

Systematic Review and Future Trends of Pine Wilt Disease Prevention and Control Strategies

Yunxiang Pan

*College of Biological Science and Technology, Beijing Forestry University, Beijing, China
826735562@qq.com*

Abstract. Forest resources are important assets for China, and they have ecological and economic value at the same time, so we should give them priority attention in national development. Pine wilt disease (PWD) is caused by *Bursaphelenchus xylophilus*, and it is one of the most dangerous forestry diseases that can threaten the ecological security of forest ecosystems in many regions. In forestry development, we should strengthen prevention and control of pine wilt disease, and full management measures can be used to reduce the damage to forest resources. We examine the damage characteristics and transmission mechanisms. Also, we review prevention-control technology systems including physical methods, chemical methods, and biological control for PWD. It is worth noting that we analyze the key challenges in prevention and control, which includes poor drug penetration, uneven liquid distribution, and low control efficiency, so the results can be used as a reference for full disease management. Our objectives are to promote healthy growth of pine trees and enhance forest resource quality. Also, we should safeguard China's ecological environment. Next, future research directions and new technology developments are discussed, such as precision control, nanotechnology applications, genetic research and other new technologies. This can offer theoretical foundations and practical insights for integrated pest management of pine wilt disease.

Keywords: Pine Wilt Disease, *Monochamus Alternatus*, Biological Control, Chemical Control, Integrated Management

1. Introduction

Forest resources are very important natural assets in China. Pine wilt disease (PWD), which is caused by the pine wood nematode *Bursaphelenchus xylophilus*, is one of the most destructive forestry diseases in China and it can threaten ecological security of forest ecosystems and cause damage to forest resources. It is worth noting that we should use integrated management strategies to prevent and control PWD, which can help reduce the forest resource degradation.

Forests work like Earth's pulmonary system. They provide ecosystem services including water conservation, air purification, climate regulation, and biodiversity maintenance and these functions can be very important for keeping environment stable and supporting human life in the long term. In fact, forest conservation is considered important for addressing global challenges. These include greenhouse gas emissions, biodiversity loss, soil erosion, water scarcity, atmospheric pollution, and

ozone depletion. PWD is a devastating forest epidemic. It can threaten the forest ecosystem stability and constrain sustainable forestry development in China, so enhanced PWD management should be a conservation priority.

Climate change is accelerating and human disturbance is increasing. Forest pest outbreaks can become more frequent and severity can also increase [1]. Forest pests can impair forestry production and ecological security, suppressing tree growth and reducing timber yield and the quality is also affected and trophic networks are disrupted so ecosystem imbalance can be caused [2]. These impacts can make it hard to develop sustainable forestry and maintain the ecological barrier functionality. In fact, the pest-affected areas are expanding and pathogen diversity is increasing, which has constrained mountainous forestry economic development and farmer livelihood improvement. Among forest pathogens, PWD is one of the most severe forest diseases. It has rapid onset and extensive transmission and management is difficult. Its dissemination has caused extensive pine mortality across China, impacting regional forestry economies and community livelihoods.

2. Pine wilt disease

Bursaphelenchus xylophilus, known as pine wood nematode, is parasitic nematode affecting pine species. Adult specimens measure about 1 mm and females have conical tails with rounded termini and males display ventrally curved claw-shaped tails. It is listed as major quarantine pest and invasive alien species in China [3]. This nematode is transmitted by vector insects. *Monochamus alternatus*, the Japanese pine sawyer beetle, is one important vector. In fact, nematode invasion can disrupt pine vascular systems and physiological metabolic dysfunction is induced, causing tree mortality. *B. xylophilus* has wide host range. It can infect at least 51 *Pinus* species and 16 non-*Pinus* species. In China, 17 susceptible tree species are documented including *Pinus massoniana*, *P. yunnanensis*, as well as *P. thunbergii* [4].

Pine wilt disease, also called pine witherment disease, is a systemic infection with rapid pathogenesis, high virulence, and extensive transmissibility, but it is hard to manage so it is called "pine tree cancer." In fact, without intervention, infected pines can almost all die. After *B. xylophilus* invades, resin secretion becomes less and needles lose water and turn yellow, then become reddish-brown with a "fire-scald" look, and finally the tree dies [5]. Uncontrolled epidemics can destroy entire pine forests in a few years and this causes serious economic loss. It is worth noting that three mechanisms are suggested: enzyme-mediated tissue degradation via cellulase and pectinase secretion, phytotoxin-induced physiological suppression, and cavitation that disrupts water and nutrient transport [6].

PWD incidence shows clear seasonality. The prevalence increases from summer to autumn. Hot and humid weather can increase disease incidence, and this is related to life cycles of *M. alternatus*. In summer and autumn, environment conditions help nematode reproduce while beetles can emerge and feed, which makes transmission and infection worse [7].

It is worth noting that PWD originated in North America. However, the epidemic can be most severe in Asia and can cause extensive pine mortality. In 1982, we first detected it in Nanjing of Jiangsu Province. Then the disease spread across southeastern coastal areas, inland regions, and also northern China. According to National Forestry and Grassland Administration (2025 Announcement No. 4), 18 provincial-level administrative regions including Jiangsu, Zhejiang, Anhui, Chongqing, Sichuan, Liaoning, Jilin, Shandong, Fujian, Hubei, Guangdong, and Guangxi are designated as PWD epidemic areas, and this shows that the disease has become a serious problem in these regions [8].

3. Current research status

PWD has rapid transmission and high pathogenicity. At the same time, the management is complex and it can be a global threat to pine forest ecosystem. It is worth noting that researchers from different countries have investigated control technologies to stop PWD dissemination by targeting the transmission vectors and pathogens. They developed biological and chemical control methods, as well as physical control approaches. Each approach has advantages but also limitations. The method should be chosen based on epidemic intensity, forest stand characteristics, as well as environmental requirements. In the following, we can summarize the research progress for these control methods.

3.1. Biological control

Biological control has good environmental sustainability and it is specific to pathogens, so in principle we can use it as a promising approach for PWD management in forest ecosystem when we consider the long-term effect and the safety to non-target organisms. In the practice, there are various applications we can choose. Pathogenic microorganisms can be used to target *B. xylophilus* and *M. alternatus*. Also, predatory natural enemies can be introduced as another method. In fact, PWD transmission is expected to depend on *M. alternatus*, so the biological control efforts can focus on this vector species and we can expect good control effect.

We can release parasitoid wasps including *Scleroderma guani* and *S. chuan* at density of 500–1000 individuals per mu between May and June in plantation and natural forests, and 40%–60% *M. alternatus* larval mortality can be achieved so population suppression can be significant. Standing dead trees should be retained. It is worth noting that they create habitat for woodpeckers and other avian predators and the vector regulation can be enhanced [9].

In biopesticide applications, we use drone monitoring with entomopathogenic formulations. It is worth noting that during cloudy periods or evenings, *Metarhizium* and *Beauveria* powders can be applied to lower pine trunks during larval stages before adult emergence, or we can use powder cannons to deliver these materials and this can reduce *M. alternatus* populations and restrict PWD transmission [10].

Pheromone-based regulation can be used as a management tool. Also, if we put *M. alternatus* sex pheromone traps in field with 30-meter intervals, we can capture adult beetles [11], while mating disruption applied at forest margins can prevent invasion into healthy stands. It is worth noting that combined implementation can reduce *M. alternatus* populations by over 60%, and this can lower transmission risk in principle, which means healthy forest can be protected from pest invasion and the disease spread can be stopped.

3.2. Chemical control

In chemical PWD management, formulations with systemic penetration ability are needed and commonly used compounds include avermectins and neonicotinoids. Fumigants are also used. Enamectin benzoate (typically 3% microemulsion, 50 mL per bottle) is now the standard agent for trunk injection because it can show good efficacy [12]. However, thiacloprid and chlorpyrifos have been banned or restricted because they can cause high environmental risk [13]. Advances in chemical and molecular biology continue to yield new compounds. It is worth noting that fluensulfone, a nematicide for root-knot nematodes registered in the United States, can provide mechanistic insights for PWD pesticide development [14].

Several methods can be used. Trunk injection and crown spraying are common, and fumigation is also used for infected wood. In fact, trunk injection can be a better choice because the pesticide use efficiency is high. Dosage depends on diameter at breast height (DBH): we use 1 bottle for tree <20 cm DBH and 2 bottles for 21-30 cm DBH, while for 31-40 cm DBH it should be 3 bottles, and it is worth noting that the solution uptake is expected to complete within 3-5 days and we record actual dosage for each tree.

Trunk injection of emamectin benzoate can suppress PWD spread. It is proved that *Pinus tabuliformis* mortality is reduced and the survival rate of trees is improved after we use this method in the field and this shows that trunk injection can be a good way to control PWD [12]. But chemical control has some problems. In fact, the improper implementation including inappropriate fumigation technique can compromise the tree health and this is a big problem for forest managers who want to protect the trees from dying because of wrong operation [15], and we should also note that pesticide residues can cause environmental contamination and there are non-target impacts on avian and beneficial arthropod populations while resistance can develop in both *M. alternatus* and *B. xylophilus* populations [13].

3.3. Physical control

Physical control has three parts: infected wood treatment, vector suppression, and also forest stand management. First, we can chip the infected wood to make fiberboard. Heat treatment or incineration can also be used, and the pathogens can be removed [16]. For example, Hezhou City carried out felling and on-site incineration or heat treatment for the infected trees and surrounding pines within 200 meters [17]. Second, physical vector trapping uses netting, pheromone traps, and also black light traps. It can exploit insect phototaxis to capture adult *M. alternatus* [18]. Third, stand management can improve canopy ventilation and light penetration by removing diseased trees and dead trees, and also using selective pruning. Then the pine stress resistance can be enhanced [18].

3.4. Comprehensive comparative analysis

Biological control can provide environmental sustainability and target specificity. It is worth noting that most nematicidal compounds only show stable activity in laboratory conditions. Field applications have environmental variability and this can affect pathogenic microorganism and biopesticide performance and the efficacy is not consistent [19]. Therefore, biological control can only serve as an auxiliary PWD management strategy at present. Chemical trunk injection has shown efficacy in some regions. But non-target impacts and regulatory restrictions on high-risk compounds including thiacloprid and chlorpyrifos can limit the wide application [13]. Physical control is environmentally compatible. It has sustainability without chemical contamination. But for large-scale forest applications, much technical expertise and labor investment can be required.

In PWD management, we should follow basic principle. Biological control is the main strategy. Chemical control can be used as supplement and physical control is the foundation. We should integrate multiple approaches based on forest type, epidemic severity and ecological requirements, and in fact we should combine these different methods so that we can develop a full management system which is expected to achieve good control results [20].

4. Stage issues and mitigation strategies

4.1. Current challenges

It is worth noting that chemical control has a main limitation we should consider. The pesticide utilization efficiency is low. Pine xylem pit membranes have average pore diameters of 20–50 nm, and they can work as nanoscale filters. Conventional nematicides such as avermectin have molecular diameters exceeding membrane permeability thresholds, which can prevent vascular system penetration. Also, suberized outer bark tissue and needle epicuticular waxes impede compound penetration. When drones are used for application in the field, droplets run off because of surface tension or adhere to outer surface without penetrating inner tissue, and we can see that the actual pesticide utilization is less than 30%. This inefficiency can increase control costs while reducing efficacy, because target organisms are not exposed to enough pesticide.

Vascular incompatibility can cause uneven distribution of compounds. The xylem and phloem transport pathways in trees show selectivity regarding the molecular size and polarity. Also the compound affinity is important, which means tree vascular system can choose what to transport based on these properties and this characteristic can make it hard for conventional compounds to enter. In fact, it is hard for conventional formulations to adapt to vascular tissue characteristics. This can prevent long-distance transport via transpiration stream or phloem sap. Following trunk injection, compounds just accumulate around injection sites and we find that they can fail to disperse to terminal branches and crown regions, and these regions are most susceptible to nematode infection, so there exist control blind spots and the protection is not complete.

We should also consider ecological risk and the resistance evolution. When pesticides are applied initially, satisfactory control can be achieved, but non-target organisms may be harmed and ecosystem function can be disrupted. Also, it is worth noting that selection pressure can drive resistance development in the pest and pathogen populations, and the control efficacy is expected to be reduced which makes it hard to maintain good control.

Physical control similarly demonstrates limitations, primarily low efficiency and high implementation costs. Large-scale applications require extensive labor and time investments, constraining operational effectiveness.

4.2. Mitigation approaches

Pesticide utilization is not efficient. We should use biological control to replace chemical applications and environmental quality can be improved. Also, trunk injection should be chosen rather than drone spraying. It can help deliver chemicals directly into vascular system and the efficiency can be higher [21]. At the same time, new formulation development can improve compound penetration and translocation capabilities. It is worth noting that routine monitoring and early warning in epidemic and surrounding regions should be strengthened. Then timely detection and intervention can be achieved and range expansion can be prevented.

We recommend zone-specific management strategies. In core epidemic areas, physical control methods can be used. This includes infected wood decontamination and chemical trunk injection. It is expected to help contain the epidemic. In the mild epidemic areas, we should implement biological control where natural enemy release and biopesticide application can be used together with pheromone regulation which can minimize chemical use and maintain control effect without causing environmental problems. Healthy protection zones need monitoring and biological control and this can establish epidemic barrier. It is worth noting that ecologically fragile regions such as

alpine areas should prioritize biological control and this can balance conservation and epidemic management [22].

5. Research prospects

Many studies have been done on conventional PWD chemical control. In fact, we should explore sustainable pathways to make the management green and efficient. First, precision control technologies including geographic information systems [23] can help build site-specific application systems. We use "individual tree-specific strategies" based on intraspecific variation in these systems. Second, new pesticide formulations including biodegradable polycaprolactone-based controlled-release granules can enhance efficacy and reduce environmental impact. Third, integrated chemical-biological control networks combining nematicides with *Beauveria bassiana* beetle-specific strains [24] can establish the diversified management models and we can use them in practice.

Nanotechnology has good potential. In study by Cai et al. [25], multifunctional nanocarriers can help control PWD. PLGA-PEG systems can load avermectin and the translocation efficiency is improved by 4.2 times compared to normal formulations. At the same time, the efficacy duration can reach 90 days. Also, pH-responsive mesoporous carbon nanospheres target xylem acidic environments. It is worth noting that we can control the compound release within 72 hours. These applications can provide solutions for long-term PWD management. More research should be done.

Molecular detection and genetic approaches can provide more options. In fact, Cheng et al. [26] developed dual-gene combined PCR amplification with specific primers targeting ribosomal DNA internal transcribed spacer and the genomic regions, and established rapid *B. xylophilus* detection systems. It is worth noting that Tian et al. [27] emphasized that we should expand resistance gene diversity in the future work. Also, functional genomic studies can enable gene editing to disrupt *B. xylophilus* pathogenicity-related genes and reduce virulence and pine resistance gene research can help develop PWD-resistant varieties [26, 27].

In general, Chinese PWD management technologies now can move to green solutions. We also expect the system to be durable, and it should be precise and intelligent. In fact, the full integration of physical and chemical control technologies, together with biological control and new IT methods, can help establish multi-level management systems. Also, we use GIS precision application and nanotechnology, and genetic engineering is included. It is expected to realize scientific PWD governance that is sustainable, and this can protect the forest resource security in China.

6. Conclusion

Pine wilt disease (PWD) is one of the most destructive diseases in China's forestry. It has rapid onset. Also, transmission is widespread and control is difficult. This disease threatens forest ecological security. It can also affect sustainable forestry development. For PWD prevention, we can use biological control and chemical control. Physical control is also available. But each has limitations. Biological control is environmentally friendly. But environmental factors affect it. The efficacy is unstable. Currently we can only use it as auxiliary measure. Chemical control through stem injection has a good performance. However, pesticide utilization is below 30%. There are issues including uneven distribution and ecological risks. Resistance is also a problem. Physical control is sustainable. But it has high costs and low efficiency. Therefore, actual prevention should follow integrated principle. Biological control should be main method. Chemical control is auxiliary. Physical control is the foundation. We should implement differentiated strategies based on

forest land types and epidemic levels, while considering various ecological requirements. Future PWD control technologies will develop toward greening, precision, intelligence, and long-term effectiveness. This includes GIS for precise tree-by-tree control. Also, PLGA-PEG nanocarrier drug delivery systems can improve conduction efficiency. And gene editing can be used to interfere with *Bursaphelenchus xylophilus* pathogenicity genes. At the same time, we can breed disease-resistant pine varieties. It is worth noting that we should integrate physical and chemical control with biological methods, and we should also combine traditional and new technologies to construct a multi-dimensional prevention system, and through this system scientific management and long-term governance of PWD can be achieved. This can safeguard China's forest resource security.

References

- [1] Lan, Y. J. (2025). Application and effectiveness evaluation of biological control technology in forest pest and disease control. *Agricultural Science and Technology Innovation*, (31), 51-53.
- [2] Shi, Y. R., & Yuan, H. M. (2025). Research and application of biological control technology for forest pest and disease. *Forestry Science and Technology Information*, 57(3), 163-165.
- [3] Wang, L. C., Chen, F. M., Dong, X. Y., Tian, C. L., & Wang, Y. (2023). Study on feeding and oviposition characteristics of *Monochamus alternatus*. *Journal of Nanjing Forestry University (Natural Sciences Edition)*, 47(2), 219-224.
- [4] Duan, X. Y. (2025). Occurrence and prevention technology of pine wilt disease. *Modern Horticulture*, 48(24), 120-122.
- [5] Zhang, L. (2025). Study on identification methods and distribution characteristics of pine wilt disease in Anhui Province. *Modern Agricultural Science and Technology*, (17), 57-60.
- [6] Liu, Z. (2025). Research progress on pine wilt disease control using gene editing technology. *Heilongjiang Science*, 14(16), 107-109.
- [7] Lao, X. Y. (2025). Pine wilt disease prevention technology. *Rural Science Experiment*, (22), 101-103.
- [8] National Forestry and Grassland Administration. (2025). Announcement of the National Forestry and Grassland Administration (No. 4 of 2025): Pine wilt disease epidemic area in 2025. Retrieved from official government website.
- [9] Zhang, M. Q. (2023). Application of biological control technology in forest pest and disease control in Shaanxi Province. *Southern Agriculture*, 17(16), 18-20.
- [10] Chen, L., Liao, S. L., & Ye, L. F. (2025). Prevention and control strategies and suggestions for pine wilt disease in Lianping County. *Modern Horticulture*, 48(24), 117-119.
- [11] Xie, M. C. (2013). Impact of dead pine wood cleaning on *Monochamus alternatus* population. *Forestry Investigation and Design*, 33(1), 97-102.
- [12] Wang, H. M. (2025). Preliminary report on experiment of tree trunk injection of emamectin benzoate for prevention of pine wilt disease. *Henan Forestry Science and Technology*, 12(4), 6-8.
- [13] Pan, S. J. (2023). Research progress on biological control technology of pine wilt disease. *Journal of Anhui University (Natural Science Edition)*, 47(4), 92-99.
- [14] Qin, G. Y. (2016). Research progress on chemical control of pine wilt disease in China. *Henan Agriculture*, (23), 38-40.
- [15] Chen, Y. (2022). Analysis of comprehensive control strategy for pine wilt disease. *Seed Science and Technology*, 40(1), 97-99.
- [16] Wang, J. W., Sun, Q., Sun, T. Y., et al. (2024). Research progress on comprehensive prevention and control technology of pine wilt disease. *Shandong Forestry Science and Technology*, 54(4), 91-99.
- [17] Jiang, Y. (2025). Occurrence characteristics and comprehensive prevention and control measures of pine wilt disease in Hezhou City. *Southern Agriculture*, 19(2), 184-186.
- [18] Sang, W., Gao, Q., Zhang, C. Y., et al. (2022). Research and application progress of physical control in Chinese agricultural pests. *Journal of Plant Protection*, 49(1), 173-183.
- [19] Jin, C. (2025). Research progress on biological control of pine wilt disease. *Liaoning Forestry Science and Technology*, (2), 66-69.
- [20] Li, Y. (2025). Characteristics and prevention and control technology research of pine wilt disease, common forestry pests and diseases. *Digital Agriculture and Intelligent Agricultural Machinery*, (8), 82-85.

- [21] Liao, L. D. (2024). Analysis of occurrence characteristics and prevention technology of pine wilt disease in Pingle County. *Southern Agriculture*, 18(24), 215-217.
- [22] Guo, S. C. (2024). Exploration on application of biological control technology for alpine pine wilt disease. *Farming Technology*, (30), 142-145.
- [23] Xu, G. X., Yu, R. B., Yang, C. X., et al. (2023). Prediction of invasion risk of pine wilt disease in western Sichuan based on GIS spatial technology and MaxEnt model. *Journal of Beijing Forestry University*, 45(9), 104-115.
- [24] Li, Z. Z. (2015). History, progress and current status of China's use of fungi to control pests. *Chinese Journal of Biological Control*, 31(5), 699-711.
- [25] Cai, F. P., Xiu, M. F., Pan, H., et al. (2025). Comprehensive prevention and control of pine wilt disease: Multi-dimensional collaborative governance from traditional strategies to nanotechnology. *Shandong Forestry Science and Technology*, 55(6), 93-98.
- [26] Cheng, W. J., Luo, Z. J., Chen, L., et al. (2021). Establishment of dual-gene detection method for pine wilt disease. *Hubei Forestry Science and Technology*, 50(2), 60-65.
- [27] Tian, C., Kuang, S. Y., Li, D. B., et al. (2024). Research progress on host plant resistance genes of pine wilt disease. *Liaoning Forestry Science and Technology*(4), 51-54.