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VITICULTURE REVIEW ARTICLES

Climate change and viticulture in Latin America: toward knowledge-based and territory-driven adaptation strategies

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ABSTRACT

Climate change is reshaping global viticulture, and Latin America—characterised by highly diverse climates and uneven scientific and technological capacities—faces differentiated adaptation pressures. This systematic review synthesises peer-reviewed studies published between 2020 and 2025 across Argentina, Chile, Mexico, Uruguay, and Brazil. Using the PRISMA methodology, 43 articles were identified and classified into four adaptation pathways: (1) vineyard expansion into new areas, (2) adaptive agronomic management, (3) protection against extreme climate events, and (4) technological innovation and climate monitoring systems.

Results show that, although all four pathways are represented, scientific evidence is strongly dominated by agronomic strategies such as irrigation optimisation, canopy and phenology management, soil conservation, biodiversity enhancement, and the use of drought-tolerant rootstocks or microbial bioinputs. In contrast, key non-agronomic dimensions—including economic feasibility, territorial planning, governance arrangements, and ecosystem-based approaches—remain underexplored, limiting the development of integrated and scalable adaptation frameworks. Spatial expansion toward higher elevations and cooler latitudes is advancing in several regions but is constrained by water availability, frost risk, and insufficient territorial assessments. Technological innovation, particularly climate monitoring and decision-support tools, is progressing rapidly, although accessibility gaps persist for small and medium-scale producers.

Overall, this review highlights a critical research gap and underscores the need for territorially grounded, interdisciplinary adaptation strategies that integrate agronomic, socio-economic, and institutional dimensions.

KEYWORDS: climate change, viticulture, adaptation strategies, Latin America

INTRODUCTION

Climate change has become a defining challenge of the twenty-first century, affecting ecosystems, socio-economic systems, and agricultural production worldwide. Rising temperatures, altered precipitation, more frequent extremes and shifting hydrological cycles all threaten food security and the viability of farming systems (IPCC, 2022). Viticulture is particularly sensitive because grape quality and typicity depend on specific agroclimatic conditions (van Leeuwen *et al.*, 2024; Hannah *et al.*, 2013). In recent decades, notable advances have been observed in phenological aspects, particularly in relation to higher sugar levels and lower acidity, producing notable imbalances in wine profiles (Fraga *et al.*, 2016; Arias *et al.*, 2022). Projections warn that up to 90 % of low-elevation coastal vineyards, such as those in some parts of southern Europe and California, may become unsuitable due to intensified drought and heatwaves (van Leeuwen *et al.*, 2024; Droulia & Charalampopoulos, 2021).

The growing wine industry in southern England is an illustration of climate-driven expansion, where warmer conditions now permit reliable ripening of cool-climate varieties and have accelerated the adoption of canopy and water management strategies (Gannon *et al.*, 2023), supported by projections of increasing suitability by 2040 (Nesbitt *et al.*, 2022). Global assessments highlight varietal choice, site optimisation and precision technologies as key strategies in cool climates (Sacchelli *et al.*, 2016), while resilient clones are increasingly emphasised (Baltazar *et al.*, 2025; Tortosa *et al.*, 2020). Regions such as Patagonia and the Andean highlands are similarly beginning to form adaptation pathways (Cabré & Núñez, 2020; Verdugo-Vásquez *et al.*, 2023).

Considering that climate change can generate both favourable and adverse outcomes for viticulture, it is important to recognise the diverse climatic contexts across Latin America – from the semi-arid, high-elevation areas of Argentina and Chile to the humid subtropical zones of Brazil, the temperate Atlantic regions of Uruguay, and the warm, dry environments of Mexico – which produce differentiated adaptation needs. These efforts also face uneven scientific and technological capacities, reinforcing the importance of coherent, context-responsive strategies. Within this framework, territorial adaptation provides an operational lens, integrating biophysical, agroecological, socioeconomic, and institutional responses that sustain viticultural viability. This perspective draws on the concept of terroir as a natural–human system (van Leeuwen & Seguin, 2006), aligns with wider notions of adaptation in vulnerable contexts (Smit & Wandel, 2006), and reflects evidence that wine regions require strategies tailored to local conditions (Resco *et al.*, 2015).

Developing resilient viticulture in Latin America therefore requires agronomic innovation, varietal shifts, and territorial strategies grounded in ecological sustainability (Jerez *et al.*, 2024; Reyes & Salazar-Parra, 2023). Current initiatives include expansion into cooler zones, adaptive management, protection against extremes, and improved climate monitoring (Farreras & Abraham, 2020; Miccichè *et al.*, 2025; Pereira, 2020). However, many remain isolated and lack the systemic integration needed to link scientific expertise, local knowledge, and territorial governance, limiting collective learning and regional cooperation. Moreover, nature-based solutions, such as regenerative viticulture, remain under-explored despite their potential to strengthen agroecosystem resilience (Abad *et al.*, 2021; Muñoz-Sáez *et al.*, 2020).

This article addresses these gaps by presenting a systematic review of the scientific literature published between 2020 and 2025 on adaptation strategies in viticulture across Latin America's five leading wine-producing countries (Chile, Argentina, Mexico, Uruguay, and Brazil). Through the application of PRISMA methodology (Page *et al.*, 2021), the study identifies, analyses and synthesises adaptation approaches from both agronomic and territorial perspectives, providing a critical assessment of thematic gaps and technological readiness.

MATERIALS AND METHODS

This systematic review article was carried out following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Page *et al.*, 2021), with the aim of identifying, analysing and synthesising the adaptation strategies of the wine sector to climate change in five Latin American countries.

1. Information sources

The literature search was conducted using the following academic databases: WOS, SCOPUS, MDPI, and PubMed. These databases were selected for their extensive disciplinary coverage and standardised indexing procedures that support systematic and reproducible searches. Their breadth enables the inclusion of studies from diverse climatic, agronomic, and territorial contexts, which is essential for capturing the full range of adaptation strategies reported in the literature. Together, these features ensure a robust evidence base for subsequent analysis.

2. Search strategy

The search was conducted on 28 February 2025. Relevant keyword combinations were used in the title, abstract and keywords of the articles, including terms such as 'climate change', 'viticulture', and 'adaptation strategies', along with the names of the target countries: Chile, Argentina, Mexico, Uruguay, and Brazil respectively.

The search structure was adapted to maximise the retrieval of relevant articles.

3. Eligibility criteria

Articles in English that were published between 2020 and 2025 and explicitly addressed the issue of adaptation to climate change in the wine sector were included. Priority was given to studies focusing on the main wine-producing countries in Latin America: Chile, Argentina, Mexico, Uruguay, and Brazil. Books, book chapters, conference papers, abstracts, non-peer-reviewed technical reports, and studies that only tangentially mentioned the topic were excluded. To limit the search to vineyard management, terms that shift the focus to other links in the production chain were excluded. Thus, studies focusing on 'wine' and 'winery' were omitted, as these words are usually associated with winemaking, marketing, and consumption processes, rather than agricultural practices and climate change adaptation strategies in viticulture. This methodological delimitation enabled extraction of specific evidence on vineyard resilience to climate change, ensuring that the results obtained are representative of agricultural practices and their adaptation in Latin America.

4. Reference management and data extraction

Bibliographic references were managed using Mendeley software, which facilitated the organisation and elimination of duplicates. Data extraction was carried out independently by three researchers to ensure objectivity in the selection of information.

5. Study selection

The review process ended on 28 October 2025, with the consolidation of the information collected for analysis and discussion in this article. The selected articles were cross-categorised in four tables using the following information: a) country of origin, b) climate phenomenon studied, c) impact of the phenomenon on viticulture, d) research methodology, and e) proposed climate change adaptation strategy.

Each table in this study examines a major adaptation strategy, highlighting how its application varies according to territorial contexts and the specific impacts experienced by the wine sector. The first table focuses on the strategy of vineyard expansion into new areas, which seeks to relocate vineyards to cooler or higher-elevation regions to mitigate rising temperatures. The second table addresses adaptive agronomic management, emphasising practices designed to enhance vineyard resilience under changing climatic conditions. The third table centres on protection against extreme weather events, with strategies aimed at minimising damage caused by increasingly frequent and severe climatic phenomena. Finally, the fourth table explores technological innovation and climate monitoring, outlining how advanced management tools are being developed and implemented to strengthen the sector's adaptive capacity. Finally, as reported in Figure 1, by adopting the aforementioned inclusion and exclusion criteria, it was possible to select 43 eligible articles.

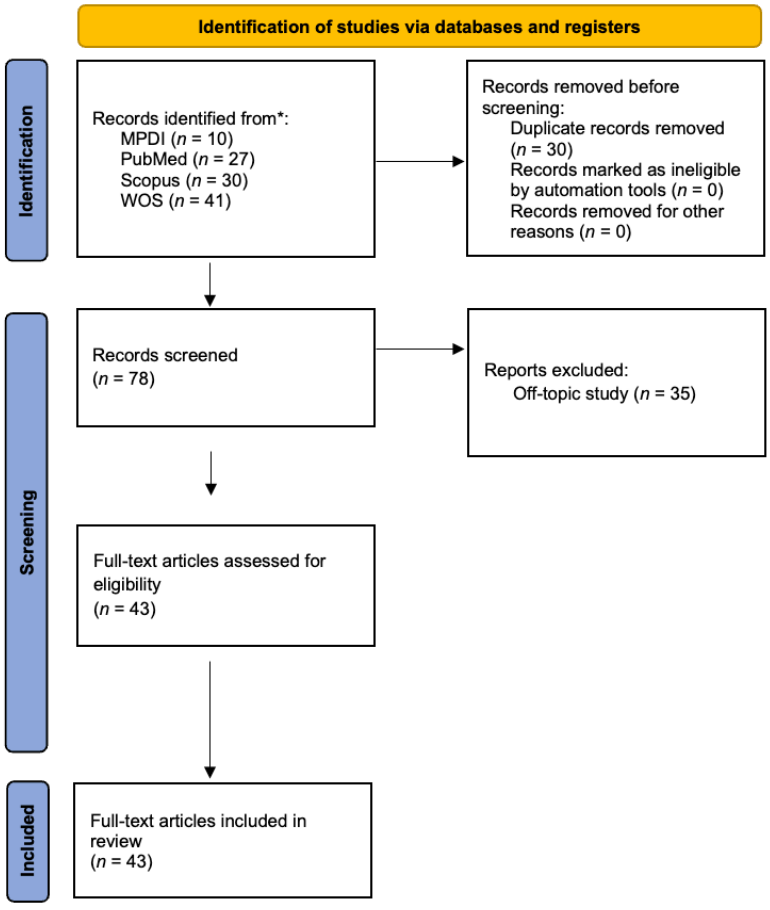


FIGURE 1. Flowchart for the search process and selection of the studies considered in the present review.

RESULTS

1. Geographical distribution identified in the review article

The countries with the highest scientific output related to the topic of the present systematic review were Chile with 15 articles and Argentina with 11 articles. These were followed by Mexico with 7 articles, Brazil with 6 articles, and Uruguay with 4 articles. Figure 2 illustrates the geographical distribution of the 43 articles from which data were collected for this study.

2. Adaptation strategy 1: vineyard expansion to new areas

Over the past five years, the discussion on climate change and viticulture has intensified in Latin America, especially in Argentina and Chile, which jointly account for about 9 % of global wine grape production. Within this context, expanding vineyards into new territories has become a key adaptation strategy, mirroring global patterns.

Analysis of Table 1 shows a clear shift toward cooler, higher-elevation areas, consistent with van Leeuwen *et al.* (2024). In Mendoza, Argentina, rising temperatures and increasing water scarcity have driven producer's upslope to delay phenology and preserve acidity (Straffelini *et al.*, 2023). However, moving vineyards to higher elevations also introduces new vulnerabilities, including greater UV-B exposure, increased frost risk, and higher operational demands linked to more remote and climatically variable sites (Straffelini, *et al.*, 2023; van Leeuwen *et al.*, 2024; Hugalde *et al.*, 2020).

Cabré and Núñez (2020) forecast that temperature and precipitation changes will continue to reduce suitability in Mendoza and San Juan, intensifying the search for cooler sites such as Salta and Catamarca. This mirrors global trends of marginal zones emerging as new winegrowing regions (Jones *et al.*, 2005; Moriondo *et al.*, 2013; Mindlin *et al.*, 2024). However, these relocations imply qualitative losses, including decreases in colour intensity, aroma and acidity, and increases in alcohol, affecting typicity (Hannah *et al.*, 2013; van Leeuwen *et al.*, 2024). Arias *et al.* (2022) also shows that a 1 °C warming advances harvest by 15 days, reinforcing elevation as a natural buffer.

In Chile, Verdugo-Vásquez *et al.* (2023) identifies central regions as the most impacted, while southern and coastal zones offer better prospects. Mindlin *et al.* (2024) support this with evidence from pilot vineyards in Aysén, where cold-climate viticulture is feasible but limited by logistical challenges, highlighting the need for territorial planning and infrastructure.



FIGURE 2. Geographical distribution of the selected studies.

TABLE 1. Data concerning vineyard expansion to new areas.

Country/state	Climatic phenomena	Impact	Methodology	Findings	References
Argentina/Mendoza	Increased temperature +0.7 % between 2010–2020, water scarcity, heavy rainfall +16 to +23.3 mm per decade, hail 2–3 severe events per year.	Vineyards moved to higher and colder areas. Imbalance in ripening: more sugar, less acidity, poorer quality wine.	Weather analysis and Mann–Kendall test.	Greater challenge in irrigation and soil management.	Straffelini *et al.* (2023)
Argentina/Mendoza and San Juan	Temperature and precipitation changes (+2 °C between 2015–2039 and up 20 %–10 % rainfall).	Change in geography and viticultural aptitude. Lower quality of grapes.	Prospective analysis 2075–2099 with bioclimatic scenarios.	Displacement to cold areas (Salta and Catamarca). Reduction of colour (40 %), aromas (30 %), and acidity (30 %). Increase in alcohol (2 %). Expected loss of 21–42 % in Mendoza and San Juan.	Cabré and Núñez (2020)
Argentina/Mendoza	Rising temperatures (+3.2 °C by 2100), water scarcity (+14 % evapotranspiration), more CO_2 (up to 410 ppm today and 421–936 ppm by 2100).	Phenological advance: higher sugar, lower acidity. Shorter ripening period.	Physiological and biochemical screening.	1 °C increase brings forward harvest by 7.4 days. High elevation viticulture mitigates global warming, but increases UV-B exposure and frost risk.	Arias *et al.* (2022)
Brazil/Rio Grande do Sul, Santa Catarina y Valle del São Francisco	More days above 35 °C and a 10–15 % drop in the water balance during ripening.	Thermal stress and phenolic imbalance.	Analysis uses time series from meteorological stations and ETC CDI indices with Mann–Kendall and Sen's slope tests.	Southern states lose suitability, while the São Francisco Valley remains viable. Higher-elevation zones gain potential, indicating a shift in Brazil's viticultural areas.	Fowler *et al.* (2020)
Chile/all the valleys in Chile	Rising maximum temperatures (+0.83 °C) and declining nighttime cooling (Tmin –0.33 °C).	More affected in the central area, less affected in coastal and southern areas.	Climate trends assessment.	Risk in grape quality and production.	Verdugo-Vásquez *et al.* (2023)
Argentina/Mendoza, Salta, Catamarca, Tucumán, Jujuy, Patagonia	Temperature increase and reduced rainfall.	Advanced phenology, lower acidity, risks to quality and ripening.	Agroclimatic scenario analysis and biophysical studies.	High-elevation areas are viable alternatives; risks of UV radiation and late frost remain.	Hugalde *et al.* (2020)
Argentina/Cafayate, Valle Fértil, Valle de Uco, San Patricio del Chañar, Trevelin, Sarmiento y Chile, Valle del Elqui, Casablanca, Valle del Bío Bío	Temperature increase +2 to +3 °C, seasonal variability, shifts in precipitation (–10 to +40 mm month–1) and extreme events (strong drying or wetting depending on storyline).	Suitability thresholds for grape growing affected. Some regions may shift Winkler zones. Yield and quality impacted depending on region.	Climate storylines approach (CMIP6) combining global warming levels with large-scale circulation shifts. Bioclimatic indices (CIDs) applied to eight key valleys.	Some regions (*e.g.*, southern Chile and Argentina) may benefit from warmer conditions; others may face risks from heat or drought. Results support climate-informed decisions on varietal selection, irrigation, and regional expansion.	Mindlin *et al.* (2024)

In Brazil, Fowler *et al.* (2020) report a similar movement to higher sites, confirming elevation shifts as a regional adaptation trend.

Although warming may enable expansion, several studies stress that water availability remains a major constraint in the Andean regions of Chile and Argentina. As irrigation relies on winter snowfall and meltwater, projected declines in winter precipitation and hydrological drought pose severe risks (Mindlin *et al.*, 2024; Verdugo-Vásquez *et al.*, 2023). Evidence from Mendoza further shows that water scarcity and governance constraints already limit viticulture and may hinder new winegrowing developments (Straffelini, *et al.*, 2023; Arias *et al.*, 2022).

Overall, the available evidence points to vineyard expansion into new regions as being both a necessary and complex response to climate change. Its success will depend not only on identifying suitable agroclimatic zones but also on the integration of agronomic innovation, environmental sustainability, and effective territorial governance.

Climate change is reshaping the global geography of wine production, prompting the expansion of vineyards into new regions as an essential adaptation strategy (van Leeuwen *et al.*, 2024; Andrade *et al.*, 2024; Moriondo *et al.*, 2013). Projections suggest that up to 90 % of existing wine-growing areas located in coastal and low-lying zones, such as southern Europe and California,

could become unsuitable for viticulture due to severe drought and more frequent heatwaves (van Leeuwen *et al.*, 2024; Droulia & Charalampopoulos, 2021; Hannah *et al.*, 2013). At the same time, global warming is creating new opportunities for vineyard establishment at higher latitudes and elevations, with emerging regions identified in southern England, Tasmania, and the northwestern United States (Jones *et al.*, 2005; Moriondo *et al.*, 2013).

However, the expansion of viticulture into new territories could also generate tensions, particularly regarding natural ecosystems and land traditionally used for food production (Hannah *et al.*, 2013). Adaptation measures, such as the selection of heat-tolerant varieties and rootstocks, adjustments to trellising systems, and improved soil management practices to conserve water resources, have been proposed (van Leeuwen *et al.*, 2024; Fraga *et al.*, 2016). Nonetheless, these strategies may prove insufficient in certain contexts, underscoring the importance of planning that considers water availability, soil health, and biodiversity (Santos *et al.*, 2020). The expansion of wine production is therefore not merely a reactive measure but part of a broader structural reconfiguration of the global viticultural landscape (van Leeuwen *et al.*, 2024). Notably, a scientific debate emerged in 2013: while Hannah *et al.* (2013) forecast a significant reduction in the suitability of major traditional wine regions such as Bordeaux, the Rhône Valley, and Tuscany by 2050, van Leeuwen *et al.* (2013) criticised these projections as overly pessimistic and methodologically flawed, arguing that the resilience and adaptability of viticulture were underestimated.

More recently, van Leeuwen *et al.* (2024) reaffirmed that climate change is indeed transforming viticultural regions worldwide, bringing both risks and new possibilities. Complementing this perspective and using MaxEnt modelling, Ji *et al.* (2021), projected a redistribution of global viticultural zones, suggesting that Latin America could gain relative suitability while traditional wine regions undergo decline. Table 1 presents data regarding vineyard expansion strategies in the countries analysed.

3. Adaptation strategy 2: adaptive agronomic management

Table 2 summarises the main adaptive strategies related to viticultural agronomic management across key Latin American wine-producing regions, with Argentina and Chile standing out for their scientific contributions. Water management remains a central axis of adaptation. In Mendoza, Mezzattesta *et al.* (2022) shows that monitoring water potential in shallow soils from the Valle de Uco region improves irrigation efficiency while enhancing grape quality – defined here as oenological parameters such as sugars, acidity, anthocyanins, and polyphenols. Complementarily, Monnet *et al.* (2022) demonstrate that cover crops stabilise soil moisture and reduce evaporative demand. In Baja California, Hernández García *et al.* (2024) projects substantial yield declines under intensified drought, reinforcing the need for efficient irrigation systems, while Macías-Gallardo *et al.* (2024) highlight structural limitations in water access as an additional stressor. Uruguay mirrors these concerns: Pereyra and Ferrer (2024) show that regulated deficit irrigation and soil-water zoning buffer strong interannual rainfall variability.

Soil health and biological inputs are also central to adaptation. In Brazil, Mendes Júnior *et al.* (2024) reports improved water-use efficiency and stress resistance following the application of Bacillus and Pseudomonas strains, whereas Kokkonen *et al.* (2024) note limited gains in soil carbon from compost amendments. In Chile, Aguilera *et al.* (2022) reviews the role of arbuscular mycorrhizal fungi (AMF) in enhancing nutrient uptake and drought tolerance, while Pino and Griffon (2024) find that microbial consortia increase root vigour and cluster weight when vineyards remain moderately degraded. Franck *et al.* (2020) and Callili *et al.* (2025) add that drought-tolerant rootstocks maintain physiological performance and yield under severe thermal and hydric stress illustrating the strategic importance of below-ground biodiversity and genetic adaptation.

Pruning, canopy manipulation and artificial shading are increasingly recognised as effective tools for microclimate regulation. Late pruning delays ripening and preserves acidity under warming, as shown by Salazar-Parra *et al.* (2023) and Reyes and Salazar-Parra (2023). Ribera-Fonseca *et al.* (2023) emphasise that shoot thinning and bunch regulation reduce thermal stress and improve vegetative balance. Controlled heat experiments by Cirrincione *et al.* (2024), Domínguez *et al.* (2024) and De Rosas *et al.* (2022) confirm declines in acidity, anthocyanins, and polyphenols under elevated temperatures, while Rasera *et al.* (2023) report reduced photosynthesis under +2 °C scenarios. Artificial shading systems further strengthen these findings. Studies such as Villalobos-Soublett *et al.* (2021) and Miccichè *et al.* (2025) show that shading reduces bunch temperature, lowers radiation load, and moderates diurnal thermal amplitude, thereby maintaining acidity and colour stability. Research by Pallotti (Pallotti *et al.*, 2023; Pallotti *et al.*, 2025), Uzun (2025), and Menezes *et al.* (2024) confirms reductions in excessive sugar accumulation and improved protection against overripening.

As microclimate regulation through pruning, canopy management and shading strengthen physiological resilience, a complementary dimension of adaptation emerges in the form of biodiversity, which supports vineyard stability through ecological processes operating above- and below-ground.

Functional biodiversity provides resilience through ecological interactions. Jerez *et al.* (2024) show that cover crops enhance soil structure in rainfed vineyards, while Muñoz-Sáez *et al.* (2020) document declines in bird diversity linked to land-use change. Rodríguez-San Pedro *et al.* (2020) demonstrate that insectivorous bats reduce pest pressure intensified by warming. Below-ground biodiversity, particularly AMF communities, reinforces this buffering effect. Aguilera *et al.* (2022) and Fourment *et al.* (2020) show that AMF enhance nutrient acquisition, drought tolerance, and resilience to extreme events.

TABLE 2. Data concerning adaptive agronomic management. (part 1/4)

Country/state	Climatic phenomena	Impact	Methodology	Findings	References
Argentina/Mendoza	High daytime temperatures and cold nights, low rainfall (250 mm/year) by the end of the century.	Vines on shallow soil have lower vigour and yields.	Water potential (ΨS) monitoring in Malbec.	Irrigation in SS (shallow soil) optimises water without affecting yield. Higher concentration of polyphenols (+75 %) and anthocyanins.	Mezzattesta *et al.* (2022)
Argentina/Mendoza	Rising temperatures (+0.6–0.7 °C), increasing water deficit due to declining snowfall (–10 % year^{-1}) and reduced river flows.	More heavy summer rains and changes in pests/diseases.	Survey (DCE) with 226 people on environmental impacts in vineyards.	Promotion of sustainable irrigation and water storage.	Farreras and Abraham (2020)
Brazil/Valle de San Francisco	Increased temperatures (mean annual 26.5 °C), water scarcity (low annual precipitation of 578 mm).	Loss of carbon soil and water stress.	Evaluation of vineyards with biofertilisation.	Use of *Bacillus* and *Pseudomonas* bacteria improves stress resistance and water efficiency.	Mendes Júnior *et al.* (2024)
Brazil/Veranópolis	Climate change and soil management in subtropical vineyards.	Use of grape pomace as an organic amendment.	Evaluation in vineyards with compost and vermicompost.	No increase in soil organic carbon after three years of cover crop implementation.	Kokkonen *et al.* (2024)
Brazil/Três Corações, Minas Gerais	Thermal increases of +1.2 to +2.3 °C, together with a 20–25 % annual rise in rainfall, though more seasonally concentrated.	Accelerated ripening, loss of acidity (–30 %) and lower yields (–25 %) in vineyards of south-eastern Brazil.	Comparison of conventional and double-pruning systems in a three-cycle field trial (2021–2023) in south-eastern Brazil using 16 *Vitis vinifera* cultivars in randomised blocks.	Double pruning adapts tropical vineyards to cooler conditions, enhancing fruit and wine quality.	Ragoni-Maniero *et al.* (2025)
Brazil/São Manuel, estado de São Paulo	A thermal rise of +1.5 °C and rainfall excesses during flowering (+110 mm) followed by deficits at ripening (–80 mm).	Fruit set drops by 18 %, N and K uptake by 22–28 %, and cluster uniformity declines (+12 %).	'BRS Vitória' grafted onto three contrasting rootstocks was assessed for yield and nutrient efficiency.	'IAC 572' performed best under warming and concentrated rainfall, reaching 49.7 t·ha^{-1} and 58 % higher N and K uptake.	Callili *et al.* (2025)
Chile/Itata y Cauquenes	Decline in winter rainfall of ~20–30 % over the past decade, causing a persistent ten-year drought and reduced irrigation capacity.	Rainfed vineyards without access to irrigation.	Climate assessment (CONAF, CAMELS) and interviews with winegrowers.	Agroecological strategies to conserve water and improve resilience.	Jerez *et al.* (2024)
Chile/Caliboro	High summer temperatures (+1 °C) in Chile's Central Valley by 2030, rising to (+1–2 °C) by 2040–2070 and (+3–4 °C) by late century.	Changes in bud break and phenological shortening. More sugar, less acidity.	Analysis of climatic trends (INIA) and experimental evaluation in País vineyard.	Late pruning delays ripening and improves wine quality in warm conditions.	Salazar-Parra *et al.* (2023)
Chile/Temuco, Valle de Malleco y Cautín	Reduced rainfall ~20 % decrease, up to 250 mm loss over the last 40 years, more water stress, late frosts.	Water scarcity, rising soil temperatures, a decline in microbial biodiversity, and reduced yields.	Management of pruning and bunch loading to adapt the grapevine cycle. Techniques to control excessive vigour and improve canopy-to-crop ratio.	Reconsider vineyard design and planting strategies.	Ribera-Fonseca *et al.* (2023)
Chile/Caliboro	Temperature increase over 30 °C. Spring frosts have become more frequent.	Reducing photosynthesis and yields. Even occurring frost in October, disrupting budburst and reducing productivity.	Evaluation in País vineyards (phenology, yield).	Late pruning is an effective phenological adaptation to climate change, especially for País in dry-farmed vineyards.	Reyes and Salazar-Parra (2023)

TABLE 2. Data concerning adaptive agronomic management. (part 2/4)

Chile/Temuco	~20 % less rainfall, a 20–30 % reduction in river discharge and +3–4 °C warming by 2050.	Affected growth, plus fungal diseases and nematodes.	Meta-analysis on arbuscular mycorrhizas.	Arbuscular mycorrhizal fungi (AMF) improve nutrient uptake, enhance drought tolerance, boost photosynthesis, and reduce soil diseases in vineyards.	Aguilera *et al.* (2022)
Chile/Valles del Maipo y Colchagua	≈250–300 mm/year and native vegetation remnants are small (0.004–0.54 ha, conditions that intensify biological stress.	Less native vegetation reduces bird diversity.	Survey of 120 sites in the Metropolitan Region and O'Higgins.	Conserving native vegetation, reducing chemical use, and enhancing habitat connectivity to protect biodiversity in vineyards.	Muñoz-Sáez *et al.* (2020)
Chile/from Atacama to Bíobío	+1.9 to +3.0 °C and a 40–100 % reduction in rainfall by 2050–2060 → increased climatic risk and loss of viticultural suitability.	Greater water stress, reduced yield and quality, and increased pest and disease pressure.	Construction of a Local Climate Risk Index comparing the present with 2046–2065.	Water infrastructure (reservoirs), irrigation efficiency (drip systems), and access to state support programmes.	Cuevas-Zárate *et al.* (2025)
Chile/Las Cardas	Global mean temperatures rising by +2 to +5 °C, together with shifts in rainfall patterns, will intensify water scarcity.	Irrigation at 30 % ETc reduces vegetative growth and physiological performance, lowering yield, particularly in Cabernet-Sauvignon.	Cabernet-Sauvignon (CS) and Syrah (Sy) on naturalised rootstocks, 140 Ru and own roots were tested under 100 % *vs* 30 % ETc, measuring morphophysiology and transcriptomic responses (RNA-Seq, qPCR).	Drought-tolerant rootstocks such as R32 performed best, showing greater leaf area, root growth, and trunk size under deficit.	Franck *et al.* (2020)
Chile/Paine	Rising temperatures and increasing rainfall variability.	Greater pest outbreaks in Mediterranean vineyards, heightening the risk of grape damage and economic losses.	A 12-week summer trial in three organic vineyards compared bat-exclusion and control plots, measuring herbivory, cluster damage, acoustic activity, and diet.	Insectivorous bats proved an effective ecosystem service, markedly reducing pest damage to grape clusters (r^2 = 0.82).	Rodríguez-San Pedro *et al.* (2020)
Latinoamérica (Argentina, Brazil, Mexico, Uruguay, Chile)	Warming trends (often +1.5–4 °C), increased heat accumulation, reduced water availability, strong temperature–rainfall variability, and higher frequency of extreme events (hail, storms, hurricanes, shifting frost regimes).	Faster phenology, heat/water stress, imbalances in sugar–acid and colour compounds, yield variability, and increased biotic pressure in warm–humid regions.	Systematic synthesis of peer-reviewed studies across major Latin American wine-producing countries.	Shift to cooler/higher sites, efficient irrigation, canopy/phenology adjustments, shading and protection structures, agroecological soil–water practices, tolerant cultivars, and climate-monitoring tools.	Gutiérrez-Gamboa and Fourment (2025)
Mexico/Baja California	Less winter rains, with averaging 364 mm and showing a declining trend of –21.6 mm per decade.	Lower yields (–18 % to –35 % with Livneh model; –44 % to –78 % with ERA5).	Climate models (Livneh and ERA5).	Implementation of efficient irrigation in Baja California.	Hernández García *et al.* (2024)
Mexico/Baja California	Cooling trends in warm – dry regions.	The vine cycle accelerates and ripening time shortens sharply, bringing harvests forward by ~6–8 weeks.	Exploratory qualitative study based on 12 semi-structured interviews.	Shift towards better-adapted varieties and rootstocks, and more efficient water management incorporating treated or desalinated water.	Salas Quesada (2025)
Mexico	Growing-season warming (+1.2 °C by 2050, up to +4 °C by 2100) and hotter nights (+4.5 °C).	Advance phenology and harvest, reducing suitable viticultural years in Baja California and the northern Altiplano.	Climate modelling (RegCM4.7, RCA4, RCP2.6/8.5) shows rising heat indices and uncertain rainfall.	Advance operations and harvest; adjust irrigation and canopy to protect acidity and aroma; and relocate vineyards to cooler areas as suitable years decline.	Castillo *et al.* (2023)

TABLE 2. Data concerning adaptive agronomic management. (part 3/4)

Mexico/en Santo Tomás, San Vicente y Guadalupe	Rising temperatures.	Higher alcohol, polyphenols, colour intensity and acidity in wines from warmer regions, altering their chemical and sensory style.	Physico-chemical analysis of 69 commercial wines (Cabernet-Sauvignon and Tempranillo), plus PCA and ANCOVA.	Oenological management includes heat-tolerant yeasts *(Lachancea. thermotolerans)* to regulate pH, ethanol, and volatile acidity, supported by irrigation and canopy adjustments to lessen warming effects.	Castro-López *et al.* (2024)
Mexico/el Marqués y Colón	Mean temperature was +1 °C above the 1981–2023 average and rainfall fell by ~40 %.	Dry, low-moisture soils restricted early growth, with yields relying heavily on summer rain.	Sentinel-2 indices and meteorological data were used to assess phenology and thermal conditions in high-elevation vineyards (>2,000 m).	Heat-tolerant varieties, early irrigation and sensor-based climate-responsive management.	Del Río *et al.* (2024)
Mexico/Guanajuato	Annual water balance is negative (–105 to –138 mm).	Sustained deficit stresses vines, increasing sugars in the conventional vineyard and acidity in the organic one.	Two commercial sites (organic *vs* conventional) were assessed using soil, Syrah/Tempranillo grape analyses and 17 years of climate data with PCA.	Organic practices and better moisture retention can improve acidity and balance in semi-arid regions.	Macías-Gallardo *et al.* (2025)
Uruguay/Garzón, Maldonado	Fewer cold units, more rainfall at maturity.	Delayed bud break, more fungal diseases, less colour and aromas in wine.	Interviews with winegrowers and technical advisors.	Use of resistant varieties and adapted rootstocks.	Fourment *et al.* (2020)
Argentina/Mendoza	Water scarcity stems from reduced rainfall, with precipitation falling by up to (50 %).	Decreased grape yield and wine quality.	Analysis of irrigation management strategies adopted by producers.	Implementation of efficient irrigation systems such as drip irrigation and optimised schedules.	Monnet *et al.* (2022)
Uruguay/Depto de Canelones y Montevideo	Increased frequency of extreme climate events, with 71 % of winegrowers reporting more storms and hail in recent years.	Direct damage from extreme events. Altered phenology.	Semi-structured interviews with 38 winegrowers and technical advisors.	Soil biodiversity plays a key role in resilience to climatic stress.	Fourment *et al.* (2020)
Uruguay/Montevideo	Genetic and epigenetic changes in the vine due to climate variability.	Increased incidence of fungal diseases, weakening of vine structure and productivity.	Analysis of the epigenetic contribution to vine stress tolerance.	Epigenetic changes help improve vine tolerance to heat and water stress.	Fourment and Gallusci (2024)
Uruguay	High inter-annual rainfall variability (484 mm in 2020 *vs* 539 mm in 2021), intensifying water deficit during critical growth stages.	Periods of severe soil water deficit (>60 % of TAW depletion) reducing vegetative growth and increasing vine stress.	Two-year field trial comparing control *vs* deficit irrigation; soil water balance and must analysis.	Regulated deficit irrigation and zoning based on soil-water capacity.	Pereyra and Ferrer (2024)
Brazil/São Paulo	Increase average temperature in southern Brazil (+2 °C).	Temperature rise negatively affects vine growth and grape composition.	Randomised experimental design with irrigation and shading treatments.	Developing cultivars with greater tolerance to heat stress is crucial.	Rasera *et al.* (2023)
Argentina/Mendoza	Simulated increase in canopy temperature – (+1.5 to +2.0 °C) – (active warming system).	Earlier budbreak (by 16 days) and earlier harvest (by 14 days); lower acidity and anthocyanins.	Active canopy warming system applied to Malbec and Pinot noir vines.	Varietal differences in thermal response; advanced phenology affects wine profile.	Cirrincione *et al.* (2024)

TABLE 2. Data concerning adaptive agronomic management. (part 4/4)

Argentina/Mendoza	Increase in temperature in the microclimate of the grape canopy (+2–4 °C increase in mean diurnal temperature).	Higher temperatures directly affect vine phenology and berry composition.	Controlled experiments increasing temperature in Malbec and Pinot noir canopies.	Phenological shifts confirmed; need for adaptation measures based on varietal selection in adaptation planning.	De Rosas *et al.* (2022)
Argentina/Mendoza	Temperature increase (canopy warming).	Advanced all phenological stages, altered acidity and anthocyanin levels.	Canopy warming applied to vines; changes monitored in phenology and grape chemistry.	Optimised irrigation and canopy techniques can mitigate negative effects.	Domínguez *et al.* (2024)
Chile/Coquimbo, Valle del Elqui	High temperatures commonly reach 24.5–25.8 °C, while annual rainfall is extremely low (39–141 mm year), producing severe water deficit conditions.	Damage to vine physiology. Modifications in berry ripening and wine profile.	Experimental design in vineyard with Muscat of Alexandria under shading nets.	Shading nets modify microclimate and improve grape quality under heat stress.	Villalobos-Soublett *et al.* (2021)
Argentina/Mendoza	Increase in temperature in the microclimate of the grape canopy (+2–4 °C increase in mean diurnal temperature).	Temperature rise directly affects vine phenology and grape chemistry.	Canopy warming experiments in Malbec and Pinot noir vines.	Heat leads to earlier phenological stages; varietal differences in response observed.	De Rosas *et al.* (2022)
Chile/Talca	Temperature increase of +1.7 °C (1950–2004) and +2.04 °C projected by 2049; heatwaves reduce yield up to 35 %, intensifying water restriction.	Significant reduction in amino acids and nitrogen compounds in musts.	Review of viticultural adaptation strategies and stress physiology.	Selection of resistant varieties and rootstocks is essential for adaptation.	Gutiérrez-Gamboa *et al.* (2021)
Uruguay/Maldonado, Garzón	Strong seasonal–spatial variability (rainfall 214–933 mm; mean temperature 17.8–18.8 °C), oceanic cooling of (2–4 °C), and heatwaves reaching up to (20 days > 35 °C).	Affects grape composition, especially under warm conditions; yield differences based on exposure.	Field study in four Albariño plots + multivariate analysis (PCA).	Ocean exposure influenced grape quality more than yield; Albariño showed high phenotypic plasticity.	Fourment and Gallusci (2024)
Chile/Curicó	Water deficit and thermal stress.	Reduced yield and quality, especially in chronically low-productive vineyards.	Application of microbial consortia in three commercial vineyards.	Root development, vegetative vigour, and cluster weight improved under proper management; no immediate effects in degraded vines.	Pino and Griffon (2024)
Mexico/Baja California, Querétaro, Guanajuato, Coahuila	Increased temperature and altered rainfall patterns.	Reduced yield; negative effects on quality and profitability.	Regression models with climatic, economic, and production data.	Adaptive practices recommended such as soil mulching, canopy management, and cultivar replacement.	Macías-Gallardo *et al.* (2024)
Chile/Valle del Itata	Decline in winter rainfall of ~20–30 % over the past decade, causing a persistent ten-year drought and reduced irrigation capacity.	Phenological advances or delays; increased fungal diseases; lower wine quality.	Semi-structured interviews with 38 winegrowers and 3 technical advisors.	Use of resistant varieties, adapted rootstocks, and cover crops improves resilience.	Jerez *et al.* (2024)
Brazil/São Paulo, Piracicaba	High temperatures (>30 °C) severely reduce photosynthesis and accelerate senescence.	Reduced net photosynthesis, accelerated senescence, early leaf fall.	Controlled experimental design using *Vitis labrusca* 'Niagara Rosada' with thermal simulation based on IPCC projections.	Leaf removal strategies and shoot positioning can be adjusted to reduce direct radiation exposure and limit excessive berry temperature.	Rasera *et al.* (2023)

New evidence from Mexico (Salas Quesada, 2025; Castillo *et al.*, 2023; Castro-López *et al.*, 2024; Del Río *et al.*, 2024) demonstrates that canopy adjustment, drought-tolerant varieties, thermotolerant yeasts, and high-elevation irrigation strategies collectively sustain grape composition under accelerated warming.

Taken together, these studies reveal a growing convergence around key pillars of adaptive agronomic management: efficient water use, biological innovation, the development of climate-resilient genetic material, and the conservation of ecological functions. The diversity of contexts, from the arid landscapes of Baja California to the temperate Atlantic climate of Garzón in Uruguay, and the emerging cold-climate viticulture in southern Chile, highlights the necessity of site-specific strategies that draw upon both traditional knowledge and emerging scientific advances.

Adaptive agronomic management has become a cornerstone for mitigating the impacts of climate change on viticulture, bringing together traditional knowledge and scientific innovation to ensure the sector's long-term sustainability.

Climate change is altering grapevine phenology and physiology, significantly affecting both yields and the quality of grapes destined for wine production (van Leeuwen *et al.*, 2024; Alba *et al.*, 2024; Prada *et al.*, 2024). In recent years, adaptive agronomic management has been the subject of the most extensive scientific attention globally. Various strategies have been developed and tested, including the selection of drought-resistant varieties (Baltazar *et al.*, 2025), the adoption of late pruning techniques, and improvements in canopy management practices to delay ripening and maintain a balanced grape chemical composition (Reta *et al.*, 2025).

In parallel, research by Larrey *et al.* (2025) and Chen *et al.* (2024) emphasises the role of new rootstocks specifically adapted to conditions of water scarcity and heat stress, improving both water and nutrient uptake efficiency (Darriaut *et al.*, 2022; Keller, 2020). Other studies highlight the value of cover crops and the promotion of functional biodiversity as effective strategies for enhancing soil resilience and controlling erosion, thereby reinforcing the stability of viticultural ecosystems (Visconti *et al.*, 2024; Abad *et al.*, 2021; Dittrich *et al.*, 2021).

In warmer viticultural regions, adaptive practices such as artificial shading have been investigated (Micciché *et al.*, 2025; Pallotti *et al.*, 2023; Pallotti *et al.*, 2025; Uzun, 2025; Menezes *et al.*, 2024; Santesteban, 2019), along with the application of regulated deficit irrigation to alleviate heat stress and enhance fruit quality (Pallotti, 2024; Sánchez-Ortíz *et al.*, 2024; Losciale *et al.*, 2024). Table 2 summarises key findings regarding adaptive agronomic management strategies across the selected countries.

4. Adaptation strategy 3: protection against extreme climate events

Table 3 examines adaptation strategies to extreme weather events within Latin American viticulture, with a particular focus on responses to hail, winter rainfall, droughts, and spring frosts. The analysis reveals that adaptation measures in Argentina and Chile are largely shaped by local water availability, topographic conditions, and broader climate change trends. Nevertheless, existing literature related to general crop management practices is more extensive than that on specific, targeted adaptation strategies.

In Argentina, particularly in Mendoza, the relocation of vineyards to higher and cooler elevations has emerged as a primary response to rising temperatures and water scarcity. While this strategy has mitigated some climatic pressures, it has also generated challenges, such as ripening imbalances and potential shifts in wine style. As highlighted by Straffelini *et al.* (2023), hail remains a major climatic threat in the region, prompting the expansion of protective measures such as anti-hail nets (the effectiveness of which was not quantified in the study). However, such protection measures do not address other persistent risks, including soil erosion on sloped terrains, which reinforces the relevance of soil conservation practices and controlled drainage systems in hillside vineyards. This situation highlights the necessity of addressing not only the direct impacts of extreme events but also their cascading effects on soil health and vineyard biodiversity.

In Chile, adaptive responses vary across regions, reflecting local climatic and geographic diversity. In the Itata Valley, reduced winter rainfall has severely affected rainfed vineyards. Resilience efforts have focused on the implementation of cover crops and cross-ploughing techniques to retain soil moisture and alleviate water stress during drought periods (Jerez *et al.*, 2024). These practices illustrate a broader trend toward soil management strategies that prioritise water conservation and yield stability in traditionally vulnerable systems.

In central Chile, climate change has triggered an increase in the number of days exceeding 30 °C and a higher frequency of spring frosts. These conditions are projected to cause a loss of vineyard area by 2050, with the Maipo, Colchagua, and Cachapoal regions identified as the most affected. Simultaneously, a reduction in rainfall over the past two decades has exacerbated the water crisis in rainfed vineyards. Research in País vineyards highlights the combined use of agricultural insurance and soil management as key tools to mitigate the impacts of drought and frosts, contributing to greater production stability under adverse climatic scenarios (Reyes & Salazar-Parra, 2023).

Despite these insights, cold-climate viticulture emerging south of the 38th parallel in both Argentina and Chile remains largely unstudied. Vineyards such as Otronia, Nant y Fall in Argentina, and Trapi del Bueno and Coteaux de Trumao in Chile, are leading pioneering efforts in these southern latitudes, where extreme climatic conditions are driving the development of new local adaptation strategies that warrant deeper scientific attention.

Collectively, the findings demonstrate that successful adaptation to extreme events in viticulture depends on a combination of factors: water resource availability, vineyard elevation, and regional climate variability. In Mendoza and

TABLE 3. Data concerning adaptive protection against extreme climate events.

Country/state	Climatic phenomena	Impact	Methodology	Findings	References
Argentina/ Mendoza	Rising temperatures (+0.7 °C), hydrological drought since 2010, and heavier rains (+16 to +23 mm per decade, +17 % intensity).	Displacement of vineyards to higher and colder areas. Imbalance in ripening: more sugar, less acidity, poorer quality wine.	Weather analysis and Mann–Kendall test.	Controlled drainage and vegetative barriers are recommended.	Straffelini *et al.* (2023)
		Displacement of vineyards to higher and cooler areas. Risk of erosion in vineyards on slopes.		Agro-ecological strategies and controlled drainage to reduce erosion.	
Chile/Valle del Itata	Megasequence, reduced winter rainfall, less irrigation water.	Rainfed vineyards without access to irrigation.	Climate assessment and interviews with winegrowers.	Resilience in Itata Valley vineyards with vegetative cover crops and cross ploughing to conserve moisture.	Jerez *et al.* (2024)
Chile/Valles de Maipo, Colchagua y Cachapoal	Rising temperatures > 30 °C (+30 days in recent decades), more spring frosts.	Loss of vineyards by 2050. Greater impact in Maipo, Colchagua, and Cachapoal.	Experimental evaluation in País vineyards (phenology, harvesting).	Use of agricultural insurance and soil management to mitigate drought. Late frosts are a key threat. Use of agricultural insurance recommended for rainfed varieties.	Reyes and Salazar-Parra (2023)

central Chile, challenges are dominated by soil erosion and declining water resources, while in southern Chile, efforts focus on soil moisture conservation and maintaining productivity in rainfed vineyards. This convergence of challenges suggests that future strategies must move beyond reactive measures, fostering integrated approaches that address immediate climatic threats while promoting the long-term sustainability of viticultural ecosystems.

At a global scale, the frequency and intensity of extreme weather events in viticulture have increased markedly because of climate change, causing significant disruptions in production (Droulia & Charalampopoulos, 2021; Fonseca, *et al.*, 2024; Jones *et al.*, 2022; Sgroi & Sciancalepore, 2022). Among the most critical events are spring frosts, hailstorms, heat waves, and episodes of extreme precipitation. Spring frosts, occurring during early vine development, often destroy young shoots and drastically reduce yields, while hailstorms can severely damage leaves and fruit, compromising both quantity and quality (Leonel *et al.*, 2025). Heat waves accelerate the ripening process, leading to lower acidity levels and alterations in the phenolic profile of grapes, with consequent impacts on wine quality (Miccichè *et al.*, 2025). Similarly, heavy rainfall events increase the risk of fungal diseases, reduce the concentration of essential grape compounds, and contribute to soil erosion and nutrient loss (Liu *et al.*, 2025).

To confront these challenges, viticulture has developed a range of adaptive strategies, combining vineyard management practices, technological innovations, and the selection of resilient grape varieties. Active protection measures such as thermal fans and sprinkler irrigation systems have been employed to mitigate frost risks, although their effectiveness and sustainability depend heavily on local climatic and water resource conditions (Baillet *et al.*, 2025). In hail-prone regions, protective netting has proven highly effective in minimising crop losses without adversely affecting fruit quality (Pallotti *et al.*, 2025). Adaptations to mitigate the impact of heat waves include partial shading and the application of kaolin, both of which help reduce bunch temperatures and preserve the chemical integrity of grapes. Studies conducted in Sicily have demonstrated that shading not only delays over-ripening but also enhances the phenolic structure and aromatic balance of wines (Miccichè *et al.*, 2025).

Regarding heavy rainfall, canopy management techniques and the use of ground covers have emerged as key strategies for controlling soil moisture levels and reducing disease incidence, particularly in humid viticultural regions such as northwest China (Liu *et al.*, 2025). Table 3 presents data related to adaptive responses to extreme climatic events across the selected countries.

5. Adaptation strategy 4: development of technological innovation and climate monitoring

Climate change is increasingly impacting wine production worldwide, altering phenological cycles, water availability, and grape quality (Simeunović *et al.*, 2025). In response, technological innovation has emerged as a key adaptation strategy, integrating precision agriculture tools, advanced climate modelling, and process digitisation (Ferro & Catania, 2023). Technologies such as remote sensing, IoT-based sensors, and artificial intelligence have proven instrumental in mitigating the effects of global warming while enhancing vineyard sustainability (Poblete-Echeverría & Tardaguila, 2023).

A cornerstone of technological adaptation lies in the integration of climate data and predictive models to optimise vineyard management. Research has shown that combining

multispectral imaging with meteorological data enables early detection of drought risks and enables more efficient irrigation management (Zarco-Tejada *et al.*, 2013; cited in Ferro & Catania, 2023). In Mediterranean regions, the deployment of soil moisture sensors has reduced water consumption without compromising grape or wine quality (Simeunović *et al.*, 2025). Climate modelling has also proven critical for anticipating extreme weather events and adjusting agricultural practices proactively (Caffarra & Eccel, 2011; cited in Poblete-Echeverría & Tardaguila, 2023).

Advances in machine learning have improved pathogen detection, enabled the identification of diseases, such as mildew and *Botrytis*, and reduced the need for phytosanitary applications (Ammoniaci *et al.*, 2021). In parallel, drone-based remote sensing has facilitated the early detection of vine diseases – up to 10 days earlier than traditional field inspections – enabling faster and more targeted interventions (Rossi *et al.*, 2013; cited in Ferro & Catania, 2023).

The successful implementation of technological solutions has been closely linked to co-development processes involving both researchers and practitioners. Collaboration between viticulturists and scientists has enhanced the adoption of monitoring and decision-support systems, improving the precision of vineyard management (Santesteban, 2019). Similarly, the digitisation of vineyard operations through integrated decision-making platforms has optimised data use and improved operational efficiency (Araújo *et al.*, 2024).

Looking to the future, viticulture faces the challenge of balancing technological innovation with sustainability. Emerging tools, such as blockchain for production traceability and robotics for automated tasks, hold great promise for transforming vineyard management. However, their widespread adoption will require investment, capacity building, and ensuring accessibility (Simeunović *et al.*, 2025). Ensuring that both large and small producers can benefit from digital transformation will be essential. Ultimately, the strategic integration of technological innovations offers a means for viticulture to not only withstand the challenges of climate change but to also emerge as a model for sustainable agricultural production in the coming decades.

Table 4 presents data regarding the development of technological innovation and climate monitoring strategies across the selected countries.

In Latin America, climate change has accelerated the adoption of technological innovations in viticulture, enabling improvements in vineyard management and helping to mitigate the effects of extreme climatic events. Based on the analysis of this strategy (Table 4), four major trends have been identified that are reshaping production systems and contributing to the consolidation of a more resilient viticulture.

First, climate prediction and modelling have made it possible to anticipate extreme events and adjust management practices proactively. In Mendoza, Argentina, where a +2 °C increase is projected by 2050, the use of mixed logit economic models, now incorporating data from 226 producers, has optimised decision-making processes in vineyard management, reducing vulnerability to new pests and diseases (Farreras & Abraham, 2020). In Uruguay, the integration of climate models with sensor technologies has proven essential in anticipating phenological changes and adjusting practices to buffer irregularities in vine development and thermal stress (Jerez *et al.*, 2024; Fourment *et al.*, 2020).

Second, real-time monitoring through smart sensors has played a crucial role in optimising water use in areas experiencing water scarcity. In Argentina, humidity and temperature sensors have helped optimise irrigation in shallow-rooted Malbec vines, enhancing water use efficiency and mitigating the impacts of water deficits (Mezzattesta *et al.*, 2022).

Third, early detection and disease control strategies have been critical in reducing the effects of thermal stress and the proliferation of pests and fungal infections, risks that have intensified under the new climate regime. In Uruguay, advanced monitoring combining climate models and field sensors has enabled dynamic adjustments to agricultural practices, minimising adverse effects on grape production (Jerez *et al.*, 2024; Fourment *et al.*, 2020).

TABLE 4. Data concerning the development of technological innovation and climate monitoring.

Country/state	Climatic phenomena	Impact	Methodology	Findings	References
Argentina/ Mendoza	Temperature increase of (+0.6–0.7 °C) and growing water deficit from reduced Andean snowfall.	Changes in pests and diseases.	Survey (DCE) of 226 people in Mendoza. Econometric models (Mixed logit).	Use of climate predictive models and environmental sensors to anticipate extreme events and adjust agricultural practices.	Farreras and Abraham (2020)
Argentina/ Mendoza	High daytime temperatures, cold nights, high UV-B radiation. Low rainfall (250 mm/year).	Vines on shallow soils (SS) show reduced vigour and yield.	Monitoring of water potential in Malbec.	Humidity and temperature sensors optimise irrigation and vineyard management.	Mezzattesta *et al.* (2022)
Uruguay/Garzón Maldonado y Chile, Valle del Itata	More extreme events (storms, hail), fewer cold units (<0 °C), and more hot hours with temperatures > 35 °C.	Earlier phenology; heat and water stress; increased disease pressure.	Interviews with winegrowers and advisors (2014–2016).	Advanced monitoring with weather models and sensors to adjust practices in real-time.	Fourment *et al.* (2020) Jerez *et al.* (2024)

Fourth, the digitisation of vineyard operations and the implementation of management platforms have streamlined decision-making processes by providing real-time access to climatic and production data. In Mendoza, the integration of environmental sensors with digital management systems has facilitated timely adaptations to vineyard operations in response to climate variations (Farreras & Abraham, 2020). Similarly, in Uruguay, the use of web-based remote sensing and satellite monitoring has supported the adjustment of agricultural strategies based on evolving meteorological and soil conditions (Jerez *et al.*, 2024; Fourment *et al.*, 2020).

Overall, technological innovation has not only helped viticulture counteract the impacts of climate change but has also contributed to making the sector more sustainable and efficient. Nevertheless, barriers to accessibility, particularly for small and medium-sized producers, highlight the urgent need for investment in digital infrastructure and capacity building. The strategic and inclusive adoption of these technologies will be critical to securing the future resilience of viticulture and maintaining high-quality production standards in the face of growing climatic uncertainty.

6. Technology readiness levels (TRL) of viticultural adaptation strategies

The four adaptation strategies identified in Latin American viticulture exhibit marked variation in technological maturity when assessed through the technology readiness level (TRL 1–9) framework. TRL classification considers the strength of experimental evidence, field validation, producer adoption, and institutional support, recognising that each strategy contains practices situated at different maturity levels.

Strategy 1: vineyard expansion into new areas remains at low maturity (TRL ≈ 4.0). Modelling and pilot studies highlight the potential of high-Andean and southern Patagonian territories (Mindlin *et al.*, 2024; Arias *et al.*, 2022), yet infrastructural limitations, frost risk, and uncertain long-term performance constrain progression toward advanced TRLs.

Strategy 2: adaptive agronomic management shows intermediate maturity (TRL ≈ 4.5). Core practices (regulated deficit irrigation, canopy adjustments, and cover crops) are experimentally validated and moderately adopted (Monnet *et al.*, 2022; Salazar-Parra *et al.*, 2023), while emerging approaches, such as microbial biofertilisers and epigenetic modulation, remain at early-stage TRLs.

Strategy 3: protection against extreme climatic events reaches higher maturity (TRL ≈ 5.5). Anti-hail nets, frost-protection systems, and drainage solutions demonstrate robust field performance across several regions (Straffelini *et al.*, 2023; Jerez *et al.*, 2024), although uptake is shaped by financial capacity and access to formal risk-management instruments.

Strategy 4: technological innovation and climate monitoring attains the highest maturity (TRL ≈ 6.0). Environmental sensors, predictive models, and digital decision-support systems have consolidated technological foundations and are increasingly integrated into vineyard management (Farreras & Abraham, 2020; Mezzattesta *et al.*, 2022), despite persistent accessibility gaps for smaller producers.

Overall, the TRL assessment highlights asynchronous technological evolution across adaptation pathways. While monitoring systems and climate-event protection approaches are approaching operational consolidation, vineyard relocation and advanced agronomic innovation remain constrained by territorial specificity, cost structures, and limited large-scale validation. Progression toward TRL 7–9 will depend on expanded researcher–producer interfaces, improved governance mechanisms and sustained investment in digital and institutional infrastructures in rapidly warming agroclimatic regions.

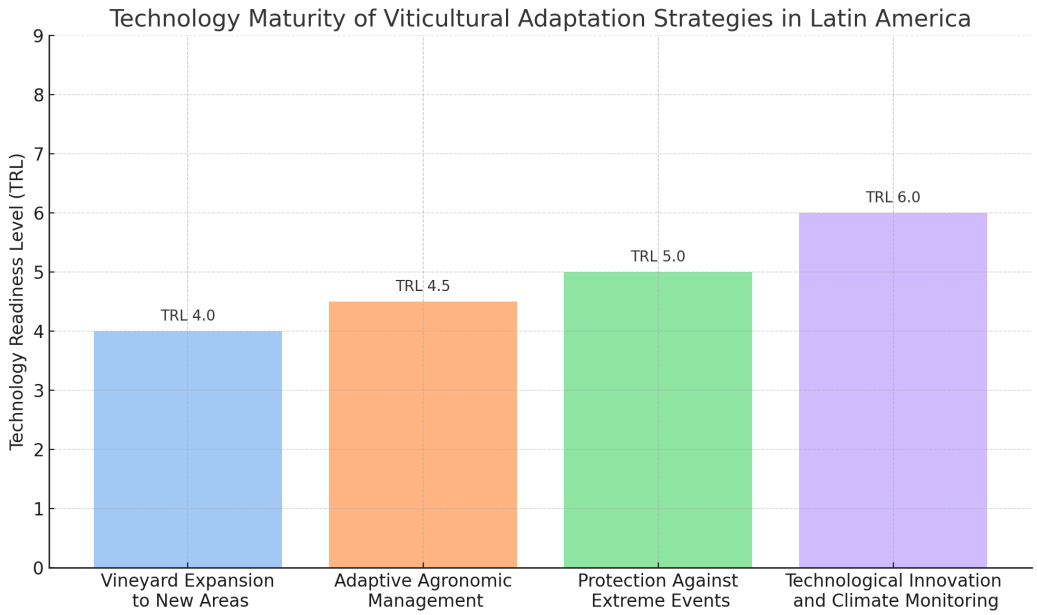


FIGURE 3. Technology readiness levels (TRLs) associated with each strategy.

7. Critical assessment of selected papers

A critical review of climate change adaptation strategies in the viticulture sector exposes structural limitations that undermine both their effectiveness and their long-term viability. One of the principal weaknesses lies in the fragmentation of available knowledge, which remains predominantly focused on agronomic adjustments, such as modifications to pruning practices, the selection of drought-tolerant rootstocks, and the optimisation of irrigation systems. While these practices offer tangible benefits, their isolated application fails to capture the systemic complexity of the climate challenge. What remains missing is an integrated vision that situates viticulture – from vineyard management to winemaking – within a broader, dynamic agrarian innovation ecosystem.

This narrow perspective is compounded by territorial blind spots. Significant gaps persist in the exploration and strategic development of emerging viticultural regions that may gain importance as climatic conditions shift. Areas such as Patagonia and the high-elevation zones of the Andes are beginning to present new agroclimatic opportunities driven by changing isotherms, altered hydrological cycles, and increased thermal amplitudes. However, comprehensive studies characterising these territories' viticultural potential and terroir profiles and the suitability of non-traditional grape varieties remain scarce, hindering the capacity for forward-looking and territorially-strategic planning.

Adaptation strategies also show uneven levels of technological maturity. Certain responses, such as canopy management adjustments, the use of shading systems and the advancement of harvest dates, have reached notable technical consolidation. By contrast, other promising approaches, like varietal diversification using ancestral cultivars, vineyard layout redesigned to mitigate solar exposure, and proactive soil management to enhance water retention, are still at early stages of validation and transfer, limiting their immediate applicability and slowing the development of coherent adaptation frameworks.

Nature-based solutions, particularly regenerative viticulture, are notably underdeveloped within the adaptation agenda. Despite their potential to restore soil health, foster functional biodiversity, and enhance agroecosystem resilience, these approaches remain marginal in both policy frameworks and applied research initiatives. There is a pressing need for studies that quantify their impact on productivity, grape quality, and resilience to extreme climatic events.

Another critical gap lies in the lack of robust economic assessments. Few studies systematically evaluate the costs and benefits associated with different adaptation strategies, complicating informed decision-making, especially for small and medium-sized producers who face tighter financial constraints. Holistic evaluation tools that integrate impacts on yield, wine quality and market competitiveness are urgently needed to guide adaptation investments in an increasingly volatile global context.

In conclusion, effectively adapting viticulture to climate change requires moving beyond atomised technical solutions toward a fully integrated strategy. This strategy must incorporate emerging territories, promote balanced technological development, and underpin decision-making with rigorous technical and economic criteria. Only through such a comprehensive and forward-thinking approach can the sustainability and resilience of viticulture be secured in the face of growing climatic uncertainty.

CONCLUSION

This systematic review shows that research on climate change adaptation in Latin American viticulture is expanding, yet remains uneven across strategies, regions, and methodological approaches. Four types of dynamics currently structure the adaptation landscape.

First, viticultural expansion toward cooler southern latitudes and higher elevations is increasing, responding to thermal stress and shifting agroclimatic suitability. The emergence of cold-climate frontiers – particularly in southern Chile and Argentinian Patagonia – illustrates new opportunities for production, although they are limited by frost exposure, shorter growing seasons, and logistical constraints. These dynamics highlight the need for robust territorial assessments, especially regarding hydrology, frost risk, and socio-economic feasibility.

Second, the renewed interest in ancestral and Criolla grape varieties reflects the search for materials with greater tolerance to drought, heat and disease pressure. However, evidence on their oenological performance, market acceptance, and long-term adaptive potential remains insufficient for strategic integration.

Third, regenerative and biodiversity-based practices are gaining attention as pathways to strengthen agroecosystem resilience. However, studies remain predominantly agronomic, with limited interdisciplinary evaluation of ecological outcomes, economic implications, and enabling policy conditions.

Fourth, digital and technological innovations, such as real-time climate monitoring, predictive modelling, and precision viticulture, are advancing rapidly, although inequalities in access, infrastructure, and technical capacity continue to restrict adoption among small and medium producers.

Across countries, emerging patterns show differentiated priorities: elevation shifts and drought-focused management in Argentina and Chile; double-pruning and tropical adaptation in Brazil; disease-resistant materials and rainfall-variability responses in Uruguay; and high-elevation viticulture and water-efficiency measures in Mexico, alongside the growth of cold-climate initiatives in Patagonia.

Overall, this review identifies a central limitation in the regional evidence base: the predominance of agronomic approaches over integrated frameworks incorporating economic assessment, territorial planning, governance capacity, and explicit TRL evaluations. Advancing climate resilience in Latin American viticulture will require coherent, territorially grounded strategies that align scientific knowledge, local practices, and inclusive governance.

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