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THE IMPACT OF FOREST WINDBREAKS ON BIODIVERSITY AND MICROCLIMATE IN VITICULTURAL ECOSYSTEMS – A LITERATURE REVIEW

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Abstract

This study critically reviews literature concerning the influence of forest curtains on microclimate regulation and biodiversity maintenance in viticultural habitats. It synthesises national and international findings on how these linear vegetation structures affect biotic components such as pollinators, natural predators, avifauna, and soil microbiota. Furthermore, it examines their impact on principal microclimatic parameters:temperature, wind speed, relative humidity, and evapotranspiration. Forest curtains were found to increase relative humidity by 5-10%, reduce wind speed by 30-45%, enhance evapotranspiration by 12-18%, and elevate minimum night temperature by up to 1.5 °C. Ecologically, these structures increased densities of pollinators and natural predators by 30-50%, thereby promoting diversity and abundance of beneficial species. Consequently, forest curtains contribute to production stability and resilience while protecting vine crops from abiotic stress. The review emphasises the necessity of integrating such systems into sustainable viticulture and climate adaptation strategies in Romania.

Key-words: *forest curtains; viticulture; biodiversity; microclimate*

INTRODUCTION

Climate change, characterised by more frequent droughts, heatwaves, and strong winds, is placing increasing pressure on European and Romanian vineyards, negatively affecting grape quality and yield (Prada et al., 2024). Therefore, comprehensive long-term strategies, such as the use of forest curtains, are required to provide ecological and microclimatic protection.

Forest curtains are rows or belts of trees and shrubs planted in a linear formation. These structures help regulate climate and conserve biodiversity by reducing wind force, retaining soil moisture, and decreasing heat stress (Brandle et al., 2004; Jose, 2009; Den Herder et al., 2014).Traditionally, these tree belts protected crops and marked territory in Mesopotamia, ancient China, and medieval Europe (Burel & Baudry, 1995). Today, regulations support their restoration. However, Romania's forest curtain network, which covered over 600,000 hectares from 1950 to 1980, declined after 1990 (Vizitiu et al., 2019; Enescu et al., 2025).

The effectiveness of forest curtains is determined by variables such as species composition, orientation, porosity, height, and vertical stratification (Enescu et al., 2025). These factors influence microclimate, ecological stability, and biological connectivity. Forest curtains can enhance biodiversity, reduce water stress, and improve both the quantity and quality of viticultural products. However, implementation is often constrained by land disputes, policy restrictions, and insufficient funding.

The main objectives of this study are as follows:

1. Typological classification of forest curtains and analysis of eco-agroclimatic functions.
2. Evaluation of the effects on the main microclimatic parameters (wind speed, temperature, humidity, evapotranspiration).
3. Examining the impact on beneficial biodiversity and ecological connectivity.

This review offers an integrated perspective on the role of forest curtains as adaptive strategies for climate change and their contribution to sustainable wine production.

MATERIALS AND METHODS

To achieve the specified objectives, a comprehensive and critical review of the scientific and technical literature was conducted, complemented by a review of relevant policy documents. The approach was developed using the PRISMA standards adapted for synthesis studies in environmental science and agroecology (Moher et al., 2009), to synthesise empirical, conceptual and policy data.

Bibliographic searches were conducted in the leading international scientific databases (Web of Science, Scopus, ScienceDirect, SpringerLink, MDPI, and Google Scholar), as well as in institutional resources such as the FAO Agroforestry Database and the archives of the Agforward and Agroforestry-Platform projects. The following search terms were used, individually and in logical combinations (AND/OR), for complete thematic coverage: "shelterbelt", "windbreak", "hedgerow", "vineyard", "viticulture", "microclimate", "evapotranspiration", "biodiversity", "agroforestry", "CAP", respectively their Romanian equivalents ("perdele forestiere", "gard viu", "viticultură", "microclimat", "biodiversitate").

Papers published between 1990 and 2025 were considered to integrate both classical theoretical foundations and modern discoveries regarding agroforestry and climate change adaptation. To ensure the rigour and usefulness of the synthesis, the following inclusion criteria were used:

(i) Experimental studies, meta-analyses or reviews providing quantifiable data on the effects of forest canopies on microclimate (wind speed, temperature, relative humidity, evapotranspiration) or biodiversity (insects, birds, small animals, related plants);

(ii) Relevance to viticulture or related agricultural ecosystems (e.g. orchards and perennial crops);

(iii) Methodological quality of the studies: detailed description of experimental design, replication, reporting of instruments and measurement errors;

(iv) Availability of data that can be used in comparative studies (percentages, mean differences and standard deviations).

Purely theoretical publications without empirical confirmation, those with inadequate data and those that referred exclusively to natural forest ecosystems with low agricultural relevance were rejected.

The selected data were collected, processed and thematically grouped into two major conceptual dimensions. The microclimatic component includes wind speed, temperature, relative humidity and evapotranspiration. The biodiversity component includes beneficial species (e.g. pollinators, predators, birds and mammals), floristic diversity and the function of ecological corridors.

In the final stage, the data were conceptually and quantitatively combined to identify useful patterns and ranges for viticultural management. Summary tables and conceptual diagrams were created to illustrate the relationships between microclimatic factors and their associated biodiversity.

RESULTS AND DISCUSSIONS

Forest curtains are an essential component of green infrastructure in viticulture, playing a role in regulating the microclimate, conserving soil and stimulating biodiversity (Brandle et al., 2004; Den Herder et al., 2014). These structures reduce wind speed, stabilise temperature and increase local humidity, generating optimal conditions for vine development and maintaining ecological balance (Castle et al., 2022).

A wind curtain, also known as a forest curtain, is a linear construction of trees and/or shrubs intentionally planted to reduce wind speed, regulate air flows and radiation and provide favourable microclimatic effects downstream. Hedgerows, on the other hand, are smaller vegetative strips dominated by shrubs or small trees that serve a variety of purposes, including plot demarcation, habitat for biodiversity, and, to some extent, microclimatic protection (Den Herder et al., 2014; Castle et al., 2022).

Structurally, forest shelterbelts can be grouped as follows:

High shelterbelts consist of one to six rows of trees, typically reaching heights of 5 to 12 meters or even more for fast-growing species. They provide significant wind protection, with observed effects of up to 10–20 times the height of the downstream shelterbelt (Brandle et al., 2004). However, these structures require a significant amount of land and could lead to competition for water and nutrients.

Hedgerows are vertical layers of small shrubs and trees. They are more accessible to small farms, providing a balance between microclimatic and ecological function (Den Herder et al., 2014; Castle et al., 2022).

Mixed multi-row curtains are layered vegetative systems that include herbaceous plants, trees and shrubs (Kratschmer et al., 2024). These systems combine aerodynamic efficiency with high ecological value (Kratschmer et al., 2024). Riparian variants located along watercourses improve agroclimatic attributes by filtering nutrients and strengthening banks (Rubio-Delgado et al., 2024). Single-row shelterbelts, also known as simple rows, can provide moderate protection in confined spaces, using little land (NRCS, 2021).

From a functional perspective, forest curtains can be oriented towards (Brandle et al., 2004; Castle et al., 2022):

a) Agricultural protection – reducing wind speed and mechanical stress on crops;

b) Wind erosion control – stabilising soils and reducing particle losses;

c) Microclimatic regulation – moderating thermal amplitudes and conserving moisture;

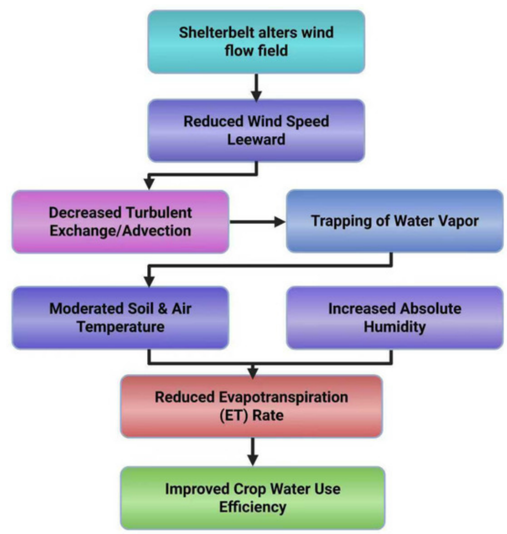
d) Supporting biodiversity and ecological connectivity – providing habitat and biological corridors;
and
e) Multifunctional functions, which combine elements from the previous categories

The effectiveness of a forest curtain is determined by a series of interconnected physical and biological characteristics. Height (H) is a determinant of the spatial extent of the protective effect, with a rule of thumb indicating a downstream zone of influence of approximately ten times the height of the structure (Brandle et al., 2004; NRCS, 2021). Porosity (P) – the proportion of open spaces in the vegetative mass – is another essential factor; values of 40–60% maximise wind speed reduction without producing adverse turbulence (Gonzales et al., 2018). Vertical stratification and the number of rows influence both aerodynamic performance and ecological value. In addition, the perpendicular orientation of the canopy to the prevailing winds, as well as its composition of native species, contributes to durability and ecological resilience (Den Herder et al., 2014; Rubio-Delgado et al., 2024). In the viticultural context, heights of 5–8 m and moderate porosities are considered optimal for a compromise between protection and ecological functionality (Enescu et al., 2025).

Forest curtains provide numerous ecosystem benefits, which manifest in the form of pedological, ecological, and microclimatic effects. They function as aerodynamic and thermodynamic shock absorbers by reducing the kinetic energy of the wind and creating a zone of low speed downstream through their semipermeable effect. The height, density (porosity) and structure of the vegetation affect their efficiency (Brandle et al., 2004; Cleugh, 1998). According to studies conducted in the United States, the type of curtain and local conditions can reduce wind speed in the protected region by 20 to 50% (Smith et al., 2021). Structures with medium porosity (30-50%) allow moderate wind dispersion, extending the protection zone up to 20-30 H downstream, according to Aili et al. (2025).

Figure 1 illustrates the microclimatic changes that occur as a result of the use of forest curtains.

Figure 1. Conceptual diagram of how forest curtains modify the microclimate



Source:https://www.mdpi.com/agriculture/agriculture-15-02004/article_deploy/html/images/agriculture-15-02004-g001-550.jpg

The following table summarises the main findings found in the international literature regarding the changes occurring near vineyard forest curtains:

Table 1. The magnitude of changes in microclimatic parameters following the use of forest curtains

Microclimatic parameter	Amplitude change (%)	Main sources
Wind speed	-30 to -45 %	Brandle et al. (2004); Favor (2025)
ET_0 (potential evapotranspiration)	-12 to -18 %	Veste et al. (2020); Enescu et al. (2025)

Air temperature (maximum)	-1,5 to -3,0 °C	Brandle (2009); Allen et al. (1998)
Relative humidity	+5 to+10 %	Den Herder et al. (2014)
Minimum night temperature	+0,8 to +1,5 °C	Brandle et al. (2004); Oke (2002)
Duration of the optimal growing season	+7–10 days/season	Enescu et al. (2025)

Comparatively, in Mediterranean wine regions (France, Spain), the effects are similar: a 15–20% reduction in evapotranspiration, a 2–3 °C decrease in maximum temperatures, and a 1–2 °C increase in nighttime minimums (Veste, 2020). In these regions, windbreaks are essential for maintaining water balance and the stability of wine production.

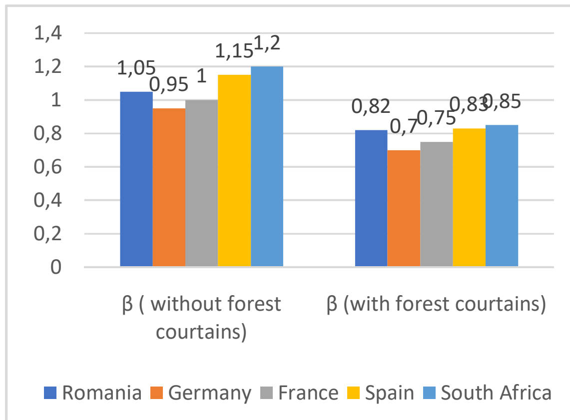
From an energetic perspective, the effect of curtains is also reflected in the modification of the Bowen ratio (β = H/LE), which expresses the proportion between sensible heat flux (H) and latent heat flux (LE). In the presence of curtains, the Bowen ratio decreases by 20–40%, indicating a more efficient use of available energy for evaporative processes (Favor, 2025). This creates a more humid and cooler microclimate, reducing the thermal and water stress on the plants. More efficient use of solar energy for evaporation and transpiration is suggested by the data synthesised in Table 2, which shows an average decrease in the Bowen ratio from 0.15 to 0.30 in plots protected by shelterbelts (Cleugh, 1998; Brandle et al., 2004).

Table 2. Effect of forest curtains on Bowen ratio (compared average values)

Country	β (unprotected)	β (with forest courtains)	Δβ (%)
Romania	1.05	0.82	-21.9
Germany	0.95	0.70	-26.3
France	1.00	0.75	-25.0
Spain	1.15	0.83	-27.8
South Africa	1.20	0.85	-29.2

The reduction confirms that the curtains help to increase the latent heat flux (LE), i.e. the energy dedicated to water evaporation. This makes the microclimate more humid and more stable in terms of temperature. This effect is used in viticulture to prevent oxidative stress and maintain photosynthetic consistency during the heat period (Enescu et al., 2025).

Figure 2. Effects of using forest curtains on the Bowen ratio



A detailed study carried out in a South African vineyard protected by a curtain of tall poplars (~6 m) showed an annual decrease in wind speed of 27.6% (up to 39.2% during the growing season) and a reduction in ET_0 of 15.5–18.4%, which led to an estimated decrease of 18.8% in effective evapotranspiration (Kunneke et al., 2020). Thus, protected viticultural systems benefit not only from a more favourable microclimate but also from a higher efficiency of water resource use.

In addition to the effects on energy flows, protection against wind causes a more stable stomatal conductance, a larger leaf area and increased vine productivity (AVF, 1995). Therefore, forest curtains modify the local microenergy balance, reducing the sensible heat flow and increasing the latent evaporative contribution, which contributes to a beneficial physiological "cooling" of the crops.

However, there are also disadvantages. In the first years after installation, trees can compete with vines for light, water and nutrients, which can reduce local productivity (Enescu et al., 2025). Also, maintenance involves additional costs — periodic pruning, crown management, irrigation and fertilisation — that need to be evaluated economically. The aerodynamic design of the curtain is essential: height/length ratio (at least 1:10), continuity and optimal porosity (40–60%) are critical factors for efficiency (Brandle, Hodges & Zhou, 2004).

For effective implementation, the local context must be considered — prevailing wind direction, topography, row orientation, canopy density, and fungal disease risk. In areas with excessive humidity, stagnant air behind the curtain can favor the development of cryptogamic diseases. Thus, curtain design should be carried out through an integrated approach, balancing microclimatic benefits and phytosanitary risks.

Beyond their original function of providing microclimatic protection, the idea of forest curtains has acquired significant ecological relevance in the context of sustainable agriculture and the increasing pressures that climate change is exerting on viticultural systems. From maintaining biodiversity and landscape connectivity to controlling energy, water, and organic matter flows, these linear woody plant structures provide a diverse range of ecological services (Den Herder et al., 2014). The implementation of forest curtains restores biological functions lost in viticulture, where monoculture predominates and disrupts the ecological balance. These functions include soil and microclimate stabilization, providing habitats for pollinators, natural predators and insectivorous birds, and, over time, increasing the resilience of the agricultural ecosystem (Kratschmer et al., 2024; Enescu et al., 2025).

The structural and functional complexity of these structures contributes to their ecological relevance. The existence of layers of trees, shrubs and herbaceous vegetation, or vertical diversity, produces a variety of microhabitats, local microclimates and a continuous supply of trophic resources (nectar, pollen, seeds). In addition, they serve as links between habitat fragments, which promotes species dispersal and gene flow, especially in intensively exploited agricultural landscapes (Den Herder et al., 2014). As it reduces population isolation and stimulates the capacity for recolonisation following disturbances, this connection is crucial for the stability of biological communities (Kratschmer et al., 2024).

Regarding entomofauna, research conducted in temperate and Mediterranean viticultural systems provides empirical evidence that the diversity and abundance of beneficial insects increase significantly around hedgerows and flower strips. Therefore, compared to exposed plots, solitary bees, hoverflies, parasitic wasps and ladybirds are substantially more widespread in plots enclosed by forest curtains (Kratschmer et al., 2024). Depending on the methodology, the time interval for monitoring and the composition of plant species, the observed increases can range from 20% to 50% (Veste et al., 2020). When native nectar-producing species were used and flowering was staggered throughout the season, experimental installation of hedgerows in Mediterranean wine regions of Spain resulted in increases in beneficial insect abundance of up to 50% (Bhardwaj et al., 2024).

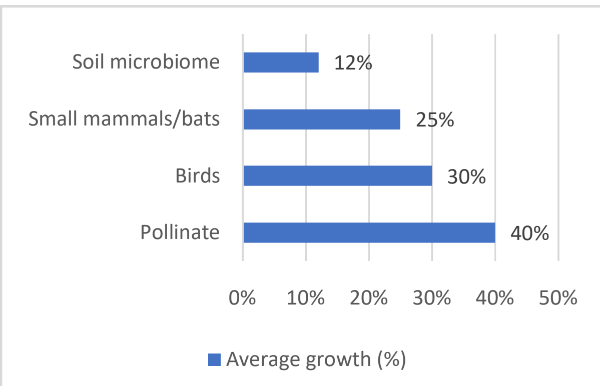
These effects have a variety of mechanisms. First, the maintenance of pollinator colonies throughout the growing season is possible due to the continuous supply of nectar and pollen, which also reduces the seasonality of resources. Second, the vertically layered structure of the hedgerows, which consists of a grassy layer, trees and shrubs, provides shelter, breeding sites and protected microclimates for many beneficial insects during their larval stages. Third, these structures serve as real biological corridors, facilitating migration and recolonisation following disturbances such as pesticide application or agricultural work (Kratschmer et al., 2024; Kaczmarek et al., 2022). In Romania, institutional reports and local studies indicate an increase in the density of natural pollinators and predators by approximately 30 to 45% in the vicinity of mixed hedgerows, although published data remain scarce and fragmented. These values are comparable to those reported in other parts of Europe (Enescu et al., 2025).

Bird communities also benefit indirectly from the positive impact on entomofauna. By providing trophic nutrients and protection, hedgerows and forest curtains increase the diversity of avifauna species, especially insectivorous birds. The number of species and the density of bird populations in plots connected to forest curtain networks have increased significantly, according to studies carried out in the wine regions of France, especially in Bordeaux (Bordeaux Economics WP, 2021). Their presence strengthens biological control services by reducing the stress exerted on them by pests such as homoptera and lepidopteran larvae. Similar findings have been made in Germany, where vineyard plots well integrated into linear ecological networks were clearly preferred by insectivorous birds (Hausmann et al., 2023).

Less research has been conducted on the effects on bats and small mammals, but what is known indicates that forest curtains can support stable populations of bats and micromammals. By providing food, shelter and migration routes, linear vegetation structures have contributed to the conservation of a significant portion of the original mammal groups in the silvopastoral landscapes of Central Europe and the dehesa agroforestry systems of Spain (Rubio-Delgado et al., 2024). The nocturnal insects that are protected in these microecosystems are particularly beneficial to bats, which helps in the biological control of nocturnal pests of grapevines. Higher densities of bats and micromammals are observed near native curtains in Romania, according to institutional statistics; however, solid scientific confirmation is needed (Kaczmarek et al., 2022).

Forest curtains have a major impact on soil and soil microbiota, in addition to fauna. They improve the stability and structure of soil aggregates, stimulate microbial activity and affect the dynamics of organic matter. According to research on the so-called small woody elements (SLM), microbial diversity and water retention capacity are favorably correlated with the presence of linear woody vegetation (Rubio-Delgado et al., 2024). According to relevant statistics, the humus content increases by 0.2-0.4% and the water retention capacity improves by 10-15% in areas adjacent to forest curtains in the sandy soil wine-growing regions of southern Oltenia. These improvements contribute to the stabilisation of the vine root system and the reduction of erosion. The mechanisms involve the constant supply of leaf detritus, the wetter microclimate below the canopy, and the activity of macrofauna, especially earthworms, which accelerate mineralisation and humus formation (Rubio-Delgado et al., 2024).

Figure 3. Average increase in functional biodiversity in the vicinity of vineyard forest curtains



The provision of complex ecosystem services, such as biological pest management, pollination, soil conservation and enhanced ecosystem resilience, reflects the integration of all these biological and edaphic effects.

The existence of pollinators indirectly supports the conservation of floral diversity in the row strips and the overall stability of the agricultural ecosystem, even if pollination is not a necessary step in viticultural production (Kratschmer et al., 2024).

The increase in the number of natural predators, such as parasitic wasps, syrphids and carabids, also diminishes the demands of phytophagous pests. This reduces the need for chemical treatments and promotes the shift to integrated and regenerative viticulture (Den Herder et al., 2014).

However, the benefits of forest curtains are not always the same. They come with some trade-offs and risks that require careful management through intelligent design and management. In arid or semi-arid areas, trees and vines compete for water, and if spacing and plant types are not chosen correctly, this can reduce the amount of fruit or crops produced (Veste et al., 2020). In addition, curtains can provide shelter for harmful animals or insects, and if not checked regularly, they can spread diseases to plants that are more susceptible to disease (Rubio-Delgado et al., 2024). Also, when trees grow too tall and are not controlled, they can block too much sunlight from reaching nearby vines, which affects how well the vines can produce food. This problem can be avoided by placing the curtain in the right direction and preventing tree branches from blocking too much light (Favor, 2025). These trade-offs show why careful planning is important. When choosing plant species, it is best to choose native species that are high in the food chain and that are well-suited to vines. Examples include nectar-producing plants such as *Crataegus monogyna, Cornus sanguinea, Prunus spinosa,* and *Rosa canina* (Den Herder et al., 2014). Also, the presence of layers in the plant structure - such as trees, shrubs, and evergreens - helps to maintain available resources over time and reduces the chance that plants will compete too much.To check the health of the ecosystem, methods such as the use of Malaise traps, bird surveys, and metabarcoding can provide clear and accurate results (Kaczmarek et al., 2022).

Table 3. Effects of using forest curtains on biodiversity - summary

Taxonomic group	Romania	Spain	Germany (central/western)	France	South Africa	Observations
Pollinating insects	estimated growth +30–45% (limited local studies)	+20–50% (hedgerows)	+20–40%, taxon-dependent	+25–45% (diversified wine-growing areas)	+30–50% (protected dry areas)	high impact when vegetation provides resources throughout the season
Birds	reported growth (institutional data)	species growth and density	+ esp. insectivores in well-connected landscapes	+diversity in the plot connected to habitats	limit data; ecological studies indicate positive effects	standardised studies needed
Small mammals/bats	reported growth (monitoring)	birds and mammals kept in dehesas	local increases in connected habitats	positive regional data	maintaining species diversity in silvopastoral systems	beneficial bats in nocturnal insect control
Soil microbiome	reported improvements (humus +0.2–0.4%)	increases related to canopy detritus and organic management	varied data; benefits when there is continuous organic input	similarly, depends on soil management	positive effects in systems with permanent vegetation	

Source: adapted from Enculescu et al.2025;Montoliu et al., 2025; den Herder et al., 2017; Böhm et al., 2024;Kratschmer et al. 2024;Andriamanantena et al., 2022;Veste et al., 2020

CONCLUSIONS

A critical review of the literature and case studies on forest screens in viticulture verifies their complex and multifunctional significance, which extends far beyond the traditional purpose of wind protection.In the face of accelerating climate change, marked by prolonged droughts, heat waves and extreme weather events, the perception of forest screens has shifted from simply reducing mechanical stress on crops to a strategic tool for agroecological adaptation and resilience of the viticultural ecosystem. According to the accumulated evidence, forest screens can influence microclimate, biodiversity, soil quality, as well as energy and water flows, resulting in a more stable and sustainable agricultural environment (Brandle et al., 2004; Den Herder et al., 2014; Enescu et al., 2025).

International comparative analyses confirm that the effects of forest curtains are consistent, but variable in intensity, depending on climatic conditions, topography, agronomic management and the biological composition of the canopy. In Mediterranean wine regions, for example, the effects on evapotranspiration reduction and temperature attenuation are comparable to those in Central and Eastern Europe, which underlines the applicability of design and management principles at a large scale (Veste et al., 2020; Rubio-Delgado et al., 2024). In Romania, although empirical data are more fragmentary, the observed trends are consistent with international models, indicating the potential for integrating forest curtains into national strategies for adapting to climate change and developing sustainable viticulture (Enescu et al., 2025).

In conclusion, forest curtains are essential tools for the sustainability of viticulture, combining microclimatic, ecological, pedological and aesthetic functions. They contribute to protecting crops against abiotic stress, supporting functional biodiversity, optimizing the use of water and energy resources and promoting the resilience of the viticultural ecosystem to climate change. To achieve these benefits, their design and management must be integrated, adaptive and based on a thorough understanding of the local context. This involves choosing appropriate species, maintaining the layered structure, monitoring the microclimate and biodiversity and continuously adjusting management to ensure an optimal balance between agricultural production and ecosystem conservation (Den Herder et al., 2014; Kratschmer et al., 2024; Enescu et al., 2025).

Thus, the integration of forest curtains in Romanian viticulture systems is not only an agricultural protection option, but a multidimensional adaptation strategy, which can transform viticultural landscapes into more resilient, productive and diversified ecosystems. In a world characterized by climate instability, these structures become strategic green infrastructures, capable of combining productive efficiency with ecological and social functions, generating long-term benefits for farmers, communities and the environment (Enescu et al., 2025; Castle et al., 2022).

Therefore, we conclude that the promotion, restoration and smart management of forest curtains in viticulture must be a priority in sustainable agriculture and climate change adaptation strategies, supported by integrated policies, adequate financing and knowledge transfer to farmers. Adopting this holistic approach not only protects grape production and quality, but also contributes to the conservation of biodiversity, the stability of ecosystems and the resilience of Romanian and European agricultural landscapes as a whole (Den Herder et al., 2014; Enescu et al., 2025).

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