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Review article

Wood fiber biomass pyrolysis solution as a potential tool for plant disease management: A review

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A R T I C L E I N F O

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A B S T R A C T

Wood vinegar is a high-value acidic byproduct of biomass pyrolysis used for charcoal production. It is widely used in agriculture and forestry. The adverse effects of synthetic fungicides on the environment and human health have prompted the increasing use of biofungicides as alternatives to traditional products in integrated plant disease management programs. In recent years, there has been an increasing interest in the potential of wood vinegar as a disease management tool in agriculture and forestry. In this paper, the composition and preparation process of wood vinegar and its application in agriculture and forestry were introduced, and the effect and mechanism of wood vinegar against fungi, viruses and bacteria were summarized. The potential of wood vinegar as a sustainable and eco-friendly alternative to conventional chemical fungicides is also discussed. Finally, some suggestions on the application and development of wood vinegar were put forward.

1. Introduction

Globally, agriculture, forestry, and industry produce an estimated 200 billion tons of lignocellulosic biomass every year, with the majority produced via forestry and agricultural waste in large agricultural countries such as China, Brazil, India, and Australia [1]. Biochar has the function of carbon sequestration, emission reduction and sink enhancement, so the technology of preparing biochar by biomass pyrolysis has been popularized and applied in the world. Through dry distillation of agricultural and forestry waste (such as straw, branches and wood chips), the internal lignocellulosic macromolecules (cellulose, hemicellulose and lignin) undergo a cracking reaction to produce three products: biochar, wood vinegar, and pyrolysis gas [2]. The properties and applications of biochar and pyrolysis gases have been extensively studied [3–5]. At present, biochar has been widely used in many fields such as soil remediation, crop production, climate change mitigation and energy production, pyrolysis gases also have a variety of potential applications, such as direct use in the production of thermal and electrical energy (e.g. gas combustion in spark ignition and compression ignition engines) or the production of liquid biofuels through synthesis. Wood vinegar has a special smoky aroma and sour taste, it is an acidic red-brown liquid with a pH value between 1.5 and 3.7, and a specific gravity generally greater than 1.005 [6,7], it is located at the top of the bio-oil, and the heavy fraction at the bottom is called tar [8]. Wood vinegar is divided into crude wood vinegar and refined wood

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vinegar. As a by-product of biochar, crude wood vinegar contains a large amount of tar and harmful substances. If not handled properly, it will cause new environmental pollution, while refined wood vinegar is stable in nature, does not pollute the environment, and has no toxic effect on humans and animals. Therefore, it is very urgent to excavate and develop the function of wood vinegar, and it has become a research hotspot in recent years [9,10]. More and more studies have shown that wood vinegar has the effect of preventing plant diseases and insect pests. Currently, wood vinegar is widely used in plant disease management because of its antimicrobial properties.

Plant disease outbreaks have resulted in a substantial decrease in the yield of essential staples and cash crops, which poses a growing threat to the intricate global food insecurity crisis [11]. Plant diseases are detrimental effects of microorganisms on plants. Under suitable environmental conditions, pathogenic microorganisms can infest plants and hinder their normal growth and development, leading to lower yields, lower quality, and even death, which directly affects the profitability of farming. Plant diseases cause substantial annual agricultural losses [12]. Historically known as the 'Irish famine', in 1845–1846 the pathogenic blight fungus (*Phytophthorainfestans*) caused a potato late blight pandemic in Ireland that led to a massive famine, resulting in 1.1 million deaths [13]. The 1942 rice brown spot pandemic triggered a famine in India, where two million people died from starvation [14]. The world population is estimated to be close to 8 billion today and is expected to increase by c. 21.3 % to 9.7 billion by 2050 [15]. Considering this trend, total food production will have to increase by 70 % in the coming decades to meet the significantly increased market demand. Since the 'Green Revolution', intensive agriculture is no longer sufficient to provide global food security. To ensure food safety and quality, minimizing disease-related losses is considered a key step in achieving the recently adopted global sustainable development goals (SDGs) [16,17].

The current widely used strategy to control plant diseases is the application of harmful synthetic chemical fungicides [18]. Although these synthetic fungicides are fast acting and highly targeted, providing better control of plant diseases, the side effects of these chemicals have a significant negative impact on the environment and ecological niche [19–22]. These pesticides harm the environment, threaten biodiversity, and damage human health, and their chemical residues can induce other diseases and potential hazards [23]. They have become some of the most significant environmental toxins affecting soil, water, cropsand animals, including humans [24–28]. Currently, sustainable agricultural guidelines prohibit the use of large amounts of synthetic pesticides in crop and fruit production [29–31]. Therefore, safe, efficient and environment-friendly biological control methods have become a hot topic for research and development as a prospect for plant disease control [32]. The recovery of wood vinegar during charcoal burning makes full use of the natural resources and turns waste into a valuable product, which not only solves the problem of efficient use of agricultural waste, but also serves as a suitable substitute for traditional products in integrated disease management programs.

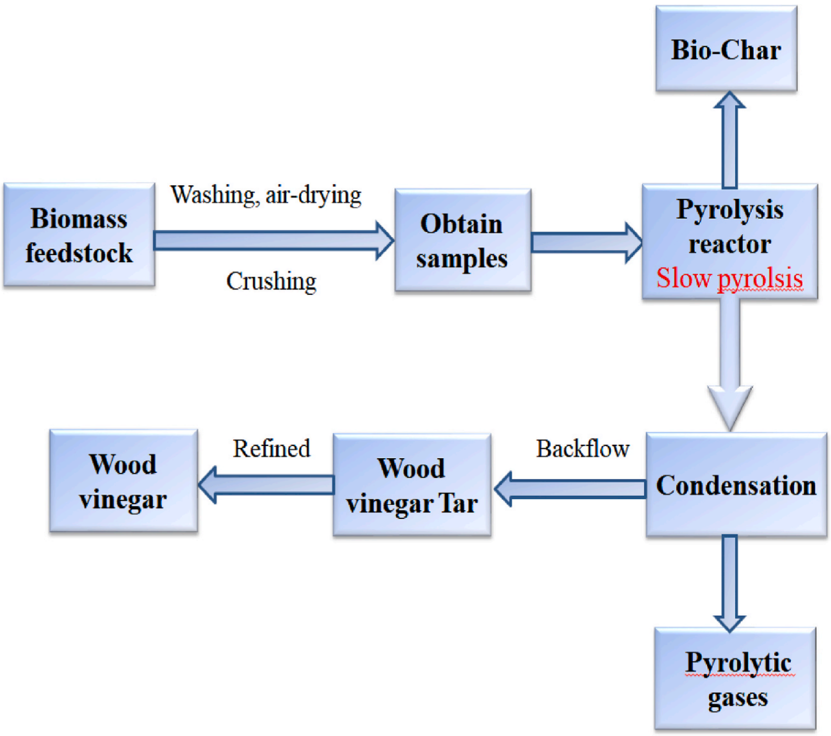

Fig. 1. Wood vinegar preparation process. Note: The selected biomass raw materials must undergo pre-treatment such as washing, air drying, and crushing to avoid impurities affecting the results, and then enter the pyrolysis reactor for slow pyrolysis (The ratio of water/oil phase in the liquid product obtained by slow pyrolysis is the highest). In this process, the liquid collected by condensation reflux is crude wood vinegar, which contains tar and cannot be used directly. Finally, it can be used after refining.

Although the liquids obtained from the pyrolysis of lignocellulosic biomass have been extensively studied over the last two decades as a potential source of fungicidal compounds, the efficacy, mechanism of action (antibacterial mechanism) and limitations of the application of pyrolysis liquids against plant diseases (fungal, bacterial and viral diseases) require a systematic literature review. This paper reviews the process of wood vinegar preparation, component properties, effects of different raw materials, preparation processes, and refining methods on the active ingredient content, outlines the application mechanism and potential limitations of wood vinegar in plant disease management, and discusses the potential of wood vinegar as a sustainable and eco-friendly alternative to conventional chemical fungicides; ultimately, providing a reference for research in related fields. This review also highlights the need for further research to fully understand the potential of wood vinegar as a plant disease management tool and to optimize its use in different agricultural and forestry systems. To enable the more favorable development of biomass pyrolysis as a production method for the optimal use of agricultural and forestry waste, while positively contributing to the environment and ecology of the planet is important for both environmental protection and sustainable agricultural development.

2. Preparation process and composition characteristics of wood vinegar

2.1. Preparation process of wood vinegar

Wood vinegar is a high-value by-product of biomass pyrolysis, which occurs during charcoal production. In the process of pyrolysis and carbonization of agricultural and forestry biomass to prepare biochar, the brown liquid produced by condensation reflux is called wood vinegar. This is crude wood vinegar containing tar and other substances and is generally collected from a temperature of 90 °C

Table 1
Effect of each influencing factor on the chemical composition of wood vinegar.

Pyrolysis raw materials	Three majo elements (wt%)	Pyrolysis temperature°C	Refining method	Chemical composition content (%)					References
	Cellulose: Hemicelluloe: Lignin			Phenols	Acids	Ketones	Aldehydes	Alcohols	
Apple branch	44:20:23.6	100~200	R + A	51.33	18.50	8.98	2.28	0.74	[45]
		201~300		24.69	40.05	7.52	2.45	1.18	
		301~500		34.66	28.37	12.49	3.09	0.36	
Walnut branch	45.36:18.26:28.43	90~150	R + A	29.00	20.27	9.14	4.17	0.55	[46]
		151~310		39.29	45.82	4.46	0.84	–	
		311~550		62.86	8.02	8.18	0.28	0.43	
Walnut branch	45.36:18.26:28.43	230~370	R + A	32.68	30.78	14.97	–	1.08	[47]
		90~550	E	6.98	79.81	5.09	–	–	[48]
Lacebark pine wood	–	90~550	R + A	21.73	40.23	19.66	4.64	1.07	[49]
Eucommia branch	45.12:22.94:26.29	550	R + D	74.48	10.63	10.76	5.69	0.28	[50]
Lychee wood	–	100~600	R	6.61	–	13.76	–	–	[51]
Mangosteen branch	–	400	R	34.62	29.10	8.08	–	1.33	[52]
Durian branch	–			26.92	30.59	9.94	0.18	0.88	
Rambutan Branch	–			65.69	29.65	9.38	0.28	1.53	
Blueberry branch	–			27.19	29.61	9.30	–	1.93	
Pine branches	–	500	R + D	12.18	57.31	–	–	–	[53]
Fir wood shavings	50.68:13.45:35.11	250	R + A	13.00	19.50	28.00	9.50	6.00	[54]
		350		17.20	10.00	23.00	7.80	4.00	
		450		24.30	8.00	22.10	7.90	2.00	
		550		23.80	6.20	19.50	6.00	9.10	
Fir wood shavings	50.68:13.45:35.11	250~550	R + A	17.50	10.00	21.00	7.50	4.00	[55]
Bamboo wood shavings	54:21.7:24.3			21.50	14.00	14.60	3.00	12.00	
Cotton straw	47.70:18.80:21			19.00	11.00	20.00	4.00	15.50	
Soybean straw	–	500	R + D	6.62	42.64	31.27	–	1.23	[56]
Corn stalks	32:27.82:15.42			7.99	47.55	27.15	–	0.32	
Corn cob	41.87:36.93:24.33			12.62	38.51	35.68	–	1.55	
Rice straw	41.94:45.78:21.51			11.90	13.12	39.60	–	10.49	
Rice husk	21.9:19:17.8			14.56	48.75	31.20	–	3.67	
Bitter apricot hulls	22.45:21.49:35.78	170~370	R + A	42.83	23.00	6.23	12.54	0.59	[57]
Pine nut shells	33.97:15.22:38.42	500	R	53.88	3.78	20.93	3.91	2.74	
Date kernels	20.83:18.18:38.30	150~400	R + A	35.93	8.20	26.88	15.44	–	[58]
Pineapple sticks Waste	– –	200~500	R + A + E	69.50	2.67	7.76	1.05	0.90	[59]
Banana sticks Waste	31.2:13.6:17.6 –	350~550	R	11.00	14.00	26.00	–	29.00	[60]

Note: R, A, E and D represent standing method, activated carbon adsorption method, extraction method and distillation method respectively.

until there is no further liquid outflow, while non-condensable gases such as CO_2, CO and CH_4 are exhausted to the atmosphere [33]. The specific preparation process is shown in Fig. 1. The biomass structure mainly includes cellulose, hemicellulose, and lignin, and also inorganic minerals and organic extracts, such as sugars, starch, and proteins [34]. The proportions of cellulose, hemicellulose, and lignin in different types of biomass vary, with the proportions of the three components in woody biomass being 40 %–50 %, 20 %–30 %, and 20 %–30 %, respectively; 35 %–45 %, 25 %–35 %, and 10 %–20 %, respectively, in herbaceous biomass; and 30 %–40 %, 15 %–25 %, and 15 %–25 %, respectively, in agricultural biomass [35]. Wood vinegar refining, also known as wood vinegar separation, aims to separate tar and other substances present in crude wood vinegar. Refining methods for wood vinegar include static activated carbon adsorption, distillation, low-temperature freezing and thawing, papain enzyme digestion, organic solvent extraction, electrolysis, distribution, and multilayer filtration. The commonly used refining methods mainly include static method, distillation method, extraction method and activated carbon adsorption method [36]. The static method is to use the instability of some components in the wood vinegar, which is easy to precipitate by oxidation or polymerization, and to be separated by refining. The method is simple in operation, simple in equipment and low in cost, but the effect of this method on the performance of wood vinegar is related to the standing time, so it is time-consuming. Distillation is a method of separation by using different boiling points of each component in wood vinegar. The distillation method is usually divided into atmospheric distillation and vacuum distillation. The method has high classification degree, good product quality, good stability [37]. Extraction is a method to separate and purify the target components by using the principle of similar miscible. The extraction method can realize the separation of organic components in wood vinegar, so as to realize the purification and enrichment of its components. This method can effectively separate the aqueous phase and organic phase of wood vinegar [38]. Activated carbon adsorption method is to treat wood vinegar by using activated carbon with huge specific surface area, rich pore structure and excellent adsorption performance to achieve the purpose of refining. This method can effectively remove tar and harmful impurities, but due to poor selectivity, it will also reduce other components to varying degrees, and the pertinence in the refining process is not high [39]. At present, the general sources of wood vinegar extract include corncobs, walnut branches, juniper branches, walnut shells, apple branches, Mongolian oaks, bitter apricot shells, hardwood sawdust, mixed wood chips, Quercus, birch, miscellaneous wood, sorrel, sour date shell, burlap branch wood, ginkgo, and willow hill wood.

The composition of wood vinegar is complex, and its physicochemical properties and composition vary depending on the raw materials used, preparation processes, and refining methods (Table 1) . The effect of biomass raw materials on the chemical

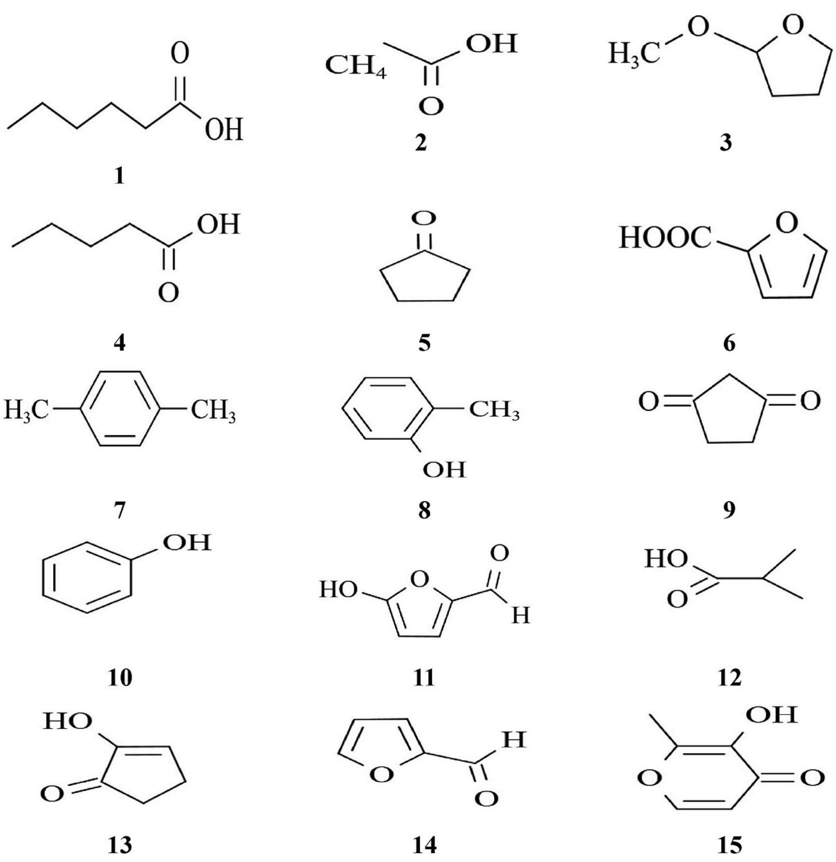

Fig. 2. Structure of chemical composition of wood vinegar. Note: 1. Hexanoic acid, 2. Propionic acid, 3. Methoxytetrahydrofuran, 4. Valeric acid, 5. Cyclopentanone, 6. Furancarboxylicacid, 7. P-xylene, 8. Methylphenol, 9. Hexyl Dione, 10. PPhenol, 11. Hydroxymethyl-2-furanaldehyde, 12. Dimethylpropionieacid, 13. 2-Hydroxy-2-cyclopenten-1-one, 14. Furfural, 15. Maltol.

composition and content of wood vinegar is related to the content of cellulose, hemicellulose and lignin in biomass. Wu et al. [40] found that the higher content of hemicellulose in bamboo led to the highest content of acids in bamboo wood vinegar, while Chinese fir with high lignin content could produce more phenols during pyrolysis. Phenols in wood vinegar are produced by lignin decomposition, acids are produced by hemicellulose and cellulose degradation during pyrolysis [41], ketones are derived from polysaccharide depolymerization and monosaccharide isomerization in hemicellulose, and alcohols are attributed to the broken side chains of aliphatic alcohol hydroxyl groups. The decomposition of lignin, hemicellulose, and cellulose may form aldehydes during pyrolysis [42]. In the preparation process of wood vinegar, temperature is the main factor affecting the chemical composition of wood vinegar. When the pyrolysis temperature range of wood vinegar increases from below 350 °C to above 350 °C, the content of acids and phenols decreases and increases respectively. There is a significant linear relationship between the chemical composition of wood vinegar and temperature [43]. The refining method has the least influence on the chemical composition and content of wood vinegar. Different refining methods have their own advantages and disadvantages. In order to realize the diversified application of wood vinegar, researchers have proposed different refining methods combined treatment, using the complementary advantages and disadvantages of different separation methods. The separated wood vinegar has high quality, wide adaptability and strong effect [44]. Therefore, when the application of wood vinegar in the field of plant disease management is studied and analyzed, many influencing factors such as pyrolysis raw materials, pyrolysis process and refining method should be comprehensively analyzed.

2.2. Composition of wood vinegar

Wood vinegar sap is a mixture that contains more than 500 organic components such as acids, alcohols, phenols, aldehydes, ketones, etc [61], of which the organic content is 7 %–15 %. Acetic acid accounts for approximately 50 % of the organic content, with the remainder largely comprising of n-propionic acid, butyric acid, and n-valeric acid, while the other components of the extract are mostly trace elements such as Ca, K, Fe, Na, and Mg, as well as vitamins B1 and B2 [62]. Compounds used in this study, wood vinegar can be divided into crude and refined vinegar according to their composition [40]. The crude wood vinegar contains chemical components which are easy to oxidize, polymerize and change color, and its nature is unstable; the oily wood tar component is mixed in during the extraction process, and it will adhere or precipitate in the wood vinegar. The crude wood vinegar contains methanol, formaldehyde, 3,4-benzopyrene, and similar compounds that are toxic to organisms, so it needs to be separated, refined or distilled and purified to prepare a refined wood vinegar that is useable in agricultural production. The appearance of crude wood vinegar is brown and translucent, with a layer of tar attached to the surface, which gradually adheres to the inner wall of the container after long-term storage. Refined wood vinegar is stable in nature, shows no particulate material, is transparent, and light yellow or colorless [63]. The content and proportion of each component in wood vinegar may vary depending on the source of the raw materials, charring method, and processing technology; however, the main components are largely the same. The chemical composition of common wood vinegar is shown in Fig. 2 [64].

3. Application of wood vinegar in plant disease management

As a new green natural material, wood vinegar is not only easily degradable but contains acids and phenolic active substances with insecticidal and antibacterial effects; its use alone or in combination with pesticides delivers good disease control effects and has received wide attention from researchers [65]. Currently, wood vinegar are widely used in plant disease management because of their antibacterial and antiviral properties [66]. Many studies at home and abroad have found that the broad-spectrum antibacterial effect of wood vinegar is closely related to its phenolic and acid complex components [67,68]. The strains used for the wood vinegar inhibition studies can be divided into bacteria and fungi. To date, research on the inhibitory effect of wood vinegar on plant pathogenic

Table 2
The main bacterial and viral species affected by wood vinegar treatment.

Bacteria	Fungus		Virus
	Mycete	Phytopathogen	
Escherichia coli	*Aspergillus niger*	*Fusarium graminearum*	Tobacco foliar disease (TMV)
StaphylococcusaUreLs	*Trichoderma viride*	*Colletotrichun lagenarium*	Pepper virus disease
Aerobater aerogenes	*Trichoderma koningii*	*Phytophthora capsici*	*Encephalomyocarditis virus* (EMCV)
Bacillusprodigiosus	*Trichoderma* sp.	*Valsa mali*	*Porcine Reproductive*(SARS)
Proteusvulgaris	*Phanerochaete chry sosporium*	*Verticillium dahice*	*Respiratory Syndrome Virus* (PRRS)
Bacillusmegaterium	*Poria placenta*	*Cochliobolus satizus*	
Corynebacterium pekinense	*Rhizopus nigricans*	*Phytophthora infestans*	
BacilLussubtilis	*Trichoderma reesei*	*Botrytiscinerea*	
Epi.zooticlymphangitis	*Mocor racermosus*	*lorosporium fructigenum*	
Aeromonas hydrophila	*Aspergillus oryzae*	*Alternaria solani*	
Pseudomonasaeruginosa	*Penicillium glaucum*	*Phytophthora infestans*	
Poria plaoenta	*Rhizopus arrhizus*	Alternariabressicae	
Pseudomons		Glomerrella cingnlata	
T. viride		*Alternaria alternate*	
		Physalosporapiricola	
		Alternaria brassicae	

fungi in plant disease management application research has been the major focus [66]. The main bacterial and viral species affected by wood vinegar treatment are shown in Table 2.

3.1. The effect of wood vinegar on pathogenic fungi

Several vitro studies have investigated the fungal inhibitory activity and mechanism of inhibition of wood vinegar, and different concentrations and species of wood vinegar have shown different inhibitory effects on different plant pathogenic fungi. Oramahi et al. [65]studied the antibacterial activity of 0.5 %, 1.0 % and 1.5 % (v/v) oil palm trunk wood vinegar against a white-rot fungus, *Trametes versicolor*, and a brown-rot fungus, *Fomitopsis palustris*. The results showed that the wood vinegar at three concentrations showed strong antibacterial activity against *Trametes versicolor*, especially at 1.0 % and 1.5 % concentrations, which could completely inhibit the growth of *Trametes versicolor*. However, a higher concentration of oil palm trunk wood vinegar is needed to achieve the effect of inhibiting the growth of *Fomitopsis palustris*. In addition, potato late blight fungus (*Phytophthora infestans*) stopped growing in 3.0 % wood vinegar rye medium [69], 100 mg mL^{-1} wood vinegar can inhibit mycelial growth of *Rhizopus stolonifera* [70], wood vinegar at a concentration of 3.0 % or more can inhibit mycelial growth of ginseng black spot fungus (*Alternaria panax*), and at a concentration of 2.25 % or more can inhibit mycelial growth and spore germination of ginseng gray mold (*Botrytis cinerea*) [71]. As shown in Fig. 3, the different types of wood vinegar showed different inhibitory effects on different plant pathogenic fungi. For example, the wood vinegar of walnut branch had no inhibitory effect on *root rolof flax*, but had inhibitory effect on other five plant fungal diseases. However, the wood vinegar of eucommia branch had inhibitory effect on *root rolof flax*, but had no inhibitory effect on other five plant fungal diseases. The control effects on plant fungal diseases have also been studied in field experiments. Wood vinegar alone has been shown to effectively inhibit fungal diseases in various crops. Gao et al. [72]field experiment showed that the application of wheat straw vinegar diluted 200 times could significantly reduce the infection rate of fusarium head blight (FHB) and the content of deoxynivalenol (DON) by 66 % and 69 %, respectively. The control effect of wheat straw vinegar diluted 200 times was equivalent to that of typical chemical fungicides. Jung [73] found that wood vinegar could be used instead of chemically synthesized pesticides to suppress apple Streptomyces alternate (*Alternaria alternate*), which causes apple defoliation. Liu et al. [74]studied the inhibitory effect of a wood

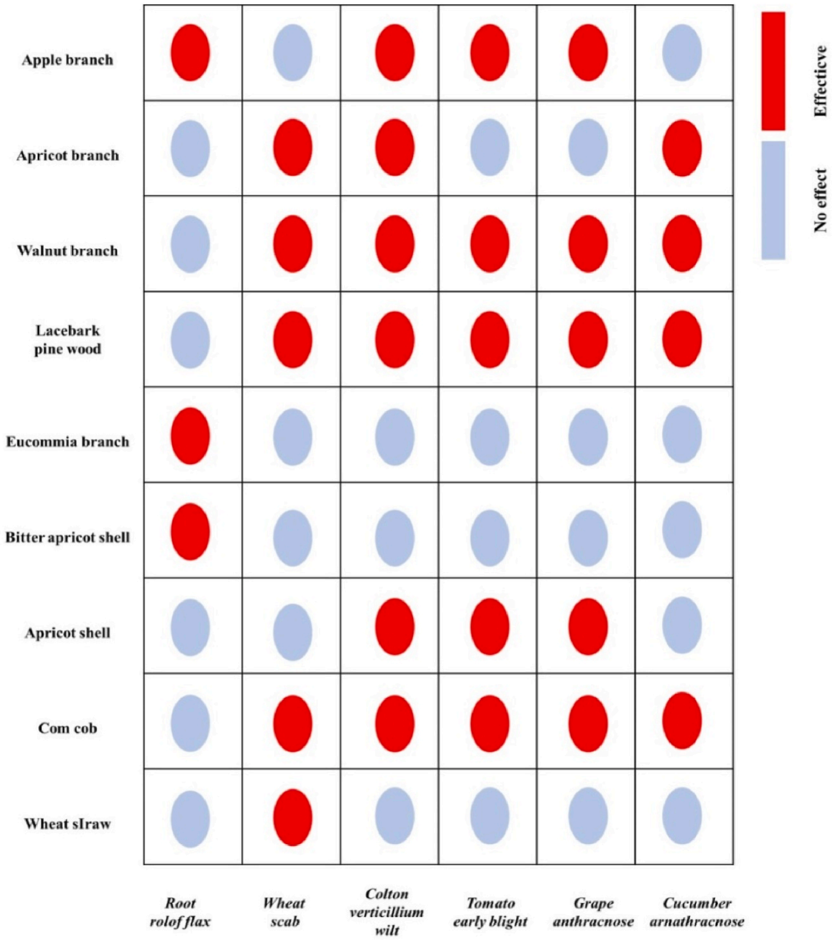

Fig. 3. Inhibitory effects of different types of wood vinegar on different plant pathogenic fungi.

vinegar on peach anthracnose (*Colletotrichum gloeosporioides*) and found that the inhibition rate was similar to that of chlorothalonil. Soil-borne diseases are common fungal diseases of crops, and Japanese scholars have systematically studied the inhibitory effect of wood vinegar on soil-borne disease and have demonstrated significant inhibitory effect on *Rhizoctonia*, *Sclerotinia* and *Fusarium* [75]. Zheng et al. [76]used 1000 times diluted wood vinegar for foliar spraying of organic tobacco and found that wood vinegar treatment led to an increased tobacco yield and improved tobacco quality while also reducing the incidence of black tibia, a soil-borne disease of tobacco.

3.2. The effect of wood vinegar on pathogenic bacteria

Wood vinegar has strong antibacterial activity [77]. The ability of wood vinegar to inhibit bacterial growth is related to the phenolic substances in its main components [78]. Feng et al. [79]studied the antibacterial effect of Eucommia ulmoides wood vinegar on *Staphylococcus aureus*, *Escherichia coli*, *Proteus vulgaris*, *Bacillus subtilis*, *Bacterium prodigiosum*, and *Enterobacter aerogenes*. The results showed that Eucommia ulmoides wood vinegar had a certain degree of inhibition on all bacteria. Otherwise, In tests, refined sorrel husk wood vinegar was found to be most effective against the soft rot pathogens of celery [*Erwinia carotovora* subsp. *carotovora* (*Jones*)] and melon fruit spot pathogens (*Acidovorax avenae* subsp. *Citrulli*), and it had a reasonable inhibitory effect against the bacterial brown spot pathogen Pseudomonas tolaasii (*Pseudomonas tolaasii Paine*) [80]. Wood vinegar can also change the number of soil microorganisms, thereby indirectly controlling the disease. Treatment of tomato plants with 100-times diluted wood vinegar increased the number of soil microorganisms, thus inhibiting the tomato early blight soil pathogen (*Alternaria solani*), indirectly controlling tomato early blight. A 600-fold diluted solution of wood vinegar affected soil microorganisms in the melon root system and enhanced the ability of the melon to resist soil-borne diseases [81]. Bacteria and other microorganisms in the soil account for 70–90 % of all microorganisms. Bacterial diversity, on the one hand, affects the health of the soil and plays a role in the process of plant resistance to diseases; on the other hand, it inhibits the pathogenic bacteria of soil-borne diseases and achieves control of plant diseases.

3.3. The effect of wood vinegar on plant viruses

A few studies on the inhibition of plant viruses by wood vinegar have reported direct inactivation of tobacco mosaic viruses [82]. Zheng et al. [76]showed that the application of wood vinegar alone or in a combination with a reduced pesticide concentration of 10–20 % in tobacco fields could reduce the occurrence of tobacco mosaic disease, which may be related to the avoidance effect of wood vinegar on the virus-vector, the insect aphid. Sun et al. [83]added wood vinegar to pepper leaf curl diseased plants and found that pepper virus disease prevention was enhanced by 71 %, and correspondingly reduced the viral load by 40 %.

4. Mechanisms of action

4.1. Mechanism of antibacterial action of wood vinegar

The mechanism of action of wood vinegar against bacterial diseases is largely through reducing the rate of bacterial division, destruction of bacterial cell membrane which leads to leakage of bacterial internal electrolytes, and inhibition of bacterial protein synthesis, all of which contribute to achieve inhibition of bacterial infection [84]. When high concentrations of wood vinegar are added to disease-causing bacteria, it can lead to electrolyte, protein, and sugar exudation in the bacterial cells, inhibit bacterial protein synthesis, cause cell metabolism disorders, and eventually lead to (bacterial) cell death [85]. Jia et al. [86]studied the mode of action of eucommia ulmoides leaf vinegar against *Bacillus subtilis*. The results showed that under the combined action of polyphenols (CA) and acetic acid, eucommia leaf vinegar exerts its antibacterial effect by destroying bacterial cell wall and cell membrane, increasing cell permeability, causing cell structure damage, releasing cell components, and leading to cell death. Duan [87]studied the effects of four wood vinegar solutions on the growth curve, bacterial cell permeability, bacterial fluid protein content, and soluble sugar content of three bacteria strains and showed that the inhibitory effect of wood vinegar was mainly achieved by inhibiting the rate of bacterial division, disrupting the bacterial cell membrane, causing the leakage of bacterial internal electrolytes, and inhibiting bacterial protein synthesis. Bouyahya et al. [88]studied the role of compounds in wood vinegar in the process of bacterial inhibition and concluded that organic acids promote cytoplasmic acidification and affect microbial metabolism, and that the antibacterial activity of phenolic compounds lies in their ability to alter the structure of microbial cell membranes, which in turn affects their function. Otherwise, Peng et al. [89]studied the effects of different organic solvent extracts of herbaceous fruits on the growth curve and membrane permeability of *Staphylococcus aureus* and found that ethyl acetate and chloroform extracts had the best bacterial inhibition effect, whereas wood vinegar inhibited bacterial growth by shortening the logarithmic period of bacterial growth, increased cell membrane permeability, consequently reducing protein content and increasing the conductivity of the bacterial solution.

4.2. Mechanism of antifungal action of wood vinegar

Wood vinegar can alter the morphological structure of pathogenic fungal spores and inhibit spore germination and biological dry weight [70,90]. Xue et al. [70]showed that the higher the concentration of wood vinegar, the better the inhibition rate of biological dry weight and spore germination of peach black root mold. In addition, wood vinegar with complex composition may change the permeability of the cell membrane of the pathogenic fungus and inhibit the rate of division or protein synthesis of *Fusarium graminearum*, leading to the exudation of proteins, carbohydrates, Na^+ and K^+ or induction of metabolic disorders, thus inhibiting fungal diseases [91]. Wood vinegar can induce and stimulate plant antioxidant defense-related enzymes, promote the accumulation and expression of plant antioxidant enzymes, inhibit plant membrane lipid peroxidation, and reduce hydrogen peroxide content to improve plant resistance to diseases. Chen et al. [92]investigated the inhibitory effect of wood vinegar on gray mold in fresh grapes and showed that the wood vinegar improved resistance to gray mold and reduced the damage caused by oxidative stress by stimulating antioxidant defense-related enzymes (SOD, APX and POD) in grapes. Wood vinegar may also inhibit the growth of pathogenic fungi by interfering with the expression of several genes involved in multiple signaling pathways [93]. Zhang et al. [94]studied the mechanism of action of apricot hull wood vinegar on *Aspergillus fumigatus* and found that it inhibited mold growth by interfering with the expression of genes in the fungal signal transduction pathway. Appropriate concentrations of wood vinegar can increase the activity of enzymes related to nutrient conversion in the soil, increase the content of quick-acting nutrients in the soil, change the structure of the soil microbial community, and enhance plant resistance to diseases [95,96]. Liu et al. [91]showed that wood vinegar significantly increased soil sucrase, phosphatase, and urease activities, and this increase in soil enzyme activity promoted the degradation of large organic compounds into small molecules, such as sugars, amino acids, soluble organic carbon and nitrogen, which provided a carrier or substrate for microbial development and promoted an increase in the number and activity of microorganisms [97], thus enhancing the resistance of wheat to root rot.

4.3. Mechanism of antiviral action of wood vinegar

Currently, there are no clear findings regarding the mechanism of action of wood vinegar against plant viruses. The Watanabe team conducted an in-depth study on the antiviral mechanism of wood vinegar in the medical field, showing that the antiviral activity of wood vinegar against *Encephalomyocarditis virus* (EMCV) was due to the presence of phenol [98,99], a major antiviral compound. Moreover, acetic acid, the main organic acid in wood vinegar solutions, significantly enhanced the activity of phenol when inactivating EMCV. Therefore, an acidic medium containing phenol and acetic acid is suitable for EMCV inactivation. In addition, the structural diversity of the phenol derivatives contained in wood vinegar is highly relevant to the viral inhibitory activity, with substituents influencing the antiviral activity of the compounds, with phenolic compounds containing methyl groups exhibiting higher activity than those containing methoxy groups (e.g., 2-methylphenol > 2-methoxyphenol). In addition, the relative positions of the functional groups play a key role in the viral inhibitory activity (e.g., 2,6-dimethoxyphenol >3,4-dimethoxyphenol). Li et al. [100]showed that wood vinegar, a Japanese larch lysis product, exhibited strong anti-EMCV activity. Catechol and its substituents were the main antiviral compounds in this wood vinegar. These components exhibit different levels of antiviral activity depending on the position and structure of the functional groups attached to the aromatic backbone. The researchers also investigated the effect of catechol derivatives on the host immune system and found that the derivatives directly produce ROS, inactivate EMCV, and induce the production of cytokine Il6.

5. Challenges of wood vinegar in plant disease management

5.1. The key bacterial inhibiting substances in wood vinegar and their interactions are unknown

Currently, only acids and phenolics in wood vinegar have been identified as bacteriostatic agents. However, it is difficult to accurately identify the key substances responsible for bacterial inhibition in a complex wood vinegar matrix because the functionality of wood vinegar is the result of the interaction of several compounds that may be subject to interference by other compounds [101]. Therefore, a method for the fine separation of phenolic substances in wood vinegar into multiple fractions containing only a few compounds is urgently needed, so that the interactions between the compounds and the substances that play a key inhibitory role can be clearly determined.

5.2. Lack of convenient and feasible application methods of wood vinegar

Although many studies have confirmed the effective antibacterial action of wood vinegar, in most cases the treatments are applied directly, and although simple and convenient, the functional substances fail faster and are easily oxidized, which is not conducive to maintaining an optimal antibacterial effect. This method has a single application scenario, which makes it difficult to adapt to complex and diverse practical needs.

6. Prospects for future research

Biomass raw material resources are abundant worldwide, and the production of wood vinegar is significant. As a green material, wood vinegar have gradually been recognized and are now starting to receive attention. In the coming years, with the progress in science and technology, it is likely that wood vinegar will have a broad market space with applicability in the plant disease management space. Future research should focus on the following aspects: First, mechanism research, which is the theoretical basis for the application of wood vinegar. At present, most domestic and foreign research on wood vinegar focuses on its refining process and application performance, but there are relatively few studies on its application mechanism, which in turn causes difficulties in elucidating mechanisms of action such as its antibacterial mechanism. Through the mechanism research, the active components of wood vinegar in the application process should be explored, and according to the physical and chemical properties of the active components, the research should focus on the refinement and enrichment process of the active components to improve the application effect of wood vinegar. Additionally, a wood vinegar containing high concentrations of active components should be prepared through directional pyrolysis, which, in turn, will promote the efficient application of wood vinegar. Second, some research has shown that wood vinegar solution mixed with pesticides can improve the efficacy and reduce the required level of pesticide. Consequently, the study of wood vinegar in disease management application technology with other pesticides should be assessed to scientifically determine its synergistic effect and explore the mechanisms by which it improves the efficacy of pesticides. This will lead to the development of value-added and efficient disease management products. Finally, we propose that national or industrial standards should be formulated as soon as possible to regulate the quality standards of wood vinegar production and manufacturing. This will provide a basis for the research and utilization of special wood vinegar, promote the application of wood vinegar in plant disease management, and provide strong support for the green development of agriculture.

7. Conclusion

Lysate from lignocellulosic biomass can be considered a cost-effective biological fungicide with great potential for controlling plant diseases. According to current scientific literature, the antibacterial properties of wood vinegar depend on the raw biomass materials and the pyrolysis methods used. Wood vinegar is widely used in plant disease management, and its effect is significant. There are few studies on the antibacterial mechanisms of wood vinegar. Future research should also focus on the mechanism of its composition and application performance, to reveal the application mechanism of wood vinegar and provide a theoretical basis for its application. Promoting the popularization and application of wood vinegar in plant disease management will also provide strong support for the green development of agriculture.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Hongyin Zhou: Writing – original draft, Conceptualization. **Yan Shen:** Writing – original draft. **Naiming Zhang:** Methodology, Investigation, Funding acquisition. **Zhizong Liu:** Data curation. **Li Bao:** Project administration. **Yunsheng Xia:** Validation, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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