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Research Article

Comprehensive Control Effect of Chemicals Combination against Kiwifruit Canker in Hubei Province, China

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Abstract

Kiwifruit Canker, caused by *Pseudomonas* syringae pv. Actinidiae (*Psa*), represents one of the most severe threats to the kiwifruit industry in Hubei Province, necessitating the development of efficient control strategies. To explore sustainable approaches for enhanced efficacy and reduced chemical application, field trials were conducted in two 'Hongyang' kiwifruit orchards in Xianning City and Xinzhou, Wuhan, Hubei Province. Results demonstrated that individual applications of kasugamycin, copper hydroxide, or carbendazim provided only 30-45% disease control efficacy. However, when the three agents were combined with propylene glycol, the control efficacy increased to 71.98% and 72.5% at the two trial sites in 2021. Further enhancement was observed in 2022 with the addition of ionic silicon, achieving control efficacies of 77.72% and 80.03%, respectively. Field observations also indicated a significant alleviation of symptomatic expression in treated plants, accompanied by a 13.4% and 33.2% increase in the weight leaves in 2022. These findings provide a promising practical basis for developing integrated management protocols to effectively control Kiwifruit Canker.

Keywords: Kiwifruit canker; *Pseudomonas* syringae pv. Actinidiae (*Psa*); Field trials; Chemicals control; Control efficacy

Introduction

Kiwifruit bacterial canker, caused by *Pseudomonas syringae* pv. *actinidiae* (*Psa*), represents a significant threat to global kiwifruit production due to its aggressive pathogenicity [1-4] and rapid dissemination [5]. *Psa* has since been identified in over 20 major kiwifruit-producing countries, including Italy, New Zealand, South Korea, Turkey, and China, demonstrating its widespread epidemiological impact [5-9]. The pathogen caused necrotic leaf lesions, blossom rot, stem cankers with bacterial exudate, and progressive dieback [5,10]. *Psa* infection not only causes direct damage but also triggers systemic physiological stress, resulting in tree vigor decline and shifts in the rhizosphere microbiome that promote secondary infections by opportunistic pathogens [11,12]. The *Psa* transmission occurs through multiple vectors, including rain splash, wind-driven aerosols, and contaminated pruning tools, enabling rapid intra-orchard spread under conducive environmental conditions [5,13]. Economic analyses have quantified yield losses exceeding 50% in severely affected orchards, with complete plantation loss occurring in epidemic scenarios [10,14]. Chemical intervention has been established as a critical component in the integrated management of kiwifruit bacterial canker have been routinely employed in disease control strategies [15-17]. However, single-chemical control often suffers from inconsistent effectiveness and a high propensity to drive pathogen resistance [18,19]. Consequently, optimizing chemicals combinations has emerged as a critical focus in current chemical control strategies. Research demonstrated that combining kasugamycin with ketone-based formulations can achieve a control efficacy of 71.6% against kiwifruit bacterial canker [20]. Combined treatments were more effective against kiwifruit canker in

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Guiyang, with tetramycin-benziothiazolinone (5:1) and tetramycin-tebuconazole (2:1) achieving 68.12% and 66.83% control, respectively [21]. Similarly, in Sichuan, a combined application of kasugamycin, tebuconazole, propineb, and prochloraz significantly reduced the disease index of kiwifruit canker to 4.67, compared to 17.00 in the control [22].

The increasing identification of coexisting pathogen communities in diseased plants has drawn attention to their co-occurrence patterns and interspecific interactions. Bacterial and fungal pathogens often coexist and act synergistically to exacerbate diseases [23,24]. For instance, the fungus *Cytospora pyri* promoted the dispersal and virulence factor production of the bacterium *Erwinia amylovora* [25]. Similarly, co-infection with Verticillium dahliae (fungus) and *Pectobacterium* spp. (bacterium) aggravated potato early dying syndrome [26], while fungal *chlamydospores* could enhance bacterial fitness and persistence [27]. Consequently, applying fungicides to control fungal infections can prevent the development of complex disease syndromes. Carbendazim, a broad-spectrum benzimidazole fungicide, demonstrates high efficacy against diverse fungal pathogens [28,29]. Incorporating carbendazim into the spray program effectively controls fungal infections, thereby preventing the development and spread of complex disease syndromes while enhancing fungicidal protection within the integrated management strategy. Silicon enhances leaf growth in plants by modulating endogenous hormones, improving photosynthetic efficiency, and stimulating cell division and expansion [30]. Furthermore, the incorporation of an silicone adjuvant into the chemicals formulation enhances droplet adhesion, significantly reduces surface tension, and promotes superior spreading and penetration of the spray solution on the foliage [31,32]. Propylene glycol is employed as a cosolvent in the formulation to effectively improve the solubility and stability of multiple active ingredients [33,34]. Composite application of different chemicals not only strengthens plant resistance but also serves as an effective strategy to reduce the pathogen selection and improve control performance.

In China, research on the epidemiology of kiwifruit bacterial canker has primarily been conducted in Shaanxi, Sichuan and Zhejiang provinces, with particularly extensive studies carried out in Shaanxi [2,3,35,36]. In previous studies , field monitoring over an annual cycle revealed two distinct infection peaks in branches and leaves [37]. Leaf infections peaked during early summer and late autumn, with secondary elevations observed in late spring and early winter [37]. Hubei Province, recognized as both the origin and a major production region of kiwifruit in China, has witnessed its cultivation area exceed 130,000 hectares. The presence of kiwifruit bacterial canker has been increasingly observed across major cultivation zones in the province. Epidemiological surveys have revealed that the disease has become widely distributed in key production areas including Shiyan, Xiangyang, Wuhan, and Xianning, posing significant constraints to the sustainable development of local kiwifruit industries [38,39].

The laboratory tests and field trials in some regions have confirmed the efficacy of combined chemical treatments. However, the efficacy of multi-component combinations including kasugamycin, copper, and a fungicide for infection with silicon and propylene glycol against *Psa* under field conditions in Hubei Province remains unclear. To address this issue and develop efficient management strategies against kiwifruit canker in Hubei, systematic field trials were conducted in Xianning City and Wuhan from 2021 to 2022. A multi-component spraying model comprising bactericides, fungicides, micronutrients, and synergistic additives was designed and evaluated. This study aimed to compare the efficacy of individual and combined treatments, assess the effects of propylene glycol and ionic silicon, and establish a practical and theoretical basis for *Psa* control in Hubei. The findings are expected to provide a reference for developing integrated chemical strategies in other affected regions.

Materials & Methods

Plant Materials and Experimental Sites

The study was conducted using 3- to 4-year-old 'Hongyang' red-fleshed kiwifruit plants. Two experimental sites were selected in major kiwifruit production regions of Hubei Province (Figure 1). In Xianning City, trials were carried out at Plot 14 of Shenshan Xingnong Technology Peninsula South Base. This site was chosen due to its geographical isolation from other orchard canopies, minimizing cross-contamination risks from adjacent infected plants. The 4-year-old 'Hongyang' cultivar was grown under pergola training systems across a 0.33-hectare area. The field survey on April 10, 2021 showed that the kiwifruit bacterial canker disease index was 31.64 with an infected plant rate of 61.32%, while the survey on April 5, 2022 revealed a disease index of 26.14 and an infected plant rate of 59.09%. The other field trials were conducted at a commercial kiwifruit orchard (Yang Linsen Agricultural Technology) in Wuhan, China. The demonstration plots primarily cultivated the popular red-fleshed 'Hongyang' kiwifruit and were supplemented with compatible varieties including the red-fleshed 'Miliang'. The field survey on April 9, 2021, showed a kiwifruit canker disease index of 32.31 and an infected plant rate of 60.05%, while the survey on April 4, 2022, recorded a disease index of 23.68 and an infected plant rate of 57.89%. Both selected plots are long-term monitoring sites with natural *Psa* infection. The trial utilized 4-year-old kiwifruit vines trained to flat-top pergola systems, covering a cultivated area of 0.8 hectares.

Field Efficacy Trials for Kiwifruit Canker Control

Field trials were conducted during 2021-2022 to evaluate the efficacy of various chemical treatments against kiwifruit canker. The experimental design consisted of five treatments arranged in a randomized complete block design with three replicates per treatment (Table 1). In 2021, the chemical combination treatment involved the application of kasugamycin, copper hydroxide, carbendazim, and propylene glycol. In 2022, the treatment was modified to five chemicals including kasugamycin, copper hydroxide, carbendazim, propylene glycol, and ionic silicon. Propylene glycol serves as a cosolvent to enhance the dissolution of various components [34], while ionic silicon promotes leaf growth in plants [30]. Each replicate comprised one row of 20 kiwifruit plants, totaling 15 experimental rows (Figure 1).The field trial was conducted in a kiwifruit orchard using an umbrella-shaped trellis system. The planting configuration followed a wide-row spacing system with 5 m between rows and 3 m between plants within rows. Due to the natural lateral growth habit of kiwifruit branches, no significant canopy overlap was observed between adjacent rows. During chemical applications, sprays were uniformly administered to both sides of each row.

Table1: Different treatment groups of the high-efficiency chemicals against kiwifruit canker in the trial. Ionic Silicon was only added in 2022.

Treatment	Chemical	Manufacturer	Concentration	usage	
				2021	2022
Ka	4% kasugamycin	Beijing Green Agriculture Science and Technology Group	50mL/15L	√	√
Co	46% copper hydroxide	Corteva Agriscience	50g/15L	√	√
Ca	50% carbendazim	Hebei Guanlong Agrochemical	20g/15L	√	√
Mix	4% kasugamycin	Beijing Green Agriculture Science and Technology Group	30mL/15L	√	√
	46% copper hydroxide	Corteva Agriscience	30g/15L	√	√
	50% carbendazim	Hebei Guanlong Agrochemical	15g/15L	√	√
	40% Ionic Silicon	Yunnan Mengniu Biotechnology	30ml/15L	×	√
	10% propylene glycol	Yunnan Mengniu Biotechnology	30ml/15L	√	√
CK	sterile water	—	—		

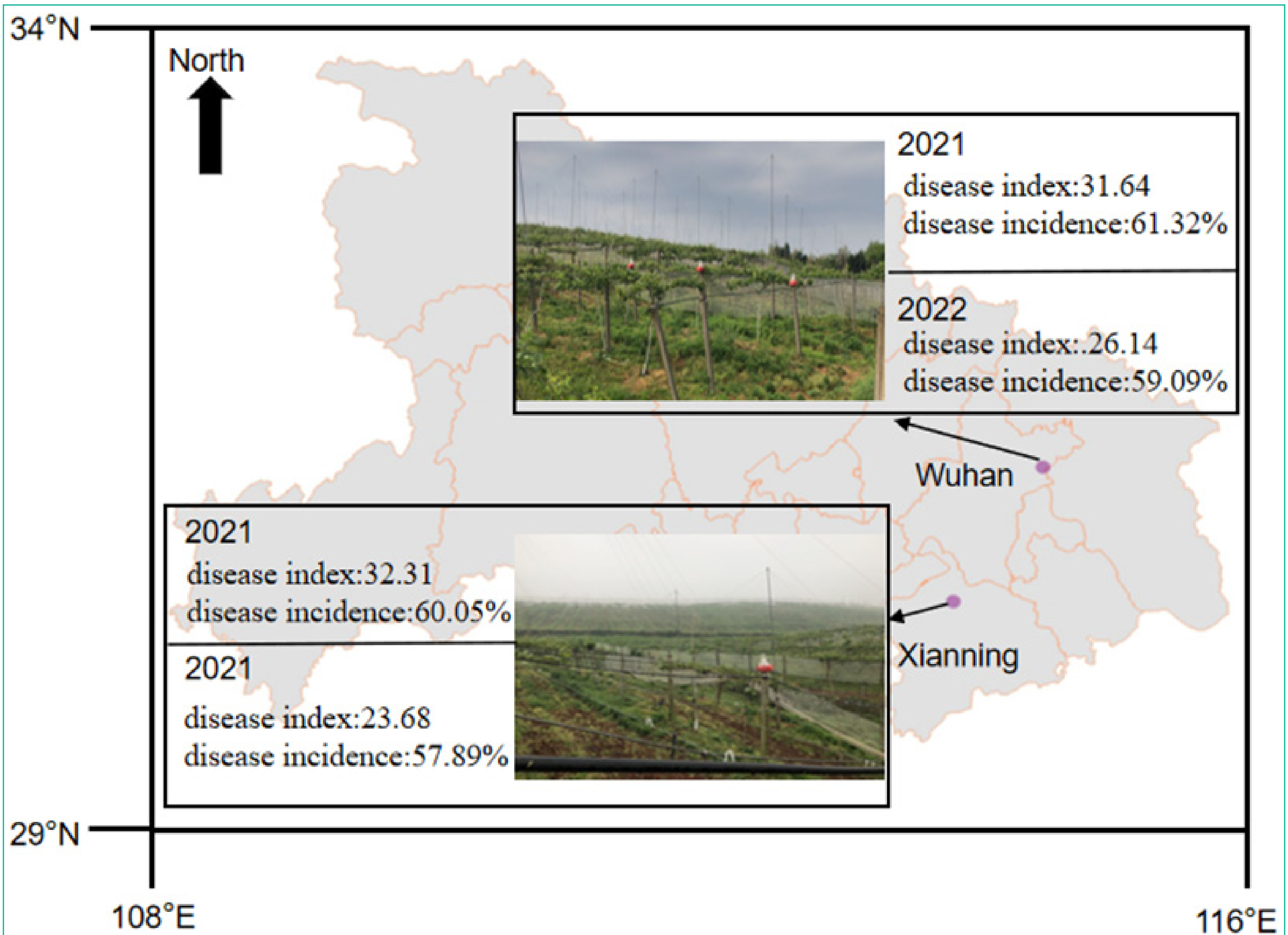

Figure 1: The sampling sites. The disease index and incidence rate of kiwifruit canker in 2021 and 2022 are also described. An investigation in Xianning showed that the disease index of kiwifruit canker was 31.64 with 61.32% of plants infected on April 10, 2021, while on April 5, 2022, the disease index was 26.14 with 59.09% of plants infected. The survey in Wuhan showed that the kiwifruit canker disease index was 32.31 with 60.05% infected plants on April 9, 2021, while on April 4, 2022, the disease index was 23.68 with 57.89% infected plants. The map was generated using the Lingen Biocloud Platform (http://www.cloud.biomicroclass.com/).

The chemical solutions were prepared with thorough tank cleaning between treatments to prevent cross-contamination. The spray tank must be thoroughly cleaned before preparing the solution. For treatments requiring bactericide adjuvant, half the tank was first filled with water and then 30 mL of bactericide adjuvant was added. The mixture was stirred until foam completely disappears before other active ingredients were introduced. Other treatments were prepared by direct mixing of components with water. The nozzle must be maintained in an upward position to ensure uniform spray distribution across leaves and branches. For lower plant sections, the nozzle should be oriented vertically forward to facilitate top-down uniform spraying. The chemicals was administered in two applications with an inter-treatment interval of 18-20 days. In Xianning, the first and second applications in 2021 were conducted on April 13 and May 3, respectively, while in 2022 they were carried out on April 9 and April 27. Similarly, in Wuhan, the first application in 2021 took place on April 14 followed by the second on May 5, whereas in 2022 the applications were administered on April 10 and April 28, respectively.

Table 2: The control effect of the trial against kiwifruit canker of two years in Xianning. Different lowercase letters in the same column in the table indicate significant differences in the 0.05 level, and uppercase letters indicate significant differences in the 0.01 level. Ka: 4% kasugamycin; Co: 46% copper hydroxide; Ca: 50% carbendazim; Mix (2021): 4% kasugamycin, 46% copper hydroxide, 50% carbendazim and 10% propylene glycol; Mix (2022): 4% kasugamycin, 46% copper hydroxide, 50% carbendazim, 10% propylene glycol and 40% Ionic Silicon.

Year	Group	15 days after the first time for applying chemicals		15 days after the second time for applying chemicals				
		Average percentage of diseased plants	Average disease index	Average percentage of diseased plants	Average disease index	Average control effect	Total weight of leaves	Percentage of weight growth
2021	Ka	62.75%	37.75	62.75%	40.20	43.85%Bb	/	/
	Co	57.14%	28.57	56.86%	32.35	40.29%Bb	/	/
	Ca	62.75%	30.39	69.23%	40.38	29.94%Cc	/	/
	Mix	60.78%	32.35	48.98%	17.35	71.73%Aa	/	/
	CK	58.82%	31.37	78.00%	59.50	/	/	/
2022	Ka	59.09%	31.82	63.64%	34.09	45.09%Bb	106.50	1.91%Bb
	Co	47.62%	25.00	57.14%	28.57	41.43%Bb	105.50	0.96%Bb
	Ca	66.67%	29.76	66.67%	41.67	28.25%Cc	105.00	0.48%Bb
	Mix	59.09%	26.14	27.27%	11.36	77.72%Aa	118.50	13.40%Aa
	CK	59.83%	32.03	96.88%	62.50	/	104.50	/

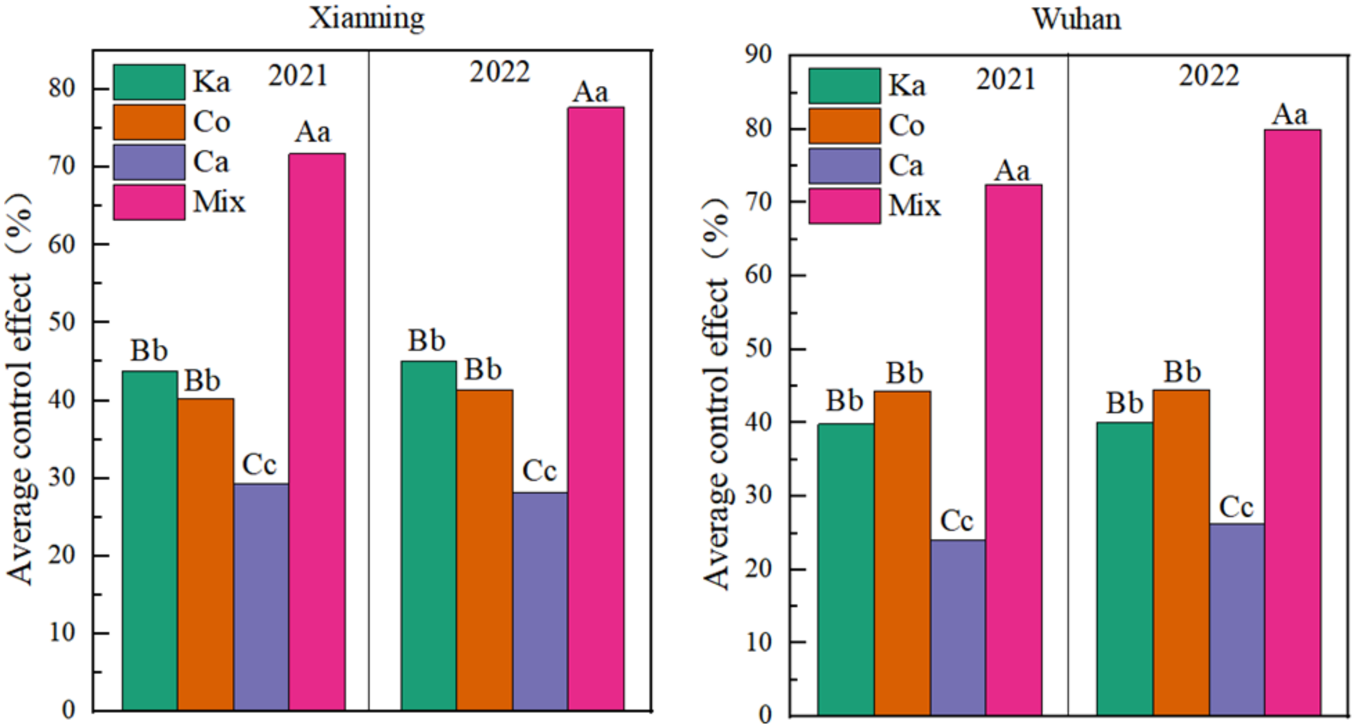

Figure 2: The control effect of the trial against kiwifruit canker of two years in Xianning and Wuhan. Different lowercase letters in the same column in the table indicate significant differences in the 0.05 level, and uppercase letters indicate significant differences in the 0.01 level. Ka: 4% kasugamycin; Co: 46% copper hydroxide; Ca: 50% carbendazim; Mix (2021):4% kasugamycin, 46% copper hydroxide, 50% carbendazim and 10% propylene glycol; Mix (2022):4% kasugamycin, 46% copper hydroxide, 50% carbendazim, 10% propylene glycol and 40% Ionic Silicon

Disease severity assessments for kiwifruit bacterial canker were performed on all experimental plants before the first application and 15 days after the second application. Disease severity was assessed on a per-plant basis, with the total number of surveyed plants and the number of diseased plants at each grade recorded. the disease severity assessment was referred to the "Pesticide Efficacy Testing Guidelines (Part 2: Section 103): Fungicide Efficacy against Citrus Canker" and the Shanxi Provincial Local Standard "Technical Specification for Integrated Control of Kiwifruit Bacterial Canker" (DB61/T 1167-2018). The grading was performed on a per-plant basis as follows: Grade 0:No visible lesions on the entire plant; Grade 1:Distinct lesions visible only on leaves, with the total infected leaf area not exceeding 10%;Grade 2:Distinct lesions present on both leaves and branches, but the lesion coverage is below 15% of the branch circumference, and the main trunk is either lesion-free or has lesion coverage below 25%; Grade 4: Plant death, or lesion coverage on the main trunk exceeding 50%.Disease severity was classified using a simplified grading system, and disease indices and control efficacy were calculated. The disease incidence rate (%) was calculated as: (Number of diseased plants/Total number of plants surveyed) × 100.The disease index was calculated as: [∑(Number of diseased plants × Representative value of the grade)/(Total number of plants surveyed × Maximum representative value)] × 100. The control efficacy (%) was calculated as: [1 - (Disease index of control before treatment × Disease index of chemical treatment after treatment)/(Disease index of control after treatment × Disease index of chemical treatment before treatment)] × 100.

Table 3: The control effect of the trial against kiwifruit canker of two years in Wuhan. Different lowercase letters in the same column in the table indicate significant differences in the 0.05 level, and uppercase letters indicate significant differences in the 0.01 level.Ka:4% kasugamycin;Co:46% copper hydroxide;Ca:50% carbendazim; Mix (2021) :4% kasugamycin, 46% copper hydroxide, 50% carbendazim and 10% propylene glycol; Mix (2022): 4% kasugamycin, 46% copper hydroxide, 50% carbendazim, 10% propylene glycol and 40% Ionic Silicon.

Year	Group	15 days after the first time for applying chemicals		15 days after the second time for applying chemicals				
		Average percentage of diseased plants	Average disease index	Average percentage of diseased plants	Average disease index	Average control effect	Total weight of leaves	Percentage of weight growth
2021	Ka	61.54%	30.77	53.85%	26.92	39.84%Bb	/	/
	Co	64.71%	30.88	52.94%	25.00	44.35%Bb	/	/
	Ca	63.64%	32.95	59.09%	36.36	24.14%Cc	/	/
	Mix	71.43%	35.71	28.67%	14.29	72.50%Aa	/	/
	CK	53.33%	36.67	66.67%	53.33	/	/	/
2022	Ka	54.55%	27.27	54.55%	31.82	40.09%Bb	129.00	1.98%Bb
	Co	47.62%	29.76	57.14%	32.14	44.54%Bb	126.50	0.00%Bb
	Ca	57.14%	28.57	71.41%	41.07	26.18%Cc	127.00	0.40%Bb
	Mix	57.89%	23.68	26.32%	9.21	80.03%Aa	168.50	33.20%Aa
	CK	46.67%	31.67	86.67%	61.67	/	126.50	/

Figure 3: The surface symptom of marked diseased plant in 2021. (A) the first investigation on Apr 13th; (B) the second investigation on May 5th; (C) the third investigation on May 19th.

Impact of Chemical Combinations on Kiwifruit Tree Physiology

The impact of chemical combinations on kiwifruit trees was evaluated through continuous monitoring of marked severely affected plants before the first application and during subsequent observations. In 2021, assessments began on April 13 and were repeated every 20 days for three total observations, while the 2022 evaluations followed the same 20-day interval schedule starting from April 10. Leaves weight of kiwifruit was conducted 15 days after the final application. The Xianning trial plots were sampled on May 12, 2022 and the Wuhan plots were sampled on May 13, 2022. The silicon fertilizer could promote leaf growth [30] and thus the leaf sample from each treatment group was weighed to quantify the promoting effect in kiwifruit. For each treatment group, ten leaves located at the 9th to 10th position from the shoot apex were selected per replicate, totaling thirty leaves per treatment group. Samples were surface-sterilized with distilled water, blot-dried using sterile gauze, and immediately stored in ice-cooled containers. The total weight of a hundred leaves (L_{100}) was calculated as following:

$$L_{100} = \frac{L_a}{30} \times 100$$

The percentage of weight growth (WG) was calculated as following:

$$WG = \frac{L_a - L_{CK}}{L_{CK}} \times 100\%$$

L_a means the total fresh weight of leaves for each treatment. L_{CK} means the total fresh weight of leaves for each treatment.

Data Analysis

The transformed field efficacy data were subjected to statistical analysis using SPSS 23.0 software. One-way ANOVA was performed followed by Duncan's new multiple range test (DMRT) for multiple comparisons to determine significant differences among treatments at two probability levels ($P < 0.05$ and $P < 0.01$). All values are presented as mean ± standard error of three independent replicates.

Results

Field Efficacy Evaluation of Single Chemical Against Kiwifruit Bacterial Canker

The field efficacy trials demonstrated consistently limited control efficacy of individual bactericides against kiwifruit canker across both Xianning and Wuhan trial sites during the two-year investigation. The results revealed that 50mL/15L kasugamycin monotherapy achieved average control effect ranging from 39.84% (2021) to 45.09%(2022), while 50g/15L copper hydroxide applications yielded average control effect of 40.29% (2021)-44.54% (2022) (Table 2 and Figure 2). Notably, the 20g/15L carbendazim treatment showed the lowest control efficacy, with values of only 29.14% in 2021 and 28.25% in 2022.These results collectively indicated that single chemical interventions provided unsatisfactory protection against *Psa* infection in the studied regions. Therefore, an integrated bactericide formulation was developed to optimize disease control.

Impact of Single- Chemical Treatments on Kiwifruit Leaf Biomass Growth

The biomass of kiwifruit leaves was further measured in Xianning and Wuhan. The results demonstrated that single-chemical treatments had limited efficacy in promoting leaf growth. In the Xianning experimental area, kasugamycin treatment increased leaf weight by 1.91% relative to the control group, while copper hydroxide and carbendazim treatments showed increases of 0.96% and 0.48%, respectively (Table 2). Similarly, in the Wuhan experimental zone, the corresponding increases were 1.98% for kasugamycin, 0.00% for copper hydroxide, and 0.40% for carbendazim (Table 3). These results aligned with previous efficacy trials demonstrating limited disease control from single-chemical treatments, with all treatments exhibiting less than 45% effectiveness. The findings confirmed the inadequate protective efficacy of monotherapies against kiwifruit canker. Consequently, subsequent studies focused on evaluating the effects of multiple drug formulations on disease prevention and control as well as plant growth.

Sequential Observations of Kiwifruit Disease Plants after Application of Composite Chemicals

In our previous publication, PCR tests were conducted on tree cross-sections, branch segments, and leaves, which confirmed that the symptoms were indeed caused by *Psa* [39]. This study tracked the healing progression of *Psa* infections through sequential observations. In the first investigation, severely infected plants exhibited open wounds with profuse bacterial ooze and rust-colored exudates (Figure 3A). Subsequent examination revealed active healing, with wounds drying and showing no fresh exudation (Figure 3B). The rust-colored infection sites had desiccated. When scraped, they revealed darkened and softened xylem underneath. These observations indicated partial recovery of the affected tissue. However, complete rehabilitation had not been achieved. The final observation marked complete wound resolution, with all rust-colored lesions disappeared and the previously damaged xylem turning brown and firm (Figure 3C). Notably, new xylem formation surrounded the healed areas, demonstrating successful compartmentalization of the infection. In the third survey, one marked diseased plant each from the control group and the combined treatment group was felled for examination. The stump in the control group displayed unhealthy dark brown discoloration at the base. The tissue exhibited a soft texture, and the cross-section appeared completely covered in bacterial ooze (Figure 4A). By contrast, treated plants presented dry, brown-colored basal tissue lacking bacterial exudate (Figure 4B). These morphological differences confirmed complete recovery of tree health status after treating with complex reagent.

In 2022, a systematic follow-up evaluation of kiwifruit canker treatment efficacy was conducted. Initial observations revealed severe disease symptoms in marked infected trees, where pruned lateral branches showed extensive bacterial exudates consisting

Figure 4: Comparison of tree stump symptoms. (A) control group and (B) treatment group.

of rust-colored ooze and dark brown pustules at wound surfaces (Figure 5A). The remaining tree portions exhibited leaf wilting and necrosis. subsequent examination demonstrated significant symptom improvement. Subsequent examination demonstrated significant symptom improvement after the application of complex reagent. Wound surfaces no longer displayed bacterial exudates, showing instead yellowish-white basal tissue with overall green coloration (Figure 5B). The treated plants completely lacked bleeding sap and showed no leaf wilting symptoms. Final assessment confirmed complete wound healing (Figure 5C). The xylem exhibited full recovery with enhanced tree vigor, while the entire plant displayed healthy growth characteristics including normal leaf development without wilting or necrosis, along with proper flower and fruit production. These sequential observations confirmed the efficacy of complex reagent in controlling kiwifruit canker progression.

Field Efficacy Evaluation of Composite Chemicals against Kiwifruit Bacterial Canker

The application of the compound formulation significantly reduced the average disease index to 11.36 and 9.21 after two years of treatment. In 2021, the average disease control efficacy reached 71.73% and 72.50% at the two experimental sites respectively. The incorporation of ionic silicon further enhanced the efficacy to 77.72% and 80.03% (Table 2,3 and Figure 2). Furthermore, the results demonstrated significant leaf growth promotion. Measurements conducted on May 12, 2022 in Xianning trial site showed a 13.40% increase in leaf fresh weight compared to controls, while more pronounced enhancement of 33.20% was observed in Wuhan trial site on May 13, 2022 (Table 2 and 3). Notably, these improvements significantly exceeded those achieved by previous single-chemical treatments of 1.91%-1.98%.

Discussion

Over the past decade, persistent outbreaks of bacterial canker have caused substantial economic losses across major kiwifruit-producing nations, creating an urgent global demand for effective control solutions. Field trials in Hubei assessing three conventional single-treatments (kasugamycin, copper hydroxide, and carbendazim) revealed limited control efficacy, ranging from 24.14% to 45.09%. Kasugamycin, a bactericide derived from the small gold actinomycete, demonstrates limited effectiveness in plant exterior applications [40]. Copper hydroxide exerts its bactericidal effect by releasing active copper ions that form a protective film on plant surfaces, providing both protective and surface sterilization functions [41,42]. Although copper hydroxide eliminates surface bacteria, its poor plant absorption

Figure 5: The surface symptom of marked diseased plant in 2022. (A) the first investigation on Apr 10th；(B) the second investigation on Apr 28th; (C) the third investigation on May 13th.

permits internal pathogen survival and subsequent population regrowth, leading to disease recurrence [43,44]. Meanwhile, repeated exclusive application of a single has induced bacterial resistance. Consistent with the presented findings, laboratory antimicrobial assays conducted in Shaanxi, Guizhou, Sichuan and Hubei provinces similarly demonstrated the ineffectiveness of kasugamycin, copper hydroxide and carbendazim as single product against kiwifruit canker pathogens [22,45-48]. These findings collectively demonstrated that conventional single-bactericide exhibit fundamentally limited efficacy against kiwifruit canker and necessitated integrated combinatorial strategies for sustainable disease management.

The low efficacy of single-bactericide treatments against kiwifruit canker in Hubei orchards, typically between 24.14% and 44.54%, prompted this investigation into the synergistic potential of combined bactericides. The two-year field trials across two locations demonstrated consistently superior performance of the combinatorial treatments, reaching over 70% disease control efficacy. Notably, treated plants showed significant symptom reduction and improved vigor, with hundred-leaf weight increasing by 13.40% and 33.20%, respectively. Similar results have been observed in other regions where combined bactericides were employed against kiwifruit canker. Laboratory bioassays demonstrated that a ternary mixture of ethylicin, kasugamycin, and tetramycin at a 1:1:2 volumetric ratio achieved 99.14% bacterial inhibition [40]. Field trials in Xiangxi region showed that a 1:1 mass ratio mixture of tetramycin and PHMG, achieved optimal ulcer disease control with 74.65% efficacy [45]. Moreover, field trials in Guizhou Province revealed that a 5:1 tetramycin-thiodiazole-copper formulation conferred 68.12% control efficacy against kiwifruit canker [21]. The primary component of the bactericide synergist is 10% propylene glycol, which serves to thoroughly dissolve the active ingredients of all components and facilitate rapid penetration of the solution into plant epidermal cells [47]. Silicone adjuvants, a class of surfactant additives, significantly enhance bactericide performance by improving leaf adhesion, dramatically reducing spray solution surface tension, optimizing droplet spreading on foliage, and promoting cuticular penetration [16,31]. Furthermore, the inclusion of silicon, a key plant nutrient, contributed to enhanced leaf metabolic activity and photosynthetic efficiency [48-50]. These results further confirmed that the development of mixed chemicals for the prevention and control of kiwifruit canker disease is feasible, and appropriate chemical combinations could significantly improve the antibacterial rate and efficacy against canker bacteria.

The combined chemical formulation developed in this study shows promising potential for managing kiwifruit canker across different production regions. However, its effectiveness depends on proper integration with routine orchard management practices to achieve comprehensive disease control [51,52]. Although this study focused solely on evaluating combined fungicide efficacy against bacterial canker in Hubei's kiwifruit region, it presents a novel chemical control strategy. By safely blending broad-spectrum fungicides and bactericides to leverage their complementary strengths alongside adjuvants, this approach maximizes each component's efficacy [53-55]. The established model offers an adaptable framework for managing kiwifruit canker and other diseases, allowing tailored combinations based on regional crops, geographical conditions, cultivation practices, and predominant pathogens.

Conclusions

This study confirms that the combined application of kasugamycin, copper hydroxide, and carbendazim with propylene glycol significantly enhances disease control efficacy, achieving 71.98% and 72.5% across two experimental orchards in 2021. Further incorporation of ionic silicon in 2022 resulted in even higher efficacy, reaching 77.72% and 80.03%, respectively. In addition to effective pathogen suppression, the combined treatments significantly alleviated disease symptoms and increased leaf weight by 13.4% and 33.2% in 2022. These results demonstrated that agent-solvent-silicon integration not only improved control effectiveness but also promoted plant growth. The study provided a practical and sustainable strategy for integrated management of Kiwifruit Canker, with potential for application in other affected regions.

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