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Comprehensive Overview of *Populus simonii* Research in the Recent Years

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Abstract

As an important ecological tree species in northern China, *Populus simonii* plays a crucial role in maintaining ecological balance and promoting environmental sustainability. The academic community has conducted a series of in-depth studies on this species, covering key areas such as genomics, survival mechanisms, and genetic breeding. Through the analysis of the genomic structure and function of *P. simonii*, we have not only revealed the molecular basis for its adaptation to harsh environments but also identified key genes that promote its growth and resistance to pests and diseases. Furthermore, exploring the survival mechanisms of *P. simonii* has deepened our understanding of its stress resistance traits, including how it effectively copes with abiotic stresses such as drought, salinization, and heavy metal pollution. In genetic breeding, significant progress has been made through the application of modern biotechnology, improving the growth rate and wood quality of *P. simonii* and enhancing its environmental adaptability and disease resistance. These research findings have not only enriched our knowledge of the biological characteristics of *P. simonii* but also provided a solid scientific foundation for its application in ecological restoration, forestry production, and environmental management.

Keywords

Breeding, Ecological Restoration, Genomics, *Populus simonii*, Resistance Mechanisms

1. Introduction

Over the past decade, significant advancements have been made in the research of *P. simonii*, a fast-growing deciduous tree native to northern China. Known for its strong adaptability and excellent compatibility in mixed stands, *P. simonii* is often used as an ideal parent for short-rotation forestry and the selection of clonal varieties of poplar trees [1]. In the realm of ecological protection, *P. simonii* plays a crucial role, especially in combating land desertification and in environmental restoration projects, demonstrating its unique value [2]. In recent years, the academic community has engaged in in-depth discussions and research on various aspects of *P. simonii*, including genomics, resistance mechanisms, population studies, breeding, and afforestation techniques. These research outcomes have not only deepened our understanding of the biological characteristics of *P. simonii* but also provided a solid scientific foundation for its protection, management, and utilization. By integrating the related literature published during this period, we can clearly observe the development trends in the field of *P. simonii* research and the potential of this tree species in future ecological restoration and sustainable forestry practices.

2. Research Progress of *P. simonii* Genomics

P. simonii is widely distributed in the northern hemisphere and has a long history of cultivation. It is of great value to ecological environment protection and economic development. However, the lack of complete genomic information has limited the development of new varieties with greater adaptability and commercial value for a long time. In recent years, scientists have made breakthrough progress in studying the genome of *P. simonii*. In 2016, Mohaddeseh Mousavi *et al.* [3] constructed the genome reference sequence of *P. simonii* for the first time and identified thousands of high-quality single nucleotide polymorphism sites (SNPs). On this basis, in 2020, Hainan Wu and his team further improved the genetic map of *P. simonii*, successfully located 336 contigs on 19 pseudochromosomes, and predicted nearly 40,000 functional genes [4]. In the same year, the chloroplast genome of *P. simonii* was also determined, which contains 131 complete gene sequences [5]. Not only that, the successful assembly of the poplar ring mitochondrial genome is considered a more significant breakthrough. Research shows that the mitochondria a ring-shaped molecule encoding three proteins, with a total length of 781.5 kb [5]. Recently, Yilian Zhao [6] used fluorescence *in situ* hybridization (FISH) technology to construct a high-resolution karyotype map, which further improved the quality of the *P. simonii* genome assembly. These research results deepen our understanding of the genetic diversity within the poplar species and provide valuable information for comparative genomics research on poplar and identification of genetic variation in F_1 hybrids. They also contribute to the development and development of genetic resources of other plant species. Genome assembly provides strategy and direction.

3. Research Progress on the Molecular Mechanism of Nitrogen Absorption and Utilization in *P. simonii*

Nitrogen is an essential nutrient element for plant growth and development.

Appropriate amount of nitrogen application (such as 5 mmol/L) can effectively promote the growth of plant seedlings [7]. Nitrogen in soil exists in different forms, including nitrate (NO_3^-), ammonium nitrate (NH_4NO_3) and ammonium nitrogen (NH_4^+). These various forms of nitrogen will affect specific genes and specific interaction networks. For example, *PsAAAP*21 [8] and ptc-miR169i/b-D6PKL2, ptc-miR393a-5p-AFB2, and so on can adjust the root system structure of *P. simonii* [9]. Plants absorb nitrogen through the amino transporter (AMT). Chunxia Zhang's research showed that *P. simonii* overexpressing *PsAMT*1.1 can show better growth traits under low-nitrogen conditions, such as increased plant height, stem diameter, photosynthetic rate, and total biomass [10] In addition, nitrogen absorption can also induce the expression of *PtrPAL*1-5 genes [11], affecting lignin and antibiotic content, which is crucial for the plant's defence mechanism. The Dof family plays an important role in nitrogen assimilation and utilization, highlighting its importance in regulating plant nitrogen metabolism [12]. At the same time, many candidate genes and regulatory factors related to nitrogen transport have been identified, such as *NRT*3.1, *NPF*5.1 and *NLP*8.1 [13]. These findings deepen our understanding of how plants use nitrogen and help improve crop breeding strategies to increase crop productivity and sustainability in low-nitrogen environments (**Figure 1**).

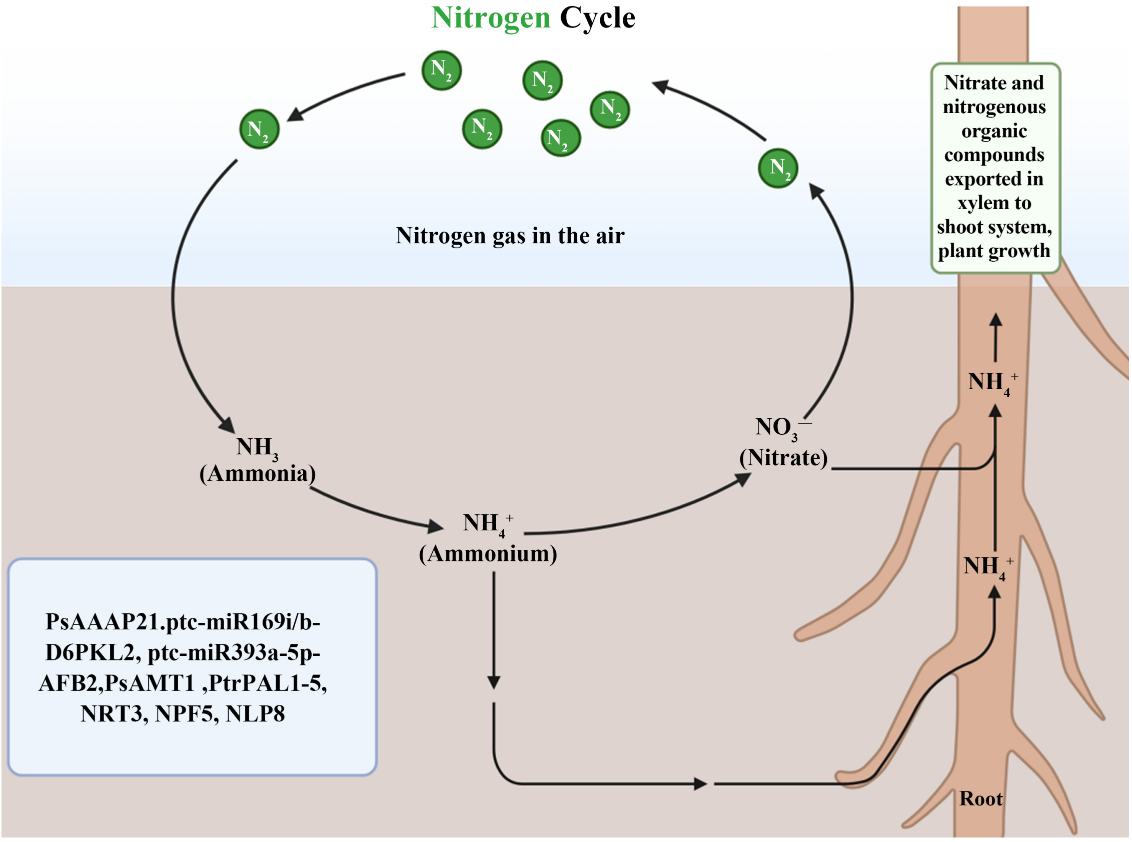

Figure 1. The illustration of Nitrogen cycle in *P. simonii*.

4. Research Progress on the Resistance Mechanism of *P. simonii*

P. simonii is a highly adaptable tree species that can adapt to various environmental stresses, including biotic and abiotic stresses. *P. simonii* performs well in dealing with heavy metal pollution. Studies have shown that as the age of small-leaf poplar trees increases, it can reduce the heavy metal content in the wood part while increasing the accumulation of heavy metals in the leaves [14]. Not only does this help improve the quality of contaminated soil, it is also critical to ensuring the safety of timber production. In addition, C.-H. Yang [15] research found that the *PsnPI-PLC6* gene in *P. simonii* under cadmium stress conditions will transiently up-regulate its expression. This change enhances the plant's ability to scavenge reactive oxygen species (ROS), thus improving the overall resistance of forest trees and improving forest trees' resistance to environmental stress. These findings reveal the physiological mechanism of *P. simonii* in response to heavy metal stress and provide a scientific basis for using this species for soil remediation and environmental management.

P. simonii exhibits remarkable drought tolerance, a trait critical to its survival in semi-arid environments. S Meng's [2] research found that under drought conditions, *P. sibiricum* will increase its own and ammonium ion transporter-related genes (nitrogen is a key nutrient for plant growth, and the improvement of its absorption efficiency will help *P. sibiricum* to survive in a water-scarce environment, life-sustaining activities), thereby improving the efficiency of nitrogen absorption. In addition, some studies have reported that the root system development of *P. simonii* also shows that the application of nitrogen can improve the drought resistance of seedlings [16]. This fully demonstrates that, as a key nutrient for plant growth, nitrogen absorption efficiency is crucial to the survival of *P. simonii* in a water-scarce environment Shangzhu Gao [17] focused on *PxbHLHo2* in *P. simonii*. This gene can positively respond to drought stress by regulating the opening and closing of leaf stomata and ABA signaling. Changjian Du [18] confirmed molecular markers related to drought tolerance and identified two candidate genes and five key regulatory genes significantly related to drought stress response through homologous gene analysis. In addition, members of the MAPK signalling pathway (*PsnMAPK7-2*, *PsnMAPK16-1*, *PsnMAPK19-2*, *PsnMAPK20-2*) also play an important role in the drought resistance process of *P. minifolia* [19]. Fangyuan Song [20] identified four key regulatory factors (*PtoeIF-2B*, *PtoABF3*, *PtoPSB33*, and *PtoLHCA4*) that play important roles under drought stress and confirmed their functions. In summary, *P. simonii* has improved its adaptability to arid environments through a variety of molecular mechanisms and physiological pathways. These mechanisms include but are not limited to the regulation of nitrogen metabolism and changes in the activity of transcription factors. These findings are crucial not only for understanding the survival strategies of *Populus* spp. but also for understanding the survival strategies of *Populus* spp. and providing valuable reference for research on drought-tolerant breeding of other plants.

P. simonii needs to cope with a variety of temperature stresses during its growth and development. Research has found that certain genes in *P. simonii* can be expressed under temperature stress, thereby enhancing its tolerance to temperature changes. For example, low-temperature conditions can induce the expression of *PsnICE*1 in *P. simonii*, which responds to the abscisic acid response element (ABRE) and activates downstream stress genes that scavenge reactive oxygen species (ROS), thus enhancing the plant's tolerance to low temperature [21]. Under high-temperature conditions, the research of Jiahong Xu [22] found that *lncPs*3 and *eIF*2*D* genes cooperatively up-regulate expression, which indicates that lncRNA also plays a key role in temperature response. At the same time, high temperature will also promote the expression of *HSF* family genes in *P. simonii*, which shows that related genes may play an important role in the adaptation process of seedlings to temperature [23]. The research of Nan Xu [24] further pointed out that high temperature will inhibit the electron transfer capacity of the photosynthetic system in leaves. Still, increasing CO_2 concentration can alleviate the photosynthetic inhibition caused by high temperature. These findings deepen our understanding of how *P. simonii* adapts to different temperatures through molecular mechanisms and provide potential improvement strategies for future plant breeding.

Salt-alkali stress is often accompanied by metabolic dysfunction. *P. simonii* triggers a complex series of molecular coping mechanisms to cope with this adverse condition. Research has found that NAC transcription factors are particularly significant under salt stress, and *NAC*42 [25], *NAC*86, *NAC*105, *NAC*139, *NAC*163, *NAC*15, and *NAC*149 show specific spatiotemporal patterns under salt stress [26]. The research of Xiaojin Lei [27] further deepened our understanding of this phenomenon. He clarified the specific process of *NAC*83 regulating downstream gene expression. Similarly, Wangyuting [28] also found *PsnNAC*090 specifically expressed in the roots of *P. simonii* under salt stress. In addition to *PsnNAC*090, *PsPRE*1 [29] [30] and *PsnPLC* [31] also play an important regulatory role in the *P. simonii* root system responding to stress. In addition, the expression patterns of related members of the *F-box* family [32], *XTH* family [33] and *HD-Zip* family [34] also changed significantly under salt stress. Under alkaline stress, it is often accompanied by the specific expression of HSF family genes. Qing Guo's [35] research on *PsnHSF*21 found that this gene is self-activating under alkali stress. A series of other genes, such as *EXPA*8, *EXPA*4, *EXPA*3, *EXPA*1, *EXPB*3, *EXP*10, *PME*53, *PME*34, *PME*36, *XTH*9, *XTH*6, *XTH*23, *CESA*1, *CESA*3, *CES*9, *FLA*11, *FLA*16, *FLA*7 and *PsnWRKY*70, are also involved in the alkali stress response process plays a key role [36]. Finally, it is worth mentioning that the interaction of *P. microphylla* with arbuscular mycorrhizal fungi is also crucial for improving salt-alkali tolerance. Fengxin Dong's research shows [37] that related interactions can change the expression pattern of *PxNHXs*, thereby affecting photosynthesis and ion absorption to enhance related salt-alkali tolerance. If the nitrogen absorption efficiency of *P. simonii* is improved under saline-alkali stress, the damage caused by the stress can also be reduced [38]. These research results jointly deepen our understanding of the stress resistance of *P. simonii* at the molecular level and provide potential molecular targets for improving the tolerance of *P. simonii* to salt-alkali stress.

The biotic stress resistance mechanism of *P. simonii* is also a research hotspot. Ruiqi Wang identified four transcription factors related to disease resistance, including *AtWRKY*75, *ANAC*062, *AtMYB*23 and *AtEBP*, through the leaves of poplar (*P. simonii* × *P. nigra*) [39]. Further studies have shown that *PsnWRKY*70 enhances poplar resistance to Rhizoctonia allochthonii by activating genes related to pathogen-related molecular patterns (PTI) and effector-induced immunity (ETI) [40]. Exogenous application of sorbitol can further induce *PsWRKY*25 and *PsCERK*1 to improve the resistance of *P. simonii* to diseases [41]. These findings demonstrate the complex disease resistance mechanism of *P. microphylla* and point out the key role of specific transcription factors in regulating plant immune responses and provide relevant biotechnological means to enhance plant resistance to disease.

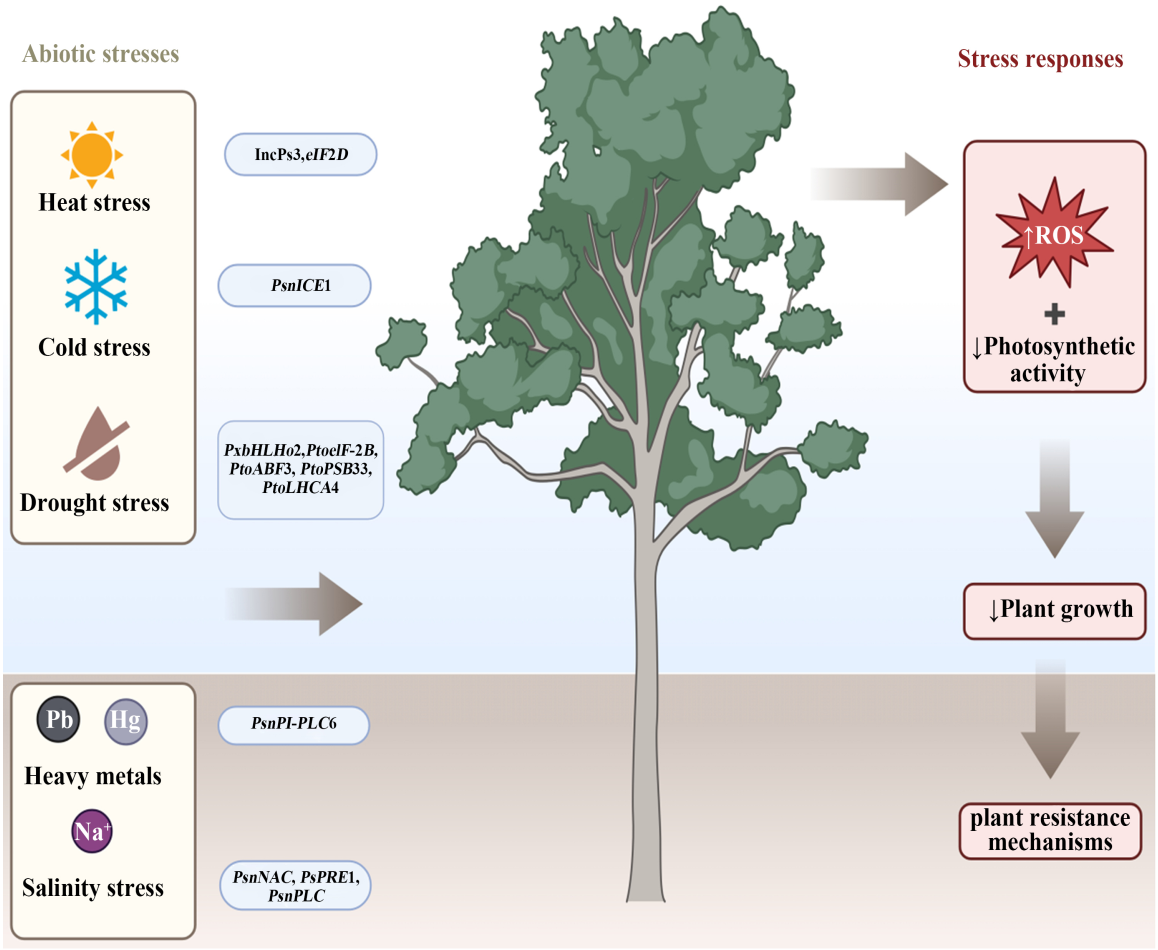

Figure 2. Schematic abiotic stresses resistance in *P. simonii*.

In addition to the above, Yuting Wang [42] also characterized 9 *PtSROs* in Populus plants that can respond to different kinds of abiotic stress. Shenmeng Wang [43] found 10 *YABBY* family genes expressed under three abiotic stresses: heat, salt and osmosis in poplar (*P. simonii* × *P. nigra*). Kewei Cai [44] identified 33 potential *PsIAAs* and 35 *PsARFs* in the entire genome of *P. microphylla*. Among them, the *PsIAA7* gene is a central hub and interacts with many Aux/IAA and ARF proteins. These findings indicate that these genes are not only involved in specific stress responses but may also intersect to form a comprehensive network to improve the overall adaptability of the plant (**Figure 2**).

5. Research Progress on the Protection of Wild Poplar Populations of *P. simonii*

Human activities are the most important factor leading to the decline and fragmentation of the natural population of *P. simonii*. The study of Zunzheng Wei [45] used 20 microsatellite markers to analyze the genetic variation and structure of 16 natural populations. The results revealed differences in the levels of genetic diversity among different populations, and obvious subpopulation structures were observed. Junjie Dai [46] and Qiaoting Zhai [47] used the MJS model to study *P. simonii* populations with different degrees of decline and explored the relationship between sap flow rate (SF) and the degree of decline. found that soil moisture conditions and decline of small-leaf poplar mainly changed the peak sap flow rate timing, but not its onset. The research of Jiaxuan Zhou [48] focused on the interaction between lncRNA regulatory factors and target genes when *P. microphylla* was distributed in different regions, and found the existence of different regulatory types, which may affect Populus microphylla's ability to adapt to environmental changes. Yang Yuli's research shows [49] that the random forest and multi-layer perception models can more accurately detect and monitor vegetation decline, providing new tools for plant ecology research. These studies were carried out from multiple dimensions such as genetic diversity, ecological response, environmental adaptability and vegetation decline monitoring of *P. simonii* populations, and are of great significance to understanding and protecting the survival of this wild *P. simonii* in the environment.

6. Progress in Breeding Research of *P. simonii*

Research on small-leaf poplar breeding mainly focuses on shortening the breeding cycle, improving plant morphological structure, improving environmental adaptability and stress resistance. Considering the long life cycle of forest trees, shortening the breeding cycle has become a key point in breeding work. As one of the most active points of plant growth, the terminal bud is not only a reproductive organ, but also an important environment sensing organ, which directly impacts the overall shape and structure of the plant. In terms of research on terminal bud growth of *P. microphylla*, Wangyiran [50] and others used haploid breeding technology, and through morphological comparison and omics analysis, compared the terminal bud growth differences between the diploid and male parent of *P. microphylla*, which enhanced the improved understanding of the growth regulation mechanism of *P. simonii*. Polyploidization is also of great significance in forest tree breeding and genetic improvement. Ying Zhang [51] used a callus regeneration strategy to construct allodiploid plants, and these plants showed better abiotic stress tolerance. Caixia Liu [52] induced poplar haploid based on anther culture method and found that the induced diploid lines showed high variability, and some lines showed the potential to become model plants for genetic and breeding research. Research by Ma Hongwen [53] showed that although the stomatal density of triploid leaves is significantly smaller than that of diploid leaves, the chlorophyll content is significantly higher than that of diploid leaves, and the stomatal length and stomatal width are significantly greater than that of diploid leaves. It is worth mentioning that there is also research supporting that polyploidization will considerably reduce the viability of *P. microphylla* stamen pollen [54]. In terms of improving the stress tolerance of *P. simonii*, Xiao-Xiao Zhang [55] and Jian Wu [56] used colchicine to induce varieties with fast growth, easy cutting propagation, and tolerance to salt-alkali and drought. Wang Yang [57] introduced exogenous genes (such as betA and TaLEA) and suppressed expression genes (such as *PsnWRKY*70) to increase betaine content and cultivated plants with high resistance to drought and salinity. PeERF1 transgenic'84k' poplar also plays a positive regulatory role in response to drought [58]. Regarding hybridization, research by Ding Changjun [59] showed that hybrid plants can protect photosynthetic organs by regulating energy dissipation and show superiority under salt-alkali stress. In terms of cutting propagation, it has been found that the rooting abilities of leafy and leafless poplar cuttings are different. Adventitious root formation can be promoted by applying different concentrations of IBA and sucrose on the top of leafless cuttings, with the combination of 0.2 mg/ml IBA and 2 mg/ml sucrose having the best effect. Photosynthesis may also affect the formation of adventitious roots in leafy poplar cuttings [60]. Finally, in terms of genome-wide association mapping research, Zunzheng Wei [61] and others identified three key markers closely related to morphological characteristics through SSR markers, which is of great value for accelerating poplar breeding of fast-growing and highly resistant varieties. At the same time, image technology can be used to screen resistant *P. microphylla* through leaf morphological characteristics [62], and Peng Liu [63] further explored the mechanism of *P. microphylla* leaf morphology and found that the *PtoYAB*11 gene promotes the unique shape of *P. microphylla* leaf margins. Wenguo Yang [64] further explored the morphogenesis mechanism of *P. microphylla* through specific SNPs. The above research progress shows that through different breeding strategies and technologies, the growth traits of *P. simonii* can be effectively improved, and its environmental adaptability and stress resistance can be improved, which is very important for forestry production and ecological protection.

7. The Application and Ecological Benefits of *P. simonii* in Afforestation

P. simonii is important in afforestation, especially in soil and water conservation and ecological environment improvement. To maximize these benefits, *P. simoniis* are typically planted in leeward locations to reduce wind damage and promote their growth [65]. Research by Dong Cheng [66] pointed out that if *P. simonii* is mixed with plants such as *Hippophae rhamnoides* and *A. fruticose* [67], it can conserve water and soil more effectively and significantly improve the plant's resistance to drought resistance [68]. This is because *P. microphylla* is able to transfer water from shallow soil layers to deep layers during the soil wet-to-dry process, which helps maintain plant growth under drought conditions [69]. Research by Ping Liu [70] found that in semi-arid areas, *P. simonii* stands of different ages showed different hydrodynamic characteristics. Elizabeth R. Rogers [71] further studied the water use efficiency of *P. simonii* and its hybrids at different ages. In terms of improving the environment, although *P. simonii* can be used for vegetation restoration [72], *P. simonii* is not the best choice compared to black locust and larch [73]. Among fire prevention strategies, mixed planting of poplar and fir (Abies fabri) can reduce fire risk because this mixed forest is relatively challenging to burn [74]. In terms of wood production, Wu Xinhua [75] explored the longitudinal distribution of wood quality changes in artificially planted *P. simonii*. However, in northern China, poplar windbreaks have generally experienced widespread decline and death, mainly due to extreme drought [76]. These studies show that in afforestation projects, multiple factors such as poplar planting location, mixed plant species, forest age, fire prevention needs, and soil and water conservation functions should be comprehensively considered to achieve the best ecological benefits.

8. Research on Sex Identification of *P. simonii* and Protoplast Expression System

In addition to the research mentioned above, research on *P. microphylla* also involves gender identification and the development of plant protoplast expression systems. Adult poplar poplars can be sexually distinguished by observing the seed hairs produced by female plants, which is a morphological identification method. In the seedling stage, researchers have developed an early sex identification technology based on male-specific sequences. This technology can accurately identify gender in the early stages of plant growth and is of great significance for forest tree breeding and gender-related research [77]. In plant cell research, protoplast transient expression systems are a powerful tool for studying gene function and cell signalling. However, for *P. microphylla*, there are relatively few research reports in this area. Chengjun Yang's work optimised the protoplast extraction method and determined an extraction system suitable for *P. microphylla* [78]. This provides a basis for further molecular biology research and gene function verification.

9. Conclusion and Outlook

As a fast-growing deciduous tree, poplar (*P. simonii*) has made significant progress in research on genomics, resistance mechanisms, population research, breeding and silviculture. Future research could use genetic information to breed improved varieties with enhanced adaptability and stress resistance. In addition, by continuing to carry out population research and ecological applications, poplar can be used more effectively.

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Data Availability Statement

Data are based on the author's own judgements or taken from publications cited and properly referenced.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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