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Review

The Advancement and Prospects of the Tree Trunk Injection Technique in the Prevention and Control of Diseases and Pests

Qingqing Shang, Hongcai Lu, Mengdi Yang, Yujie Wu and Qing Chen *

School of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China; qqshang@njfu.edu.cn (Q.S.); luhc@njfu.edu.cn (H.L.)
* Correspondence: qchen@njfu.edu.cn

Abstract: Traditional spraying of pesticides causes significant drift losses, and the residues of pesticides can also affect non-targeted organisms in the environment. Tree injection technology is a precise and targeted pesticide delivery method used in the prevention and treatment of tree and fruit tree pest infestations. It uses the tree's xylem to transport the injected pesticides throughout the entire plant, reducing pesticide exposure in an open environment. This review summarizes the basic principles and development process of tree injection technology, compares its advantages with other application techniques, describes the development of injection equipment and key information to be aware of, and proposes suggestions for future research directions in injection application techniques.

Keywords: crop protection; tree trunk injection; pesticide application

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1. Introduction

The tree trunk injection technique is a chemical application technology used to prevent and treat tree diseases [1] which allows pesticides to be administered inside the tree [2]. In traditional orchards and forests, insecticides and fungicides are often applied through methods such as foliar spraying or irrigation [3]. Although these methods are effective at killing pests, they often produce negative effects such as environmental pollution, human exposure, and the risk of accidental ingestion by other organisms [4]. The tree trunk injection technique can inject pesticides directly into target trees, reducing human exposure to the pesticides and the risk of unintended diffusion beyond the intended targets [5]. Therefore, it can be a suitable option for densely populated areas where other pesticide application techniques are not feasible [6].

Foliar spraying technology is the most common method of pest control, but its efficiency is low due to losses caused by spray drift [7–9]. For trees with a large crown and dense foliage, spraying is challenging [10]. In addition, some pesticides that are easily deposited in the body are restricted or banned from use. Soil drenching is an alternative to foliar spraying, which applies pesticides to the soil around the tree, allowing the roots to absorb the pesticides for pest control [11]. Although only a small portion of the effective component of the pesticide is absorbed into the tree, the residual portion remains in the soil for a long time and can cause continuous environmental impacts [12].

The technique of injecting pesticides into the trunk of a tree allows for direct delivery to its internal structure without creating any adverse environmental effects [9]. This approach permits the use of a wide range of agents that can be injected and absorbed to attain optimal therapeutic effect with the least amount of phytotoxicity. As the pesticides administered through tree trunk injection circulate internally, they endow long-term resistance against infestations by parasitic organisms that threaten the tree's health [13]. In comparison to alternative treatment methods, the practice of tree trunk injection affords greater protection over a prolonged duration, thus reducing the frequency of pesticides administration [9].

2. Mechanism of Tree Trunk Injection

2.1. Transportation within Plants

Plants absorb carbon dioxide, water, and inorganic nutrients from the environment, which need to be transported to the required parts for utilization. There is evident division of labor in nutrient absorption between the underground and aboveground parts of terrestrial plants: the root system obtains water and inorganic nutrients from the soil solution, most of which is transported to the aboveground parts for the needs of stems, leaves, flowers, and fruits. In tall trees, the transport distance can reach hundreds of meters. Non-photosynthetic organs such as roots, stems, flowers, fruits, etc., obtain organic substances from photosynthetic organs, primarily the leaves [14]. In addition, various plant organs also influence each other through the transmission of hormones. Upon localized application, artificially synthesized internal absorption of pesticides (insecticides, herbicides, etc.) and growth regulators can spread throughout the plant body, also achieved through the transport system [15].

The conducting tissues within the plant body primarily consist of xylem and phloem, as depicted in Figure 1. Xylem, located in the wood, is composed of numerous dead cells connected by xylem vessels [16]. These vessels possess perforated end walls, forming hollow conduits whose function is to transport water and inorganic salts absorbed from the roots to various parts of the plant [17]. Additionally, the arrangement of xylem vessels also influences the fundamental structure and functional properties of the wood. Phloem, on the other hand, is the tissue responsible for transporting organic substances within the plant's bark [18]. It is composed of a series of interconnected tubular living cells. Numerous small pores, known as "sieve pores", are present on the cross-walls between adjacent cells, allowing for the exchange of protoplasm and the formation of a pathway for the transport of assimilates. Research has indicated that the lateral movement of minerals is facilitated through both active transport by thin-walled cells in the xylem and diffusion through cell walls, gradually spreading toward the inner regions of the heartwood.

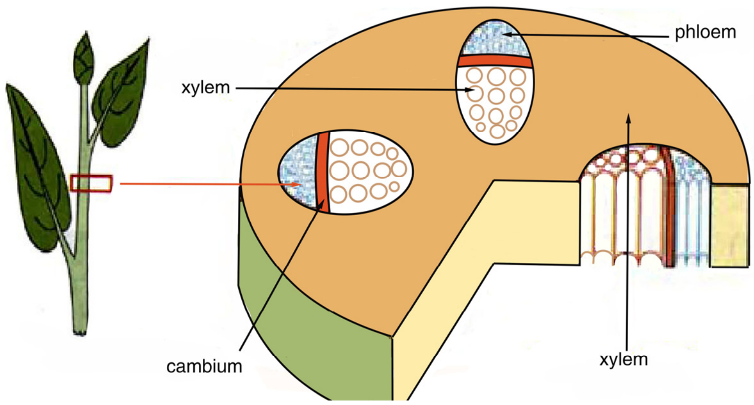


Figure 1. Cross-sectional and longitudinal diagrams of woody plants' anatomy.

2.2. Theory of Transpiration-Cohesion-Tension

The theory of transpiration-cohesion-tension is a significant concept in the field of plant physiology, elucidating the mechanism of water transport within plants [19]. This theory was introduced by the Irish scientist H.H. Dixon in the late 19th century. Through experimental research, Dixon discovered that water within the plant is transported through the interplay of transpiration, cohesion, and tension.

Transpiration refers to the process in which water vapor evaporates from the plant and enters the air. After water molecules inside the plant evaporate from the surface of the leaves, they form a chain of water molecules that extends downward into the plant's roots, thus forming a pathway for water transport [20,21]. The formation of this pathway is the result of the interaction between cohesion and tension.

Cohesion refers to the mutual attraction between water molecules, enabling them to form a continuous chain-like structure. Tension, on the other hand, refers to the pulling force acting on the end of the water molecule chain. This tension arises because the end of the water molecule chain is exposed to air, where water molecules are comparatively sparse. As a result, the water molecule chain experiences a pulling force. This pulling force causes the water molecule chain to extend upwards, ultimately forming a water transport pathway from the roots to the leaves [19,22–24].

Understanding the intricacies of water molecule movement can aid in comprehending the absorption and transport mechanisms of pharmaceuticals injected into tree trunks [25]. As the pesticides traverse, they distribute themselves throughout various compartments of the tree. Depending on the specific objective, pesticides can exert their effect on tree leaves, branches, bark, or roots, among other regions. For instance, pesticides used for disease and pest control can form a protective layer on the leaves, thwarting insect invasions. Similarly, nutrient-supplying pharmaceuticals can be absorbed through the tree's root system, providing the necessary nourishment for the plants.

2.3. Hypothesis of Stress Flow

The Pressure-Flow Hypothesis, also known as the Driven Membrane Theory, is a theory that describes the translocation of organic substances in plant vasculature [26]. This theory was originally proposed by German botanist E. Münch, and it explains that the flow of organic matter in plants is driven by the pressure gradient generated by the plant itself, and that this flow occurs through the vasculature [27].

According to the theory of hydraulic conductivity, plants absorb water and nutrients from underground and convert them into organic matter, which then moves into the vascular bundle through intercellular spaces. The movement of these substances is regulated by two pressures within the plant: root pressure generated at the root and vapor pressure created by transpiration in the aboveground leaves [28,29]. Transpiration in leaves leads to significant water loss, creating a negative pressure region between the leaves and the air. This negative pressure region drives the movement of water within cells towards the leaves, resulting in upward transport of water in the vascular bundle and simultaneous transport of organic matter. In the roots of the plant, water and dissolved inorganic salts enter the plant, and root pressure facilitates their upward transport.

3. The Development Process of Tree Trunk Injection

The practice of introducing pesticides into plants through cutting or puncturing has a long history. Since the 12th century, Arabian horticulturalists have been applying dyes and fragrances onto plant wounds to influence the color and scent of flowers and fruits [30]. In the 15th century, Leonardo da Vinci injected poisonous solutions containing arsenic into tree trunks, rendering the apples toxic [30]. In 1853, Hartig treated symptoms of inorganic compounds deficiency in trees by injecting solutions containing ferrous sulfate and ferric chloride into their trunks [30]. In 1894, American botanist Ivan Shevyrez began experimenting with tree trunk injections for pest control [31]. Since the 20th century, significant advancements have been made in the fields of botany, plant physiology, agriculture, and forestry. In the 1940s, effective treatment for Dutch elm disease (*Ophiostoma Ulmi Biusman*) was discovered through tree trunk injections of propiconazole benzoate solution [6,32–40]. In 2004, Calzarano's experiment proved that grapevines receiving trunk injection of Cyproconazole were in better nutritional condition and had higher yield and lower mortality rate than those without such injections, demonstrating the beneficial effect of fungicide injection through the trunk on root rot [41]. Injecting pesticides or antibiotics into a tree trunk has proven to be an efficient method for treating diverse tree diseases and preventing the invasion of harmful pests [6,42–45]. In 2013, Akinsanmi's experiments showed that biannual application of phosphite during autumn and spring root wash periods effectively controlled tree decline in Australian macadamia trees [46]. In 2018, Dalakouras discovered the potential of RNA interference for crop protection, utilizing tree trunk injections of hairpin RNAs (hpRNAs) and small interfering RNAs (siRNAs) to efficiently absorb and transport RNA molecules throughout the xylem and phloem tissues, triggering RNAi to eliminate pests that chew on the wood or feed on the sap [47].

4. Advantages of Trunk Injection

4.1. Easy and Accessible Operations

The technique of trunk injection not only overcomes the limitations imposed by tree height and affected areas, but also simplifies the control of pests and diseases that are difficult to manage using conventional methods such as foliar application. This includes pests and diseases such as upper canopy insects, root pests, sap-sucking insects protected by wax covers, boring insects, and vascular diseases. Additionally, trunk injection is not constrained by environmental conditions and can still be implemented under continuous rainfall or severe drought without water shortage, making it a feasible chemical control method in such circumstances [48,49].

4.2. High Pesticides Utilization Rate and Prolonged Efficacy

Due to the height of the trees themselves, traditional liquid spraying methods are insufficient in reaching the topmost ends of taller trees. This leads to significant wastage of the pesticidal solution. Furthermore, such waste can infiltrate the soil and rivers through rainfall, resulting in environmental pollution. Insufficient absorption of the pesticides by the trees also diminishes its effectiveness in controlling diseases and pests. On the contrary, tree trunk injection technology allows for precise control over the amount of pesticides entering the tree's system [9]. This greatly enhances the efficiency of pesticides usage and avoids the influence of environmental factors such as rainfall and sunlight [50,51], thus extending the efficacy period. With its highly effective prevention and treatment results, this technique fundamentally improves the efficiency of pesticides usage while also preventing environmental pollution [52]. In the control of pear psylla, the therapeutic effect of injecting azadirachtin and abamectin into the trunk is superior to that of spraying insecticides on the leaves [53]. Trees that were treated with trunk injection since the first season still showed a moderate level of control effectiveness in the second season [53].

4.3. Wide Range

Due to the internal distribution of the liquid within the trees, the tree injection method effectively eliminates highly concealed pests [8]. In contrast, conventional external spraying techniques fail to directly address pests with strong concealment, resulting in significantly lower effectiveness in preventing and treating tree diseases and pests [54]. For instance, data show that tree injection techniques achieve a control rate of over 95% for the citrus long-horned beetle, with a larval mortality rate exceeding 90%, demonstrating remarkable efficacy [55,56].

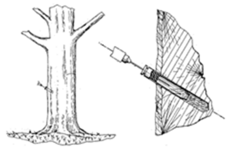
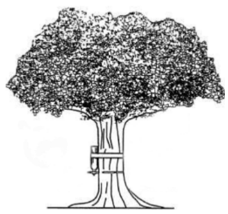
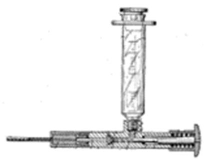
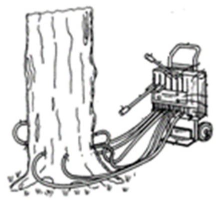
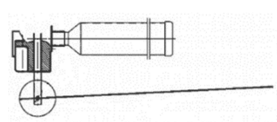
4.4. Reducing the Contamination of Pesticides

Traditional pesticide spraying techniques can lead to a significant residue of chemicals on the surface of trees, including trunks, leaves, and fruits. This, in turn, can result in substantial environmental contamination as the excess chemicals are washed away by rainwater and find their way into rivers and soil, posing a serious threat to both the environment and human health [8,57,58]. Moreover, the spraying techniques inevitably have adverse effects on the natural predators of pests, with the potential to even eliminate these beneficial organisms [59], thereby compromising the effectiveness of pest control efforts. In contrast, tree trunk injection methods do not generate pesticide pollution in the ecological environment. Instead, they contribute to the protection of non-target organisms and the personal safety of applicators, ensuring that the application of chemically potent pest control substances remains clean [60,61]. This approach fulfills the requirements of environmental conservation, ecological preservation, and personal safety.

5. Injecting Methods and Devices

The machinery for injecting tree trunks with pesticides has undergone nearly a century of development, progressing from gravity-based, pressure-based, and hydraulic to mechanized methods [49,62]. This evolution has resulted in faster pesticides infusion, reduced labor intensity, and the emergence of various injection techniques [48], as depicted in Table 1.

Table 1. Some equipment for tree trunk injection.

Classification Basis	Name	Explanations of Measures and References	Features
No-Pressure Injection	Duane Cronenwett	Insert the capsule-shaped container into the borehole and administer the pesticides by piercing the sealed cap with an external needle [63].	
Low-Pressure Injection	West Otho S	Injecting a treatment liquid into a hole drilled into a trunk of a tree comprising a container for receiving the treatment liquid and a closure for closing the container [64].	
	William	The needle portion of the device may be inserted into the plant either by applying force to the body of the device or by drilling hole sized relative to the width of the needle in the plant and inserting the needle therein [65].	
	Gillespie John	Utilize manual hydraulic cylinders for the infusion process, enhancing the efficiency of pesticides administration through multiple outlets [66].	
High-Pressure Injection	Peter Wild	Improvement design of pesticides injection device, merge the connecting rod and piston rod, with both ends of the merged component equipped with pistons [67].	
	Qingqing Shang	Portable high-pressure large-capacity tree injection device, incorporating a circular self-retracting serrated blade and a needle with excellent sealing properties to the tree trunk [68].	

5.1. Low-Pressure Injection Method

The technique of low-pressure injection is commonly employed for the purpose of stem injection, where a solution is introduced into trees using lower pressure. Before using the injection device, bore 1–5 holes on the trunk (depending on tree diameter) using a drill bit [69], reaching a depth of 3–5 cm into the woody tissue, with the holes slanting downward at approximately 30 degrees [8]. In 1977, William and his colleagues designed a manual tree injection device that operates on a similar principle to intravenous injections in humans or animals [67], characterized by its small size and simple structure. It gradually inject the pesticide into the tree using the syringe, allowing it to enter the tree's xylem vessels through transpiration. In 1994, a method was developed in the United States that involves cutting the output tube into several small sections, connecting them with a three-way joint, and puncturing holes in a circular pattern around the tree [64]. The third joint is inserted into the hole, and pesticide is delivered evenly and simultaneously into the tree through the output tube. This method has the advantage of increased injection speed and even distribution of pesticides, avoiding the risk of high concentrations of pesticides causing damage to the tree trunk. The technique of low-pressure injection can be employed for purposes such as fertilization, pesticide application, nutrient supplementation, and pest management, among others. It is applicable for a wide range of trees and plants. Furthermore, it is important to select the appropriate pesticide based on the type of tree and to avoid the use of pesticides that may be harmful to the tree's health [65,70].

5.2. No-Pressure Injection Method

The no-pressure injection method involves taping the pesticide bottle to the tree trunk, inserting a needle into the tree, and slowly allowing the pesticides to enter the tree through the needle [54]. This method is cost-effective, does not require specialized equipment, and is effective in preventing and treating disease. However, the injection and flow rate of the pesticides are slow, relying on the natural diffusion of the pesticides into the xylem. Additionally, this method may lead to damage to the tree's phloem and cambium tissues due to prolonged exposure to the pesticides around the injection site. This method of injection is suitable for smaller vegetation such as trees, flowers, and shrubs. It is commonly utilized for purposes such as fertilization, pesticide application, and nutrient supplementation. Additionally, the pressure-free injection method is relatively safe and minimally harmful to the trees.

5.3. High-Pressure Injection Method

The method of high-pressure injection refers to the utilization of mechanical pumps or hand-press piston pumps [71]. It employs specialized high-pressure injection apparatus to forcefully inject the required insecticides, fungicides, and micro-fertilizers into the trees and plants. The injection pressure varies depending on the trees. In 1985, Gillespie John developed a tree pesticides device that employed a manually operated hydraulic cylinder for injection [66]. The hydraulic cylinder piston is connected to a connecting rod, which controls the suction of hydraulic fluid. The device is equipped with six independent hydraulic cylinders, capable of outputting in six different directions. Three cylinders are grouped together, and their pistons are driven by a single main handle. Therefore, by manipulating a single handle, the simultaneous injection of liquid into three hydraulic cylinders can be achieved. In 2003, Peter Wild and others made improvements to the design of the liquid injection gun developed in 2001 [72]. The modified product combines the power rod and the piston rod. Both ends of the combined rod have pistons, with one end being the pesticides chamber piston, and the other end being located in the compressed gas chamber. This allows the gas to directly propel the piston without causing vibrations.

6. Critical Technological Challenges

To prevent and control diseases and pests in forests and fruit trees as well as regulate their growth and development through trunk injection, it is crucial to master the selection of injection agents and proper dosage preparation. Choosing appropriate timing, injection sites, and depths is also necessary for effective trunk injection treatment.

6.1. Selection of Injectable Pesticides

When selecting and configuring injection agents for trees and fruit trees, it is important to consider the species, injection pressure of the equipment, and the resistance of pests and diseases. It is advisable to prioritize the use of systemic agents that facilitate the transportation and conduction of the medication. There are two types of systemic injection agents: emulsifiable concentrate and aqueous concentrate [70,73,74]. For effective transportation of the pesticides, both of these agents should have a pH ≤ 7, presenting an acidic or neutral nature. It is crucial to avoid using alkaline agents with a pH > 7 as they can be strongly adsorbed by the negatively charged cell walls in the woody tissues of trees, thereby affecting the pesticide's distribution. Experimental results have shown that the aqueous concentrate has better transportation efficiency and causes less damage to the plants compared to the emulsifiable concentrate [75].

In the management of forest pest control, it is advisable to opt for long-lasting efficacious agents such as imidacloprid and phoxim as stem injection agents. For the control of pests and diseases in fruit trees, it is recommended to use fungicides like carbendazim, insecticides like fenvalerate, and acaricides like thiodicarb which have shorter residual periods, lower toxicity, or exhibit less translocation to flowers and fruits [76,77]. When formulating pesticides, it is important to consider the injection pressure of the stem injection equipment and the tree species and accordingly select an appropriate concentration. The concentration for pest and disease control in fruit trees should be about 5% to 10% lower than that for forest trees.

6.2. Injection Site and Depth

Due to the inherent characteristics of the tree trunk injection technique, careful consideration should be given to the choice of injection position and dosage. Different tree species and ages require different injection positions. Generally, the injection site on the tree trunk is recommended to be less than 1 m from the ground [78]. For fruit trees, injections should be administered below the first branch. The injection depth should be determined based on the size of the tree, the thickness of the bark, and the purpose of pest control [51]. In the case of foliage-feeding pests, injections should be targeted towards the cambium layer, allowing the pesticidal solution to be transported through the tree's transpiration vessels to the crown and leaves. On the other hand, when treating pests at the tree roots, injections should be directed towards the phloem layer, facilitating the movement of the pesticides through sieve tubes to the roots for effective pest control. The ideal injection depth is when the needle exit point is located on new wood that is 1–2 years old [75]. It should not be excessively deep, as that may hinder the transfer of the pesticidal solution, nor too shallow, as it could harm the phloem layer and compromise the efficacy of the treatment.

6.3. Timing of Administration

As trees continue to grow, the characteristics and types of pests and diseases affecting them also change. In the process of trunk injection pesticide application, the injection timing should be adjusted based on the target of prevention and control [13,79]. For most folivorous pests, the best time to inject pesticides is before they hatch. For aphids and mites, the best time is before their population outbreak. As for boring pests such as *Anoplophora glabripennis* and *Agrilus planipennis*, pesticides should be injected during their first to third instar larval period and adult emergence period, respectively. Considering the mortality rate and residual amount caused by *Bursaphelenchus xylophilus* infection, it is expected that abamectin should be injected into the trunk from November to February of the following year, and emamectin benzoate should be injected from October to April of the following year. When administering injections into the trunk of a tree, there is a possibility of residual pesticides remaining within the tree. Therefore, it is imperative to adhere strictly to the recommended safety interval for pesticide residue when treating fruit trees. Cease pesticides administration within two months prior to the harvest season in order to prevent any lingering pesticide residues [80].

The dosage for each injection hole is determined based on the tree diameter, injection pressure, concentration and efficacy of the pesticides [81]. If high-pressure, high-concentration injection is employed, it is generally recommended to use 1–3 mL of pure pesticides for every 10 cm of tree diameter. Please calculate the dosage for each injection hole accordingly. If low-pressure, high-volume injection is used, please calculate the dosage for each injection hole based on the concentration of the pesticides solution and the number of injection holes. The variance in the wood tissue structure and physiological characteristics among different tree species can potentially result in variations in the efficacy of stem injection techniques. Certain tree species may exhibit greater sensitivity towards pesticides absorption and distribution, whereas others may display a poorer response to injected pesticides [82]. Consequently, when employing stem injection techniques, it is crucial to tailor the pesticides selection and injection method based on the specific tree species in question.

6.4. Protection of Injection Wound

The technique of trunk injection may potentially have negative implications on the vitality of trees. The introduction of pesticides through this method has the potential to inflict harm upon the tree's tissues, thereby posing risks such as leaf shedding, trunk decay, or an overall decline in tree health. Moreover, an excessive or frequent administration of pesticides through trunk injection could disrupt the tree's nutrient balance, consequently impacting its growth and well-being. Therefore, following the administration of pesticidal injections to trees, it is inevitable that injection wounds will occur [83–85]. In order to prevent wound infection, it is advisable to incorporate an appropriate amount of plant growth regulators into the injected pesticides, thus ensuring proficient wound care for the trees [75]. Spring and summer seasons result in faster wound healing for sweet oranges injected with streptomycin compared to autumn or winter. The damage caused by injecting into the scion is less than injecting into the rootstock [86].

7. Conclusions and Prospects

7.1. Summary of Trunk Injection Technology

The tree trunk injection technique offers a rapid, efficient, and precise method for delivering pesticides directly into a tree's transport system. Undoubtedly, this has opened up new pathways for chemical control of pests and diseases affecting trees and fruit crops, and has demonstrated promising practical applications. However, due to significant climatic variations and unique characteristics of tree species and pests/diseases in different regions, necessary adjustments and optimizations in injection techniques and equipment are needed. Compared to foliar spraying, the trunk injection technique requires a lower pesticide dosage, yet the injection devices are more costly and the operation requires skilled and qualified personnel [9,50–53]. Although the current cost is still relatively high, the technique remains irreplaceable in managing specific pests and diseases.

7.2. Looking Ahead to Future Research Directions

The research on the prevention and control techniques for different tree species and pest management of fruit trees under various climatic conditions needs further in-depth exploration. This can be mainly reflected in the following aspects:

(1) The focal point of the research lies in the investigation of the physiological and mechanical characteristics of xylem and phloem tissues in various tree species and their relationship with the applied injection pressure of trunk injection pesticides based on climatic factors. Additionally, the study also encompasses the exploration of intelligent trunk injection devices.

(2) Research and development of specialized biopesticides for systemic absorption in different types of trees, including various fruit trees. The structural organization, permeability, and root distribution of various trees and fruit trees can affect the design and formulation of bioactive internal absorbents used in conjunction with them [38,70,73,74,76,77]. This

necessitates in-depth research on the absorption mechanisms, physiological activities, and relevant pests and diseases of trees.

(3) The electrification and intelligence of tree trunk injection technology are trends in modern agricultural technology [87–89]. Electrification can replace traditional manual or manpower-driven injection equipment, improving productivity and accuracy. By utilizing electric devices, a continuous and stable flow of injection can be achieved, while reducing uncertainties associated with manual operation. Intelligence can be achieved by incorporating sensors and control systems, enabling automated control and monitoring. These systems can collect data on the environment and tree conditions, and automatically adjust the injection flow and application method based on predefined parameters. Moreover, intelligent systems can also provide remote monitoring and control functions, allowing remote operations and data sharing, enhancing farmers' production management capabilities.

(4) The investigation into the distribution, conduction, absorption, and potential harm caused by the long-term presence of pesticides within different tree species is a complex topic that necessitates the integration of diverse fields of knowledge and research methodologies [15,51,69]. Conducting such studies requires a comprehensive consideration of the physicochemical properties of the pesticides, the physiological and mechanical characteristics of trees, and environmental factors. This holistic approach aims to enhance the safety and efficacy of plant protection agents and facilitate sustainable agricultural development.

(5) Intelligent monitoring of the efficacy of tree injection for forest pest control [90,91]. By monitoring the physiological indicators of trees, such as leaf temperature, chlorophyll content, and photosynthetic rate, the health status of trees can be evaluated. These data can be used to assess the occurrence and development of pests and diseases, thus allowing for timely adjustments to prevention and control measures. By monitoring the sensors on the surface or inside the trees, the presence and distribution of pests and diseases can be detected in real-time. For example, insect traps and breeding point monitors can be used to collect relevant data, and image processing technology can be used to analyze the type and quantity of pests and diseases. Intelligent monitoring systems can also monitor the distribution of internal pesticides in trees. By installing pressure sensors and flow control devices at the injection site, the release and diffusion of injection pesticides can be monitored in real-time, which can help to evaluate the absorption and distribution effect of pesticides and ensure effective prevention and control of pests and diseases.

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