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Peculiarities of the development of reproductive organs of ornamental crabapples (*Malus* spp.) depending on drought resistance

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The current task for both pomiculture and ornamental horticulture is the formation of plant cultivars resistant to different environmental stress and maintaining their high productivity. Drought is one of the most significant environmental factors that inhibit plant growth and development and cause a set of morphological, physiological, and biochemical changes in plant organisms. The aim of our research was to discover the relationship between the development of the reproductive organs of ornamental crabapples and the physiological indicators determined by drought stress factors. The four species and three cultivars of the ornamental crabapples (*Malus* spp.) from the collection of the National Dendrological Park “Sofiyivka” of NAS of Ukraine were involved in the study: *M. × floribunda* Siebold ex Van Houtte, *M. halliana* Koehne, *M. niedzwetzkyana* Dieck, *M. × purpurea* (A. Barbier) Rehder, *M. × purpurea* ‘Ola’, *M. × purpurea* ‘Royalty’, and *M. × purpurea* ‘Selkirk’. Drought resistance was determined by the following quantitative indicators: leaf water content, relative turgidity, leaf water deficit, and excised leaf water retention capacity. The leaf water content ranged from 60.0% (*M. × floribunda*) to 67.2% (*M. × purpurea*), the relative turgidity ranged from 81.7% (*M. × purpurea* ‘Ola’) to 98.9% (*M. halliana*), and the leaf water deficit ranged from 6.8% (*M. halliana*) to 24.4% (of *M. niedzwetzkyana*). As a result, the leaves of *M. halliana* lost the smallest amount of water in 24 hours (50.2%), whereas *M. × purpurea* ‘Ola’ leaves lost the largest amount (77.4%). The development of the reproductive organs was estimated based on the fertility and viability of pollen grains, percentage of fruit and seed set. Pollen fertility ranged from 79.8% (of *M. niedzwetzkyana*) to 95.0% (*M. × purpurea* ‘Ola’); its viability varied from 5.1% (*M. niedzwetzkyana*) to 51.5% (*M. × floribunda*). The highest fruit set percentages were recorded in *M. floribunda* (80.5%), while the lowest was in *M. × purpurea* ‘Royalty’ (16.4%). The average percentage of seed sets was 48.5%. The development of the reproductive organs of *Malus* specimens depended on their drought resistance. The fruit and seed set percentages had a strong negative correlation with the water deficit in leaves determined during the period of drought stress. The percentage of fruit set was also strongly correlated with relative turgidity. The leaf water deficit and relative turgidity were the most important physiological indicators in the drought resistance study, taking into account the need to maintain crop yield and the decorative effect of *Malus* plants.

Keywords: correlations; fruit and seed set; leaf water deficit; ornamental apple tree; relative turgidity; stress conditions.

Introduction

The growth and development of plants can be affected by numerous environmental factors (Kosakivska, 2003; Dai, 2019). The manifestation of the adaptation of plants in response to stress can be a set of morphological, physiological, and biochemical changes (Kosakivska, 2003). There are various strategies to improve environmental stress tolerance in plants to maximize survival and maintain their morphological structure and functional characteristics under adverse environmental factors that determine their resistance to one or another stressor. The ability of plants to adapt to environmental stress depends on the nature and intensity of the adverse factors and is determined by a number of genetic mechanisms, to begin with, the amount of genetic diversity and the genetic basis for traits limiting adaptability (Kumar et al., 2018; David-Schwartz et al., 2019; Zhang et al., 2020). There is a distinction between biological resistance, which determines the plant's ability to preserve all its functional and structural features, and agronomic stability, which is the preservation of crop productivity in adverse environmental conditions. The stress-response program of plants involves numerous components, including reactive oxygen species, membranes, G-proteins, calcium, redox homeostasis, NADPH oxidases, protein kinases, and underlying signaling mechanisms of hormones (Sewelam et al., 2016). Such phytohormones as salicylic acid, auxins, gibberellins, cytokinins, and abscisic acid coordinate various

ways of the signal transmission of plants during their response to environmental stressors (Farooq et al., 2009; Khan et al., 2012). Oxidative stress is one of the main limiting factors of growth which occurs in plants due to various environmental factors and affects biological processes through the generation of increased concentrations of reactive oxygen species. Malfunction or inability of antioxidant defense mechanisms to restrain excessive production of reactive oxygen species in adverse conditions leads to disruption of various cellular, physiological, and biochemical functions (Apel & Hirt, 2004; Farooq et al., 2009; Gill & Tuteja, 2010). The above-mentioned has a significant impact on the yields and quality of different crops (Xie et al., 2019).

The plants of the genus *Malus* (family Rosaceae Juss. subfamily Amygdaloideae Am., tribe Maleae Small, subtribe Malinae Rev.) are mostly medium-sized deciduous trees, rarely shrubs, which are commonly grown in the temperate and moderately warm climatic zones of the Northern Hemisphere (Langenfeld, 1991). The morphologically diverse genus *Malus* counts, according to different checklists, from 36 to 64 recognized species names (<https://npgsweb.ars-grin.gov>; <https://wfoplantlist.org>; <https://powo.science.kew.org>), which in nature are represented by a complex diffuse system of populations, ecotypes, forms, and cultivars (Langenfeld, 1991, Höfer & Meister, 2010). As a result of long-term natural selection and crossbreeding, a fairly diverse gene pool of the apple tree was formed. In contrast to wild species, the number of cultivars is

constantly increasing. For example, more than 700 crab cultivars have been registered, 200 of which are sold in nurseries (Zhou et al., 2020). Therefore, assessing the resistance of *Malus* specimens to adverse environmental factors is relevant both for use in selection work and in the context of the problem of the preservation and enrichment of plant diversity.

The research on the identification of apple stress-resistance genes and *de novo* assembly of the apple genome has increased in the latest years (Dong et al., 2018; Peace et al., 2019; Korban, 2021), and as a result of study of apple tree (*Malus* spp.) stress resistance, it turned out that the same genes can control tolerance to both biotic and abiotic stressors (Zhang et al., 2021). Resistance traits have different genetic control but influence each other through metabolic processes. Low resistance to one of the stress factors of the environment weakens the plant organism and reduces its resistance to another stressor, even if it is high. For example, the protective potential decreases in drought-weakened or frost-damaged apple plants, and they become susceptible to pathogens (Mody et al., 2009). According to the results of the research by Hungarian scientists, during severe and prolonged droughts, an increase in the concentration of sucrose in leaves can be considered a stress indicator, however, during temporary dry periods an increase in the concentration of glucose and fructose can be observed likewise (Nemeskeri et al., 2015). Drought stress and its intensity can affect the attractiveness of apple trees to herbivorous insects. High-stress plants were most attractive to caterpillars, and aphid population growth was the highest on non-stressed plants and the lowest on low-stress plants (Mody et al., 2009). It has been reported that the expression of the Myb4 transcription factor of the *Osm4* gene improves physiological and biochemical adaptation of transgenic apple plants to cold and drought stress (Pasquali et al., 2008). Identifying the sources of resistance to environmental stressors is closely related to issues of evolution, taxonomy, and geography of plants, and it is a relevant direction for studying the gene pool of the apple tree (Cornille et al., 2019; Volk et al., 2021).

Consequences of global climate change, such as dangerous weather cataclysms, sudden weather changes, floods, strong winds, showers and rains, hail, and droughts lead to significant ecological and economic losses worldwide. Plant growth and development depends upon many factors. But in the current climate change, the degree of moisture deficit is becoming the important influence limiting the use of the natural potential of plant resources. The tendency of intensifying droughts is observed in most territories of Ukraine, and over the past 20 years, droughts have recurred almost twice as often (Ivaniuta et al., 2020). Drought resistance, as any other plant adaptive value, must be used to evaluate account when breeding, and selecting, and introducing new cultivars (Blum, 2011). The fully comprehensive examination of plant cultivars for distribution suitability in Ukraine involving the determination of their drought resistance, frost, and cold resistance, resistance to pathogens, etc., is fulfilled by the Ukrainian Institute for Plant Variety Examination according to a 9-point scale (Kienko et al., 2016; Kienko et al., 2017).

Our capacity to forecast and manage the ecological consequences of climate change depends on understanding plastic acclimation of plants to physiological stress (Grossman, 2023), especially drought stress and underlying mechanisms in plants for its alleviation (Atta et al., 2022). Drought escape, drought avoidance, drought tolerance, and drought recovery are the mechanisms of response to drought stress of the plants (Abobatta, 2019; Ilyas et al., 2021; Pamungkas & Farid, 2022). The set of morphological, physiological, biochemical, and molecular changes in plants during drought is essential for a holistic understanding of plant resistance mechanisms (Anjum et al., 2011) and it is the object of research on plant stress resistance carried out by scientists from different countries of the world (Reddy et al., 2004; Farooq et al., 2009). Different plant species, through numerous resistance mechanisms, can reduce the use of their resources and regulate their growth to cope with adverse environmental conditions such as drought (Seleiman et al., 2021; Abdelhakim et al., 2022). These changes are reflected in morphological features, physiological processes, and the molecular level (Kovalikova et al., 2020; Ponnuru, 2022).

Plant breeding, use of exogenous plant growth regulators and proper agricultural practice are different strategies for management of drought stress (Abobatta, 2019). Grafting improves the drought stress tolerance of apples and other plants, which is primarily determined by the rootstock

(Yang et al., 2022; Xu et al., 2023), or the interstock which affects the nutrient uptake and utilization of whole apple trees (Ji et al., 2023). *Malus prunifolia* (Willd.) Borkh. is one of the most drought-resistant forms among apple rootstocks (Wang et al., 2012; Li et al., 2019). In addition, there are reports that the use of transgenic plants (MdGH3 RNAi) as rootstocks can improve scion performance under drought (Jiang et al., 2022). Some fertilizers can somewhat reduce the deleterious effects of drought stress on plants (Xu et al., 2021); it is known that potash and phosphorus fertilizers contribute to increasing the drought resistance of plants, while nitrogen fertilizers, on the other hand, reduce it. Treatment with synthetic analog of strigolactones (Xu et al., 2023), and with exogenous dopamine under drought can alleviate drought stress of apple and other plants (Yang et al., 2021; Ahammed & Li, 2023). Preparations with arbuscular mycorrhiza fungi, which form symbioses with roots of some agricultural crops, effectively reduce drought stress. Genetic control of mycorrhizal symbiosis depends on the expression of MdGH3-2/12, which also controls the drought resistance of apple trees (Huang et al., 2021).

Taking into account the narrowing of the genetic diversity of the cultivated apple species, obtaining new sources of resistance and assessment of their response to drought at the physiological and genetic level is an important issue for apple breeding (Wojcik et al., 2022; Sestras & Sestras, 2023). Numerous studies have been devoted to the impact of drought and elevated temperatures on plant productivity and crop yields due to physical damage, physiological and biochemical disturbances, and molecular changes. They indicate the importance of a critical discussion of the main responses of plants to these stresses as a basis for developing potential management strategies in the future (Fahad et al., 2017; Hussain et al., 2018; Iqbal et al., 2020). This makes it necessary to clarify the relationship between quantitative physiological indicators of drought resistance in *Malus* specimens of our collection and quantitative characteristics of the reproductive organs, which determine both the decorative value and productivity of plants.

Materials and methods

During 2016–2022, there were seven species and cultivars of the ornamental crabapples (*Malus* spp.), from the collection of the National Dendrological Park “Sofiyivka” of NAS, which became the objects of the research: *M. × floribunda* Siebold ex Van Houtte, *M. halliana* Koehne, *M. niedzwetzkyana* Dieck ex Koehne, *M. × purpurea* (A.Barbier) Rehder, *M. × purpurea* 'Ola', *M. × purpurea* 'Royalty', *M. × purpurea* 'Selkirk' (Fig. 1). These ornamental apple trees were grafted on the rootstock M9 (dwarf tree). National Dendrological Park “Sofiyivka” is located in the northern part of the City of Uman, Cherkasy region (Ukraine).

The native range of *M. × floribunda* (Japanese flowering crabapple) is Korea. It is a hybrid species from crossing *M. baccata* (L.) Borkh. and *M. toringo* (Siebold) de Vriese, and grows primarily in the temperate biome. *M. × floribunda* has high decorative value and breeding value (Wang et al., 2022). The plants of this species have the most spectacular appearance during the period of flowering and fruiting. And besides, the form of resistance most widely used in apple breeding to scab (under control by gene 'Vf') originated from *M. × floribunda* clone 821 (Belfanti et al., 2004; Joshi et al. 2011; Singh et al. 2021). The plants of this species are widely cultivated all over the world (Wang et al., 2022). They combine attractiveness with the ability to help feed the birds during the winter months with their fruits (Fig. 2). As known, the semi-parasitic mistletoe (*Viscum album* L.) grows on trees' branches and their seeds are dispersed by the birds feeding on the fruits and excreting the seeds (Gandhi, 2000). The presence in the park plantings of plants whose fruits birds will eat more readily than mistletoe fruits will help to reduce the rate of dissemination of this semi-parasitic plant.

The native range of *M. halliana* (Hall crabapple) is North-Central, South-Central, and Southeast regions of China. This species' secondary (introduced) areas are Japan and North Carolina. *Malus halliana* is used as an apple rootstock with excellent drought resistance and iron deficiency resistance and grows well in saline-alkali soil (Jia et al., 2019). It is commonly cultivated as an ornamental tree (Yin et al., 2017). The flowers of this species are used to treat metrorrhagia in Chinese traditional medicine (Cui et al., 2018), while the buds and flowers are used in the treatment

of traumatic injury, fractures, and hemorrhage. Hall crabapple tea leaves have a diuretic impact, anti-inflammatory, cardiac, and other effects, enhance memory, and prevent diabetes (Yin et al., 2017).

Malus niedzwetzkyana Dieck ex Koehne (Niedzwetzky's apple) is found in the mountain forests of Kazakhstan (Karatau and Zailiyskai Alatau), Kyrgyzstan (Jalal-Abad region), and Western China (Xinjiang region), and is among the valuable wild apple species. This species is included in the Red Book of Kazakhstan and the International Red List of Endangered Species. The *M. niedzwetzkyana* specimens are used in ornamental horticulture as well as a gene pool for apple breeding for resistance to environmental stress and as a source of red leaves, red flowers, and red fruits for apples and decorative crabapples breeding (Mezhenskyj & Mezhenka, 2021).

Malus × purpurea (A. Barbier) Rehder (Purple Crab Apple) is a gardening species that was cultivated even before 1900 (Rehder, 1927). *Ma-*

lus × purpurea is a complicated interspecific hybrid with an obscure origin. *Malus × purpurea* is a hardy-tolerant and drought-tolerant plant. Numerous cultivars and forms of *M. × purpurea* are propagated and grown in gardens and parks in different countries, including Ukraine. The leaves and fruits of *M. × purpurea* are smaller than those of *M. niedzwetzkyana*. Due to their highly ornamental attractiveness, trees of *M. × purpurea* and its cultivars adorn any landscape and can serve as a source for the breeding of ornamental apple trees.

The infraspecific taxa of *M. × purpurea* are represented by well-known cultivars 'Ola', 'Royalty', and 'Selkirk'. The ornamental and economic features and attractiveness of these cultivars are similar to those of the original nothospecies, but the 'Ola' trees have an openwork, spreading crown and large pink flowers; 'Royalty' trees have a compact, low-branched conical crown; and small 'Selkirk' trees form a broad, spherical crown (Opalko et al., 2016).



Fig. 1. Morphological diversity of *Malus* specimens under study from the collection of the National Dendrological Park "Sofiyivka" (Ukraine):
a-c – *M. halliana*, *d, e* – *M. floribunda*, *f* – *M. × purpurea* 'Ola', *g* – *M. × purpurea*, *h, i* – *M. niedzwetzkyana*,
j, k – *M. × purpurea* 'Royalty', *l, m* – *M. × purpurea* 'Selkirk'



Fig. 2. *Malus x floribunda* fruits in winter: fruits on branches (left); fallen fruits pecked by birds, and seeds (right) in the National Dendrological Park “Sofiyivka” (Ukraine)

The development of the reproductive organs was characterized by indicators of fertility and viability of pollen grains according to the method of Zoya Pausheva (Grytsay & Miasoid, 2016), and the percentage fruit set (the ratio of the number of fruits to the number of flowers), and seed set (the ratio of the number of formed seeds to the number of set fruits) according to standard methods (Racskó et al., 2006).

The research period was analyzed according to indicators of the heat mode and the amount of precipitation. The average temperatures for the period from 2016 to 2022 were mainly higher than the long-term average (1991–2020). The hottest year in terms of average temperatures was 2020 (128.2 °C), whereas the least hot was 2021 (104.6 °C). The average amount of precipitation during the years of the study was less than the long-term average (1991–2020) mm per year. The least precipitation fell

in 2019 (378.0 mm) and the most in 2021 (641.8 mm). The study of the drought intensity was carried out according to G. T. Selianinov’s hydrothermal coefficient, which was defined as the ratio of the sum of precipitation during the period with active temperatures above +10 °C to the sum of temperatures divided by 10 (Opalko et al., 2015). The value of hydrothermal coefficient determines the severity of the drought (Dmytrenko & Strokach, 2003): hydrothermal coefficient >2.0 – immoderately humid; hydrothermal coefficient = 1.0–2.0 – sufficiently humid; hydrothermal coefficient <1.0 – insufficient humidity; hydrothermal coefficient = 0.7–1.0 – dry; hydrothermal coefficient = 0.4–0.7 – very dry. Over the years of research, significant changes in hydrothermal coefficient were found (Fig. 3), which made it possible to determine the intensity of the drought.

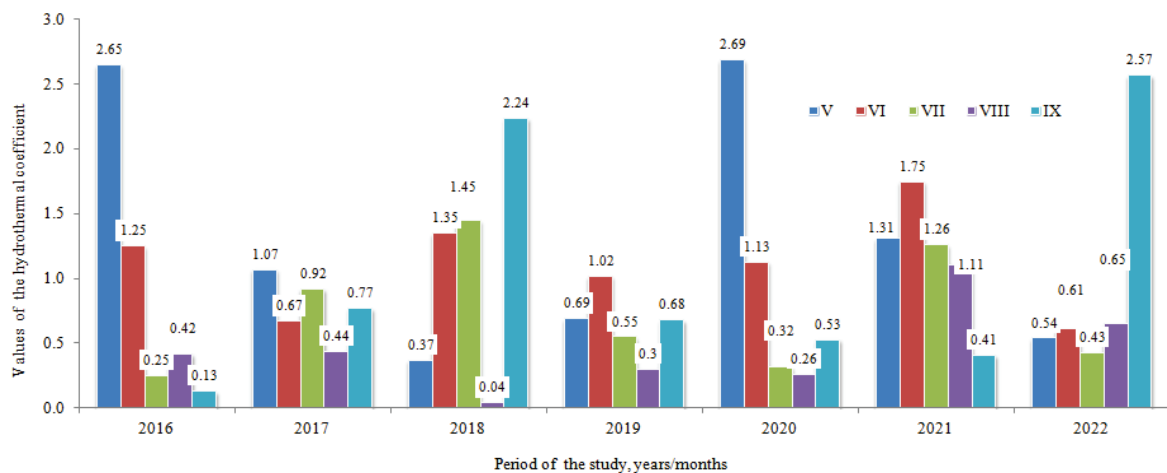


Fig. 3. The hydrothermal coefficient during May–September 2016–2022 in Uman, the Cherkasy region (Ukraine)

The amount of hydrothermal coefficient in May 2016–2022 ranged from 0.37 in 2018 to 2.69 in 2020. The average hydrothermal coefficient measured for June was 1.11, with the lowest point in 2022 and the highest point in 2021. Hydrothermal coefficient in July 2016–2022 ranged from 0.25 to 1.45, with an average of 0.74. The driest month was August, with hydrothermal coefficient ranging from 0.04 to 1.11, with an average of 0.46. The measured hydrothermal coefficient in September ranged from 0.13 to 2.57. The lowest hydrothermal coefficient was recorded in August 2018, considering the meteorological indicators of the previous and following months of 2018, though no drought was observed.

August was the driest month during the study period, with HTC 0.26, the highest average temperature of +21.3 °C, and the lowest average amount of precipitation of 19.2 mm. According to the State Technical

Committee, the driest summer was in 2020, which was confirmed by the data of our observations on the drought resistance of plants.

The drought resistance of plants was rated visually according to the 9-point scale of the Ukrainian Institute for Plant Varieties Examination (Kyienko et al., 2017) after detecting an adverse meteorological factor. Physiological indicators, particularly the water content in leaves, relative turgidity, leaf water deficit, and water retention capacity, were determined after detecting the effect of drought on the studied plants according to the laboratory-field method of Kushnirenko et al. (1975). Ten pieces of leaves were selected from the middle tier of the crown at 8:00 a.m. The percentage of leaf water deficit was determined as the ratio of the amount of water absorbed by the leaves after saturation to the total water content in the state of complete saturation. The relative turgidity was determined in

percent as the ratio of the amount of water (g) contained in the leaves before their saturation with water to the amount of water after their saturation. Water retention capacity was defined as the correlation of the loss of water over a certain period of time compared to its initial content.

Data on parameters of reproductive organs' development were determined as average of measurements of 5 individual plants. Repeatability of the drought resistance indicators determinations was 5-fold. Standard deviation (SD), mean values (\bar{x}), minimum values (min), maximum values (max), coefficient of variation (CV, %) were calculated. One-way ANOVA was performed to detect statistical significance. The differences between means were tested with Tukey's HSD. Differences with $P < 0.05$ were considered significant. Correlation analysis was performed using the Pearson's coefficient (r) and its error (Sr).

Results

Drought resistance crabapples (Malus spp.) studied. During the annual visual check, we did not detect morphological changes that would indicate the impact of drought on the studied plants, except for August 2020 (hydrothermal coefficient = 0.26). In the specified period, local

damage and loss of leaf turgor were observed on individual leaves of species and cultivars of decorative apple trees, which caused the study of physiological indicators. Drought resistance for all studied genotypes in this period (*M. × floribunda*, *M. halliana*, *M. niedzwetzkyana*, *M. × purpurea*, *M. × purpurea* 'Ola', *M. × purpurea* 'Royalty', *M. × purpurea* 'Selkirk') was rated at 5 points because of the partial leaf damage, changed colour at the edges of leaf plates or spots. Moreover, there was no significant difference in visual indicators between different species or cultivars (Fig. 4). As a result, species and cultivars of the genus *Malus* were classified as medium resistant. However, the specimens of the studied species and cultivars differed from each other according to physiological indicators (Table 1). *Malus* species and cultivars water deficit rates were the least homogeneous (CV = 55.9%). The water deficit in the leaves ranged from 24.4% (*M. niedzwetzkyana*) to 6.8% (*M. halliana*). The investigated genotypes were divided into groups, according to laboratory studies of the indicator of water deficit in leaves: high resistance to drought – *M. floribunda*, *M. halliana*, *M. × purpurea*, *M. × purpurea* 'Royalty' (water deficit in leaves ≤ 10.0%), medium resistance – *M. × purpurea* 'Selkirk' and *M. × purpurea* 'Ola' (water deficit in leaves 10.0–20.0%), low resistance – *M. niedzwetzkyana* (water deficit in leaves ≥ 20.0%).



Fig. 4. The local damage on leaf of *M. halliana* (left) and *M. × purpurea* 'Royalty' (right) under drought stress in the National Dendrological Park "Sofiyivka" (Ukraine)

Table 1

Physiological indicators of *Malus* specimens under drought stress study in the National Dendrological Park "Sofiyivka" in August 2020 (n = 5, $\bar{x} \pm$ SD)

Species/cultivar	Leaf water content, %	Relative turgidity, %	Leaf water deficit, %	Loss of water, %			
				after 2 hours	after 4 hours	after 6 hours	after 24 hours
<i>M. × floribunda</i>	60.0 ± 0.8 ^{ac}	98.6 ± 0.9 ^a	7.5 ± 0.5 ^a	11.9 ± 0.6 ^a	23.6 ± 0.6 ^a	36.9 ± 0.6 ^a	64.7 ± 1.2 ^a
<i>M. halliana</i>	61.6 ± 0.8 ^{bd}	98.9 ± 0.7 ^a	6.8 ± 0.5 ^a	9.7 ± 0.6 ^b	20.8 ± 0.6 ^b	32.0 ± 0.5 ^b	50.2 ± 1.1 ^b
<i>M. niedzwetzkyana</i>	60.7 ± 0.9 ^{bc}	91.5 ± 0.8 ^b	24.4 ± 0.7 ^b	14.1 ± 0.6 ^c	22.5 ± 0.4 ^c	33.6 ± 0.6 ^c	59.5 ± 1.0 ^c
<i>M. × purpurea</i>	67.2 ± 0.8 ^c	98.1 ± 0.7 ^a	7.1 ± 0.5 ^a	15.1 ± 0.4 ^d	20.1 ± 0.5 ^b	33.4 ± 0.7 ^c	61.5 ± 0.8 ^d
<i>M. × purpurea</i> 'Ola'	60.2 ± 0.5 ^{ac}	81.7 ± 0.7 ^c	17.1 ± 0.6 ^c	13.7 ± 0.6 ^{bc}	32.1 ± 0.5 ^d	52.0 ± 0.8 ^d	77.4 ± 0.8 ^e
<i>M. × purpurea</i> 'Royalty'	62.6 ± 0.7 ^d	89.6 ± 0.9 ^d	9.3 ± 0.6 ^d	10.6 ± 0.5 ^d	22.1 ± 0.6 ^c	40.5 ± 0.7 ^c	72.2 ± 0.8 ^e
<i>M. × purpurea</i> 'Selkirk'	61.6 ± 0.9 ^d	88.5 ± 0.9 ^d	10.3 ± 0.5 ^c	13.0 ± 0.6 ^c	29.4 ± 0.5 ^e	44.4 ± 0.9 ^f	66.2 ± 0.9 ^e
$\bar{x} \pm$ SD	62.0 ± 2.5	92.4 ± 6.5	11.8 ± 6.6	12.6 ± 1.9	24.4 ± 4.6	39.0 ± 7.2	64.5 ± 8.8
min-max	60.00–67.2	81.7–98.9	6.8–24.4	9.8–15.1	20.1–32.1	32.0–52.0	50.2–77.4
CV, %	4.0	7.0	55.9	15.5	18.7	18.5	13.6

Note: the different letters indicate statistically significant differences in the means of the compared pair according to the Tukey test.

Other totalities were quantitatively homogeneous: leaf water content, relative turgidity and water retention capacity (CV ≤ 33.0%). Leaf water content ranged from 60.0% (*M. × floribunda*) to 67.2% (*M. × purpurea*), with a mean value of 62.0%. The average relative turgidity was 92.4%; the lowest was in the leaves of *M. × purpurea* 'Ola' (81.7%), and the highest in *M. halliana* (98.9%). *Malus halliana* leaves lost the least water after 2 (9.7%), 6 (32.0%) and 24 (50.2%) hours; to the contrary, *M. × purpurea* 'Ola' leaves lost the most water after 4 (32.1%), 6 (52.0%) and 24 (77.4%) hours.

According to the methodology, high turgidity and low water deficit in the leaves indicate high resistance of plants to drought. The most drought-resistant were *M. × floribunda*, *M. halliana*, *M. × purpurea*, with relative turgidity over 98.0% and water deficit in leaves less than 10.0%.

Development of the reproductive organs of Malus specimens. Species and cultivars of apple trees differed from each other in the terms of indicators of the development of the reproductive organs (Table 2). They had

high rates of pollen grain fertility (from 79.8% to 95.0%). Depending on the species or cultivar, pollen viability ranged from 5.1% to 51.5%. The highest pollen viability was characteristic of *M. × floribunda*, *M. × purpurea* and *M. × purpurea* 'Royalty'; the least viable pollen was detected in *M. niedzwetzkyana*. The highest rate of fruiting was recorded in *M. floribunda*, *M. halliana* and *M. × purpurea* (over 50.0%), the lowest in *M. niedzwetzkyana* and *M. × purpurea* 'Royalty'. The fruiting rate of *M. × purpurea* 'Royalty' was reduced due to unfavourable meteorological conditions during the flowering period (the fruiting rate was 16.4%, the lowest in 2020, although it reached 52.7% in previous and subsequent years). That is why, its fruit and seed setting indicators were excluded from the correlation analysis to ensure the reliability of the obtained results. All *Malus* species and cultivars studied had relatively high rates of seed productivity, ranging from 26.4% to 60.5%. It is significant that species/cultivars with relatively high fruiting ratios had high relative turgidity (over 98.0%) and low leaf water deficit (less than 10.0%).

Table 2Quantitative indicators of *Malus* reproductive organs' development in the National Dendrological Park "Sofiyivka" (n = 5, x ± SD)

Species/cultivar	Pollen fertility, %	Pollen viability, %	Fruit set, %	Seed set, %
<i>M. ×floribunda</i>	92.6 ± 2.1 ^{ac}	51.5 ± 2.9 ^a	80.5 ± 3.3 ^a	58.0 ± 3.1 ^a
<i>M. halliana</i>	89.1 ± 3.0 ^a	20.5 ± 2.5 ^b	51.1 ± 3.5 ^b	60.5 ± 2.6 ^b
<i>M. niedzwetzkyana</i>	79.8 ± 2.8 ^b	5.1 ± 1.0 ^c	25.5 ± 2.3 ^c	26.4 ± 2.4 ^b
<i>M. ×purpurea</i>	93.8 ± 2.6 ^c	41.2 ± 2.9 ^d	62.5 ± 3.3 ^d	50.0 ± 2.5 ^c
<i>M. ×purpurea</i> 'Ola'	95.0 ± 2.5 ^c	36.2 ± 2.9 ^e	32.6 ± 3.0 ^e	52.2 ± 2.6 ^c
<i>M. ×purpurea</i> 'Royalty'	92.3 ± 2.5 ^{ac}	42.6 ± 2.6 ^d	16.4 ± 1.8 ^f	55.6 ± 2.7 ^{bc}
<i>M. ×purpurea</i> 'Selkirk'	93.5 ± 2.1 ^c	17.5 ± 2.0 ^b	36.4 ± 2.7 ^e	36.8 ± 2.4 ^d
x ± SD	90.9 ± 5.2	30.6 ± 16.6	43.6 ± 22.4	48.5 ± 12.4
min-max	79.8-95.0	5.1-51.5	16.4-80.5	26.4-60.5
CV, %	5.7	54.1	51.5	25.6

Note: see Table 1.

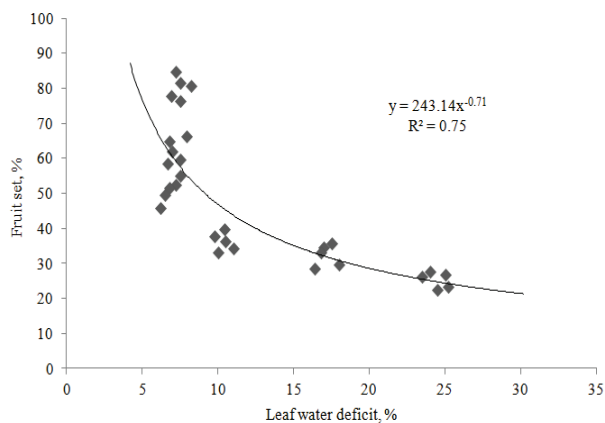
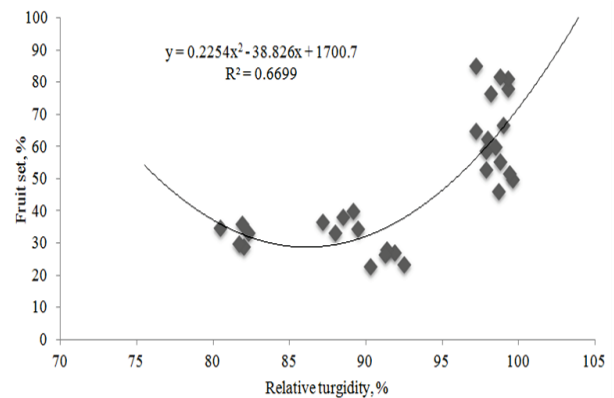
Correlation and regression analysis. Correlation analysis between leaf water content, relative turgidity, leaf water deficit, and water retention capacity on the one hand and fertility and viability of pollen grains, percentage fruit set, and seed productivity, on the other hand, showed (Table 3) a strong direct relationship ($r = 0.7265$) between the percentage fruit set and relative turgidity, and a strong inverse relationship between water deficit and percentage fruit set and seed productivity ($r = -0.7636$ and $r = -0.7228$, respectively). For all quantitative indicators of generative development, the most decisive among indicators of drought resistance was leaf water deficit, which had an inverse strong (with percentage fruit set and seed productivity) and inverse medium (with fertility and viability of pollen grains) correlation with them.

Table 3Correlation between indicators of drought resistance and the reproductive organs' development of *Malus* specimens ($r \pm S_r$)

Quantitative indicators of the reproductive organs	Leaf water content	Relative turgidity	Leaf water deficit	Loss of water after 2 hours
Pollen fertility, n = 35	0.2224 ± 0.1630	-0.1318 ± 0.1682	-0.5948 ± 0.1108*	-0.0277 ± 0.1714
Pollen viability, n = 35	0.2041 ± 0.1715	0.1607 ± 0.1671	-0.5945 ± 0.1109*	-0.1370 ± 0.1683
Fruit set, n = 30	0.2462 ± 0.1853	0.7265 ± 0.0877*	-0.7636 ± 0.0774*	-0.3006 ± 0.1689
Seed set, n = 30	0.0484 ± 0.1744	0.3800 ± 0.1589	-0.7228 ± 0.0887*	-0.5541 ± 0.1287

Note: * correlation is significant at the $P < 0.05$.

The identified correlations indicate the dependencies of the level of fruiting and seed productivity of plants on drought resistance. The species and cultivars of apple trees with a lower leaf water deficit, determined during the drought period, were characterized by higher rates of generative development. The percentage fruit set of *Malus* specimens had a strong inverse correlation with a leaf water deficit and a direct correlation with relative turgidity, which makes it possible to predict the reproductive organs' development potentiality based on these physiological indicators (Figs. 5, 6).

**Fig. 5.** Relationship between percentage fruit set and leaf water deficit in investigated *Malus* specimens**Fig. 6.** Relationship between percentage fruit set and relative turgidity in investigated *Malus* specimens

Discussion

The aim of this study was to select and improve the methods for assessing the ornamental crab-apples' drought resistance potential for use as garden design objects, as well as in plantings on streets and highways and the green zone of the cities. One important aim of the approaches discussed here is to reveal differences in drought stress resistance between different species, cultivars, and hereafter between genotypes within one species. Although in Ukraine, ornamental crabapples (*Malus* spp.) do not yet have such popularity as traditional woody park plants, interest in new ornamental crabapple cultivars nowadays has been growing rapidly. To determine the advisability of massive propagation of a particular species/cultivar of crabapples, its cultivation, and use in landscape design, and application as greenery for different city/town units, it is essential to take into account not only its ornamental value but also its ecological and biological properties, which are determined by the inheritance of concrete specimens in the interaction with environmental factors (Dirr, 2009; Seneta & Dolatowski, 2012), which is foremost judged by the probability of survival in conditions not always optimal for the cultivated plant, and by the ability to preserve in such conditions its ornamental qualities, which are the aim of the cultivation of this plant.

Drought is one of the most serious environmental factors affecting the growth and development of plants. Yield loss due to drought soon is likely to exceed losses from all other factors, as both the magnitude and duration of stress are critical (Farooq et al., 2009; Huang et al., 2021). Drought causes a wide range of plant responses, ranging from cellular metabolism to reduced growth and yield. Understanding the physiological mechanisms of response to the drought of various types of plants is an urgent issue under the conditions of the predicted increase in temperature and climate aridity. It is found that 70% of forest plants have "narrow hydraulic safety margins" against drought stress, potentially causing long-term declines in their productivity and even extinction. Hydraulic safety margins were defined as the difference between the xylem pressure at which tissue conductivity was lost and the xylem pressure at which a 50% loss of conductivity occurred (Choat et al., 2012).

Considering the need to ensure the future demand for food, it is important, equally to use economical and useful methods of agriculture, to study various aspects of drought resistance of plants (Raza et al., 2019; Seleiman et al., 2021). Strategies to increase plant water use efficiency and optimize irrigation are being developed worldwide. Some of them are based on the relationship between the change of stem water content and physiological water requirement of trees (Zhao et al., 2022), on the leaf gas exchanges and even the daily apple fruit growth (Boini et al., 2019). Long-term monitoring of the effects of drought using satellite imagery can help rationally manage the environment (Jitariu et al., 2019). However, the task of selecting drought-resistant plants for gardening is now also of particular relevance. The selection of drought-resistant plants for landscaping will ensure their longevity and will help reduce maintenance costs, primarily for irrigation (Lanza & Stone, 2016; Nuzhyna et al., 2022).

Many methods for determining plant-water relations have been characterized (Franco, 2002; Breitenstein et al., 2012; Zahid et al., 2019). Photosynthetic efficiency, lipid peroxidation, proline, phenol, chlorophyll and water content in leaves are used to understand the defense mechanisms of plant drought resistance (Mihaljevic et al., 2021). The turgor loss point and the vulnerability to xylem cavitation are widely used approaches to quantify the vulnerability of vegetative organs to drying (Grossman, 2023). The widely used method to describe plant-water relations has been to estimate water potential with a pressure chamber (Turner, 1988; Lakso, 2003; Rodriguez & Dominguez et al., 2022). The pressure chamber was used for the first time by Dixon (1914) to measure the water status of leaves and later was popularized by Scholander et al. (1964, 1965). Ritchie & Hinckley published a review of the use of the pressure chamber in 1975 (Turner, 1988). However, the practical complexity of the technique and basic theory has always been and remains present (Rodriguez & Dominguez et al., 2022), and so the technology or equivalent current measurement systems for meaningful experiments to investigate the water status dynamics of plants are not always available for biologists' and plant breeders' everyday work. For this reason, there has been an interest in the development of affordable techniques for the valuation of leaf water status of the ornamental crabapple tree and other plants, including in the drought stress resistance between different species as well as the different genotypes. The purpose of our research was to use the most accessible method, not only for scientists and biologists, but for a wide range of gardeners as well. That's why we used the weight method for determining physiological indicators of drought resistance.

Scientists are interested in clarifying the relationships between quantitative physiological indicators of drought resistance and plant productivity (Blum, 2017), as well as the search for determining physiological factors associated with a decrease in the qualitative and quantitative indicators of plant vitality or even their death, which is caused by drought (Adams et al., 2017). Several studies examine the relationship between drought stress, gas exchange parameters, and leaf photosynthetic activity (Wang et al., 2018). For agricultural crops (barley, wheat, corn, sorghum, chickpeas, peas, soybeans, canola, mustard, castor, and sunflower) in drought conditions, in 24 out of 26 cases, a positive and significant relationship between osmotic adjustment and productivity was found (Blum, 2017).

The results of the research conducted in Europe indicate that extreme summer heat and precipitation deficits lead to a decrease in the primary gross productivity of plants, which is accompanied by a slowdown in ecosystem respiration and, accordingly, an increase in the amount of anomalous net source of carbon dioxide (Ciais et al., 2005). The main cause of death of woody plants during drought is the loss of the transport function of the plant, that is, the ability of the plant to move water from the roots to the leaves (hydraulic failure), while the lack of carbon dioxide (carbon starvation) was the cause of mortality in only half of the cases (Adams et al., 2017). The yield of crop plants and their survival should not be seen as identical effects of drought stress. The stability of yield components of crop plants is a reflection of the mechanism of developmental plasticity, on which the assessment of drought resistance should be based (Basu et al., 2016).

It has been proved that the intensity of photosynthesis decreases sharply in drought conditions (Ping & Bai, 2015; Wang et al., 2018). An imbalance between used and consumed absorbed light energy occurs in dry periods. Stomatal closure is regarded as the main factor (Farooq

et al., 2009; Ping & Bai, 2015). Excess energy in apple leaves occurred when the degree and duration of water stress exceeded the tolerance of apple plants because the leaves absorbed more light energy than they could use for photosynthetic carbon fixation. Exceeding the regulatory capacity of leaves can lead to irreversible dehydration of cells, disruption of metabolism, and photosynthetic damage to plants (Kramer et al., 2004; Wang et al., 2018, 2022). A close correlation between photosynthetic activity and the water potential of apple leaves was revealed. Photosynthesis is probably the basis of the apple crop. This indicates the need to investigate how drought affects apple yield (Wang et al., 2018).

By visible morphological changes caused by drought, *Malus* species and cultivars almost did not differ in terms of drought resistance, although the physiological indicators studied, such as leaf water deficit and relative turgidity, indicated that *M. × floribunda*, *M. halliana*, and *M. × purpurea* were the most drought-resistant. To clarify this visible contradiction, more in-depth studies of drought tolerance are needed, namely, there is a need for mathematical analysis of quantitative physiological indicators and their relationships with plant growth and development indicators. The correlations between quantitative indicators of the development of the reproductive organs and drought resistance of *Malus* specimens indicate that low leaf water deficit and high relative turgidity during drought were prerequisites for high fruiting and seed productivity of apple plants. It can be assumed that the driving force for the high level of productivity (the fruit and seed set percentages) of the apple tree was its resistance to drought. In addition, leaf water deficit had a moderate inverse correlation with the fertility and viability of the pollen grains.

We support the idea that the traits conferring tolerance to environmental stressors are not static in time and physiological tolerance changes over time in response to exposure to seasonal stress (Grossman, 2023). However, we believe that drought resistance quantitative indicators have determined the level of physiological plasticity of the species and varieties of our study, which in turn reflects the success of the reproductive organs' development. Considering that it is generally difficult to find a single property of a plant that is responsible for plant productivity under drought stress conditions (Blum, 2017), the results of our research prove that it is possible to offer the determination of water deficit in leaves as a method of predicting drought resistance and productivity of the starting material (seedlings), which will increase the efficiency of the selection of valuable breeding material for apple trees.

Conclusions

Quantitative physiological indicators under conditions of drought stress, such as leaf water deficit and relative turgidity are the most important, according to our research, so they can be used as markers for predicting the productivity of apple species and cultivars. The leaf water deficit and the relative turgidity were strongly correlated with fruit set percentage of *Malus* specimens under drought stress conditions. In addition, a strong correlation was found between the leaf water deficit and the percentage of seed set, and a medium correlation between the leaf water deficit and the qualitative characteristics of pollen grains. Our study contributes to the understanding of how exactly quantitatively drought stress, as reflected by physiological parameters, affects the productivity and decorative effect of *Malus* specimens. This method can become an alternative for rating the drought resistance of the source material for the breeding of ornamental crabapple trees and other woody plants.

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The authors declare that there is no competing interest.

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