice is the difficulty of its propagation, particularly by seeds. This is associated with a number of biological features of the seeds, including the presence of a dense water-impermeable seed coat, which determines physiological (and partly physical) dormancy, as well as the uneven maturation of fruits and seeds within a single plant. An additional complicating factor is the variability of germination rates, which largely depends on the conditions of seed formation, the degree of maturity, and post-harvest processing.

In the natural range, these features are compensated by a prolonged period of natural stratification and gradual seed germination, which ensures species survival under variable environmental conditions. However, under introduction conditions, particularly in the Left-Bank Forest-Steppe of Ukraine, such mechanisms are not always effective, which is manifested in low field germination, an extended germination period, and uneven seedling emergence. This, in turn, complicates the production of standard planting material and reduces the efficiency of the species' use in landscaping.

An important aspect is also the influence of environmental conditions on seed formation. Temperature regime, moisture availability, pollination conditions, and the overall physiological state of mother plants may significantly affect seed morphological characteristics, mass, viability, and germination capacity. In this regard, the study of seed productivity under specific soil and climatic conditions becomes particularly important, as it allows the assessment of the adaptive potential of the species and the determination of optimal conditions for its propagation.

In the context of modern introduction studies, a comprehensive approach to the investigation of seed productivity is of particular importance. This includes the analysis of quantitative indicators (seed yield, number of seeds per fruit, weight of 1000 seeds) and qualitative indicators (germination energy, laboratory and field germination, viability). Special attention should also be paid to the study of pre-sowing seed treatments (scarification, stratification, combined methods), which can significantly increase germination rates and synchronize the germination process.

In this regard, a comprehensive study of the seed productivity of *Laburnum anagyroides* under the conditions of Sumy region is highly relevant. Such a study involves the assessment of quantitative and qualitative seed characteristics, investigation of the peculiarities of seed formation, maturation, and germination, as well as the identification of the main factors limiting the effectiveness of seed propagation of the species under introduction conditions. The obtained results may serve as a scientific basis for the development of effective methods for producing planting material and for expanding the use of the species in landscaping.

The aim of the study is to investigate the features of seed productivity of *Laburnum anagyroides* and to assess the prospects for its propagation under the conditions of the Left-Bank Forest-Steppe of Ukraine (Sumy region).

To achieve this aim, the following main objectives were formulated:

to study the peculiarities of flowering and fruiting of the species under introduction conditions;

to determine indicators of seed productivity (number of fruits, number of seeds, seed mass);

to assess seed quality based on germination and viability parameters;

to establish the effect of pre-sowing treatments on seed germination;

to identify the main ecological and biological factors limiting seed propagation of the species.

In general, the results of such studies have not only theoretical but also practical significance, as they contribute to the improvement of technologies for cultivating ornamental introduced species and to the expansion of the assortment of plants suitable for use in modern urban environments.

Material and Methods

The study was conducted in 2024 using seed material of *Laburnum anagyroides* collected from donor plants aged 12–15 years, which were in the generative phase of development. The experimental plants were grown under field conditions in the dendrarium of Sumy National Agrarian University (geographical coordinates: 50.9076° N, 34.7981° E), located within the Left-Bank Forest-Steppe zone of Ukraine. The climatic conditions of the region are characterized by a moderately continental climate, with relatively warm summers and moderately cold winters, which creates representative conditions for assessing the introduction potential of the species.

Seed collection was carried out in late September to early October, after the completion of the growing season and upon reaching full fruit maturity. The selection criteria included the characteristic coloration of the pods (light brown), their partial drying, and the onset of natural dehiscence. This approach ensured the collection of morphologically mature and physiologically полноценного seed material with maximum viability indicators. In the experiment, freshly collected, well-filled seeds were used (Fig. 1), which made it possible to minimize the influence of post-harvest storage factors on the experimental results.

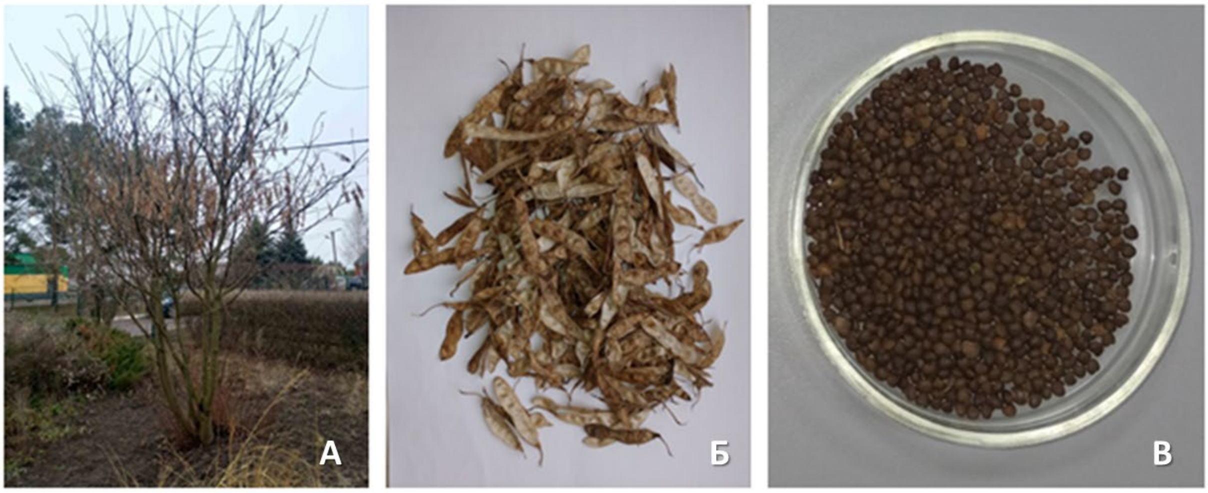

Figure 1. Donor plant (A), fruits (B), and seeds (C) of L. anagyroides

After collection, the fruits were subjected to primary processing, which included drying under natural ventilation at room temperature in order to facilitate seed extraction. Seed extraction was performed manually by opening the pods, followed by separation of fully developed seeds from underdeveloped, damaged, or infected ones. The cleaned seeds were additionally dried to an air-dry state, which ensured the stability of their mass and their suitability for further measurements.

The weight of 1000 seeds was determined in accordance with generally accepted seed science methodologies, taking into account the requirements of international standards. Weighing was carried out using Certus Balance analytical scales with a measurement accuracy of ±0.01 g. To increase the accuracy of the results, two subsamples of 500 seeds each were taken, after which the obtained values were recalculated per 1000 seeds. This approach complies with the requirements of the *International Rules for Seed Testing* (ISTA, 2004) and allows for obtaining representative data on seed mass as one of the key indicators of seed quality.

The number of seeds per fruit was determined by manual counting using a series of representative samples. For this purpose, the pods were preliminarily sorted according to the number of developed seeds into one-, two-, three-, four-, and five-seeded groups, which made it possible to assess the structure of seed productivity of the species. Taking into account the variability of this parameter is important for characterizing the reproductive potential of plants and for evaluating the efficiency of pollination and fertilization.

To determine the average number of seeds per fruit, four replicates were used, each consisting of 10 g of fruit mass. This approach ensured a sufficient sample size to obtain statistically reliable results. During the analysis, both the total number of seeds and their distribution among fruit categories were taken into account.

The obtained data were recorded in data sheets and subsequently processed using methods of variation statistics. Mean values, variability, and errors were calculated, which made it possible to assess the degree of variation of the studied traits and to ensure the reliability of the obtained results. Statistical data processing is an essential component of studies of this type, as it allows for objective interpretation of the results and the identification of patterns in the formation of seed productivity.

In general, the applied research methodology provides a comprehensive assessment of both quantitative and qualitative characteristics of *Laburnum anagyroides* seeds and creates a reliable basis for further analysis of their sowing qualities and germination characteristics under introduction conditions.

Seed mass was determined based on the average weight of 1000 seeds and the actual number of seeds in each pod, which made it possible to assess the overall seed yield potential of the plants and the structure of productivity distribution among individual fruits. For this purpose, each pod was weighed using an analytical balance, after which the seed mass was calculated using a formula that took into account the number of seeds per fruit and the mean weight of one thousand seeds.

The proportion of waste was determined as the percentage of plant material that did not contain fully developed or morphologically formed seeds, as well as mechanical impurities and plant debris. The analysis of waste made it possible to evaluate the efficiency of seed collection and its quality, which is important for planning sowing technologies and the production of planting material.

Climatic conditions during the growing season were considered as one of the factors influencing the formation of generative organs and seed productivity. For this purpose, data from the Sumy Regional Meteorological Station were used, including mean monthly air temperature and total precipitation during the 2024 growing season. The conducted analysis made it possible to assess the influence of weather conditions on flowering time, fruiting intensity, and seed quality, which is particularly important for species with limited introduction adaptability.

Statistical analysis of the obtained results was performed using the software package Statistica 9.0. Methods of variation statistics were applied to determine mean values, standard deviations, coefficients of variation, and correlation analysis between different indicators of seed productivity. The results were summarized using analytical methods with further interpretation in the context of the ecological conditions of the study region. This approach made it possible to identify patterns in the formation of the seed potential of *Laburnum anagyroides* and to assess the influence of environmental factors on both quantitative and qualitative seed characteristics.

The application of a comprehensive approach to the collection, processing, and analysis of seed material ensured the scientific validity of the conclusions regarding the introduction potential of the species and its practical value in landscaping within the Left-Bank Forest-Steppe of Ukraine.

Results

During the 2024 growing season, climatic conditions in the study area were generally characterized by a favorable temperature regime; however, moisture availability was uneven, which significantly affected the course of plant growth and reproductive processes. The average monthly temperatures from April to September remained within ranges close to optimal for the growth and development of *L. anagyroides*, ensuring the active progression of the main phenological stages. A gradual increase in temperature from spring values to the summer maximum was observed, corresponding to the general pattern of seasonal climate dynamics in the region. The highest temperatures were recorded in July, when plants were in the phase of intensive growth and formation of generative organs, a critically important stage for the establishment of future seed productivity.

At the same time, analysis of the moisture regime indicates a significant unevenness in the distribution of atmospheric precipitation during the growing season. The maximum amount of precipitation occurred in June, which had a positive effect on vegetative growth, leaf area formation, and the overall physiological condition of the plants. However, subsequently, particularly in August and especially in September, a sharp decrease in precipitation was observed, leading to the development of soil and atmospheric drought conditions. Such a shift in the hydrothermal regime is крайне unfavorable, as the second half of summer represents a critical period for seed formation, filling, and maturation. It is during this time that intensive accumulation of assimilates, their translocation to generative organs, and the completion of seed morphogenesis take place.

Moisture deficiency during this period leads to disturbances in plant water balance, reduced photosynthetic intensity, and a slowdown in biosynthetic processes, which in turn negatively affects the formation of fully developed seeds. Limited soil moisture may have resulted in partial reduction of ovules, decreased seed filling, and the formation of seeds with lower individual weight. This is also accompanied by an increased proportion of shriveled or underdeveloped seeds in the yield (Fig. 2).

The obtained experimental data confirm the identified patterns and are consistent with the weather conditions of the study year. A relatively low thousand-seed weight was recorded, along with the predominance of pods containing a limited number of fully developed seeds. Such indicators are a typical response of leguminous crops to water stress during the seed filling and maturation stages, as repeatedly reported in scientific studies. At the same time, the temperature regime throughout the growing season remained within the ecological optimum of the species, indicating the absence of significant thermal limitation of physiological processes.

Thus, the conducted analysis provides grounds to conclude that the deficit of atmospheric precipitation and the associated water stress in the second half of the growing season were the determining factors limiting the realization of the potential seed productivity of *L. anagyroides* in 2024. The temperature factor played a secondary role and did not exert a critical influence on seed yield formation.

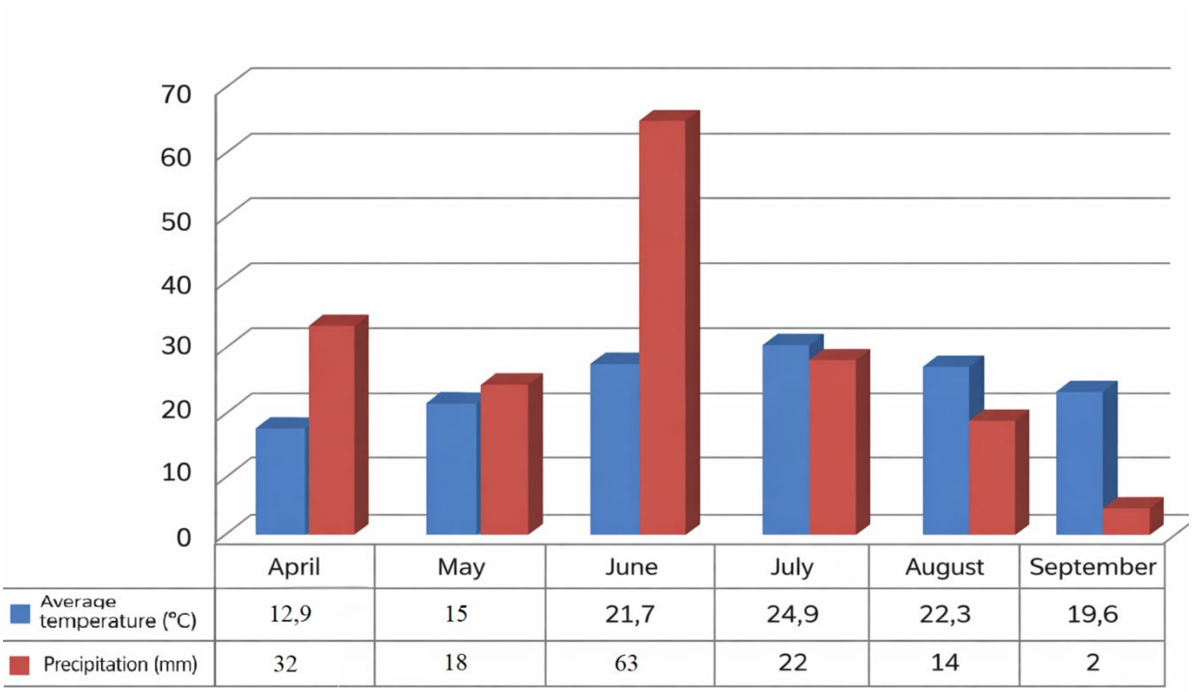

Figure 2. Average monthly air temperature and precipitation (Sumy, April–September 2024)

The Selyaninov hydrothermal coefficient (HTC) during the 2024 growing season (April–September) was 0.42, which, according to the generally accepted interpretation scale, characterizes the year as dry. HTC values below 0.5 indicate a significant moisture deficit and the development of water stress conditions for plants, especially during periods of active growth and generative development.

A more detailed analysis of the indicator dynamics across individual overlapping periods of the growing season reveals a clear trend toward deterioration of moisture conditions. In particular, during April–June, the HTC value was 0.75, corresponding to a relatively satisfactory level of moisture supply and promoting active growth of vegetative organs. Subsequently, a gradual decline in the indicator was observed: to 0.55 in May–July and to 0.47 in June–August, indicating a transition to moderately dry conditions. The most critical period was July–September, when the HTC decreased to 0.19, characterizing very dry conditions and indicating a severe deficit of available soil moisture.

It should be emphasized that this period coincides with the stages of seed filling and maturation, which are the most sensitive to water regime. Under such conditions, the transport of assimilates to generative organs is significantly disrupted, the intensity of photosynthetic activity decreases, and the synthesis of storage compounds slows down. As a result, this leads to the formation of insufficiently filled seeds, a reduction in their weight, and an increased proportion of shriveled or morphologically underdeveloped seed material.

Thus, the climatic conditions of the study year were generally suitable for plant growth and development, as confirmed by the absence of critical temperature deviations during the growing season. At the same time, the uneven moisture regime, with a pronounced precipitation deficit in the second half of the growing season, acted as a limiting factor in the formation of generative productivity. This highlights the necessity of considering the water factor as one of the key ecological determinants when assessing the reproductive capacity of introduced woody species, as well as when predicting their seed productivity under conditions of climate change.

According to laboratory studies, the average thousand-seed weight of *L. anagyroides* was 8.54 g. This value can be assessed as relatively low, indicating insufficient seed filling. This result is consistent with the identified unfavorable hydrothermal conditions of the second half of the growing season, particularly the critically low HTC values during the seed filling and maturation stages. Limited water supply during this period likely led to a decrease in the accumulation of storage substances in the seeds and their incomplete development.

At the same time, the variation in thousand-seed weight between replicates was insignificant, indicating relative uniformity of the studied material and stability of this trait within the sample. This allows the obtained results to be considered representative and adequately reflecting the influence of the environmental conditions of the year on the formation of seed productivity in the species.

To assess the degree of realization of reproductive potential, an analysis of seed set within fruits was conducted, which serves as an important indicator of the efficiency of generative processes – from flowering and pollination to seed formation and maturation. The obtained results indicate a pronounced unevenness in seed filling of pods and a limited realization of potential fertility.

In particular, it was established that the majority of fruits were single-seeded (75 units) and two-seeded (56 units), which together constitute the dominant group of fruits with low seed productivity. The number of three- and four-seeded pods was significantly lower, amounting to 26 and 10 units, respectively, while the proportion of five-seeded fruits was minimal – only 2 units. Such a distribution demonstrates a clear tendency toward a decrease in the number of fruits with higher seed set and indicates incomplete realization of the potential number of ovules within a single fruit.

The conducted analysis of variance (ANOVA) did not reveal statistically significant differences among the studied samples, as the variation of the indicators remained within the critical values according to Duncan's test at a significance level of $p \leq 0.05$ for each group (Table 1). This allows us to conclude that the studied material is relatively homogeneous and that the trait is stably expressed within the variation series.

Table 1. Quantitative characteristics of fruit seed set in *L. anagyroides*

Sample number	Number of beans pcs.				
	single-seeded	two-seeded	three-seeded	four-seeded	five-seeded
1	87	63	24	3	2
2	66	49	37	11	2
3	62	61	26	8	2
4	84	52	17	16	2
Average	75	56	26	10	2
Duncan test $_{0.05}$	*17,3*	*8,8*	*12,1*	*7,9*	*0,3*

On average, 169 fruits were recorded per sample, containing a total of 313 seeds, which made it possible to determine the mean number of seeds per pod at the level of 1.85. This value is relatively low and further confirms the limited seed productivity under the studied conditions. From a biological perspective, this may result from both incomplete fertilization and the subsequent reduction of a portion of ovules during their development.

For a more detailed analysis of the nature of the observed pattern, the proportion of fruits with different numbers of seeds was determined (Fig. 3). Structural analysis revealed the predominance of fruits with a minimal number of seeds and an extremely low proportion of multi-seeded forms. In particular, the share of fruits with high seed set is negligible, indicating a limited realization of the potential fertility of generative organs.

It should be noted that the sufficient level of moisture in June, which coincided with the period of mass flowering, would theoretically have favored effective pollination and the formation of a greater number of fully developed ovaries. Under such conditions, a higher proportion of multi-seeded fruits could have been expected. However, under the conditions of 2024, this potential was not realized: the proportion of such fruits amounted to only 1.2%. This indicates that the favorable conditions at the initial stages of generative development were offset by the subsequent moisture deficit in the second half of the growing season.

Water stress during the seed filling and maturation stages likely intensified competition among ovules for assimilates, resulting in their partial reduction and the formation of fruits containing fewer fully developed seeds. Thus, the established structure of fruit seed set reflects the combined influence of environmental factors, among which moisture deficit played the decisive role in 2024.

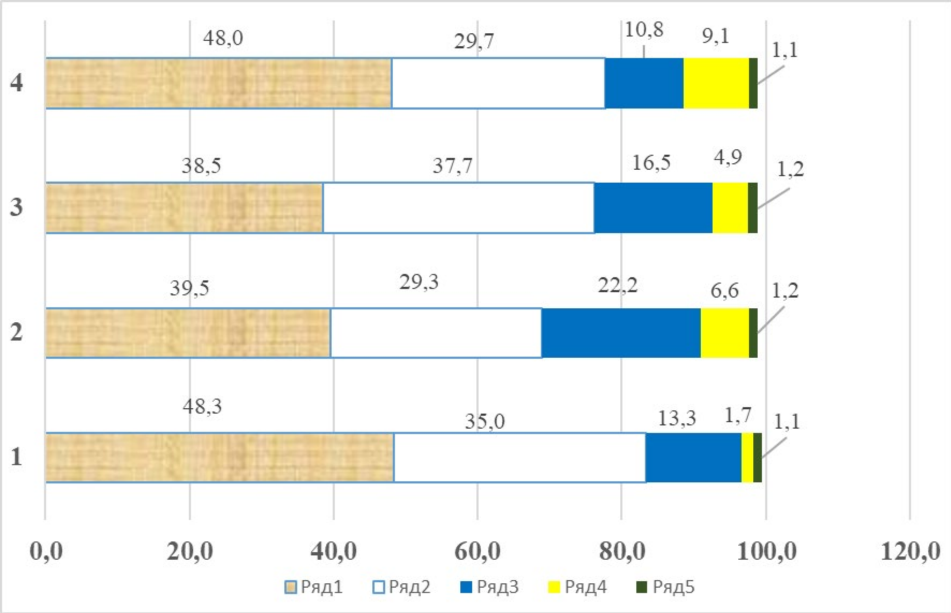

Figure 3. Proportion of L. anagyroides pods with different number of seeds, %

At the same time, moisture deficiency during the seed filling period led to an increased level of flower abortion and the predominance of one- and two-seeded pods, whose proportions were the highest, amounting to 43.6% and 32.9%, respectively. Such values indicate only partial realization of the generative development potential and are characteristic of the species under conditions of introduction, particularly under moisture deficit.

Based on the ratio between seed mass and total pod mass, it was determined that from 10 g of initial material, an average of 2.69 g of fully developed seeds was obtained. In terms of 1 kg, this corresponds to approximately 269 g, meaning that the proportion of viable seeds was about 27%. The remaining mass consisted of pod shells and underdeveloped or empty seeds.

The obtained results indicate that in 2024 the seed productivity of *L. anagyroides* was moderate. Despite the formation of a considerable number of fruits, the realization of reproductive potential was limited by unfavorable hydrothermal conditions, primarily moisture deficit during the seed filling and maturation stages. This resulted in reduced seed weight and a high proportion of low-seeded fruits.

Thus, the results of the study confirm the significant dependence of seed productivity in *L. anagyroides* on annual weather conditions and highlight the importance of considering the hydrothermal regime when assessing the prospects of seed reproduction of the species under the conditions of the Sumy region.

Conclusions

The seed productivity of *L. anagyroides* is shaped by a complex of biological and environmental factors, among which weather conditions during the growing season play a leading role, particularly the moisture regime during the seed filling and maturation stages. The results obtained in this study indicate that in 2024 the realization of the species' generative potential occurred under conditions that were not optimal for полноценне seed formation.

Analysis of climatic data for the period April–September 2024 showed that the total precipitation amounted to 151 mm, with an अत्यचно uneven distribution. The highest precipitation occurred in June, whereas in August and especially in September a sharp moisture deficit was observed (14 and 2 mm, respectively). This period corresponds to the final stages of generative organ development – seed filling and fruit maturation. The calculated hydrothermal coefficient confirmed the dry nature of the season, and in the second half of the growing period, even severely dry conditions prevailed, creating water stress for plants.

It is well known that in leguminous woody species, soil moisture deficit after fertilization significantly affects the course of embryogenesis, promotes abortion of a portion of seeds, and reduces their mass due to limited assimilate supply (Farooq et al., 2015; Shen et al., 2018). For *L. anagyroides*, this pattern is particularly characteristic, as evidenced by the high variability of seed set in pods and the significant proportion of underdeveloped seeds reported in the literature (Szentesi, 2006).

The average thousand-seed weight in the studied samples was 8.54 g, which is substantially lower than the values reported in international databases and floristic reviews (≈30–34 g) (Szentesi, 2006; Rembert, 1996). At the same time, variability between replicates was low, indicating internal consistency of the results. This discrepancy with literature data may be explained by several factors. First, reference sources typically report seed mass for samples dried to constant weight, whereas in the present study measurements were conducted on working material. Second, climatic conditions of the year – particularly moisture deficit in the second half of the growing season – likely limited the accumulation of storage substances in seeds. Third, the influence of genetic characteristics of the studied plant cannot be excluded, as introduced species often exhibit increased variability in generative traits.

Analysis of fruit structure showed that the average number of seeds per pod was 1.95, with a predominance of low-seeded fruits containing one to two seeds. This result is consistent with the findings of Á. Szentesi (2006), who demonstrated that although the species is potentially capable of forming 6–8 seeds per pod, in practice only about two fully developed seeds are produced due to abortion of the remaining ovules. Therefore, the obtained value should be interpreted not as a reduction in reproductive capacity, but as an expression of a biological characteristic of the species, intensified by unfavorable weather conditions of the year.

An important indicator is also the yield of fully developed seeds, which in this study amounted to approximately 27% of the total mass of collected material. This level indicates a substantial proportion of pod shells, empty, or underdeveloped seeds, which again corresponds with the low number of seeds per pod and the known features of the species' reproductive biology (Rembert Junior, 1996). The precipitation deficit in August–September, when final seed development occurs, likely intensified the gap between potential and actual seed productivity.

In summary, it can be stated that under the conditions of the Sumy region in 2024, the limiting factor in the realization of the seed potential of *L. anagyroides* was not the temperature regime, but water availability during the second half of the growing season. The obtained indicators of seed weight, number of seeds per pod, and yield of fully developed seeds are a logical consequence of these conditions and are consistent with literature data for the species (Poșta, 2018; Poșta & Florin, 2017).

Traditional methods of propagation of *L. anagyroides* are characterized by a number of limitations, especially under conditions of introduction (Sato et al., 1995). Seed propagation remains the main and biologically justified method of species reproduction (Poşta et al., 2017); however, it requires optimization of pre-sowing treatment techniques, which highlights the relevance of further research aimed at increasing seed productivity and developing effective propagation methods under the conditions of the Left-Bank Forest-Steppe of Ukraine.

The conducted study made it possible to establish the main patterns in the formation of seed productivity of *L. anagyroides* under the conditions of the Left-Bank Forest-Steppe of Ukraine. The obtained results indicate a complex and multifactorial nature of generative development, in which climatic conditions, particularly the hydrothermal regime of the growing season, play a decisive role.

It was determined that the water factor is the key limiting element in the realization of potential seed productivity. The dry conditions of the second half of summer 2024, characterized by a low hydrothermal coefficient (HTC = 0.42), significantly affected the processes of seed filling and maturation. As a result, a decrease in thousand-seed weight to 8.54 g was observed, indicating insufficient seed filling and limited accumulation of storage substances.

Structural analysis of fruits revealed the predominance of one- and two-seeded pods, which is a characteristic feature of incomplete realization of reproductive potential. The average number of seeds per fruit was 1.85, confirming the tendency toward reduction of a portion of ovules during development. This is likely a consequence of intensified competition for assimilates under moisture deficit, especially at the final stages of organogenesis.

The yield of fully developed seeds was approximately 27%, indicating a significant proportion of underdeveloped or shriveled seed material. This level of realization of generative potential can be assessed as partial and limited by unfavorable environmental factors. At the same time, the absence of critical temperature deviations during the growing season allows us to conclude that moisture deficit, rather than temperature regime, was the primary limiting factor.

Thus, the obtained results confirm the strong dependence of seed productivity of *L. anagyroides* on moisture conditions and emphasize the necessity of considering climatic factors in its introduction, cultivation, and assessment of reproductive capacity. The practical significance of the study lies in the possibility of using the identified patterns to predict seed productivity under climate change conditions, as well as to optimize agronomic practices aimed at improving seed quality.

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