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The Genetic Basis of Maple Leaf Color and Its Application in Landscape Design

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Abstract This study mainly analyzes the genetic causes of the color formation of maple leaves and its practical application in landscape design. Maple trees are an important ornamental tree species in temperate regions, and the leaf color changes significantly with the seasons. This change is mainly related to three types of pigments, namely chlorophyll, carotenoids, and anthocyanins. The content and proportion of these pigments directly affect the leaf color. Research has found that genes related to anthocyanin synthesis, such as *CHS*, *UFGT*, and *DFR*, as well as related transcription factors, such as MYB and bHLH, play an important role in the formation of leaf color. Different maple tree varieties have differences in the expression of these genes, thus showing various leaf colors such as red, yellow, and green. In addition to genetic factors, environmental conditions such as light and temperature also affect the accumulation of pigments and gene expression, thereby causing changes in leaf color. In landscape construction, maple trees are often used in parks, roads, and scenic areas. By reasonably combining different leaf-color maple tree varieties and combining with evergreen trees, water features, and other landscape elements, a landscape effect with clear layers and prominent seasonal characteristics can be formed. The relevant case in Kyoto, Japan, shows that when large areas of maple forests are combined with the natural environment, they can demonstrate high ecological value, cultural value, and economic value. In the future, using genetic information for targeted breeding is expected to provide more new maple tree varieties with both ornamental value and adaptability for urban greening.

Keywords Maple; Leaf color; Genetic basis; Anthocyanins; Landscape design

1 Introduction

Maple trees are very common ornamental tree species in temperate regions. People like maple trees mainly because of their attractive tree shape, wide range of heights, and rich leaf colors (Zhu et al., 2022). There are approximately 100 to 200 native species of maple trees, and many more are artificially selected varieties. They are commonly found along roadsides, in parks, residential areas, and botanical gardens, and are frequently used as tree species in landscaping. Maple trees grow quickly and have good shading effects. In autumn, the leaf colors become very vivid, so they play an important role in urban greening and seedling cultivation. Maple trees not only have strong ornamental value but also can improve the surrounding environment and provide habitats for animals. Therefore, they have both landscape value and ecological value (Luo et al., 2023a; Sun et al., 2024). In recent years, with the continuous emergence of new varieties such as dwarf Japanese maple and large shading maple, the application of maple trees in urban greening construction and garden cultivation has become increasingly widespread (Chen et al., 2019; Lin et al., 2022).

One of the most obvious characteristics of maple trees is that their leaf color changes significantly with the seasons. Different varieties of leaves can present various colors such as green, yellow, orange, and red. Sometimes, different colored patches can also appear on the leaves of the same tree (Chen et al., 2019; Gong et al., 2025). Many maple trees change from green to red or yellow in autumn, and this change directly affects their ornamental and economic value (Zhang et al., 2023). Studies have found that this leaf color change is mainly related to the decrease in chlorophyll content and the increase in anthocyanin content. This process also occurs in tree species such as ginkgo and red maple (Luo et al., 2023a; Fan et al., 2024; Sun et al., 2024). The same maple tree can have green, yellow, or red leaves in different seasons or branches, indicating that pigment metabolism is not only influenced by environmental conditions but also regulated by its own regulatory mechanisms (Yang et al., 2022;

Zhu et al., 2022). This leaf color change has a significant impact on the landscape effect. By rationally combining plants of different colors, the visual effect of the landscape can be enhanced (Wang, 2021; Mu et al., 2022).

With the continuous advancement of research techniques, people's understanding of the genetic mechanism of the color change of maple leaves has become more profound. Through genomic research, scientists have discovered some important genes related to anthocyanin synthesis, such as chalcone synthase and UFGT. At the same time, some transcription factors that can affect pigment accumulation and seasonal changes have also been found, such as MYB and bHLH (Sun et al., 2024). In the study of *Acer truncatum*, it was found that the phenomenon of gene duplication and the different expression levels of UFGT are closely related to the formation of red and yellow leaf varieties (Zhang et al., 2023). In the study of *Acer palmatum*, some gene combinations, such as ApWRKY26/ApERF4-ApMYB2, also participate in the synthesis process of anthocyanins in different seasons and play a regulatory role in the color change of leaves (Zhu et al., 2022; Chen et al., 2025). These studies indicate that the formation of the color of maple leaves is not only controlled by genetic factors but also influenced by environmental conditions. In the future, if the related physiological activities and gene expression can be regulated, there is hope to cultivate new ornamental varieties with more stable leaf colors or more obvious seasonal color changes (Zhao et al., 2020; Fan et al., 2024).

This study focused on analyzing the genetic basis of the color change of maple leaves and explored its application value in variety breeding and landscape design. By studying the relevant key genes and molecular markers, it is hoped to cultivate new varieties with brighter leaf colors, longer ornamental periods, and stronger adaptability. At the same time, the research on seasonal plant color combinations can also provide certain references for urban green space landscape design. Currently, the research results in leaf color genetics and the color configuration and spatial layout in landscape design still lack effective integration. This study attempts to link the leaf color formation mechanism with variety selection and seasonal configuration, providing ideas for ornamental plant breeding and further enhancing the visual, ecological and cultural value of maple tree landscapes.

2 Leaf Color Formation Mechanism

2.1 Functions of chlorophyll, carotenoids and anthocyanins

The color of maple leaves is mainly determined by three types of pigments, including chlorophyll a and b, carotenoids, and anthocyanins. Chlorophyll a and b are very important pigments for photosynthesis in plants. They mainly absorb blue light and red light, so in the season when plants are growing normally, the leaves are generally green (Lu et al., 2020). Carotenoids mainly include lutein and carotene. These pigments mainly absorb blue-violet light and their colors are usually yellow to orange. At the same time, they can also help the leaves reduce damage caused by strong light (Xie et al., 2023; Tian et al., 2024). Anthocyanins are water-soluble pigments present in the cell sap. Depending on their structure and the internal environment of the cells, they can manifest as red, purple or blue, and are particularly prominent in many colorful maple leaves (Chen et al., 2019; Jie et al., 2019; Gong et al., 2025).

These three types of pigments jointly determine the color of leaves and also participate in many normal life activities within the plant. Taking red maple as an example, chlorophyll is mainly related to photosynthesis, while carotenoids and anthocyanins are important substances that affect the color of leaves, and they can also help the plant adapt to external conditions such as strong light and temperature changes (Jie et al., 2019; Yang et al., 2022; Zhang et al., 2022; Gong et al., 2025). Studies have found that the formation process of these pigments is controlled by many genes, and the changes in the content of the three pigments, namely their increase or decrease, are the main reasons for the leaves to gradually change from green to yellow or red (Chen et al., 2019; Lu et al., 2020; Fan et al., 2024).

2.2 Diversity of maple leaf colors and pigment proportions

The colors of maple leaves vary mainly depending on the content and proportion of chlorophyll, carotenoids and anthocyanins. Taking a mutant red maple as an example, its leaves are divided into three types: green (GL), red (RL), and yellow (YL). Detection shows that the chlorophyll content is the highest in GL, medium in RL, and the lowest in YL; carotenoids are the most abundant in GL, and less and similar in RL and YL. The anthocyanin content in red leaves is much higher than that in green and yellow leaves, presenting a red-green mixture color; yellow leaves are due to a significant reduction in chlorophyll and the appearance of carotenoids, with very little anthocyanin accumulation, thus appearing yellow (Chen et al., 2019; Lu et al., 2020). In different red maple varieties, the degradation of chlorophyll and the large synthesis of anthocyanins together are the key to forming stable red leaves (Jie et al., 2019).

This phenomenon is also common in other maple trees and many other deciduous plants with distinct leaf colors. Generally speaking, the chlorophyll content in red-leaved varieties is usually lower than that in green-leaved or yellow-leaved varieties, while the contents of carotenoids and anthocyanins are higher. Among them, anthocyanins play an important role in the formation of leaf color (Chen et al., 2019; Zhang et al., 2022; Xie et al., 2023; Gong et al., 2025). Multi-gene studies on tree species such as red maple (*Acer rubrum*) have found that during the leaf color change process, the contents of chlorophyll and carotenoids gradually decrease, while some anthocyanins, such as anthocyanin-3, 5-diglucoside, increase continuously, eventually causing the leaf color to gradually change from green to red (Fan et al., 2024). Therefore, the different colors of maple leaves are actually related to the changes in the proportion of various pigment contents: when the chlorophyll content is high, the leaves usually appear green; when there is more carotenoids and less anthocyanins, the leaves are mostly yellow; when anthocyanins accumulate in large quantities, the leaves will turn red.

2.3 Seasonal changes and the formation of red leaves

The reddening of leaves is mainly due to changes in the quantities of several pigments within the leaves. As the seasons change and the leaves gradually age, chlorophyll gradually decreases, and the original green color becomes increasingly pale, eventually disappearing completely. As a result, the less obvious color of carotenoids becomes apparent. At the same time, many maple trees will produce more anthocyanins, or increase the existing anthocyanin content (Chen et al., 2019; Zhang et al., 2022). Studies on red maples and sugar maples have shown that in autumn, the chlorophyll in the leaves significantly decreases, and the content of carotenoids also changes, while anthocyanins accumulate continuously, especially in those leaves that change color earlier and have darker colors, this situation is more obvious (Mattila and Tyystjärvi, 2023). Transcriptome and metabolome studies have also found that during the process of leaf reddening, the expression of genes related to anthocyanin synthesis increases, thereby promoting the continuous accumulation of anthocyanins in the leaves (Fan et al., 2024; Gong et al., 2025).

The external environment can also affect the color changes of the leaves. Lower temperatures, larger diurnal temperature differences, and sufficient light all facilitate the breakdown of chlorophyll and promote the formation of anthocyanins. Therefore, the leaves on the outer part of the tree crown, or those that receive more sunlight, are usually more likely to turn red (Zhang et al., 2022; Mattila and Tyystjärvi, 2023; Xie et al., 2023). Additionally, if the branches of red maple trees are cut, the nutrient transportation within the branches will change, and the distribution of pigments in the leaves above the treated area will also change, so the leaves will turn red earlier (Yang et al., 2022). In summary, the red color of autumn maple leaves is the result of the combined effects of reduced chlorophyll, changes in carotenoids, and increased anthocyanins. These changes also form the common red-orange forest landscape seen in temperate regions during autumn.

3 Case Study: Maple Landscape in Arashiyama, Kyoto, Japan

3.1 Famous autumn foliage formed by extensive maple planting

Arashiyama, on the western edge of Kyoto, is renowned for its large expanses of Japanese maple (*Acer palmatum*) and other deciduous broadleaf trees, which form a celebrated autumn foliage landscape. Historical and planning studies describe Arashiyama and its suburban mountain area as a key scenic zone where maples, cherry trees, and pines are deliberately used as “constitution trees” of the landscape, shaping the visual character of the hillsides and river valley. The mixed forest mosaic on the slopes—dominated by deciduous broadleaf species—creates large, continuous patches of red, orange, and yellow that are visible from afar and attract millions of visitors annually (Figure 1).

Figure 1 Maple leaf scenery in autumn in Lansi
Image source: Japan food guide

This autumn scenery has become a major tourism resource and a symbol of Kyoto’s seasonal identity. Arashiyama is cited nationally and internationally as a representative destination for viewing autumn leaves, with forest color change playing a central role in visitor appeal and local tourism planning (Mu et al., 2022). Phenological research on Japanese maple foliage shows that the timing and duration of coloration directly influence visitor numbers, and delayed but compressed color periods can increase maple-viewing tourism volume (Liu et al., 2019). Such findings help explain why the extensive planting and conservation of maples in Arashiyama have been prioritized: dense maple stands ensure a reliable, visually striking autumn display that underpins seasonal festivals and economic activity.

3.2 Color contrast with evergreen trees and water landscapes

In Arashiyama, red and yellow maples are composed with evergreen conifers and the Katsura River to create strong color contrast and spatial layering. Landscape analyses of the Kyoto-Arashiyama area identify cherry trees, pine trees (evergreen), and maples as key structural elements whose differing forms and phenologies are intentionally combined to shape views from designated vantage points. On the mountain slopes, darker green pine and other evergreens provide a deep background against which bright maple crowns stand out in autumn, enhancing perceived saturation and depth of color patches (Mu et al., 2022). This arrangement produces a tiered vertical structure: dark evergreen canopy, mid-story deciduous maples, and lighter understory vegetation.

The presence of the river and surrounding water landscapes further strengthens visual impact. Studies of slope-forest color aesthetics show that scenes with strong red-green-yellow contrast, clear primary and secondary color patches, and diversified but balanced color distribution achieve superior visual aesthetic quality and higher public preference. In Arashiyama, reflections of red maples and green pines on the river surface multiply color patches and soften transitions, while the linear water body organizes views and guides sightlines along the valley. This composition of deciduous maples, evergreen trees, and water aligns closely with empirically supported rules for high-quality autumn color landscapes on urban and peri-urban slopes (Mu et al., 2022).

3.3 Demonstrating the value of maples in landscape color design

The Arashiyama case powerfully illustrates the design value of maple trees as strategic color elements in landscape planning. As “constitution trees,” maples have been used not only for ecological functions but also as key carriers of seasonal symbolism and aesthetic identity, deliberately embedded into postwar planting and scenic-area planning in Kyoto. Long-term management of Arashiyama National Forest emphasizes sustaining a historically and aesthetically valuable forest landscape, recognizing that carefully maintained deciduous broadleaf stands are essential to preserving the scenic quality that visitors seek. This underscores how maples can anchor regional landscape character when their seasonal color traits are systematically considered in planning and management.

More broadly, research on autumn-color slope forests shows that configurations rich in red and yellow foliage, with clear yet harmonious color contrasts, are particularly effective for improving visual aesthetic quality and supporting tourism and local economies (Liu et al., 2019; Mu et al., 2022). In Japan, autumn leaf-coloring events are timed to phenological stages of maple foliage to maximize tourism benefits, confirming that maple color dynamics are integrated into destination management and marketing strategies. Arashiyama exemplifies how the genetic and phenological properties of maples-stable, vivid autumn coloration and predictable timing-can be translated into landscape-scale color design, producing spaces that are both ecologically meaningful and culturally and economically valuable.

4 The Genetic Basis of Maple Leaf Color

4.1 The influence of genes related to anthocyanin synthesis on leaf color

The formation of maple leaf color is mainly controlled by some key genes, which are involved in the production of related enzymes during anthocyanin synthesis. Studies have shown that changes in the expression of genes such as CHS, CHI, F3H, DFR, ANS, and UFGT are closely related to the increase or decrease of anthocyanin content during the color change of leaves (Li et al., 2025). For example, 20 genes related to anthocyanins were discovered in the study of false-colored maple leaves. Most of these genes have the highest expression levels during the most red stage of the leaves, indicating that they play an important role in the formation of red leaves (Figure 2) (Gong et al., 2025). In red maples, the expression of these genes is usually higher in red leaves than in green and yellow leaves, thus affecting the accumulation of pigments and the manifestation of leaf color (Chen et al., 2019).

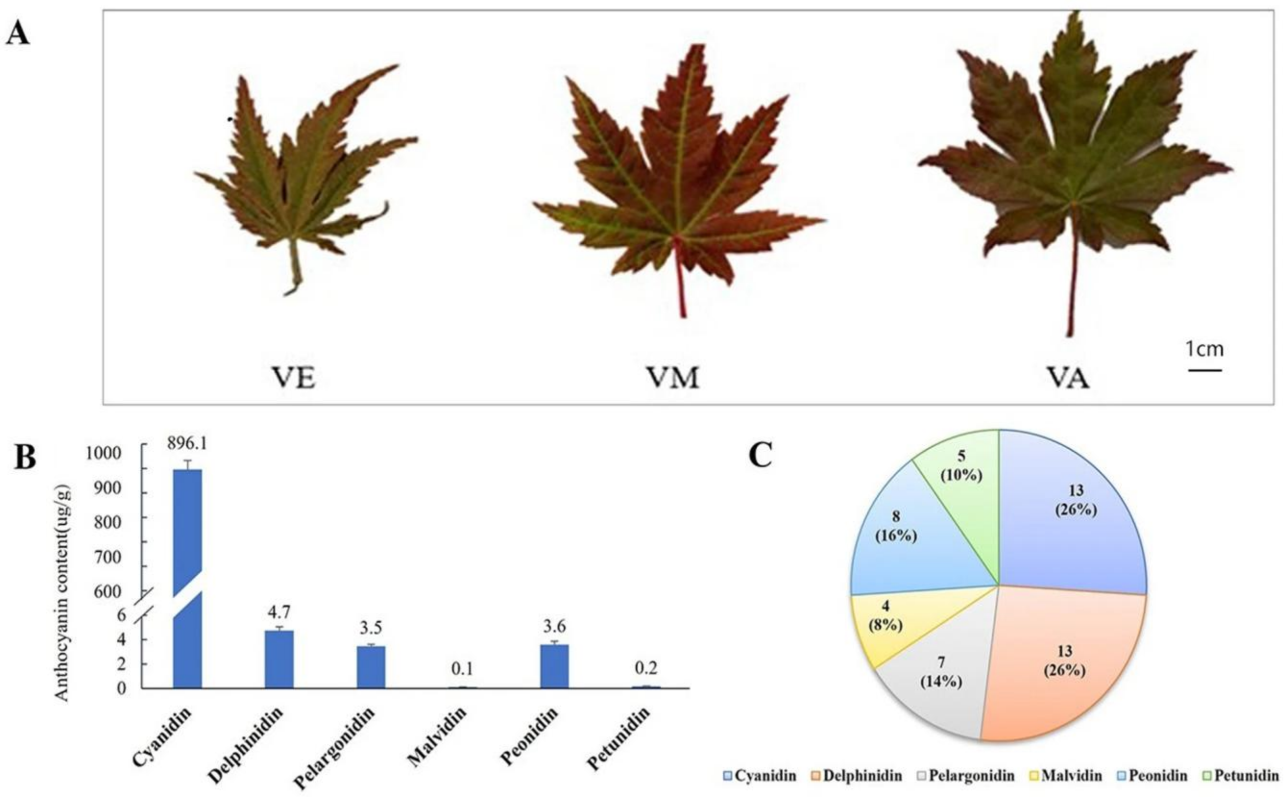

Figure 2 The leaf morphology during development (A), anthocyanin content (B) and classification (C) of *A. pseudosieboldianum mutant* (Adopted from Gong et al., 2025)

Image caption: VE (Early stages), VM (Middle stages), and VA (Late stages) represent three stages during leaf discoloration (Adopted from Gong et al., 2025)

Some genes have a more significant impact on the shade of leaf color. Comparative studies on different varieties of red maples revealed that in some red maples, there is a situation of UFGT gene duplication. When both UFGT genes maintain high expression simultaneously, the anthocyanin content in the leaves will significantly increase, indicating that this gene plays an important role in the formation of red leaves (Zhang et al., 2023). DFR is also one of the important genes affecting leaf color. When this gene undergoes mutation or its expression level decreases, the anthocyanin content will also decrease (Recinos and Puck, 2023). In maples, the expression changes of DFR and ANS usually correspond with the changes in anthocyanin content in red leaves (Chen et al., 2019; Chen et al., 2022; Gong et al., 2025; Li et al., 2025). Therefore, the quantity and expression level of these genes affect the accumulation of anthocyanins, and thereby influence the final color of the leaves.

4.2 Regulatory role of transcription factors

Apart from structural genes, transcription factors can also regulate the formation of pigments at a higher level. The production of anthocyanins is usually controlled by the MBW complex. This complex consists of three types of proteins: MYB, bHLH, and WD40, and it is activated during plant growth stages or when influenced by external environmental signals (Figure 3) (Gao et al., 2020; Yan et al., 2021; Chen et al., 2022; Fan et al., 2024; Liu et al., 2024). Studies have found that in many plants, the influence of transcription factors on pigment differences is often more significant than that of structural genes, and MYB-type transcription factors play a particularly crucial role (Recinos and Pucker, 2023). Generally speaking, MYB mainly regulates the process, while bHLH and WD40 play more auxiliary and stabilizing roles in maintaining the complex.

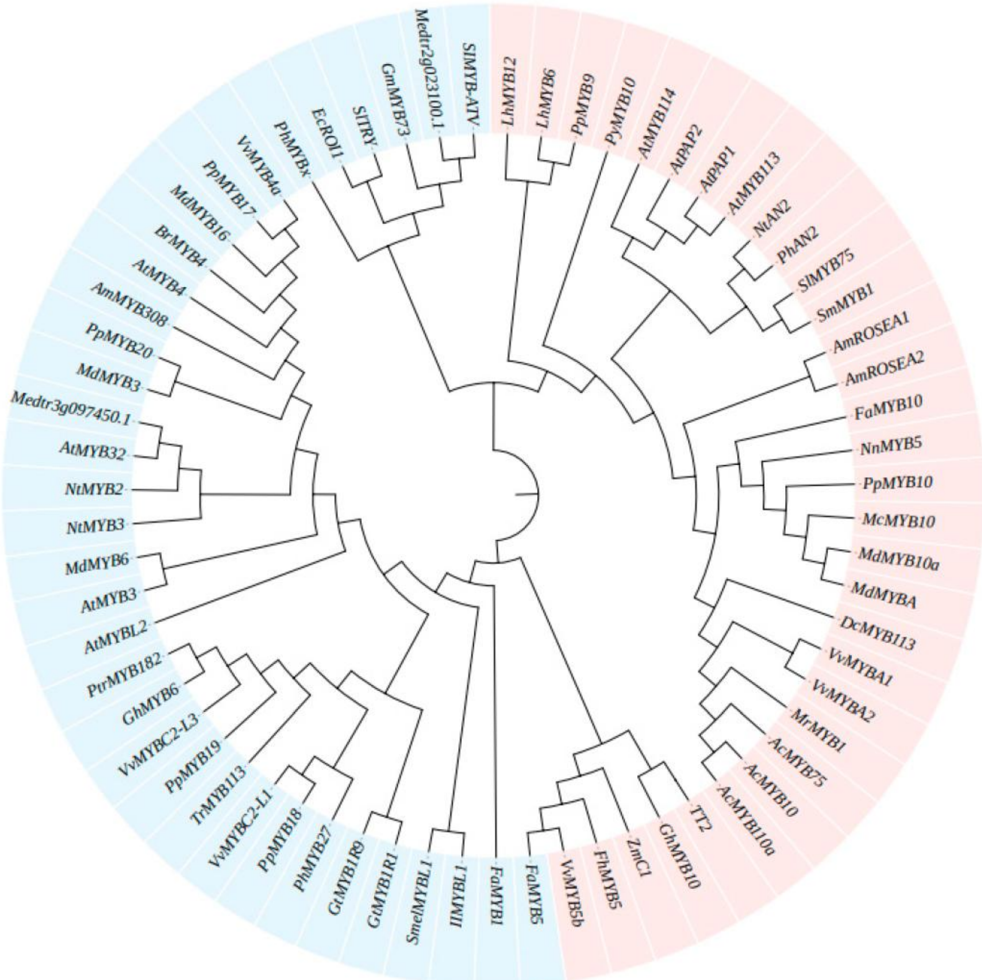

Figure 3 Phylogenetic tree of the regulation of anthocyanin biosynthesis by *MYB* genes (Adopted from Yan et al., 2021)

Image caption: The tree was constructed based on the entire protein sequences using MEGA 6 software. Blue represents the antagonistic effects of MYB factors in the anthocyanin biosynthetic pathway, and red represents the MYBs as activators to promote the biosynthesis of anthocyanin (Adopted from Yan et al., 2021)

Similar regulatory mechanisms were also discovered in the maple trees. When the color of the maple leaves changed, the expression levels of some *MYB* and *bHLH* genes would significantly alter. Genomic studies have shown that this species has a total of 95 R2R3-type *MYB* genes, among which some genes showed a significant increase in expression during the red leaf period, indicating that they may be involved in the regulation of anthocyanins (Figure 4) (Gong et al., 2025; Zhang et al., 2025). The transcriptome study conducted on the Jiwafan maple tree found that genes related to anthocyanin regulation include *46 MYB, 33 bHLH*, and *29 WD40*, indicating that the formation of leaf color is influenced by multiple transcription factors (Zhu et al., 2022). In the study of red maples, after the leaves were subjected to ring excision treatment, they gradually turned red, and some transcription factors related to anthocyanins were also activated (Yang et al., 2022). These research results indicate that MYB, bHLH, and other transcription factors can integrate different signals and regulate the expression of anthocyanin-related genes.

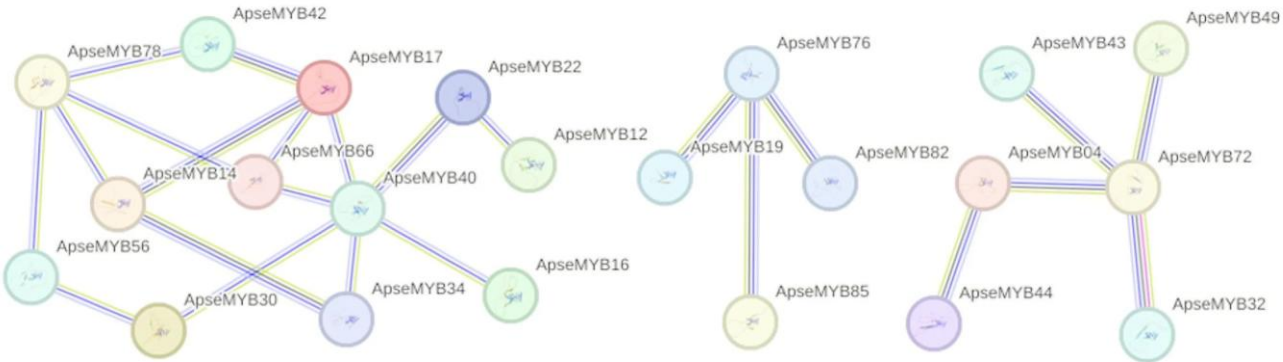

Figure 4 Analysis of the ApseMYB protein-interaction network (Adopted from Zhang et al., 2025)

4.3 Genetic expression differences lead to different leaf colors in different maple tree varieties

The differences in leaf color among different maple tree varieties are mainly related to the varying levels of gene expression, rather than a fundamental change in the metabolic pathways. After conducting a comparative study on red-leaved varieties and yellow-leaved varieties, it was found that the difference in anthocyanin content is associated with changes in the expression levels of 18 structural genes and various MYB, bHLH, and WD40 regulatory factors. Additionally, these two types of varieties also show significant differences in their gene co-expression patterns (Zhu et al., 2022).

Similar phenomena were also observed in red maples. When comparing the mutant branches of red, yellow and green colors, it was found that most of the genes related to anthocyanins had the strongest expression in red leaves, the lowest expression in green leaves, and an intermediate level in yellow leaves. This trend of change is consistent with the changes in anthocyanin content and the depth of leaf color (Chen et al., 2019). This indicates that under the same genetic background, different expression intensities of genes can affect pigment content, thereby forming different leaf colors (Figure 5).

5 Application of Maple Trees in Landscape Design

5.1 Utilizing different leaf colors to enrich landscape colorfulness

There are many types of maple trees, and their leaf colors are also very diverse, such as yellow-green, orange, red and purple, etc. By appropriately combining different colored maple leaves, a distinctive and colorful plant landscape can be created. Research indicates that maple trees with red, orange and yellow-green leaves can enhance the overall visual appeal of the landscape to a certain extent. In landscape design, if the number of red-leaved maple trees is appropriately increased, it can make the originally green-dominated environment more eye-catching and form a clear visual center (Yang et al., 2022).

Research on the color combination of plants in autumn has also found that designs featuring warm colors or creating an appropriate contrast between warm and cool colors are more likely to be favored by the public. Relevant indicators such as the autumn color index and the ratio of warm colors to cool colors are positively correlated with the attractiveness of the landscape (Luo et al., 2023b). Therefore, in actual design, attention should be paid to the combination of the main color and the auxiliary color, and the selection of maple trees with dark red, orange red and yellow leaves should be made instead of randomly mixing multiple colors. Proper control of the hue and saturation of the leaf color can enhance the overall color effect of parks and streets.

Figure 5 Leaves of maple trees in different colors

5.2 The extensive application of maple trees in parks and streets

Maple trees are valued for their attractive form and strong adaptability, and their vivid autumn foliage has led to their widespread use in urban greening around the world (Figure 6) (Melitopol et al., 2025). The Humble Administrator's Garden in China provides a representative example: in autumn, the maples create a richly layered red-leaf landscape, which, together with pavilions, water features, and surrounding plants, forms a classical garden scene imbued with traditional aesthetic Yijing (Figure 7). In the eastern United States, maples are among the most common deciduous street trees and are widely planted in residential areas, commercial districts, and parks. Species such as Norway maple, red maple, and silver maple grow relatively quickly, adapt well to urban environments, and possess broad canopies with pronounced seasonal visual changes, making them commonly used as street and shade trees (Lisica et al., 2023).

The actual situations in some cities of Europe and the United States demonstrate that maple trees play a significant role in urban greening. In the urban area of Belgrade, maple trees are one of the common street trees, with a total of 735 trees, occupying an important position in the local urban greening system. In Allen Park in Toronto, Canada, the tall Norwegian maple, due to its bright autumn foliage, contributes approximately one fifth of the ecological value and landscape value to the park. However, when planting maple trees on a large scale, it is necessary to carefully select suitable varieties, attach importance to the protection of genetic diversity, and strengthen the prevention and management of pests and diseases, so as to ensure that the urban greening effect remains stable for a long time (Ferus, 2023).

5.3 Create a unique seasonal landscape through plant combinations

By planting maple trees in combination with deciduous trees, flowering trees, shrubs and ground cover plants, a landscape with distinct seasonal changes can be formed. Research shows that by appropriately combining maple trees with spring-blooming tree species and evergreen coniferous trees, the landscape can maintain a continuous viewing effect throughout the year: flowers can be appreciated in spring, the trees are lush in summer, and the leaves show a rich variety of colors in autumn. Among them, the ornamental value of the autumn landscape is the most prominent. Reasonable plant arrangement can ensure that the landscape maintains a good visual effect from May to September. In May, it is mainly for flower appreciation, while from August to September, the main landscape elements are autumn leaves and fruits (Wang, 2021).

Figure 6 Application of maple in landscape design

Research on the autumn color landscape of urban parks has shown that three plant combinations are particularly effective: those dominated by warm colors, those that contrast warm and cool colors, and those with coordinated distribution of various colors. In these designs, the autumn leaves of maple trees are often used as the main background. As long as the main color and auxiliary color are reasonably controlled, and the proportion and diversity of colorful plants are managed well, a good viewing effect can be achieved (Luo et al., 2023b). Moreover, evergreen trees can connect the autumn and winter landscapes, making the overall visual effect more continuous (Wang and Zhao, 2020). By reasonably combining maple trees with other plant species, a landscape space with obvious seasonal changes and in line with public aesthetics can be formed.

Figure 7 Maple leaves at the humble administrator's garden
Image source: Suzhou municipal people's government website

6 Maple Variety Breeding and Genetic Improvement

6.1 Traditional breeding and molecular marker-assisted breeding

The selection and breeding of maple varieties have long relied primarily on traditional cross-breeding and seedling selection, screening based on phenotypic traits such as leaf color, tree form, and growth rate. However, leaf color traits are regulated by multiple genes and are easily influenced by environmental conditions, making traditional breeding cycles long and efficiency relatively low. In actual breeding processes, it often takes several years or even more than a decade from cross-pollination to the flowering and fruiting of seedlings, and leaf color expression requires many years of observation to confirm its stability. Furthermore, traditional breeding struggles to precisely select genes related to leaf color, and the inheritance of excellent traits involves considerable uncertainty, increasing the difficulty and cost of breeding efforts.

In recent years, with the development of molecular marker technologies, DNA molecular marker-based (such as SSR, SNP) assisted breeding has greatly improved selection efficiency. By constructing genetic linkage maps of maple, researchers have mapped QTL loci associated with leaf color, providing a basis for early screening of target traits (Zhang et al., 2023). Molecular marker-assisted breeding allows for genotype identification at the seedling stage using small amounts of leaf tissue, eliminating the need to wait many years for phenotypic observation and significantly shortening the breeding cycle. For example, molecular markers closely linked to the UFGT gene have been developed in red maple, enabling rapid identification of red-leaf genotypes and accelerating the breeding process of superior varieties (Figure 8) (Chen et al., 2019). Currently, molecular markers for several important ornamental traits in maple have been successively developed, laying a solid foundation for the genetic improvement of maple.

6.2 Application prospects of gene editing technology in leaf color improvement

With the popularization of genome sequencing technology, the genomes of various maple species have been resolved, laying the foundation for gene editing. Technologies such as CRISPR/Cas9 offer the possibility of precisely modifying genes related to leaf color. By knocking down or activating specific transcription factors (such as MYB, bHLH) or structural genes (such as DFR, ANS), the synthesis and accumulation of anthocyanins can be directionally regulated, thereby altering leaf color expression (Recinos and Pucker, 2023). Unlike random mutagenesis, gene editing technology enables site-specific modification of target genes, avoiding the linkage introduction of undesirable traits and greatly improving breeding efficiency and precision. Currently, this technology has been successfully applied in model plants such as Arabidopsis and rice for regulating anthocyanin metabolism, providing important references for the genetic improvement of maple.

Furthermore, gene editing can also be used to enhance the adaptability of maple to environmental stresses, such as improving drought tolerance or disease resistance, allowing excellent leaf color traits to be stably expressed in complex urban environments. Stress factors in urban environments, such as drought, soil salinization, and air pollution, often lead to premature leaf senescence and disrupted pigment metabolism, affecting the red leaf landscape effect. By editing transcription factors or functional genes related to stress response, the stress resistance of maple can be enhanced, ensuring normal color change under adverse conditions. Currently, the genetic transformation system for maple is not yet fully developed, but related research is progressing. Methods such as Agrobacterium-mediated transformation and particle bombardment have been successfully applied in some Aceraceae species. With the improvement of genetic transformation efficiency and the optimization of gene editing technologies, precise improvement and directional breeding of maple leaf color traits are expected in the future.

6.3 Promotion and adaptability evaluation of superior varieties

The promotion and application of new varieties require comprehensive consideration of their ecological adaptability, ornamental stability, and cultivation management requirements. Different maple varieties respond differently to environmental factors such as light, temperature, and soil pH, which directly affects leaf color expression and growth vigor. For example, some red-leaf varieties show reduced anthocyanin accumulation and greener leaves under insufficient light; while yellow-leaf varieties may shed leaves prematurely under high temperatures, significantly shortening the ornamental period (Xie et al., 2023; Zhou, 2025). Soil conditions are equally important; alkaline soils may hinder iron absorption, causing leaf yellowing and affecting the landscape effect. Therefore, multi-site, multi-year regional trials are needed before promotion to evaluate leaf color stability, pest and disease resistance, and growth adaptability, clarifying the optimal planting areas and cultivation conditions for each variety.

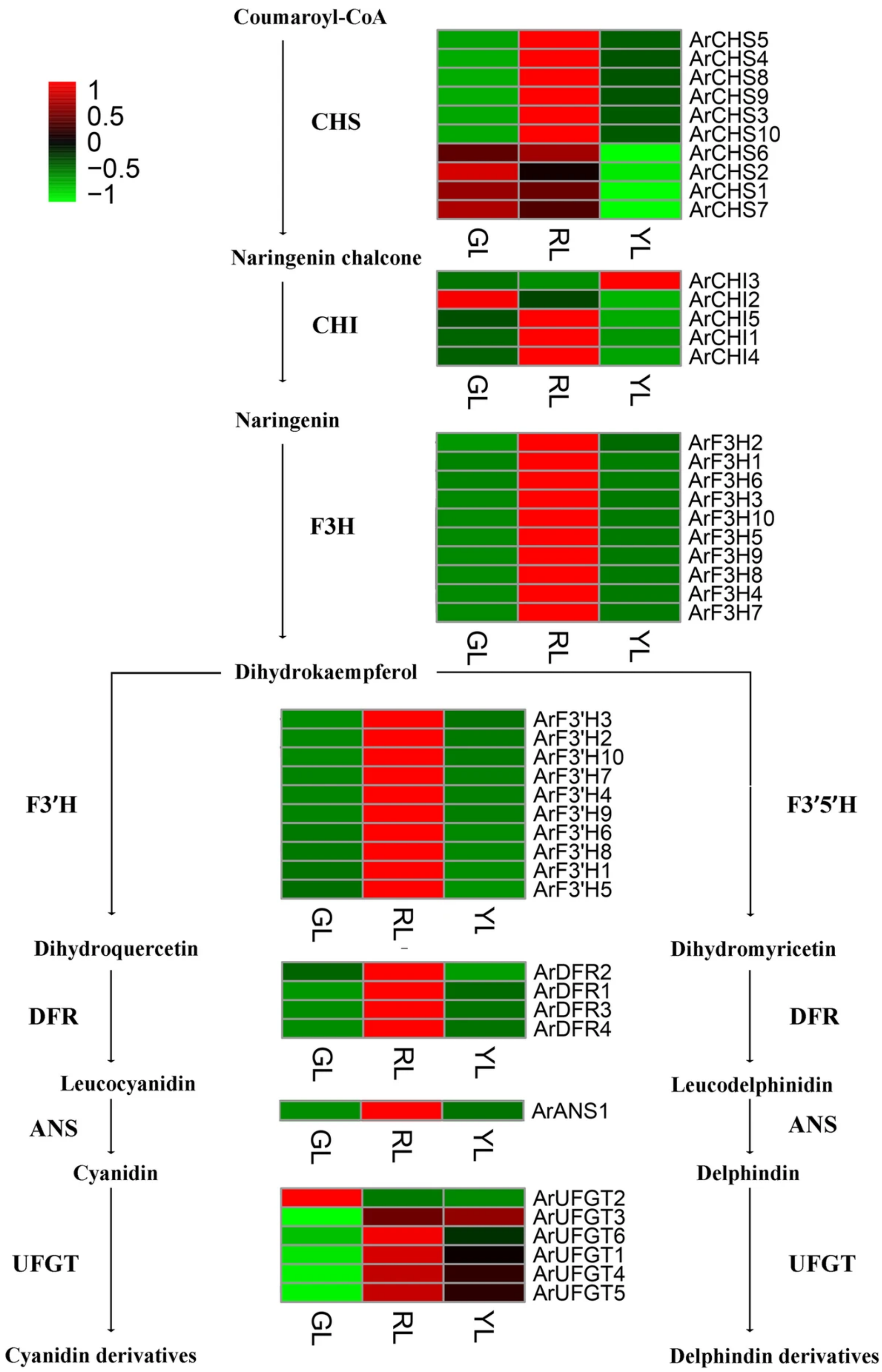

Figure 8 Heatmap of differentially expressed genes (DEGs) related to anthocyanin biosynthesis (Adopted from Chen et al., 2019)
Image caption: GL, green leaves; RL, red leaves; YL, yellow leaves; CHS, chalcone synthase; CHI, chalcone isomerase; F3H, flavanone 3-hydroxylase; F3’H, flavanone 3′-hydroxylase; F3′5′H, flavanone 3’5’-hydroxylase; DFR, dihydroflavonol 4-reductase; ANS, anthocyanin synthase; UFGT, anthocyanidin 3-O-glucosyltransfersae (Adopted from Chen et al., 2019)

Simultaneously, establishing asexual propagation systems (such as cuttings, tissue culture) to ensure the stable inheritance of excellent traits is a crucial step in variety industrialization (Lin et al., 2022). Cutting propagation is simple and low-cost, but some maple varieties have difficulty rooting, resulting in unstable survival rates; although tissue culture is technically demanding, it allows rapid propagation of superior seedlings while maintaining the excellent traits of the mother plant. Currently, tissue culture techniques for important ornamental maples like Japanese maple and red maple have matured, providing a foundation for the large-scale production of superior varieties. Furthermore, during the promotion process, cultivation technical guidance needs to be strengthened, including proper water and fertilizer management, shaping and pruning, and pest and disease control, to ensure that new varieties display their optimal ornamental effects in different regions. By establishing a comprehensive superior variety propagation and promotion system, the application of excellent maple varieties in urban greening can be accelerated, enhancing the overall quality of autumn landscapes.

7 Challenges and Future Trends in Maple Landscape Design

7.1 Impacts of urban environment on maple growth and leaf color expression

The urban environment presents specific challenges such as high temperatures, drought, soil compaction, and air pollution, which impact maple growth and leaf color expression. Research indicates that the urban heat island effect can delay autumn phenology, shorten the red leaf period, and even affect anthocyanin synthesis (Liu et al., 2019). Nighttime temperatures in city centers are significantly higher than in suburban areas, disrupting the temperature signals plants use to perceive seasonal changes, leading to delayed or insufficient leaf coloration. Additionally, air pollutants like sulfur dioxide and ozone can directly damage leaf tissue, accelerate leaf senescence, and cause leaves to fall before displaying their full red color, severely impacting the landscape effect.

Soil compaction and poor aeration limit root system development, subsequently affecting nutrient absorption and leaf pigment metabolism. Soil in urban roadsides and squares often becomes compacted due to construction traffic, reducing porosity and restricting root growth, leading to weakened tree vigor and dull leaf color. Simultaneously, the large area of impermeable pavement hinders rainwater infiltration, causing unstable soil moisture supply and frequent drought stress (Lu and Wang, 2025). Therefore, in landscape design, it is necessary to select adaptable varieties, such as Norway maple and silver maple, which tolerate urban conditions, and adopt cultivation measures like soil improvement, supplemental irrigation, and the use of mulches to maintain good leaf color effects. Furthermore, rationally configuring tree species and avoiding planting maples in severely polluted or poorly lit areas can maximize their ornamental value. Technical measures such as soil improvement in planting pits, permeable pavement around tree pits, and regular deep aeration can significantly improve the growing conditions for maples.

7.2 Challenges of climate change and maple phenological shifts for landscape design

Global climate change leads to increased temperature fluctuations and frequent extreme weather events, directly affecting the timing and duration of maple leaf coloration. For example, autumn warming can delay color transition, while early frosts may cause leaves to fall before changing color, diminishing the landscape effect (Mattila and Tyystjärvi, 2023). Over the past few decades, the peak autumn foliage period in famous maple-viewing areas like Kyoto, Japan, has shown a trend of delay and increased interannual variability, posing challenges for tourism organization and landscape management. Furthermore, changes in precipitation patterns can affect anthocyanin accumulation and leaf senescence processes; in drought years, red leaves may fall prematurely, while in rainy years, insufficient light may lead to duller leaf colors.

This requires landscape designers to consider climate change factors during planning, select varieties with stable phenological responses, and employ diverse tree species combinations to buffer the impact of climate anomalies on autumn color landscapes. For instance, combining maple varieties with different coloration periods can extend the red-leaf viewing period from 2-3 weeks for a single species to over a month; introducing other autumn color tree species like ginkgo and tulip tree creates composite landscapes with interwoven yellow, orange, and red hues, maintaining overall landscape quality even if one species performs poorly. Simultaneously, establishing long-term phenological monitoring networks, combined with meteorological data to predict leaf color change trends, provides a scientific basis for landscape management and visitor services. Japan has established a nationwide autumn foliage forecasting system, predicting optimal viewing periods across regions using phenological models to guide visitor travel and scenic area operations, an experience worthy of reference and promotion.

7.3 Application of digitalization and intelligence in maple landscape planning

With the development of Geographic Information Systems (GIS), remote sensing technology, and artificial intelligence, the planning and design of maple landscapes are progressively transitioning towards digitalization and intelligence. Through high-resolution remote sensing imagery and drone aerial photography, the species distribution, leaf color dynamics, and health status of large maple forests can be rapidly acquired, providing data support for landscape assessment and optimization (Mu et al., 2022). Multispectral and hyperspectral remote sensing technologies can invert leaf anthocyanin and chlorophyll content, quantitatively assess red leaf color saturation, and identify early signs of abnormal coloration. Combined with visitor preference surveys and scenic beauty estimation models, designers can simulate the visual effects of different configuration schemes, achieving precise design. Through virtual reality technology, decision-makers and the public can experience autumn color landscapes firsthand during the planning and design phase, participating in scheme comparison and optimization.

Furthermore, IoT-based intelligent irrigation and maintenance systems can automatically regulate water supply based on soil moisture and meteorological conditions, ensuring healthy maple growth and extending the red-leaf viewing period. Soil moisture sensors monitor root zone water content in real-time; combined with weather forecast data, intelligent control systems can initiate irrigation before a drought occurs, avoiding premature leaf fall caused by water stress. For precious ancient maple trees, monitoring equipment such as trunk sap flow sensors and leaf chlorophyll fluorescence detectors can be installed to assess tree physiological status in real-time, promptly detecting anomalies and implementing maintenance measures. In the future, digital twin technology holds the potential to construct virtual maple landscape platforms, integrating real-time monitoring data with 3D landscape models to dynamically display leaf color change processes, aiding public engagement and cultural dissemination. Visitors can access real-time autumn foliage information via mobile apps to plan optimal viewing routes, while scenic area managers can use this data to regulate visitor flow and arrange events, further enhancing the comprehensive value and cultural influence of maple landscapes.

8 Concluding Remarks

The formation of maple leaf color is not caused by a single factor but is the result of the combined effect of genetic factors and environmental conditions. From a genetic perspective, certain genes and regulatory factors influence the production and content of chlorophyll, carotenoids, and anthocyanins, causing leaves to exhibit different colors such as green, yellow, or red. Simultaneously, external environmental conditions, such as light intensity and temperature, also affect the accumulation of these pigments and influence the expression of related genes. Therefore, the leaf color of the same maple tree may vary under different environmental conditions, and the pattern of color change may not be entirely consistent. Research also indicates that some artificial measures, such as girdling, can affect the pigment accumulation process and the expression levels of related genes, thereby causing changes in leaf color. In recent years, with the rapid development of molecular biology techniques, the understanding of the mechanisms underlying maple leaf coloration has deepened, providing a solid theoretical foundation for maple variety improvement and landscape application.

Research on the genetic mechanisms of leaf color has also promoted the development of ornamental plant breeding. Through multi-omics research methods, researchers have discovered many important genes and transcription factors related to pigment synthesis, such as MYB and bHLH. Simultaneously, studies have shown that gene duplication phenomena may also affect the stability of leaf color. The discovery of leaf color mutant materials and the application of molecular marker technology have provided new methods for breeding new varieties with specific leaf colors and the ability to exhibit changing characteristics in different seasons. Due to the rich genetic diversity in maple leaf color, through directional selection, various maple varieties with different color series, such as red series and yellow series, have been cultivated, further enhancing their ornamental value. With the maturation of gene editing technology and the improvement of genetic transformation systems, precise regulation of maple leaf color is expected in the future, cultivating more excellent varieties possessing both ornamental value and environmental adaptability.

With technological advancements and the increasing demands of urban greening, the application of maple trees in landscape design is becoming increasingly widespread, but it also faces challenges such as climate change and urban environmental stress. In the future, molecular breeding based on genetic information and gene editing technology are expected to cultivate more superior varieties with stable leaf color and strong adaptability. Simultaneously, combined with digital planning tools and intelligent maintenance systems, precise design and sustainable management of maple landscapes can be achieved, enabling them to play a greater role in beautifying cities, inheriting culture, and promoting tourism. Through interdisciplinary integration, organically combining genetics, ecology, landscape design, and smart city technologies, this traditional ornamental tree species will surely radiate new vitality and vigor in modern urban landscapes, bringing people richer and more colorful autumn visual feasts.

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The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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