Journal of Polyphenols
2025, 7 (2): 70–78
journal homepage: http://jpolyph.magtechjournal.com

The impact of climate change on polyphenols in mountain grapes (*Vitis amurensis* Rupr.) in Northeast China: A mini review

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Abstract Climate change is significantly altering viticultural practices worldwide, with profound implications for the accumulation of polyphenolic compounds that determine wine's sensory and health properties. This review summarizes the effects of climate change, particularly rising temperatures, shifting precipitation patterns, and altered light conditions—on polyphenol synthesis in *Vitis amurensis* (*V. amurensis*) grapes from Northeast China, the country's highest-latitude wine region. Key findings reveal that: (1) Temperature increases accelerate phenological stages but differentially impact polyphenols, suppressing anthocyanins and flavonols while promoting tannins; (2) Precipitation variability induces water stress that can enhance anthocyanin content under moderate drought but reduce quality during extreme events; (3) Declining sunshine duration may limit polyphenol production, though certain cultivars (e.g., Beibinghong) exhibit adaptability to low light conditions. The region's unique climatic trends — stronger winter warming and reduced summer precipitation—paradoxically offer potential benefits by extending the growing season while minimizing heat stress during critical ripening periods. It is highlighted how *V. amurensis*, with its cold hardiness and naturally high polyphenol content (notably anthocyanins and resveratrol), could become increasingly valuable under climate change. However, strategic adaptation through cultivar selection, vineyard management, and stress-responsive breeding will be critical to maintain wine quality. This synthesis provides a framework for understanding climate-polyphenol dynamics in cool-climate viticulture and outlines research priorities to safeguard the future of Northeast China's distinctive wine industry.

Keywords: climate change adaptation; grape polyphenols; *Vitis amurensis*; cool-climate viticulture; Northeast China

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1 Introduction

Climate change exerts significant impacts on viticulture. Climatic factors such as temperature, precipitation, and sunlight play crucial roles in fruit quality and the accumulation/degradation of metabolites, thereby imparting distinct regional and vintage characteristics to wines. Among various compounds produced by grapevines, polyphenols hold core value in shaping wine flavor profiles, color presentation, and health benefits. These secondary metabolites are particularly sensitive to environmental variations, serving as a key entry point for deciphering climate change impacts on wine production. This article systematically elaborates how climate change affects the accumulation, transformation, and degradation of polyphenols in mountain grapes, providing theoretical foundations for winemakers to evaluate and enhance wine quality.

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These authors have no conflict of interest to declare.

Northeast China (40°N-53°N), as the highest latitude viticulture region in China, belongs to a warm temperate semi-humid continental monsoon climate. The area features cold and dry winters [1], short frost-free periods, and struggles to meet the climatic requirements for open-field cultivation of European grapevines (*Vitis vinifera* L.). *Vitis amurensis* Rupr. (*V. amurensis*), with exceptional cold hardiness and disease resistance, serves as the core wine grape germplasm resource in this region. It exhibits characteristics such as high acidity, elevated pigment content, low sugar levels, and rich color [2]. Its anthocyanin, resveratrol, amino acid, and mineral contents all surpass those of Eurasian grapevines [3]. Limited research exists on climate change impacts on polyphenolic compounds in grapes of *V. amurensis*, making this review specifically focused on discussing this topic.

Currently, major cultivated *V. amurensis* grape varieties include Shuanghong, Shuangyou, Gongniang one, Beihong, and Beimei [4]. Additionally, Chinese breeders have successfully developed hybrid varieties predominantly retaining characteristics of *V. amurensis* through crosses with Eurasian grapes, such as Zuoshan-1, Zuoyouhong, Xuelanhong, and Beibinghong [5].

2 The composition and basic characteristics of polyphenols in grapes

2.1 Fundamental characteristics of polyphenols

Polyphenolic compounds are a class of secondary metabolites widely distributed in the plant kingdom, characterized chemically by containing one or more aromatic ring hydroxyl substituents. Based on their chemical structural features, they are primarily classified into two major categories: flavonoids and non-flavonoids. This classification system holds significant theoretical value as it reveals the structural diversity characteristics of polyphenolic compounds. Such diversity contributes to their various biological activities and health benefits. Furthermore, the bioavailability of polyphenols can vary considerably depending on their source and the presence of other dietary components, which may either enhance or inhibit their absorption and efficacy in the body [6,7].

2.1.1 Classification of polyphenols

Polyphenols are classified based on chemical structural differences. Flavonoids are the most extensively studied category, characterized by a common structure consisting of two aromatic rings connected by a three-carbon bridge [8]. Non-flavonoids encompass various phenolic acids. Flavonoids include subclasses such as flavonols, flavanones, flavan-3-ols, isoflavones, anthocyanins, condensed tannins, etc. They are distinguished by the presence of ketone and hydroxyl groups on their aromatic rings and can be differentiated based on variations in substituents. Examples include quercetin, myricetin, rutin, hesperidin, naringenin, and coumarin [9]. Non-flavonoids include phenolic acids, stilbenes, lignans, hydrolysable tannins [10].

Anthocyanins in wine primarily exist as anthocyanidins (aglycones) bonded to sugar groups via glycosidic linkages [11]. In *V. amurensis* grape wines, in addition to common monoglucoside anthocyanins (in the form of 3-*O*-glucosides) such as malvidin, petunidin, cyanidin, peonidin, and delphinidin, there are also diglucoside anthocyanins (3,5-*O*-diglucosides) formed by glucosylation at the C_3 and C_5 positions. These compounds can be distinguished by the number and positions of hydroxyl and methoxy groups on their aromatic rings. Flavan-3-ols exist in both monomeric and polymeric forms, with common examples including (+)-catechin, (-)-epicatechin, epicatechin-3-*O*-gallate, proanthocyanidins, and condensed tannins.

Within non-flavonoid compounds, hydroxybenzoic acids are structurally characterized by a C_6-C_1 skeleton composed of a benzene ring linked to an aliphatic carbon chain. Examples include salicylic acid, syringic acid, vanillic acid, protocatechuic acid, and gallic acid. Among these, gallic acid is considered the most significant phenolic acid in red wine and serves as a precursor to hydrolysable tannins [9]. Hydroxycinnamic acids possess a C_6-C_3 backbone and are classified into sinapic acid, ferulic acid, coumaric acid, caffeic acid, and chlorogenic acid based on substituents on the aromatic ring [10]. Stilbenes in wine exhibit a C_6-C_2-C_6 structure, existing in trace concentrations primarily as trans- and cis-resveratrol (with trans-resveratrol being the predominant form). Red wines contain higher levels of stilbenes compared to other wine types. Additionally, wines contain low concentrations of tyrosol and hydroxytyrosol [9].

The total anthocyanin content in *V. amurensis* grapes is significantly higher than that in grapes of *vitis vinifera*, predominantly consisting of anthocyanin diglucosides, with no detected acylated anthocyanins [12]. *V. amurensis*-European hybrid grapes contain both anthocyanin monoglucosides and diglucosides, along with two types of acylated anthocyanin diglucosides [13]. Non-anthocyanin phenolic compounds are characterized by hydroxycinnamic acids and flavonols as secondary metabolites [14]. *V. amurensis* and its hybrids exhibit high myricetin content, with the average polymerization degree of flavan-3-ols in berry skins being lower than in seeds [13].

Different varieties within *V. amurensis* demonstrate distinct phenolic profiles and compositional ratios reflecting varietal characteristics. For instance, wines produced from Zuoyouhong primarily contain flavan-3-ols and hydroxycinnamic acids [12]. Wines made from Beibinghong predominantly feature anthocyanins, with lower levels of phenolic acids, hydroxybenzoic acids, and hydroxycinnamic acids, while flavonols and flavan-3-ols exist only in trace amounts [15]. Comparative studies show the following hierarchy for total phenolic content among common *V. amurensis* varieties: Zuoshan-1 and Shuanghong > Shuangyou > Zuoyouhong > Beibinghong > Xuelanhong. The total anthocyanin content generally follows: Zuoshan-1 > Shuanghong > Zuoyouhong > Shuangyou > Beibinghong > Xuelanhong [16].

2.1.2 Biological activities and health benefits of polyphenols

Polyphenolic compounds have attracted significant attention due to their broad biological activities, including antioxidant, anti-inflammatory, anticancer, and cardioprotective effects. Their antioxidant properties and ability to modulate cellular signaling pathways can help prevent chronic diseases such as cardiovascular diseases, diabetes, and cancer [17,18]. The antioxidant activity stems from their capacity to scavenge free radicals and chelate metal ions, thereby reducing oxidative stress in the body [19,20]. By regulating various signaling pathways involved in inflammation and cell proliferation, polyphenols contribute to the prevention of chronic conditions like cancer and cardiovascular diseases [8,21], highlighting the complexity of their mechanisms of action [7,22].

The classification of polyphenols in grapes and wine not only aids in understanding the functional roles of these compounds in health but also helps identify specific polyphenols that may benefit targeted therapeutic applications [19,21]. For instance, compounds such as resveratrol and quercetin can reduce cardiovascular risks by improving endothelial function and lowering blood pressure [6]. Studies have shown that flavonoids like quercetin and catechins [8], as well as non-flavonoids such as caffeic acid and ferulic acid, significantly enhance overall health [23]. Additionally, polyphenols may further amplify their health benefits by interacting with gut microbiota to promote the production of bioactive metabolites.

2.1.3 Role of polyphenols in wine flavor

Polyphenols play a crucial role in the flavor profile of wine, contributing to its sensory attributes including color, taste, and mouthfeel. They are primarily responsible for the astringency and bitterness in red wines, as well as their antioxidant properties, which enhance wine stability and aging potential [24,25].

Flavonols, as the main flavonoid pigment components in grape skins, contribute to the yellow hue of wines. In red wines, although their chromatic effects are overshadowed by the spectral dominance of anthocyanins, flavonols significantly enhance color stability as copigmentation factors through intermolecular π-π stacking interactions, being recognized as the most potent co-pigmentation agents [26]. Additionally, certain flavonol derivatives regulate wine's sensory properties. For instance, quercetin prolongs astringency by enhancing salivary protein-binding capacity, while myricetin contributes bitterness and astringency through activation of bitter taste receptors [27].

Anthocyanins, as key color compounds in grape berries and wines, impart red coloration. Their chromatic properties exhibit significant pH dependence. With increasing pH, the conjugated structure within anthocyanin molecules alters. Under acidic conditions, anthocyanins display a characteristic ruby-red hue, whereas in neutral pH ranges, the quinoidal base configuration dominates, gradually shifting solutions toward bluish-purple tones.

Flavan-3-ols and non-flavonoids (hydroxybenzoic acids, hydroxycinnamic acids, and tannins) are identified as key taste-active compounds determining wine's sensory characteristics, governing the wine body's astringent mouthfeel and bitter perception.

Certain phenolic compounds also contribute to color stabilization [28], enhance color intensity [11], and degrade volatile compounds responsible for undesirable sensory attributes such as off-flavors [28].

Wines produced from cold-climate growing regions exhibit higher anthocyanin and flavonol content [29]. Consequently, *V. amurensis* wines contain higher levels of coloring substances compared to wines of vitis vinifera. Different *V. amurensis* varieties demonstrate distinct sensory characteristics due to variations in phenolic concentration and composition. For example, color intensity among common *V. amurensis* wines may follow this order: Zuoshan-1 > Shuanghong > Zuoyouhong > Shuangyou > Beibinghong > Xuelanhong.

3 The impact of climate change on polyphenols in grapes

3.1 Impact of climate change on polyphenol content

Global warming and the increasing frequency of extreme climate events have profoundly affected viticulture. Grapevines are highly sensitive to their environment, with changes in climatic factors such as temperature, precipitation, and light intensity influencing polyphenol content in grapes.

3.1.1 The Impact of Temperatures

Global warming has accelerated grape phenological phases (budbreak, flowering, ripening, and harvest) to varying degrees. Climate-driven shifts in phenology may force traditional premium wine regions to harvest prematurely, potentially causing quality issues such as imbalanced anthocyanin-tannin ratios, reduced volatile aroma components, and decreased concentrations [30]. These multidimensional impacts not only alter harvest timing but also significantly modify wine composition and sensory characteristics [29,30]. Rising temperatures directly affect grape physiology, particularly during critical ripening stages. Studies indicate that increased temperatures enhance tannin accumulation [31]. However, key polyphenolic compounds like flavonols, anthocyanins, and aromatic secondary metabolites show suppressed synthesis and reduced concentrations [31], as plants reallocate resources to stress responses rather than secondary metabolite production [32]. This may lead to diminished wine aroma expression and color stability [33], however, these two substances are of great importance to wine quality and color stability [34]. Heat stress alters phenolic composition in wine by inhibiting key enzymatic activities during metabolism, thereby modifying fermentation pathways. Using dihydrokaempferol as a hub metabolite, low temperatures promote myricetin accumulation, while high temperatures enhance quercetin biosynthesis [32].

In Northeast China, significant temperature increases in daily average, maximum, and minimum temperatures across all seasons became evident since 1990 [35]. Scientific projections suggest continued annual and seasonal temperature rises in this region [36], potentially inhibiting the synthesis and accumulation of polyphenolic compounds like flavonols and anthocyanins in *V. amurensis*. However, some studies indicate that climate change causes greater temperature increases in winter (December-February) and autumn

(September-November), with minimal summer (June-August) warming [37]. This pattern may extend the growing season for *V. amurensis*, promoting the accumulation of sugar, which is the crucial precursor for many polyphenols [38] (particularly anthocyanins). While high temperatures inhibit anthocyanins but enhance sugar and tannin accumulation, the moderate summer temperature increases (June-August) might not significantly impair polyphenol accumulation. Overall, the warming trend in Northeast China could potentially benefit the quality of *V. amurensis* grapes.

3.1.2 The Impact of Changing Precipitation Patterns

Changes in precipitation patterns, as a key environmental driver of climate change, exert significant regulatory effects on grape growth, development, and fruit quality. Fluctuations in water availability can induce periodic water stress or waterlogging stress, both of which impose pressure on grapevines and affect fruit development. In Mediterranean climate zones, increased precipitation during critical growth periods enhances grape quality, while similar precipitation increases in continental climate zones may lead to fungal diseases and reduced fruit quality [39]. Cross-climatic zone studies confirm that moderate water deficit can induce upregulation of key enzymes in flavonol synthesis, promoting flavonol accumulation in berries [40]. Under low soil water deficit conditions due to low precipitation, plants close stomata to reduce water consumption, inhibiting photosynthesis and vegetative growth. Mild to moderate water deficit can suppress excessive vegetative growth and improve berry quality. The concentration and content of anthocyanins in berries can be enhanced through upregulation of genes involved in anthocyanin biosynthesis [39].

Additionally, the timing and intensity of rainfall significantly influence grape ripening and phenolic compound accumulation [41]. Reduced precipitation during early growth stages inhibits fruit development and negatively affects color, phenolic compounds, and aromatic component accumulation. At later stages, water deficit suppresses fruit expansion, resulting in high skin-to-pulp ratios. As fruit color, phenolics, and aromatic components are primarily concentrated in skins, high rainfall and humidity impair flavanol accumulation. Conversely, late-season water deficit promotes higher anthocyanin concentrations in grapes and subsequent wines [42]. Understanding how these precipitation variations interact with temperature and other environmental factors is crucial for developing adaptive viticultural practices to mitigate climate change impacts on grape production.

In recent decades, Northeast China has experienced decreasing annual precipitation and fewer rainy days, with summer and autumn rainfall (and rainy days) showing declining trends, while spring rainfall (and rainy days) and winter snowfall (and snowy days) have increased [43]. This trend benefits uniform budbreak in mountain grapes (*V. amurensis*), and lower late-season precipitation may help with keeping high concentrations of tannins and anthocyanins. However, annual precipitation fluctuations have intensified significantly, particularly with increased variability in summer heavy rain and storm events [44], potentially leading to more frequent severe droughts and floods. Extreme drought-flood events may pose major challenges for mountain grape cultivation in this region.

3.1.3 Changes in light conditions

Light is a fundamental factor in photosynthesis and grape growth. Changes in cloud cover and atmospheric conditions can alter the amount and quality of light reaching grapevines, affecting photosynthetic efficiency and growth rates [45]. Light influences the conversion of sugars and acids in grape berries, the accumulation of anthocyanins and phenolic compounds, and the presentation of aromas [46], particularly the light duration from flowering to harvest [47]. To combat photodamage caused by intense light, vines enhance their resistance to UV radiation and herbivory by increasing flavonols and proanthocyanidins (polymerized flavanols) in the fruit [48-50].

Grapevines growing under identical light conditions in different climate zones exhibit distinct responses in growth and fruit composition. In warm climates, excessive sunlight can decrease anthocyanin levels in grape skins, whereas in cooler climates, increased sun exposure through shoot thinning or leaf removal can boost phenolic content in grapes. Light differentially affects fruit development across growth stages, particularly after berry veraison, where sufficient light enhances total phenols, tannins, and anthocyanins in grape skins [51]. Some studies suggest diffuse light can improve photosynthesis in certain grape varieties, promoting growth and potentially elevating fruit quality [52]. Conversely, excessive shading limits photosynthesis and reduces fruit quality.

In Northeast China, solar radiation peaks in spring, followed by summer, with minimal levels in winter. May receives the highest radiation, while December has the lowest. In most areas of the northeastern region, the sunshine duration shows a general decreasing trend, with the most significant decrease in summer and the least change in autumn [53]. This trend may inhibit polyphenol synthesis in mountain grapes, particularly anthocyanins. While light conditions alone might suppress polyphenol synthesis, the inseparable correlation between light and temperature prevents definitive conclusions.

3.1.4 Responses of polyphenolic characteristics of different V. amurensis varieties to climate change

Grape varieties of *V. amurensis* respond differently to climate change. Among six common varieties (Beibinghong, Xuelanhong, Shuanghong, Zuoyouhong, Beiguohong, and Shuangfeng), Beibinghong demonstrates optimal light utilization efficiency, exhibiting strong adaptability and effective light use in high-light environments [54]. Under low light, Beibinghong shows slower total phenol accumulation, slightly lower total and individual phenolic contents, along with caffeic acid and kaempferol degradation [55].

Some varieties experience significant declines in anthocyanins and flavonols when exposed to higher seasonal temperatures, indicating unique vulnerabilities to climatic stress [31]. This variability underscores the importance of selecting appropriate grape varieties for specific climatic conditions to ensure sustainable viticultural practices amid climate change.

3.2 Impact of climate change on polyphenol synthesis mechanisms

As temperature, precipitation, and light conditions change, plants must adjust their metabolic processes to adapt to environmental conditions to sustain growth and survival.

3.2.1 Biosynthetic Pathways

The synthesis of phenolic compounds primarily occurs through the shikimate pathway, with a minor contribution from the malonic acid pathway. The shikimate pathway takes place in chloroplasts, converting phosphoenolpyruvate from glycolysis and erythrose-4-phosphate from the pentose phosphate pathway into aromatic amino acids--phenylalanine--while releasing phosphate. Under the action of phenylalanine ammonia-lyase (PAL), phenylalanine is converted into cinnamic acid via the phenylpropanoid synthesis pathway. Key enzymes in this pathway include phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), and flavonoid 3-hydroxylase (F3H) [52]. These enzymes are critical for the synthesis of flavonoids, anthocyanins, and other polyphenols. Climate change can disrupt these pathways by affecting the expression levels of genes encoding these enzymes. For instance, elevated temperatures may reduce PAL activity, leading to decreased flavonoid synthesis [32]. This reduction is often associated with downregulated expression of phenylpropanoid metabolism-related genes, requiring plants to adjust their biochemical pathways to cope with shifting climatic conditions [31]. Light serves as a key regulator of metabolic processes in many plants, significantly influencing the expression of genes involved in polyphenol biosynthesis.

3.2.2 Stress responses and polyphenol accumulation

Plants respond to abiotic stresses such as drought, high temperatures, and salinity by modulating their metabolic pathways to enhance polyphenol accumulation. Polyphenols, known for their antioxidant properties, help mitigate oxidative damage caused by environmental stress. For example, under drought stress, plants often increase polyphenol production as a protective mechanism to scavenge reactive oxygen species (ROS) and stabilize cellular structures [56]. The accumulation of these compounds is regulated by stress-responsive signaling pathways, including the activation of MYB transcription factors, which play a pivotal role in the expression of polyphenol biosynthesis-related genes. Additionally, studies suggest that interactions among various stress signals can lead to synergistic effects in polyphenol accumulation, allowing plants to fine-tune their metabolic responses based on the nature and intensity of encountered stresses [57].

4 Conclusions

The impact of climate change on grape polyphenols constitutes a complex and crucial research field involving various environmental factors and biochemical mechanisms. Global warming induces earlier grape phenological stages, potentially triggering imbalances in wine components. However, the current climate change trends in Northeast China appear beneficial for *V. amurensis* cultivation and quality. Increased temperatures may favor sugar and tannin accumulation, potentially alleviating the decoupled ration between anthocyanins and sugar, which is a big concern under climate warming. Secondly, reduced annual precipitation combined with frequent extreme rainfall events creates dual stresses on growth quality. Finally, decreased sunshine duration might inhibit anthocyanin synthesis, though actual impacts require comprehensive evaluation considering temperature-light interactions. In all, climate change presents considerable challenges to wine grape polyphenol profiles while offering innovation and adaptation opportunities for Northeast China's *V. amurensis* industry.

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