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Grapevine genotypes as natural carbon sinks: contributions to reducing the carbon footprint in the context of climate change

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Abstract

Climate change necessitates the development of productive grapevine genotypes that contribute to atmospheric CO_2 sequestration. The present study evaluated the physiological characteristics and adaptive potential of genotypes of *Vitis vinifera* L. ssp. *sylvestris*, local varieties of *V. vinifera* ssp. *sativa*, interspecific genotypes (*V. vinifera* × *Muscadinia rotundifolia*), *V. labrusca*, and *V. rupestris*, in terms of CO_2 assimilation capacity and water-use efficiency. Photosynthesis, transpiration, stomatal conductance, leaf temperature, and water-use efficiency were monitored with the PTM-48A station using the light saturation curve method for a minimum of 72 hours. The climatic trend demonstrated an increase in average temperature and a deficit of atmospheric precipitation for certain periods. It was found that within the temperature range of 28–29°C to 33–36°C, transpiration intensity increased and water use efficiency decreased in all studied genotypes, accompanied by a reduction in photosynthetic intensity. Local genotypes demonstrated a high-water loss coefficient, while interspecific genotypes, such as Ametist and Augustina, demonstrated a stable photosynthetic intensity and an increased water use coefficient. The results demonstrated that the vineyards functioned as an integrated photosynthetic system, and that it is necessary to develop productive interspecific grapevine genotypes with an enhanced potential for sequestering CO_2 from the atmosphere.
Keywords: *CO_2 sequestration, climate change, grapevine genotypes, photosynthesis*

INTRODUCTION

Climate change and the increase in atmospheric CO_2 concentration require the development of plant genotypes with increased adaptability to constantly changing climatic factors. In this regard, the use of plant genotypes with an enhanced potential for CO_2 capture and storage represents an effective ecological approach and, at the same time, an additional source of income for the agricultural sector (Mihăilescu, 2004; Alexandrov, 2023). Cultivation of such plant genotypes allows the obtaining of genotype-specific derivative products, as well as the commercialization of carbon sequestered from the atmosphere. Holders of agricultural land cultivating such plant genotypes can sell the fixed CO_2 equivalent (expressed in tons of CO_2 equivalent) to economic agents facing difficulties in the process of reducing their own greenhouse gas emissions, especially CO_2. Promoting plant genotypes that have an increased photosynthetic capacity to capture and store atmospheric carbon thus contributes both to reducing the carbon footprint and to promoting sustainable economic mechanisms (Alexandrov, 2023).

The development of genotypes with increased CO_2-sequestration potential is based on bioecological criteria such as photosynthetic efficiency, biomass accumulation, and tolerance to abiotic stresses (drought, temperature, humidity). The importance of these genotypes also stems from their ability to maintain productivity and the quality of derived products, as well as from their contribution to carbon capture and storage. Integrating these criteria into breeding programs provides a pathway for developing agroecosystems optimized for CO_2 sequestration while simultaneously increasing their resistance to changing climatic factors (Alexandrov, 2020). Agrophytocenoses represent an integrated photosynthetic system, in which efficiency depends both on the ability of genotypes to capture atmospheric CO_2 and on the efficient use of solar radiation, transformed into organic matter (Bălteanu, 2005; Ranca et al., 2025).

The initiation of active metabolic processes in the grapevine occurs within the limits of average daily temperatures of 9-10°C. In the case of the photosynthetic process, relatively stable activity is manifested within the temperature range of 25-30°C. In this temperature range, enzymatic activity and gas-exchange processes reach maximum efficiency. If the atmospheric temperature exceeds 35°C, this significantly contributes to the decrease in the intensity of the photosynthetic process. Water deficit also disrupts the water balance and contributes to the occurrence of thermal stress (Irimia, 2012).

In the case of vegetative dormancy, resistance to low temperatures varied in the range of −15 to −18°C, characteristic of genotypes from the *Vitis vinifera* L. group, while interspecific genotypes obtained by crossing with *Vitis amurensis*, *Vitis riparia*, *Vitis labrusca*, and *Muscadinia rotundifolia* demonstrated increased resistance in the range of −25 to −30 °C. However, at the beginning of the development phase of young shoots, a temperature of −1 to −20 °C posed a considerable risk (Irimia, 2012). It was found that interspecific grapevine genotypes (*Vitis vinifera* L. x *Muscadinia rotundifolia* Michx.) have an increased potential for carbon capture from the atmosphere compared to intraspecific grapevine genotypes from the *Vitis vinifera* L group.

The aim of the current study was to evaluate the physiological and adaptive potential of grapevine genotypes, in terms of CO_2 capture capacity and the efficiency of water resource use under conditions of constantly changing climatic factors.

MATERIALS AND METHODS

The object of study were the *Vitis vinifera* L. grapevine genotypes, such as ssp. *sylvestris* Gmel., ssp. *sativa* D.C. with the varieties: Fetească Albă, Fetească Neagră, and Rară Neagră, (Ampelografia Românieі, 2018), the interspecific genotypes *Vitis vinifera* L. ssp. *sativa* D.C. x *Muscadinia rotundifolia* Michx., such as Alexandrina, Ametist, Augustina, Nistreana (Alexandrov, 2020), *Vitis labrusca* L. and *Vitis rupestris*. The selected vines exhibit diverse genetic backgrounds and differing potentials for capturing CO_2 from the atmosphere.

Using the PTM-4A system, the light saturation curve method allowed the evaluation of the photosynthetic capacity (Alexandrov, 2023). The evaluations were carried out in the field, using fully developed leaves, representative for each genotype, over a continuous period of at least 72 hours. The analyzed parameters included the intensity of photosynthesis, stomatal conductance, transpiration and water-use efficiency (Irimia, 2012; Alexandrov, 2020; 2023).

The data were statistically processed using Microsoft Excel 2010 and Statistica 10 (StatSoft Inc., USA) applying appropriate descriptive and inferential tests to compare the values between genotypes and to assess the significance of the differences (Ranca et al., 2025). The tests were performed in either three or five replicates per genotype and the results are presented as mean ± standard deviation.

RESULTS AND DISCUSSION

Analysis of the average monthly temperatures in the central region of the Republic of Moldova indicated a clear upward trend of air temperature during 2023–2025 compared to the recorded long-term climatic norm. Positive deviations were evident in most months and were more pronounced during the warm season, highlighting regional warming.

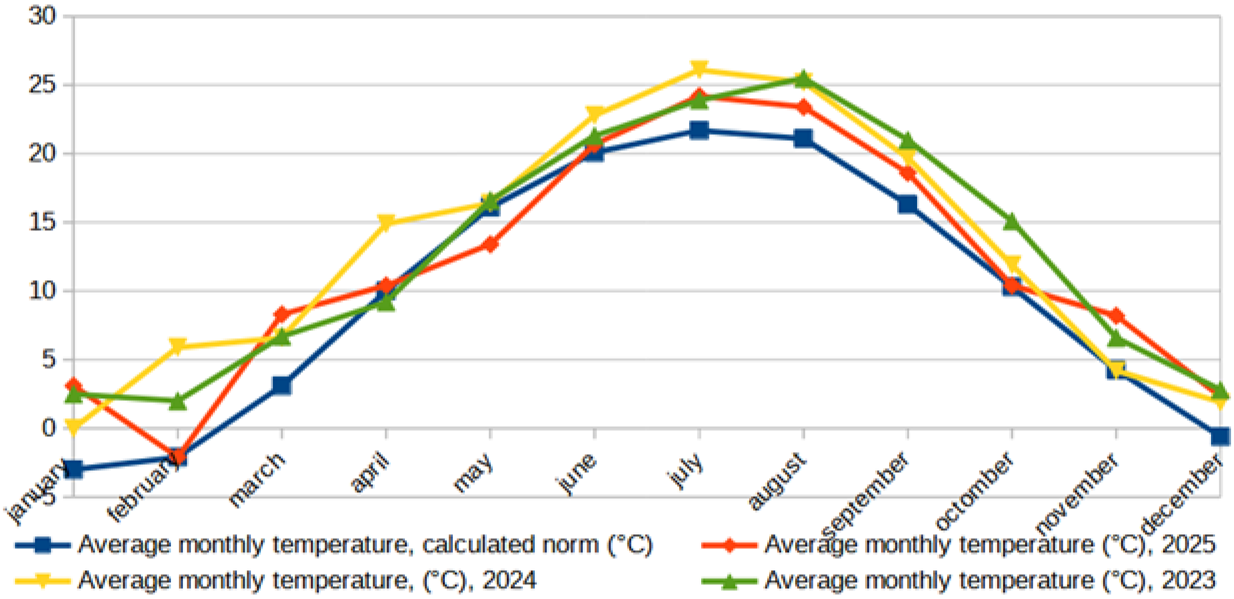

Figure 1. Average monthly temperature, period 2023-2025, compared to the calculated norm. Central area of the Republic of Moldova

The year 2025 was characterized by significantly above-average temperature conditions, with the recorded annual mean temperature (11.74 °C), (Fig. 1) exceeding the calculated norm (9.77 °C) by 1.97 °C. At the same time, annual precipitation (456.2 mm) fell below the reference value (530 mm) (Fig. 2) resulting in a deficit of 73.8 mm. The mean temperature during the vegetation period exceeded the climatic norm (18.15°C), reaching 18.85°C (www.meteo.md).

Climatic deviations, compared with the norms calculated for the Central zone of the Republic of Moldova, demonstrated an increase in average monthly temperatures, as well as a significant insufficiency of soil moisture. Changes in climatic factors negatively influenced the soil water balance, the physiological processes of plant genotypes, and the productivity of agricultural crops. Regional warming was manifested by a short and warm winter, an earlier spring, a much warmer summer, and a prolonged, warm autumn. All these factors resulted in a prolonged period of plant development, with a negative impact on the phenological stages (Republic of Moldova Climate Change Adaptation Strategy until 2020). Thus, the accumulated sum of temperatures intensifies the evapotranspiration process and amplifies the thermal and water stress of plants, having a negative impact on the physiological stability and adaptive capacity of plants.

Based on the monthly distribution of atmospheric precipitation in the period 2023–2025, in the central area of the Republic of Moldova, significant deviations from the calculated norm were found, thus confirming the intensification of climate change processes. During 2025, a pronounced deficit of atmospheric precipitation was observed for the critical period of active vegetation (May-August). According to the calculations, it was concluded that there was a deficit 2–5 times higher than the calculated norm, generating very pronounced water stress and having a negative impact on the development processes in the active period, as well as on the intensity of the photosynthesis process and biomass accumulation. Compared to 2023 and 2024, it was found that there were periods characterized by abundant precipitation, in spring (April) and autumn (September-October), thus indicating a more or less uneven precipitation. The respective losses are due to surface runoff and leaching, which do not contribute to compensating for the water deficit in the summer period (Climatic Guide of the Republic of Moldova, Multiannual Data, 2024; Republic of Moldova Low-Emission Development Strategy until 2030).

Based on the findings, an increase in the frequency of summer drought periods was observed, along with uneven precipitation. Therefore, it is necessary to develop and implement integrated strategies for adaptation to climate change, which should focus on the following principles: use of plant genotypes with increased resistance to water stress; optimization of water resources management; and adaptation of cultivation techniques and technologies to climatic changes specific to each agricultural area. Furthermore, genetic improvement and modern agricultural management must be based on expansion and use of interspecific genotypes with increased resistance; selection of genotypes with increased water-use efficiency and stable productivity; and genotypes with increased capacity for atmospheric CO_2 capture and photosynthetic stability under stress conditions.

The successful functioning of an integrated photosynthetic system depends entirely on the determination and selection of algorithms for the development of plant genotypes within an agrophytocenosis. The efficiency of this system largely depends on both the ability of plant genotypes to capture atmospheric carbon dioxide and their capacity to optimally use solar radiation, expressed through the coefficient of conversion of light energy into biomass. Effective management of these parameters enhances the ecological performance and productivity of plant genotypes, increases the carbon-capture potential of agroecosystems, and contributes to reducing environmental impact. Following the comparative analysis of grapevine genotypes, significant differences in the intensity of physiological processes were identified, highlighting specific strategies for adaptation to thermal stress conditions.

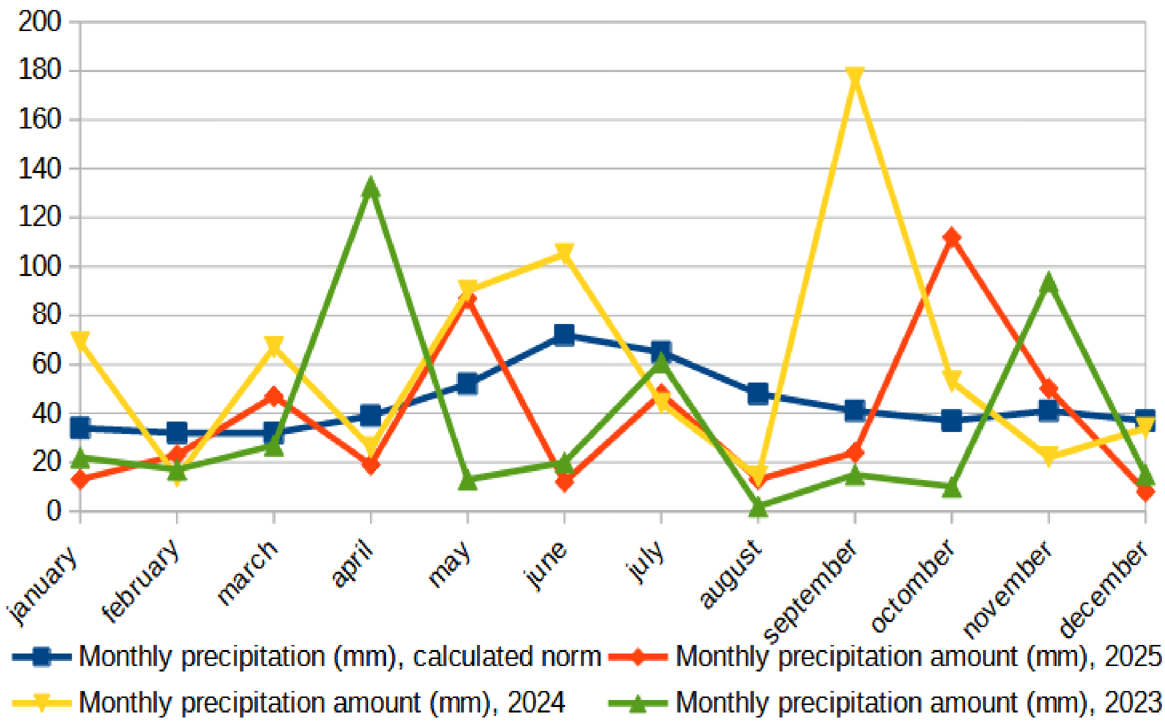

Figure 2. Monthly precipitation amount, period 2023-2025, compared to the calculated norm. Central Zone of the Republic of Moldova.

All evaluated grapevine genotypes exhibited a physiological response largely dependent on temperature values, expressed through increased transpiration intensity and stomatal conductance, and in most cases accompanied by a decrease in water-use efficiency and a slight reduction in photosynthesis intensity (Fugure 3).

The genotype *Vitis vinifera* L. ssp. sylvestris Gmel., at a temperature of 28°C, demonstrated a photosynthetic intensity of 6.17 (±0.15) µmol CO_2/m²/s, accompanied by a transpiration intensity of 0.76 (± 0.2) mmol H_2O/m²/s. At the same time, at a temperature of 33.42°C, the photosynthetic activity was relatively constant, indicating an intensity of 6.06 (±0.25) µmol CO_2/m²/s, but the transpiration intensity increased significantly, reaching 2.62 (±0.22) mmol H_2O/m²/s.

Evaluation of the cultivated intraspecific genotypes from the *Vitis vinifera* L. ssp. sativa D.C. group revealed that in a temperature range 27.5–28.5°C photosynthetic activity of the Fetească Albă variety was 8.2 (±0.18) µmol CO_2/m²/s. Transpiration reached 1.85 (±0.17) mmol H_2O/m²·s, and for the Fetească Neagră variety, the photosynthetic intensity was 8.5 (± 0.19) µmol CO_2/m²·s, with transpiration intensity of 1.78 (±0.12) mmol H_2O/m²·s. The water-use capacity was calculated according to the ratio between the photosynthetic activity (µmol CO_2/m²·s) and the transpiration intensity (mmol H_2O/m²·s). At a temperature of 28°C, the genotype *Vitis vinifera* L. ssp. *sylvestris* Gmel. showed a relatively high water-use efficiency of 8.12 (±0.17) µmol CO_2/mmol H_2O, indicating good adaptation in water-use under less stressful conditions. While at a temperature of 33.4°C, the water-use efficiency significantly decreased to 2.31 (±0.16) µmol CO_2/mmol H_2O, demonstrating a significant quantitative loss of water without a corresponding contribution of the photosynthetic process – an indication of sensitivity to thermal stress.

The genotypes from *Vitis vinifera* L. ssp. Sativa Group D.C.: Fetească Albă and Fetească Neagră at a temperature range of 27.5 - 28.44°C maintained intermediate values of water-use efficiency – 4.43 (±0.2) µmol CO_2/mmol H_2O and 4.78 (±0.21) µmol CO_2/mmol H_2O, thus suggesting a balance between the photosynthesis productivity and water consumption.

At the same time, at a temperature range of 34.56 – 35.21°C, photosynthetic activity have values of 7.25 (± 0.3) and 7.5 (±0.25) micromol (CO_2)/m^2/s for Fetească Albă and Fetească Neagră variety, respectively. Transpiration reached values of 4.43 (±0.2) and 5.04 (± 0.21) millimol (H_2O)/m^2/s for Fetească Albă variety and Fetească Neagră variety, respectively.

At a temperature of 34.56-35.21°C, intraspecific genotypes *Vitis vinifera* L. ssp. s*ativa* D.C. demonstrates a water-use efficiency in the range of 1.64 (±0.18) and 1.69 (± 0.22) µmol CO_2/mmol H_2O for Fetească Albă and Fetească Neagră variety, respectively.

The evaluation of the interspecific grapevine genotypes *Vitis vinifera* L. ssp. *sativa* D.C. × *Muscadinia rotundifolia* Michx. at temperatures of 27–28.5 °C showed photosynthetic activity values of 10.68 (±0.24) µmol CO_2/m²/s for the Alexandrina genotype, 10.96 (±0.18) µmol CO_2/m²/s for Amethyst, and 12.02 (±0.24) µmol CO_2/m²/s for Augustina. The corresponding transpiration intensities were 2.52 (±0.18) mmol H_2O/m²/s for Alexandrina, 1.75 (±0.17) mmol H_2O/m²/s for Amethyst, and 2.94 (±0.24) mmol H_2O/m²/s for Augustina.While, at a temperature of 35.57-35.84 0C, the intensity of the photosynthesis process is 9.26 (± 0.19) micromol (CO_2)/m^2/s (Alexandrina genotype), 10.3 (± 0.22) micromol (CO_2)/m2/s (Amethyst genotype) and 11.1 (± 0.25) micromol (CO_2)/m^2/s (Augustina genotype), at the same time the intensity of transpiration is 4.56 (± 0.27) millimol (H2O)/m2/s (Alexandrina genotype), 3.95 (± 0.25) millimol (H_2O)/m^2/s (Amethyst genotype) and 4.1 (± 0.22) millimol (H_2O)/m^2/s (Augustina genotype).

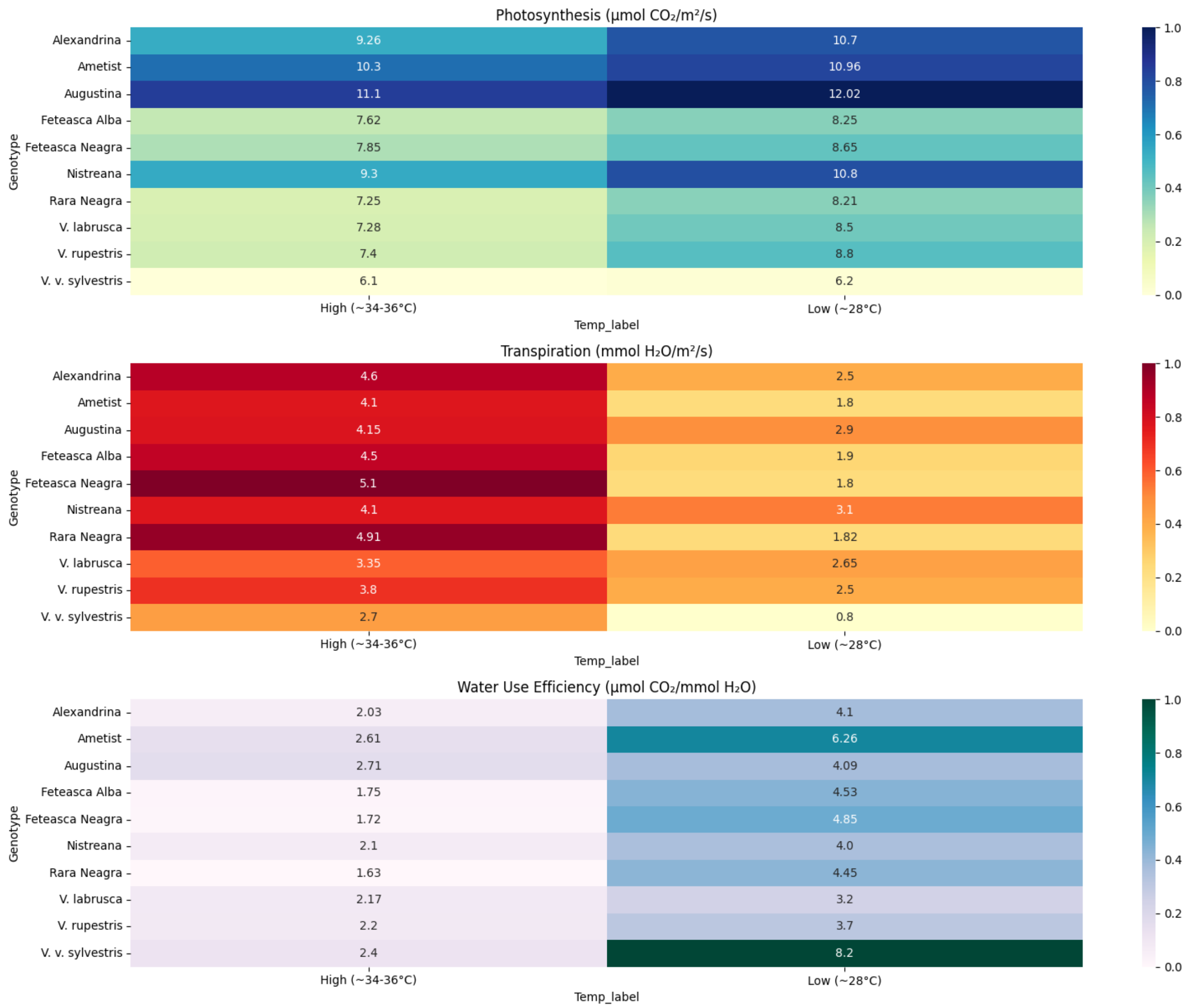

Figure 3. Physiological characteristics of grapevine genotypes

Based on the water-use efficiency indices of the interspecific rhizogenic grapevine genotypes *Vitis vinifera* L. ssp. *sativa* D.C. × *Muscadinia rotundifolia* Michx., the following conclusion was reached: at temperatures of 27–28.5 °C, the Ametist genotype demonstrated the highest water-use efficiency – 6.26 (±0.24) µmol CO_2/mmol H_2O – indicating a superior capacity to capture atmospheric CO_2 relative to water losses through transpiration.

The studied genotypes demonstrated a significant decrease in water-use efficiency at high temperatures ~35.6°C, this was due to water losses as a response to thermal stress. *Taking into account the physiological parameter indices, it was found that the grapevine genotype Vitis vinifera* L. ssp. *sylvestris* Gmel. showed good efficiency at moderate temperatures but remained sensitive to thermal stress. Cultivated genotypes from the *Vitis vinifera* L. ssp. *sativa* D.C. group, such as Feteasca Albă and Feteasca Neagră, demonstrated both productivity and thermal resistance, making them well adapted for field cultivation. Interspecific genotypes Vitis vinifera L. ssp. *sativa* D.C. × *Muscadinia rotundifolia* Michx., including Alexandrina, Ametist, and Augustina, exhibited the most favorable physiological traits, combining high photosynthetic intensity, controlled transpiration, and superior water-use efficiency.

Interspecific genotypes *V. vinifera* ssp. *sativa* D.C. x *Muscadinia rotundifolia* Michx. combine the best indices of photosynthetic intensity with physiological stability at high temperatures, having a balanced water-carbon capacity, as well as an increased potential for carbon capture from the atmosphere. The interspecific genotype *Vitis vinifera* L. ssp. *sativa* D.C. x *Muscadinia rotundifolia* Michx. "Amethyst" stands out as the most promising genotype for cultivation in conditions of high temperatures and water stress. American species (*V. labrusca, V. rupestris*, etc.) occupied an intermediate position, demonstrating a moderate development and intensity of transpiration and reductions in water-use efficiency.

Generalizing the results obtained, we find that as temperature increases, water-use efficiency decreases significantly, and at the same time the capacity to capture atmospheric CO_2 declines in most grapevine genotypes included in the study. Interspecific genotypes, especially Ametist and Augustina, demonstrated an increased capacity to maintain photosynthetic parameters and water-use efficiency under thermal stress.

CONCLUSIONS

The analysis of climatic parameters highlights that in 2025, in the Central area of the Republic of Moldova, an average annual temperature of 11.74°C was recorded, exceeding the calculated norm of 9.77 °C by approximately 1.97 °C. At the same time, the annual amount of atmospheric precipitation was 456.2 mm, lower than the multiannual norm of 530 mm by about 73.8 mm. Interspecific genotypes (*V. vinifera* ssp. *sativa* × *Muscadinia rotundifolia*) –especially Ametist and Augustina – demonstrated a strong potential for adaptation to changing climatic factors and, at the same time, a superior capacity to capture atmospheric CO_2 under climatic stress conditions. The use of such agricultural plant genotypes with a high potential for capturing atmospheric carbon dioxide (CO_2) represents not only an effective ecological measure but also an economic opportunity for stakeholders in the agricultural sector. The methodology applied in the selection and evaluation of carbon-fixation efficiency can be extended to other plant species in both agricultural and forestry systems. Genotypes characterized by a high potential to capture CO_2 can be multiplied and introduced into suitable areas, thereby contributing to the optimization of carbon-sequestration processes and reducing the impact of climate change.

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