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RESEARCH ARTICLE

Microbial Diversity as a Biological Control Mechanism for Fruit Tree Diseases: A Comparative Approach

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Abstract: The traditional methods of fruit tree pest control have long relied on chemical pesticides. This not only leads to increased resistance of pests and diseases but also adversely affects the ecological environment and fruit safety. Although biological control has gradually received attention, the current research on how to systematically use microbial diversity to achieve efficient control and prevention is still insufficient. There is a lack of in-depth exploration of its mechanisms and practical application effects. To fill this research gap, this paper proposes a biological control method for fruit tree pests and diseases based on microbial diversity. A bioremediation agent is prepared using actinomycetes from the rhizosphere soil of fruit trees, and its effectiveness is verified through field experiments. The results showed that the incidence rate of pear rust was 9.64% and 12.27% when biological and chemical agents were sprayed on pear trees. The incidence rate of pear trees in natural growth reached 39.51%, and the disease index increased by 18.09% compared with spraying chemicals. Under the action of biological and chemical agents, the incidence rate of pear scab was 8.94% and 11.18%, and the incidence rate of natural growth was 28.42%. In addition, the biological agent also showed good control effects on apple anthracnose and leafroller, with a soluble solids content of 55.08% and a vitamin C content of 63.11 mg/100g in the fruit. The proposed biological control method has a good effect on fruit tree pests and diseases, and can reduce environmental pollution and increase fruit yield compared to chemical agents.

Keywords: Biopharmaceuticals, Actinomycetes, Prevention and Control Effect, Diseases and Pests, Fruit Tree

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Introduction

The prevention and control of Fruit Tree Pests and Diseases (FTPD) has always been a difficult task for agricultural development. Although China is continuously promoting research in this area, how to effectively prevent and control pests and diseases remains a major challenge. Many scholars have conducted extensive research on the prevention and control of pests and diseases. For example, Jadhav et al. evaluated the yield loss caused by pests and diseases on wheat varieties to reduce their harm to food crops [1]. Through estimation, it was found that the avoidable wheat yield losses are relatively low, and aphids have a prominent impact on the avoidable yield losses of grain crops. At present, the main prevention and control methods for FTPD include chemical control, physical control, and biological control. With the rise of biological control methods, research on microorganisms is also increasing. Wang et al. conducted simulation experiments using large paddy soils grown in Chengdu and Guiyang to investigate the relationship between microbial diversity and rice diseases. The functional composition of microorganisms varied significantly in different regions, and the related genes enriched in paddy soils in the two regions were virulence factors and secondary metabolites, respectively [2]. Zhao et al. proposed a simulation of tobacco based on the relationship between soil-borne diseases and the ecosystem composed of microorganisms in rhizosphere soil [3]. The rhizosphere microorganisms of tobacco had a close relationship with their growth environment and metabolites, laying a solid foundation for the prevention and control of tobacco wilt disease. Microorganisms can compete with other microorganisms for living space and nutrients in pest control, thereby preventing the invasion of other pests and achieving control effects. Microbial agents also contain beneficial bacteria for plant growth, which can convert nutrients that are difficult for plants to absorb into absorbable forms, inducing plants to develop resistance to pests and diseases during the growth process. Some scholars conducted experiments to explore the relationship between microorganisms and pests and diseases. Deng et al. proposed to study the correlation between plant microorganisms and the pathogenesis of nematodes by conducting experiments on the rhizosphere fungi and bacteria of Pinus koraiensis as the research object [4]. It was found that with the occurrence of plant diseases, microorganisms showed slight changes in the early stages, and their diversity increased significantly in the later stages.

Chemical control is the most cost-effective and effective method, but long-term use of chemical pesticides can easily lead to the development of resistance in pests and diseases, making the control effect increasingly unsatisfactory. Meanwhile, chemical pesticides can have negative impacts on the ecological environment and human health, affecting the safety of fruit products [5]. Compared to chemical control, physical control is environmentally friendly and easy to operate, reducing the negative effects of environmental pollution. However, physical control methods may not be applicable to some pests and diseases, and cannot effectively control their harm to fruit trees. Compared to chemical pesticides, the cost of instruments and equipment required for physical control is higher, and there is a greater expenditure on equipment maintenance. For chemical and physical control, biological control methods can better control pests and diseases. Biological control mitigates the environmental impact of chemical methods while surpassing the effectiveness of physical control, greatly improving its persistence, safety, and environmental protection [6]. Collinge et al. proposed a biocontrol strategy using antagonistic microorganisms to address yield and quality constraints of plant diseases [7]. Raynaldo et al. proposed the use of biocontrol and other sustainable methods to address black spot caused by Alternaria alternata and black spot caused by Botrytis cinerea grey mould caused by Botrytis cinerea [8]. However, current research on microbial diversity mostly remains at the level of theoretical analysis or exploration of single microbial functions, lacking systematic experimental verification and specific application mechanism research. Therefore, this study proposes a microbial diversity-based FTPD prevention and control method, aiming to improve the effectiveness of FTPD control. This method is used to control fruit trees by adding biological agents of actinomycetes, and the effectiveness of this method in preventing and controlling pests and diseases in fruit trees is verified through experiments. This study innovatively adds actinomycetes on the basis of traditional biological control methods, and uses this new type of biological control method to control pests and diseases in fruit trees, improving the control effect through the interaction between microorganisms. This study aims to use biological agents to reduce the pollution of chemical pesticides on the environment and enhance the resistance of FTPD. Its expectation is to provide scientific basis for improving fruit yield and promoting sustainable agricultural development.

The innovation of the study is mainly reflected in the following two aspects: firstly, this study combines the characteristics of soil microbial communities to screen and apply antagonistic actinomycetes for bioremediation. Secondly, through comparative experiments between chemical agents and natural growth conditions, the control effect of biological agents on common FTPD, as well as their improvement effect on fruit quality, is comprehensively evaluated. The findings provide a theoretical basis and technical guidance for the advancement of green agriculture and ecological cultivation.

Methods and Materials

Biological Control Mechanism of FTPD Based on Microbial Diversity

Diseases and pests not only cause damage to fruit trees themselves but also directly affect fruit production. Climate, soil, and infection from disease and insect sources are all direct causes of its occurrence [9-11]. Adverse environments can easily

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damage the ecological environment of fruit trees and reduce their ability to resist pests and diseases. The common FTPD is shown in Figure 1.

Figures 1 (a), (b), and (c) show fruit tree branch canker, bacterial perforation disease, and apple mosaic, which mainly harm the trunk and leaves of fruit trees. Figures 1 (d), (e), and (f) represent common apple aphids, pear bugs, and pear psyllids, which mainly harm the young buds and new leaves of fruit trees. These pests and diseases have a significant impact on the growth and fruit yield of fruit trees and require timely prevention and control. The occurrence process of FTPD consists of three parts. Firstly, during the invasion period, pests and diseases invade the natural pores, wounds, and cuticle layer of fruit trees. The second part is the incubation period, during which pests and diseases begin to develop under suitable temperature conditions. The incubation period of different pests and diseases in fruit trees may not be the same. If the environment is suitable for the survival of pests and diseases, the incubation period will be shorter, otherwise, it will be longer [12]. The third part is the onset period, during which pests and diseases spread rapidly after a latent period, and fruit trees begin to show signs of damage. If the pest and disease control of fruit trees is not carried out promptly, it may lead to a cycle of infection caused by pests and diseases [13]. Effective prevention and control are necessary to effectively resist the harm of pests and diseases to fruit trees. The biological control mechanism of FTPD is shown in Figure 2.

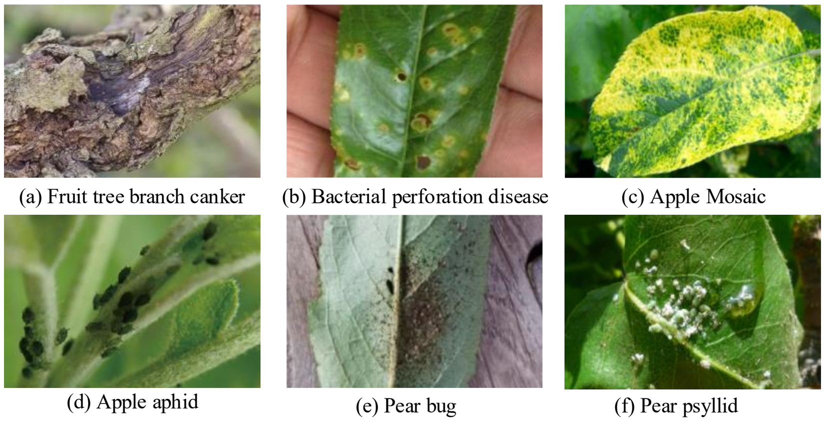

Fig. 1: Common diseases and pests of fruit trees

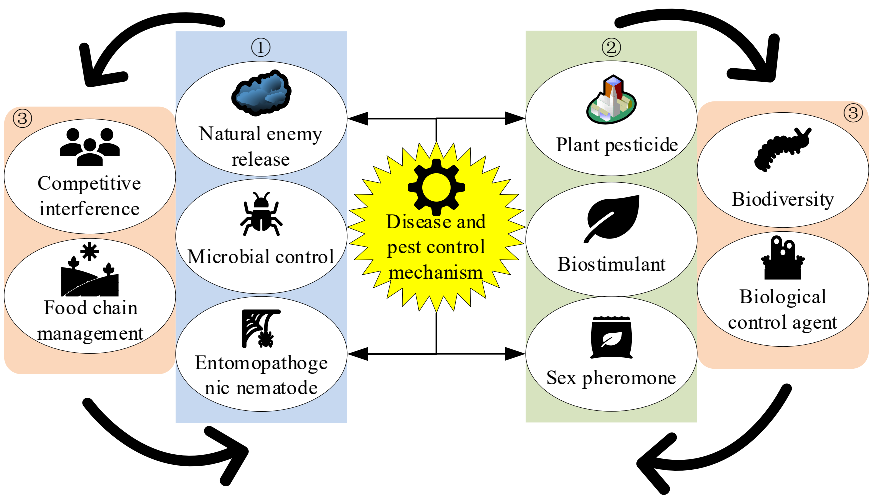

Fig. 2: Biological control mechanisms of FTPD

In Figure 2, the biological control mechanism of FTPD mainly includes three parts. Part 1 includes the release of natural enemies, microbial control, and insect pathogenic nematodes. Part 2 includes plant-based pesticides, biostimulants, and sex pheromones. Part 3 includes competitive interference, food chain management, biodiversity, and the use of biological control agents [14]. Part 1 mainly uses the release of natural enemies of pests, viruses, bacteria, and insect-pathogenic nematodes, for pest control. Part 2 achieves pest control through plant extracts and sex pheromones of pests. Part 3 mainly enriches

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biodiversity by introducing other organisms, such as organisms that compete with similar pests, to control pest numbers. Microorganisms exist in various fields of nature, and their traces of life can be found in both plants and animals [15]. Microorganisms are integral to material cycling, with their diversity supporting sustainable ecosystems [16]. In terms of agricultural development, there is an increasing amount of research on microorganisms. Beneficial microorganisms can promote plant growth and provide some of the nutrients needed for plant growth [17, 18]. This study proposes a novel FTPD biological control mechanism based on microbial diversity, which achieves effective prevention and control of pests and diseases by studying the interaction between microorganisms and FTPD. The research mechanism of FTPD prevention and control based on microorganisms is shown in Figure 3.

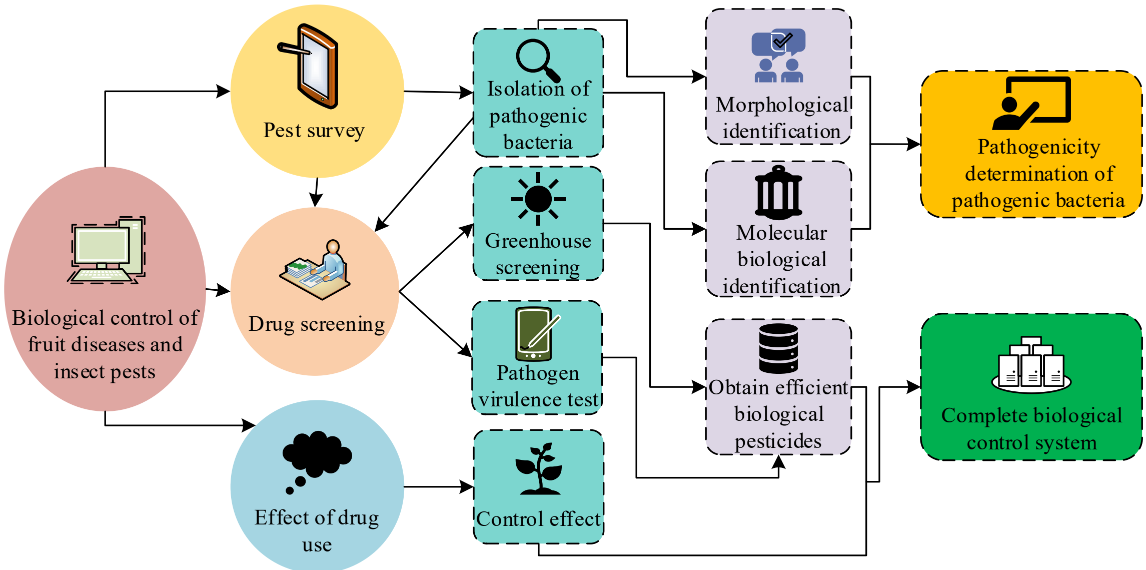

Fig. 3: Research mechanisms for biological control of FTPD

Figure 3 demonstrates the complete research process of the FTPD biological defence and control mechanism based on microbial diversity. The first step is the investigation, isolation, and identification of pathogenic bacteria. Typical disease samples are collected and identified using morphological and molecular biology methods to ensure the clarity and relevance of the subsequent prevention and control targets. The second step is the screening of microbial strains. It mainly isolates actinomycetes from the soil between fruit tree roots and selects strains with good antagonistic activity through in vitro antibacterial experiments, providing a basis for constructing efficient biological agents. Subsequently, it enters the stage of biological preparation and greenhouse pre-testing. The concentration of the agent is reasonably configured, and the method of use is optimized to ensure its safety and adaptability, providing a parameter reference for the field test. The final step is on-site prevention and effectiveness verification. In this study, the selected biological agents are applied to fruit trees, and the effects are evaluated in combination with incidence rate, disease index, fruit quality, and other indicators. During the experiment, it is necessary to calculate the incidence rate of fruit trees, and the formula is shown in Equation (1):

$$E(\%) = \frac{d}{c} \times 100\% \quad (1)$$

In Equation (1), d is the number of diseased plants, and c is the number of surveyed plants. The disease index of fruit trees is calculated as shown in Equation (2):

$$S = \sum \left[\left(p * n \right) / \left(f * C \right) \right] * 100 \quad (2)$$

In Equation (2), p and n are the number of diseased plants at each level and the severity of each level. f and C are the highest disease level and the total number of surveyed plants. The growth of fruit trees is closely related to microbial diversity. Studying the effect of biological agents on the growth of fruit trees to achieve prevention and control of pests and diseases can not only reduce environmental pollution caused by the use of chemical agents but also reduce resource

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consumption in terms of required costs. Biological agents have less impact on humans and animals, have higher safety than chemical agents, do not produce chemical residues, and play a crucial role in maintaining ecological balance.

Experimental Strategy for FTPD Biological Control Mechanism

Snow pear, produced in Hebei Province, is selected as the research object in this study. The row spacing of pear trees is 2 m×3 m. The test site is the Chengde Pear Planting Test Site, which covers an area of 0.29 hm2. Chengde City is located in the northeast, with a temperate continental climate and distinct four seasons. The annual average temperature ranges from -4 ℃ to 7℃, making it suitable for pear tree growth. Based on the characteristics of microbial diversity, this study selects actinomycetes from soil microorganisms to be added to biological agents. During the experiment, biological and chemical agents are used to spray pear trees separately, and the control effect of the agents on FTPD is tested. The colony morphology and spore morphology of actinomycetes are shown in Figure 4.

In Figure 4, actinomycetes are cultured on potato glucose agar medium. The colony grows in the form of filamentous radiation bacteria and is evenly distributed in the culture medium. The mycelial morphology is slender, with a width of about 0.9 micrometers. Actinobacteria are single-celled filamentous organisms, and their main mode of reproduction is spore reproduction [19]. Regarding the occurrence of pear tree diseases and pests, pear rust, pear scab, and pear black spot are selected as diseases, while pear aphid, Stephanotis nashi, and pear psyllid are selected as pests for control. A study is conducted on pear trees by adding biological agents such as matrine, avermectin, and Bacillus thuringiensis. The contents of matrine and avermectin are 0.4% and 1.8%, respectively, while the content of Bacillus thuringiensis is 3500 IU/mg. In addition, 7% of the stone sulfur agent and 0.3% of chlorintraniliprole are selected as chemical agents. The sticky insect board is an empty double-sided sticky insect board. Biological and chemical pesticides are sprayed on pear trees with the same growth and quantity according to the usual dosage. The remaining fruit trees grow naturally without using any pesticides. The experimental process of pest control for pear trees is shown in Figure 5.

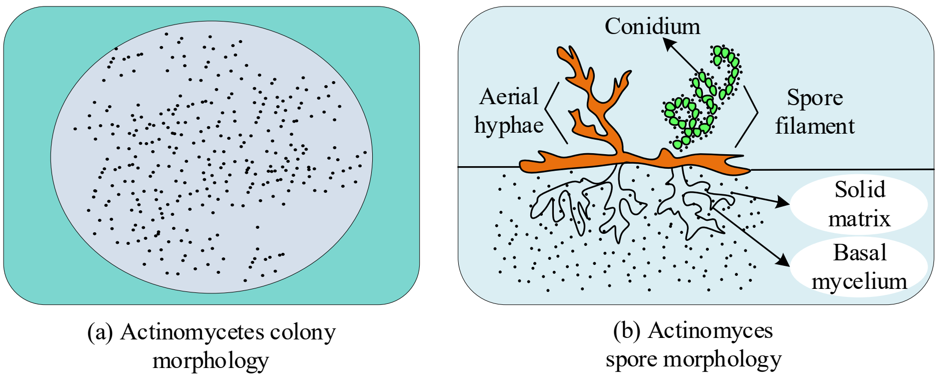

Fig. 4: Colony morphology and spore morphology of actinomycetes

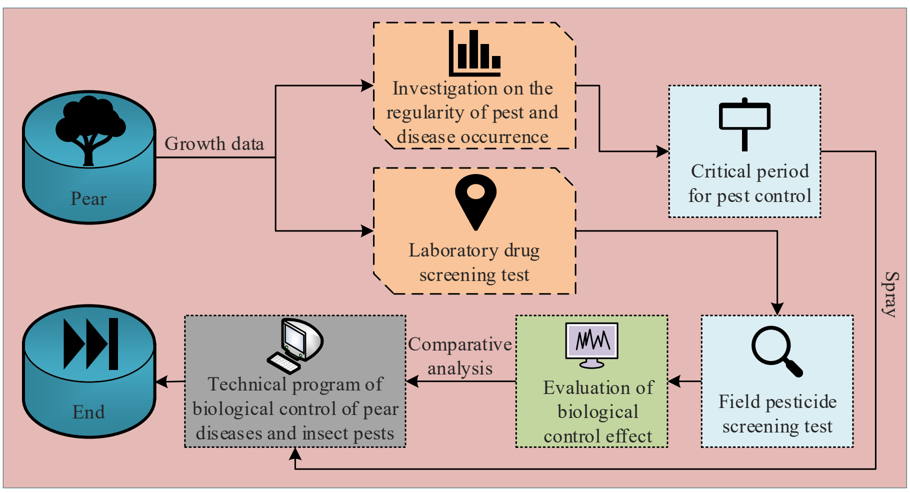

Fig. 5: Pear tree pest control experimental process

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Table 1: Experimental instruments for analysis of biological control mechanism of fruit diseases and insect pests

Experimental instrument	Instrument type	Manufacturer
Electric sprayer	3WBD-20	Shandong Ruichen Agricultural Machinery Co. LTD
Constant temperature incubator	GHP-9080	Wuxi Maret Technology Co. LTD
High speed refrigerated centrifuge	TGL-16M	Hangzhou Chuanyi experimental instrument Co. LTD
Ultra-clean table	HT-DDS	Jinan Tenghao Scientific Instrument Co. LTD
Electronic balance	JJ223BC	Tianjin Times Shuangjie instrument Technology Co. LTD
Microscope	9XF	Shanghai Optical instrument Factory
Vertical pressure steam sterilizer	XCC-18L	Qingdao Xicheng innovation environmental protection technology Co. LTD
Electronic scale	TE-X1000	Shandong Tianer Analytical Instrument Co. LTD
Temperature control electric furnace	DL-2	Jinan Ou Leibo Technology Co. LTD
Magnetic stirrer	ZNCL-T	Zhengzhou Biochemical Instrument Co. LTD

Figure 5 shows the detailed experimental process used in this study to verify the effectiveness of biological and chemical control. The first stage of development is the basic data collection stage. Before each treatment, the growth status of pear trees, the occurrence of pests and diseases, and environmental conditions are recorded to ensure consistency in the initial state between treatment groups. The second stage is treatment imposition. Firstly, pear tree samples with consistent growth are selected and divided into a biological agent group, a chemical agent group, and a natural growth group, and corresponding pesticides are sprayed under the same conditions. After entering the growth and action phase, the agents exert their preventive and control effects for a period of time. After about one week, the results are evaluated to quantify the control effect of each treatment group by investigating the incidence of pests and diseases, disease index, and fruit development indicators. The formula for the rate of insect reduction is shown in Equation (3):

$$D=\left(u-B\right)/u\times100\% \tag{3}$$

In Equation (3), u and B are the number of insect populations before and after treatment. The formula for the prevention and control effect of pests and diseases is shown in Equation (4):

$$N=\left(x-z\right)/1-z\times100\% \tag{4}$$

In Equation (4), x and z represent the pest reduction rate in the control area and the control pest reduction rate. The quality indicators are measured at the beginning of September when the pear fruit is ripe, by randomly selecting 20 pears and measuring their maximum transverse and longitudinal diameters. The fruit type index is shown in Equation (5):

$$F=L/T \tag{5}$$

In Equation (5), L is the longitudinal diameter of the fruit, and T is the transverse diameter of the fruit. The formula for the edible rate of fruits is shown in Equation (6):

$$E=m/w \tag{6}$$

In Equation (6), m is the weight of the fruit after peeling and removing the seeds, and w is the weight of a single fruit. The instruments used in the experiment are shown in Table 1. To verify the significance of differences among treatment groups, the study uses one-way ANOVA to statistically test the main fruit quality indices and the incidence of pests and diseases under the three groups of biological, chemical, and natural growth. The level of significance is set at $p<0.05$ and the analysis is done through SPSS 26.0.

Results

Comparative Analysis of the Performance of FTPD Biological Control Mechanisms

To effectively analyze the prevention and control effects of pear tree diseases and pests, three different scenarios are compared: biological agents, chemical agents, and natural growth. Figure 6 shows the correlation between nutrients in pear tree soil and various microorganisms in the soil.

In Figure 6, the correlation coefficient between organic matter and actinomycetes is 0.95, the correlation coefficient between alkaline dissolved nitrogen and nitrogen-fixing bacteria is 0.97, and the correlation coefficient between total nitrogen and bacteria also reaches 0.97. In addition, there is a significant positive correlation between effective phosphorus and phosphorus bacteria (r=0.91) and between effective potassium and actinomycetes (r=0.83). These results indicate that microorganisms play an important role in the transformation of soil nutrients, with specific flora showing high sensitivity and utilization of specific nutrients. Further analysis shows that these high correlations not only reflect the functional synergy of soil microbial ecosystems but also directly support the mechanistic basis for the growth, health, and resistance enhancement of fruit trees. On the one hand, functional microorganisms such as actinomycetes and nitrogen-fixing bacteria can decompose organic matter, release mineralized nutrients, and improve nutrient availability in the rhizosphere of fruit trees. On the other hand, functional microorganisms can enhance the systemic defence ability of fruit trees against pests and diseases by inducing the expression of plant resistance-related genes and secreting antimicrobial secondary metabolites. Therefore, the significant correlation between microbial diversity and soil nutrition is key ecological evidence for the effectiveness of biological defense mechanisms. Table 2 shows the investigation of selected pear tree diseases and pests in the cultivation area.

In Table 2, pear scab and pear aphid are the two most harmful pests and diseases in pear trees, mainly affecting the leaves, fruits, flower buds, and new shoots of fruit trees. They occur in Gu'an County and Hengshui City, Hebei Province, respectively. Next are pear rust and pear psyllid, which are second only to pear scab and pear aphid in terms of their harm to pear trees. They occur in Hengshui City and Qinhuangdao City. The comparison of various indicators of pear fruit under chemical agents, biological agents, and natural growth conditions is shown in Figure 7.

Figure 7 (a) shows a comparison between chemical agents and natural growth. The three highest indicators are obtained after treatment with biological agents, with pear fruit hardness, soluble solids content, and soluble sugar content of 13.9 kg·cm-2, 17.12%, and 16.91%. The soluble solids content of pear fruit reaches its highest level after the action of biological agents, while the hardness of pear fruit is the lowest under natural growth conditions, at 10.4 kg·cm-2. In Figure 7 (b), the difference in fruit shape index between biological agents, chemical agents, and natural growth conditions is relatively small, with a difference index of only 0.09. The fruit treated with biological agents has the highest vitamin c (Vc) content, at 9.64 mg·100 g, with a fruit shape index and pH of 0.98 and 5.37. The fruit shape index, pH, and Vc content of pear trees treated with chemical agents are 0.89, 4.85, and 7.54 mg·100 g. The fruit shape index, pH, and Vc content under natural growth conditions are 0.85, 4.21, and 6.81 mg·100 g. Among the indicators in Figure 7 (b), there is a significant difference in Vc content, with a maximum difference of 2.83 mg·100 g. Figure 7 shows that the various indicators of pear fruit treated with biological agents are higher than those of chemical agents and natural growth, with the most outstanding performance.

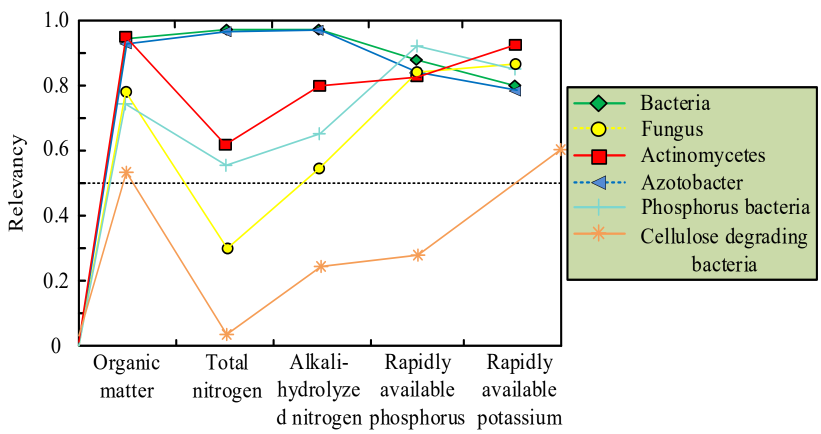

Fig. 6: Correlation between soil nutrients and soil microorganisms in pear trees

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Table 2: Survey results of pest and disease in pear cultivation area in Hebei

Names of pests and diseases	Main hazard site	Degree of harm	Site
Pear rust	Leaves and shoots	++	Hengshui City, Hebei Province
Pear scab	Leaves, fruits, flower buds, shoots	+++	Gu'an County, Hebei Province
Black spot of pear	Fruit, leaves and shoots	+	Shijiazhuang City, Hebei Province
Pear aphid	Leaves, flowers and fruit	+++	Hengshui City, Hebei Province
Pyrrhus	Leaves	+	Tangshan City of Hebei Province
Pear psyllid	Leaves, shoots, fruits and buds	++	Qinhuangdao City, Hebei Province

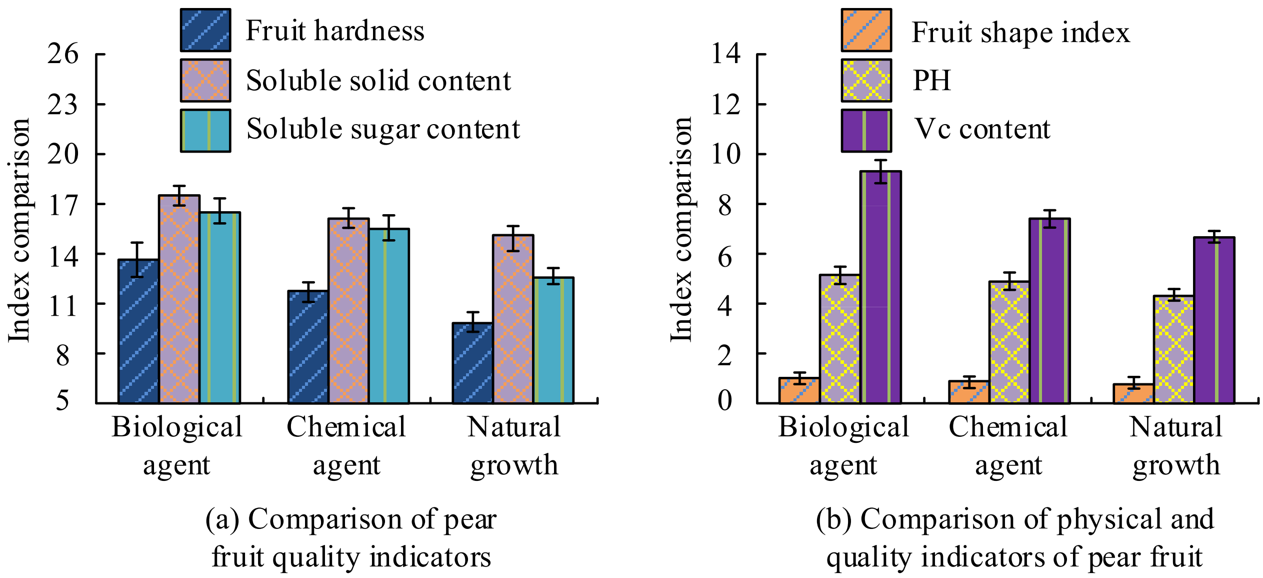

Fig. 7: Comparison of various indicators of pear fruit under the three conditions

Analysis of the Application Results of FTPD Biological Control Mechanism

An equal number of pear tree leaves and fruits are randomly selected for the experiment, and the incidence indices of pear rust, pear scab, and pear black spot are obtained under different treatment conditions, as shown in Figure 8.

In Figure 8 (a), the pear rust incidence rate of pear trees sprayed with biological and chemical agents is 9.64% and 12.27%. The incidence rate of pear trees in natural growth reaches 39.51%, and the disease index increases by 18.09% compared with spraying chemicals. In Figure 8 (b), under the action of biological agents and chemical agents, the incidence rate of pear scab is 8.94% and 11.18%, and the incidence rate of natural growth is 28.42%. The disease indices in the three cases are 4.03%, 5.29%, and 20.97%. In Figure 8 (c), the pear black spot incidence rate of biological agents, chemical agents, and natural growth is 10.22%, 13.67%, and 39.97%. The disease index of naturally grown pear black spot reaches 30.69%, while the disease index of pear black spot treated with chemical and biological agents is only 7.14% and 5.36%. The data in Figure 8 show that the incidence rate and disease index of pear trees after the action of biological reagents are the lowest compared with those of chemical agents and natural growth, indicating that it has the best control effect on pear diseases. The incidence indices of pear aphid, Stephanotis nashi, and pear psyllid in the three scenarios of pear tree pest infestation are shown in Figure 9.

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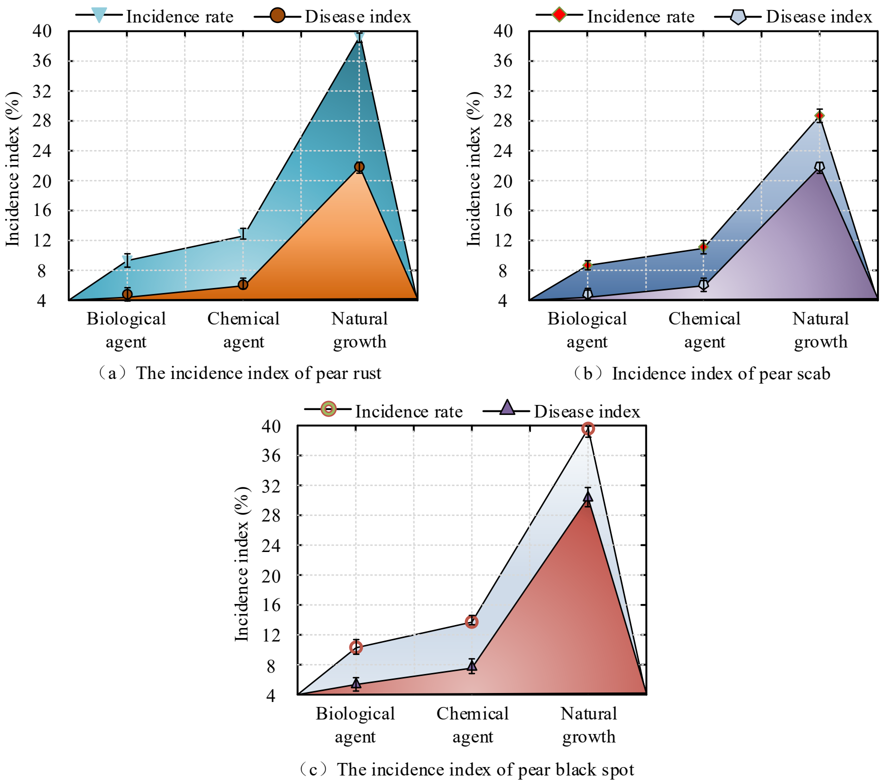

Fig. 8: Disease indicators of pear rust, pear scab, and pear black spot under different treatments

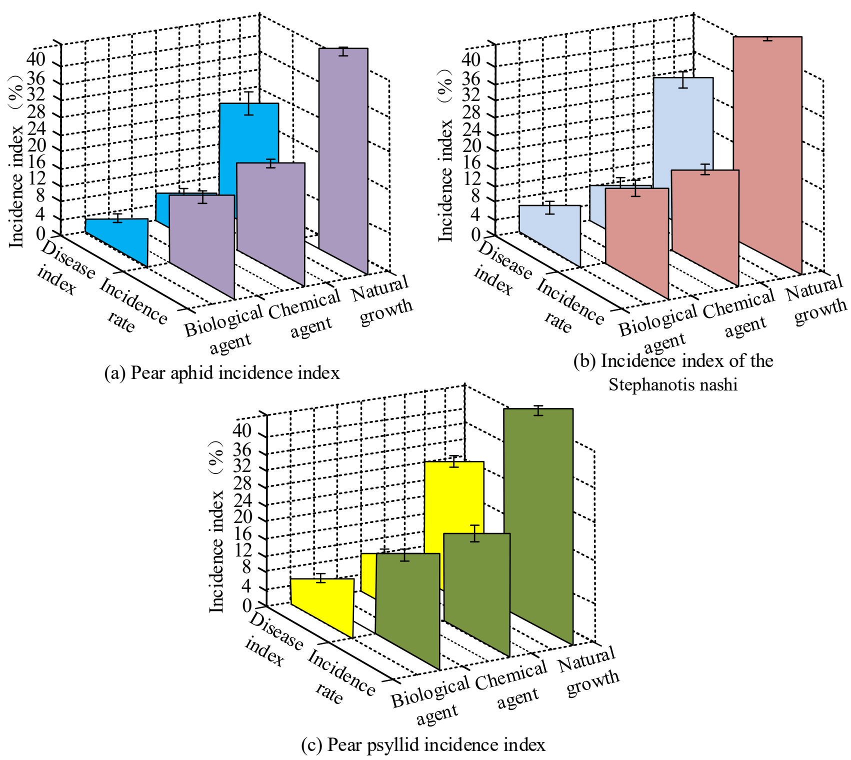

Fig. 9: Pest incidence index of pear trees under biological, chemical and natural growth conditions

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In Figure 9 (a), the incidence rate of pear aphid in pear trees under the action of biological agents is 8.84%, and that of chemical agents and natural growth is 13.29% and 38.71%. The disease indices of pear aphids under three different conditions are 3.59%, 7.94%, and 25.14%. Figure 9 (b) shows that the incidence rate of Stephanotis nashi is 9.25%, 11.53%, and 41.29% when biological agents, chemical agents, and natural growth are sprayed, and the corresponding disease index is 5.16%, 8.02%, and 32.54%. Figure 9 (c) shows that the incidence rate of pear psyllid is 10.56% and the disease index is 5.68% after pear trees are sprayed with biological agents. In addition, under the action of chemical agents, the incidence rate and disease index of the pear psyllid are 13.71% and 9.76%. Under the natural growth conditions, the incidence rate of pear psyllid among pear pests is 40.28%, and the disease index is 29.16%. This indicates that among the incidence rate and disease index, Stephanotis nashi is the highest under natural growth, and the pear aphid is the lowest under the action of biological agents. Compared to spraying chemical agents and natural growth, biological agents have the best control effect on pear tree pests. Table 3 shows the control effects of biological and chemical agents on pests and diseases.

As shown in Table 3, biological agents demonstrate a more stable and superior overall performance in pest and disease control compared to chemical pesticides. For example, in the case of pear rust, the disease reduction rate and control effectiveness of biological agents reach 82.33% and 78.29%, respectively, which are significantly higher than those of chemical agents at 69.58% and 62.14%. In terms of pest control, the most notable effect is observed against pear aphids, with biological agents achieving a pest reduction rate of 83.19% and a control effect of 80.53%, compared to 67.81% and 60.79% for chemical agents. This indicates that biological agents offer greater stability and broader effectiveness in managing major pests of pear trees. Further analysis suggests that variations in control effectiveness among different types of pests and diseases may be related to their biological and ecological characteristics and their sensitivity to microbial antagonistic mechanisms. Pear aphids, for instance, reproduce rapidly on leaf surfaces and have high metabolic activity, making them more susceptible to inhibition by actinomycete metabolites contained in biological agents. In contrast, for relatively concealed pests such as Stephanotis nashi, the biological agents still show advantages but with slightly lower efficacy, implying that pest behavior may influence the effectiveness of control measures. Overall, biological agents can effectively manage a wide range of pests and diseases while supporting healthy fruit tree growth and improving fruit quality and ecological safety.

Table 3: Effect of pest control under biological agents, chemical agents, and natural growth

Diseases and insect pests	Processing mode	Pest and disease reduction rate (%)	Pest control effect (%)
Pear rust	Biological agent	82.33±1.54	78.29±1.42
	Chemical agent	69.58±1.88	62.14±1.35
Pear scab	Biological agent	81.27±1.63	76.91±1.28
	Chemical agent	65.39±1.74	61.48±1.33
Black spot of pear	Biological agent	81.02±1.49	76.37±1.39
	Chemical agent	66.47±1.72	62.54±1.25
Pear aphid	Biological agent	83.19±1.68	80.53±1.44
	Chemical agent	67.81±1.91	60.79±1.31
Pyrrhus	Biological agent	82.19±1.61	79.25±1.33
	Chemical agent	68.47±1.85	61.83±1.26
Pear psyllid	Biological agent	81.53±1.56	80.44±1.37
	Chemical agent	68.14±1.73	63.47±1.29

Extended Validation on Apple Trees and Analysis

To verify the applicability of the proposed microbial diversity-based biological control agent to other fruit tree species, an extended experiment is conducted using "Red Fuji" apple trees from the same production area as the pear trial. The test site is located in a fruit tree cultivation area in Chengde City, Hebei Province, with a planting distance of 3 m × 2.5 m. The experimental design is consistent with that of the pear trial, including three groups: biological treatment, chemical treatment, and natural growth control. The biological treatment involves matrine at a concentration of 0.4%, abamectin at 1.8%, and Bacillus thuringiensis at 3500 iIU/mg. The chemical treatment uses 70% mancozeb and 0.3% chlorantraniliprole. The specific results are shown in Table 4.

As shown in Table 4, the biological treatment demonstrated overall superior performance in pest and disease control as well as in improving fruit quality compared to the other groups. In the control of apple anthracnose, the incidence rate in the biological group was 38.09%, significantly lower than that in the natural growth group. Although slightly higher than that in the chemical treatment group, the disease index reached 81.30%. This indicated that while the biological agent reduced the incidence rate, a certain degree of lesion remained, which may be related to the pathogen's latency period or the duration of control effectiveness. For apple ring rot, the incidence rates in the biological and chemical groups were similar, but the disease index was higher in the biological group, suggesting a difference in their ability to suppress disease progression. In terms of pest control, the biological treatment group showed significantly better control effects on leafrollers than the chemical treatment group, and slightly lower control effects on apple aphids than the chemical treatment group, but still had good inhibitory effects. In terms of fruit quality, the biological treatment group achieved a soluble solids content of 55.08% and a Vc content of 63.11 mg/100 g, indicating that the biological agent has a positive effect on improving fruit nutritional quality. Overall, the extended experiments on apple trees have validated the broad adaptability and practical application potential of the proposed biological control strategy, providing data support and theoretical basis for its promotion among different tree species.

Table 4: Comparative results of apple tree pests and diseases and fruit quality under different treatment groups

Indicator	Biological agent	Chemical agent	Natural growth
Apple anthracnose incidence (%)	38.09±0.93	16.24±0.66	54.47±2.87
Apple anthracnose index	81.30±2.52	73.19±1.26	35.58±0.74
Ring rot incidence (%)	64.90±1.60	64.95±0.81	41.69±1.74
Ring rot index	54.90±2.77	27.74±1.15	44.65±2.16
Aphid reduction rate (%)	21.70±1.80	25.91±1.87	48.24±0.96
Aphid control effectiveness (%)	21.70±2.44	26.00±2.85	61.41±2.74
Leafroller reduction rate (%)	14.36±2.80	33.25±0.72	37.99±0.99
Leafroller control effectiveness (%)	74.96±1.31	46.49±1.47	50.57±1.18
Soluble solids content (%)	55.08±1.39	40.92±1.20	53.70±1.86
Vc content (mg/100 g)	63.11±2.51	32.47±0.69	31.86±2.97

Discussion

FTPD prevention and control is vital in agricultural development, directly affecting the yield and quality of fruit trees. In the past prevention and control process, many methods often focused only on the current prevention and control effect, ignoring the long-term impact of pests and diseases, and causing negative effects on the ecological environment. Therefore, the prevention and treatment of FTPD is a long-term and arduous task. It has been shown that plant-derived bacteriostatic substances such as moringa, garlic, and neem extracts have potential in plant disease control. For example, Guo et al. found that plant extracts could effectively inhibit the root rot pathogen Ralstonia solanacearum in tomato and promote plant growth through synergistic action with green nanoparticles [13]. However, the antibacterial components of such plant extracts are easily affected by the environment, and the components are unstable and have a short duration of action. This limits its widespread application in the comprehensive control of FTPD. In contrast, the actinomycete biologics used exhibit stronger advantages in long-term inhibition of pathogens, root colonization ability, and ecological stability, reflecting the sustainability of microbial diversity strategies in practical promotion.

In addition, biological agents also showed significant effects on the incidence rate and disease index of pear diseases and pests. When detecting the incidence rate and disease index of diseased, the incidence rate of pear scab was the lowest among the three diseases, only 8.94%, after being treated with biological agents and chemical agents, respectively. In contrast, the incidence rate of disease was the highest in natural growth. When detecting the incidence rate and disease index of the pear pests, the incidence rate of pear aphid was low under the action of biological and chemical agents. This is similar to the research results of Raum et al. [20]. Although the incidence rate of Stephanotis nashi and pear psyllid was relatively increased, the extent was small, and the effect of biological agents was always more obvious than that of chemical agents. This result coincides with the research findings of Sharma and Joshi [21]. In the case of natural growth, the incidence rate and incidence index of diseases and pests of pear trees were both high, which indicated that it was very necessary to

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control diseases and pests during the growth of fruit trees. Fruit trees grown naturally are most affected by pests and diseases. If not prevented and controlled promptly, it may lead to yellowing of leaves, damage to young fruits, and even the entire fruit tree may rot. In terms of disease reduction rate, the pest reduction rate in the control of pear aphids by biological agents reached the highest 83.19%. Comprehensive data showed that biological control has achieved a control effect of over 75% on pests and diseases, demonstrating good control performance. This is similar to the research results of Vandhana et al. [22].

Based on the extended validation results of apple trees, it was also observed that the addition of actinomycetes in biological agents has significant advantages in controlling pests and diseases. This is in agreement with the findings of Kaur et al. [23]. The bacteriostatic mechanism of actinomycetes can be explained at several levels. On the one hand, actinomycetes can synthesize various secondary metabolites with antibacterial activity, such as streptomycin antibiotics, peptides, and extracellular hydrolytic enzymes. These metabolites can directly destroy the cell wall structure of pathogenic bacteria or inhibit their metabolic processes, thereby achieving effective inhibition of diseases. On the other hand, actinomycetes have strong colonisation ability in the root zone of fruit trees, which can form a competitive exclusion effect by competing with pathogenic microorganisms for spatial sites and nutrient resources [24]. In addition, some actinomycetes have the ability of group sensing interference, which can inhibit the information transfer between pathogenic bacteria and reduce their group pathogenic behavior. The synergistic effect of multiple mechanisms of action forms a stable and efficient microecological defence barrier, which enhances the overall effect of biological defence and control.

It should be noted that environmental factors such as temperature fluctuations and humidity changes can, to some extent, affect the actual prevention and control effect of microbial agents. Functional microorganisms such as actinomycetes are sensitive to environmental conditions. Under suitable temperature and humidity conditions, its metabolic activity and colonization ability are significantly enhanced, which helps to continuously release secondary metabolites and achieve effective inhibition of pathogenic microorganisms [25]. However, under conditions of high temperature, low humidity, or large temperature differences between day and night, microorganisms may face problems of decreased physiological activity and survival rate, which may affect the stability of their defense and control. Therefore, in the subsequent application promotion, this study will optimize the timing and frequency of pesticide application based on the climate characteristics of fruit tree planting areas, ensuring the adaptability and stability of biological agents in different ecological environments.

The contributions of the research are mainly reflected in the following aspects. Firstly, a novel and effective biological control mechanism for FTPD was proposed. Secondly, based on the characteristics of microbial diversity, traditional FTPD prevention and control methods have been improved. Finally, the proposed biological method was applied to the prevention and control of pear tree pests and diseases, and experimental comparisons were conducted to verify its excellent pest and disease control effect. The results of this study provide an effective and feasible method for the prevention and control of pests and diseases in fruit trees, reducing the risk of damage to fruit quality and yield, and contributing to the reduction of the impact of chemical pesticides on the ecological environment and human health.

However, the limitation of this study is that it only studied pears and apples, and its applicability needs to be further validated on a wider range of fruit tree varieties. In addition, a systematic assessment of the ecological safety and off-target impacts of biologics has not been carried out. Actinomycetes-based microbial formulations still face challenges in large-scale application, such as cost, production, and storage conditions. Future research will strengthen the multi-species validation, ecological risk assessment, and industrial feasibility analysis to promote the wide application of this strategy in agricultural production.

Conclusion

The invasion of pests and diseases can have adverse effects on fruit trees, threatening their health and yield. The traditional FTPD prevention and control methods are not effective against some pests and diseases, and have negative impacts on the ecological environment and human health. Moreover, some prevention and control methods have high costs and low applicability. In response to these shortcomings, this study proposed the use of biological control methods based on microbial diversity to diagnose the effectiveness of pest and disease control in pear trees. The biological agents made of actinomycetes were sprayed on fruit trees, and the experimental analysis was carried out from the aspects of fruit quality, incidence rate of diseases and pests and disease index. The data showed that the incidence rate of pear black spot under biological, chemical, and natural growth conditions was 10.22%, 13.67%, and 39.97%. The disease index of naturally growing

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pear black spot reached 30.69%, while after treatment with chemical and biological agents, it was only 7.14% and 5.36%. Among the three diseases of pear trees, biopharmaceuticals had the best control effect on pear rust, reaching 78.29%, and the disease reduction rate of pear rust was 82.33%. The control effect of chemical agents on pear rust was only 62.14%, with a disease reduction rate of 69.58%. Similar effects were observed in extended trials with apple trees, where the biologics showed good control of the main pests and significantly improved the nutritional quality indicators of the fruit. In summary, the proposed biological control method has the best effect on the prevention and control of pests and diseases in fruit trees, and can better improve the quality of fruits compared to chemical agents, with the advantages of safety and environmental protection.

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