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Wood Vinegar: A promising agricultural input: A review

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Abstract

With the increasing emphasis on health and environmental sustainability, organic agriculture is gaining momentum. Wood vinegar, a by-product of wood pyrolysis, has emerged as a valuable organic agricultural input. It exhibits multifaceted roles, acting as a natural insecticide effective against various pests, including sucking pests, subterranean pests, storage and household pests, as well as non-insect pests such as snails, slugs, and mites. Additionally, wood vinegar serves as a fungicide targeting soil-borne and foliar phytopathogenic fungi. Beyond its pesticidal properties, it contributes to soil health by buffering pH and stimulating beneficial microbial activity. As a plant growth regulator, wood vinegar promotes seed germination, enhances seedling vigour, supports vegetative and reproductive growth, and bolsters resistance to both biotic and abiotic stresses, culminating in increased crop yields. Furthermore, recent studies indicate its potential as a herbicide. These diverse benefits are attributed to the synergistic effects of its chemical constituents, including phenols and organic acids. Consequently, wood vinegar holds significant promise for integration into sustainable and organic farming systems.

Keywords: Wood vinegar, growth regulator, insecticide, fungicide, herbicide, yield and organic farming

Introduction

When wood is burned, it produces smoke. If this smoke is condensed into liquid form, it separates into three distinct layers: a top oily layer, a bottom layer of wood tar, and an intermediate layer consisting of a transparent, yellowish-brown liquid known as raw wood vinegar. Wood vinegar was first used by the Chinese and was also utilized by the Egyptians, Greeks, and Romans for various purposes, including embalming and sealing joints in wooden ships (Tiilikkala, K. *et al*., 2010) [45].

Wood vinegar is highly significant due to its diverse properties and wide-ranging applications. Its unique characteristics, such as high acidity, a variety of volatile compounds, and antimicrobial activity, have prompted investigation across many fields. Notably, wood vinegar has attracted attention in agriculture for its beneficial effects on plant growth, pest management, soil enhancement, seed germination, root development, and disease suppression (C. Mattos *et al*., 2019) [5]. It has proven effective against several insects, including aphids, mites, and mosquitoes (T. Higashino *et al*., 2005) [43].

Despite its growing popularity and various potential applications, there is a significant research gap evident in the lack of systematic and quantitative analyses that provide a comprehensive overview of the wood vinegar research landscape.

Researchers investigated its effects on soil fertility, nutrient availability, and microbial activity. They found that wood vinegar application increased soil organic matter content, enhanced nutrient absorption by plants, and stimulated beneficial microbial populations. Studies also investigated its effectiveness in reducing water pollution, mitigating soil contamination, and promoting environmental sustainability. Wood vinegar was found to have the potential to adsorb and neutralize pollutants, making it useful in wastewater treatment and soil remediation (E. Fanfarillo *et al* 2022) [9]. Wood vinegar is also suitable for composting, enriching the compost with essential nutrients, improving microbial activity, and reducing greenhouse gas emissions and nitrogen loss (W.O.M. Arsyad *et al 2002)* [49]. Beyond agriculture, wood vinegar finds applications in various industries.

Wood vinegar primarily consists of over 200 water-soluble compounds. Its main components include organic acids, phenolic compounds, alkanes, alcohols, and esters, with acetic acid being the most prominent. Additionally, it contains butyric acid, catechol, and phenol. Due to these compounds, wood vinegar has a wide range of potential applications. It can be used as a sterilizing agent, deodorizer, fertilizer, antimicrobial agent, plant growth promoter, antioxidant, and wood preservative (Mathew and Zakaria, 2015) [36]. Additionally, pyroligneous acid enhances the permeability of agrochemicals into leaf tissue, making them more effective. Agrochemicals tend to work best in combination with other acids, such as wood vinegar or pyroligneous acid, at a pH of 4 to 5. However, it is important to note that alkaline substances should not be mixed with wood vinegar due to adverse reactions between acids and bases. Wood vinegar protects against pests and diseases while enhancing crop vitality and quality when diluted and sprayed. When applied to the soil, it helps inhibit nematodes and increases beneficial microbes and the rate of decomposition. It acts as a biocatalyst and chelating agent, aiding nutrient absorption and facilitating pesticide use. Wood vinegar controls various pests - like sucking pest, field crop pest, household pests, storage pest and other non-insect pest -mite, snail, and slug. Based on the available research, wood vinegar can be safely used as a pesticide. Additionally, the increase in enzyme activities and productivity suggests that using wood vinegar (WV) can positively impact crop production. Specifically, the treatments with wood vinegar indicate that the doses and application frequencies significantly affect the microbial factors in the soil. It is estimated that a concentration of 3.0% will particularly enhance the number and activity of beneficial biological factors in the soil when growing wheat (Koç, İ. *et al*., 2019) [20].

Our primary objective is to address this gap by conducting a detailed examination of research productivity, collaboration patterns, and publication trends in the field of wood vinegar. This review emphasizes and advances the existing knowledge base by synthesizing and organizing the vast amount of scattered research, making it accessible to researchers, and practitioners.

Role of wood vinegar in agriculture

As a fungicide

The fungicidal activity of wood vinegar is attributed to the presence of various phenolic compounds. The combined effects of these phenolics in pyroligneous acids, rather than the action of any single phenolic compound, contribute to their effective antifungal properties (Theapparat *et al*., 2015) [44]. It is believed that the presence of furaldehydes and phenols in pyroligneous acid is primarily responsible for its antifungal activity. Phenolics resulting from lignin degradation are crucial for combating brown rot fungi (Kartal *et al*., 2004) [17]. Wood vinegar is also effective against white rot fungi (such as *Trametes versicolor and Rigidoporopsis amylospora)*, a brown rot fungus (*Gloeophyllum trabeum*), and a sapstain fungus (*Botryodiplodia theobromae*) (Oramahi and Yoshimura, 2013) [32].

Additionally, wood vinegar (WV) derived from guava (*Psidium guajava*) has been shown to control *Colletotrichum coccodes*, which causes black dot disease (El-Fawy *et al*., 2023) [10]. It is a low-cost alternative, priced at only one-third the cost of synthetic fungicides (Zulkarami *et al*., 2011) [56]. Wood vinegar contains several essential elements that play vital roles in plant life cycles and promote photosynthesis.

Moreover, WV protects vegetable and horticultural crops from fungal diseases, particularly root rots. Key substances found in WV from oak, poplar, pine, pruning litter, and forest waste include sugars, carboxylic acids, hydroxy aldehydes, hydroxy ketones, and phenolic acids, all of which exhibit antifungal activities. It is a low-cost, all-natural product that poses no negative effects on living organisms or the environment. WV has been shown to suppress various soil-borne plant pathogens.

The mycelial growth of several pathogens, including *Plasmopara viticola*, *Verticillium dahliae* (Klebahn), *Phytophthora capsici* (Leonian), *and Fusarium graminearum* (Schwabe), has been inhibited by WV produced from apricot trees. Additionally, WV has been shown to completely inhibit the growth of *Alternaria mali* (Roberts), the causative agent of apple Alternaria blight, when used at a 1:32 dilution (Jung H S., 2007) [16].

Furthermore, wood vinegar from *Cryptomeria japonica* (Linnaeus) has demonstrated potent antifungal activity against *Pythium splendens* (H. Braun), *Phytophthora capsici*, and *Ralstonia solanacearum* (Hwang *et al.*, 2005) [13]. WV produced from bamboo, coconut inner shells, and Eucalyptus wood effectively controls fungal diseases (Tiilikkala *et al*., 2010) [45]. Birch WV has also been shown to combat late blight disease caused by *Phytophthora infestans* in potatoes (Tiilikkala *et al*., 2010) [45]. Wei *et al*. (2010) [51] reported that pyroligneous acid has antipathogenic effects on several plant pathogenic fungi, including *Helminthosporium sativum*, *Cochliobolus sativus*, *Valsa mali*, and *Colletotrichum orbiculare.*

As a Bactericide

The high concentrations of phenolic compounds and organic acids in wood vinegar contribute to its antimicrobial properties Numerous studies have shown that pyroligneous acid exhibits antibacterial activity against various plant pathogenic bacteria. Wood vinegar extracted at temperatures ranging from 230 to 370 degrees Celsius has demonstrated inhibitory effects against bacteria and plant pathogens, positioning it as a potential natural bactericide (Wei *et al*., 2010) [51].

For example, Chalermsan and Peerapan (2009) [6] discovered that pyroligneous acid inhibits *Xanthomonas campestris pv. citri* and *Erwinia carotovora pv. carotovora*, both of which can cause significant harm to horticultural crops. The bacterium responsible for bacterial wilt in several crops, *Ralstonia solanacearum*, was inhibited by phenols and guaiacols derived from pyroligneous acid synthesized from Japanese cedar (Cryptomeria japonica; Young-Hee *et al.*, 2005) [54].

In similar studies, a 10% concentration of pyroligneous acid was found to have an inhibitory effect on Agrobacterium tumefaciens and X. campestris. Additionally, pyroligneous acid produced from pineapple solid biomass showed growth inhibition of the bacterium Corynebacterium agropyri, which is associated with yellow gum disease (Mahmud *et al*., 2016) [22].

As an insecticide

There is an increasing demand for sustainable agricultural practices aimed at reducing reliance on chemical pesticides. Phenolic compounds found in pyroligneous acids contribute to their pest control properties (Baimark & Niamsa, 2009) [1].

Wood vinegar, produced from oil palm empty fruit, has demonstrated termiticidal properties. Studies show that wood vinegar derived from *Vitex pubescens* exhibits termiticidal activity and a repellent effect on pests such as *Reticulitermes speratus* and *Coptotermes formosanus* when used at a 10% concentration (Oramahi & Yoshimura, 2013) [32]. Additionally, Kiarie-Makara *et al*.2010 [18] have recently shown that wood vinegar obtained from the Konara oak tree (*Q. serrata*) is particularly effective in repelling *Culex pipiens pallens* (Coquillet).

A study by Mmojieje and Hornung (2015) [25] investigated the insecticidal effects of pyroligneous acid derived from mixed wood biomass and found it to be highly effective against the green peach aphid (*Myzus persicae*) and the red spider mite (*Tetranychus urticae*), achieving over 90% mortality for both pests. In Thailand, pyroligneous acid is commonly used as an insecticide in agriculture (Mmojieje & Hornung, 2015) [25]. For example, birc tar oil has been shown to be an effective repellent against slugs (*Arion lusitanicus*) and snails (*Aranta arbustorum*) (Tiilikkala *et al*., 2010) [45]. The application of pyroligneous acid at a 1% dilution resulted in a 95% mortality rate of the aphid population on *Solanum melongena* (Regnault-Roger, 1997) [35]. Yatagai *et al*. (2002) [53] also reported the termiticidal effects of pyroligneous acid against the Japanese termite (*Reticulitermes speratus*). Other studies have indicated that pyroligneous acid is effective against houseflies (Pangnakorn *et al.*, 2014) [33].

When wood vinegar is combined with the methanol extract of *Salvia lerrifolia*, it causes mortality in the cigarette beetle (*Lasioderma serricorne*) (Hashemi *et al*., 2015) [11]. reported insecticidal activity from wood vinegars produced at temperatures ranging from 400 to 600 °C against the Colorado potato beetle (*Leptinotarsa decemlineata*). Hossain *et al*. (2017) [12] tested the insecticidal activity of wood vinegars derived from the fast pyrolysis of lignin, cellulose, and hemicellulose at 450 °C and 550 °C, finding them toxic to *L. decemlineata*, *Trichoplusia ni*, and *Acyrthosiphon pisum.*

Wood vinegar is also acknowledged as an effective insecticide against the striped mealybug (*Ferrisia virgata*) (Wititsiri *et al*., 2011) [52]. Additionally, it can have a synergistic effect when combined with the insecticide carbosulfan (Kim *et al.*, 2010) [19]. A mixture of 60% wood vinegar and 30% neem oil has been found to significantly reduce housefly populations and decrease the population of *Spodoptera litura* (Prianto *et al*., 2022) [34].

Mixing wood vinegar with compost enhances beneficial microbes and promotes root growth. In addition to inhibiting nematodes, it improves the populations of nematode predators, effectively controlling their presence. Mitsuyoshi *et al*. (2002) [24] reported its effectiveness as a termiticide and noted that it acts as a repellent to insects and other arthropods.

Tar oil derived from macadamia nut shells was used *in vitro* to protect wood against various wood-decaying fungi and wood-attacking termites (Kartal *et al*., 2011) [17]. Wood vinegar produced from *Cerbera odollam Gaertn* at 300, 400, and 500 °C showed anti termite activity against *Coptotermes formosanus* vinegar made from giant cane (*Arundo donax* L.) and identified abundant components including acids, ketones, furans, benzenes, phenols, sugars, and guaiacols. They reported that this wood vinegar was effective against *Reticulitermes flavipes*. Lastly, Shiny and Remadewi (2014) [38] indicated that wood vinegar derived from shell oil has the potential to replace synthetic chemicals as a promising new biodegradable termiticide. Guava wood vinegar has been shown to promote the growth of potato plants and reduce the incidence of black dot disease in potatoes (El-Fawy *et al.,* 2013) [10].

Wood vinegar as a herbicide

Pyroligneous acid has the potential to serve as a bioherbicide, offering a natural alternative to synthetic chemical herbicides. Its effectiveness as a herbicide is influenced by the presence of phenols, organic acids, carbonyls, and alcohols (Kim *et al*., 2001) [19]. Acetic acid, the primary component of pyroligneous acid, is already used in agriculture to manage weeds. One study demonstrated that pyroligneous acid effectively targeted the underground weed propagules of freshwater plants such as *Hydrilla* spp., sago pondweed (*Potamogeton pectinatus*), and smooth cordgrass (*Spartina alterniflora)* (Spencer & Ksander, 1999) [42].

As a growth regulator

The use of bamboo vinegar diluted to 1:500 has been shown to increase vegetable yields by 18.9% to 20.2%. This improvement is linked to enhanced vegetative and reproductive growth, as well as the overall quality of vegetables. It is believed that this effect may stem from bamboo vinegar's influence on plant hormones and photosynthesis, which contribute to the increased yield, as reported by Mu *et al*. (2006) [28].

Wood vinegar (WV) ester compounds are known to enhance chlorophyll production, boost photosynthesis, increase the production of sugars and amino acids, and stimulate plants' resistance to diseases and pests in potatoes (Chuaboon *et al*., 2016) [7]. Furthermore, wood vinegar has been shown to improve tolerance to abiotic stresses, as well as growth, production, and quality across a wide range of crops (Nakayama *et al.*, 2001) [30]. When applied as a foliar treatment, wood vinegar can increase yields in crops such as cucumbers, lettuce, cole crops, and jasmine rice, while also promoting potato growth.

Historically, wood distillates have been used in traditional agriculture to enhance seedling vigor and crop stands (Modi, 2002) [26]. In the past decade, aqueous pyroligneous acid extracts have gained popularity as germination stimulants for various plant species (Van Staden *et al*., 2000; Brown *et al.*, 2003) [48, 3]. The benefits of these aqueous smoke extracts extend beyond seed germination; they also have positive effects on flowering, root development and somatic embryogenesis.

Pyroligneous acid has been shown to induce new branch growth, elongate roots, and increase both plant height and grain yield (Tsuzuki *et al.*, 1989) [46]. Additionally, it enhances the germination of seeds from ephemeral Fynbos fires, making it useful in floriculture for promoting seed germination (Brown, N.A.C., 1993) [4].

Smoke treatment has significantly benefited various industries such as wildflowers, agriculture, horticulture, forestry, conservation, weed science, and ecosystem rehabilitation. A highly active and heat-stable compound known as 3-methyl-2H-furo[2,3-c]pyran-2-one has been isolated from plant-derived smoke water. This compound serves as a major germination cue from smoke, promoting seed germination. Notably, it can act as a substitute for red light as a trigger for germination in light-sensitive Grand Rapids lettuce seeds (Van Staden *et al.,* 2010) [48].

Wood vinegar is another product known to stimulate cell growth and serves as a catalyst for the growth of various microbes, as well as the activation of enzymes. These enzymes are crucial for several physiological and biochemical processes in plants, including photosynthesis, nutrient uptake, and cellular development.

The application of wood vinegar has significantly affected the production of various crops, including rice (Tsuzuki *et* *al*., 2000) [47], sorghum (*Sorghum bicolor*), sweet potato (*Ipomoea batatas)*, rock melon (*Cucumis melo*), French marigold (*Tagetes erecta*), zinnia (*Zinnia elegans*), scarlet sage (*Salvia splendens*), and tomato (*Solanum lycopersicum*). In a study focused on tomatoes conducted by Mungkunkamchao *et al*. 2013 [29], the use of wood vinegar resulted in increased total dry weight, number of fruits, and both the fresh and dry weights of the fruits. Additionally, it effectively enhanced the total soluble solids in the fruits.

Masum *et al.* (2013) [23] demonstrated that applying wood vinegar increased the grain yield of rice, which was attributed to an increase in tillers per hill, the weight of 1,000 grains, and the number of filled grains per panicle. Furthermore, wood vinegar also boosted the yield of soybean. Foliar sprays of wood vinegar improved the growth and yield of lettuce (*Lactuca sativa*), cucumber (*Cucumis sativus*), and cabbage (*Brassica oleracea var. capitata)* crops (Mu *et al*., 2006) [28]. It also significantly stimulated plant growth, fruit diameter, sweetness, and fruit weight in rock melon (*C. melo var. cantalupensis*; Zulkarami *et al*., 2011) [56].

Multiple studies have confirmed the beneficial effects of pyroligneous acid, particularly when applied as an organic fertilizer for crops such as rice (Tsuzuki *et al.*, 2000) [47], sugarcane, and sweet potato. Research has shown that a 20 percent concentration of pyroligneous acids significantly enhances the growth and yield of watermelon (*Citrullus lanatus*) in soilless culture (Zulkarami *et al*., 2011) [56]. Karrikins, which are present in wood vinegar, stimulate seed germination and influence seedling growth (Nelson, D.C. *et al*., 2012) [31].

Researchers have highlighted that wood vinegar exhibits both germicidal effects and indirect benefits, such as enhancing plant-induced resistance. When sprayed on leaves, it increases glossiness and greenness, enhances sugar and amino acid content, boosts leaf vitality, imparts disease resistance, and improves the taste of the produce.

It is essential to avoid mixing wood vinegar with alkaline agricultural products, as these can react negatively with the acids present. In conditions with insufficient sunlight or poor soil—situations that typically lead to reduced photosynthesis and a decline in produce taste—the use of wood vinegar can significantly enhance flavor.

As a soil conditioner

Wood vinegar (WV) has demonstrated the ability to enhance soil physicochemical parameters and support the microbiome, particularly by increasing the presence of plant-growth-promoting rhizobacteria (Sivaram *et al*., 2022) [41]. When applied to soil at a concentration of 0.1%, wood vinegar improves microbial diversity and boosts the abundance of beneficial microbes such as *Bacillus, Bradyrhizobium, Azospirillum, Pseudomonas, Micromonospora, Mesorhizobium, Rhizobium, Herbaspirillum, Acetobacter, Beijerinckia,* and *Nitrosomonas.* This increased presence of beneficial plant-growth-promoting bacteria (PGPB) at lower concentrations may enhance soil quality, leading to better plant growth and higher yields.

In contrast, applying higher concentrations of wood vinegar (5%) increases the populations of spore-forming bacterial genera like *Bacillus*, which play a crucial role in defending against pathogens and pests. Thus, wood vinegar has the potential to improve soil biological health by promoting the growth of beneficial PGPB (Sivaram *et al*., 2022) [41]. Furthermore, the use of wood vinegar enhances nutrient availability in the soil, which can be advantageous for long-term soil quality improvement (Jeong *et al*., 2015) [14]. Research on tea plants also indicates that applying pyroligneous acid can triple the levels of available phosphoric acid in the soil.

The effects of wood vinegar are most noticeable when used in moderation. High concentrations can have a germicidal effect, killing all microbes indiscriminately. However, when diluted 20 times, it significantly raises the concentration of microbes in the soil. After applying wood vinegar, the density of beneficial microbes, such as bacilli and actinomycetes, increases, along with a notable rise in *Trichoderma* levels, which helps combat damping-off diseases caused by *Rhizoctonia* and *Pythium.*

Additionally, wood vinegar accelerates decomposition and can reduce fermentation periods by half. When used in low concentrations, it enhances soil microbial life and aids in breaking down tougher fibres. When mixed with charcoal, it helps adjust the soil's pH level to favor beneficial microbes, lowering the pH from 8-9 to around 6. Typically, wood vinegar is used at a dilution ratio of 1000:1.

As a wood preservative

Bamboo and broadleaf tree wood vinegar, when applied at 0.01% to 1.00%, acts as a wood preservative that can correct discoloration caused by wood fungi. The components in wood vinegar serve as antifungal and antioxidative agents.

Characteristics of high quality wood vinegar

1. Wood vinegar should be transparent.
2. It must contain less than 1% tar.
3. Wood vinegar should be left to sit for a minimum of 1 month and a maximum of 1 year.
4. Wood vinegar produced from broadleaf trees in kilns, typically found in mountain regions, is generally safer than that produced in cities using sawdust and low-quality wood barks or artificial wood vinegar. The latter is ineffective for agricultural purposes and requires a more advanced refining process than simply allowing it to sit.

The pH of the vinegar should be approximately 3

The standard specific gravity should range between 1.010 and 1.050 g/mL.

The product should exhibit a pale yellow, light brown, or red-brown color.

It should have a distinct smoky odor.

The dissolved tar content must be less than 3%.

The ignition residue must be below 0.2%.

The product should be transparent with no suspended solids.

Please note that wood vinegar contains phenolic compounds, which can be toxic to microbial activity if used in high concentrations.

Usage of wood vinegar

Wood vinegar benefits in different crops

In apple cultivation, the disease-causing fungus *Alternaria mali*, responsible for Alternaria blotch, was completely inhibited in pyroligneous acid at a dilution of 1:32. This suggests that pyroligneous acid can serve as an alternative to chemical fungicides for managing Alternaria blotch in apples (Jung, K.H., 2007) [16].

Wood vinegar has also been shown to promote the growth and health of rice crops. Both seed treatment and foliar application with wood vinegar significantly enhanced the growth of rice plants and notably reduced the incidence of diseases. These results indicate that wood vinegar can effectively inhibit fungal diseases in rice compared to traditional agrochemical treatments (Chuaboon, W. *et al*., 2015) [7].

Additionally, seed priming with wood vinegar accelerated germination speed and increased the final germination percentage in rice. Seeds treated with wood vinegar exhibited greater shoot growth and a higher plant population at maturity. The agronomic performance characteristics related to yield, such as the number of tillers per plant and overall yield in tons per hectare, were significantly improved for primed seeds, while weed biomass was notably reduced (Simma, B. *et al*., 2017) [40].

Foliar applications of wood vinegar have also been shown to enhance yield components in rice (Berahim *et al.*, 2014) [2] and to combat Alternaria blotch in apples (Tiilikkala, K. *et al*., 2010) [45]. Furthermore, foliar application of wood vinegar led to increased vegetative growth in large-seeded peanuts and slightly improved seed yield and shelling percentage. When used as a foliar fertilizer, wood vinegar has been found to enhance yields in cucumber, lettuce, and cole crops (Jung *et al.*, 2007) [16] as well as in jasmine rice (Jothityangkoon *et al.*, 2008) [15].

smoke is effective in reducing the incidence of alfalfa anthracnose, barley powdery mildew, and cotton damping-off, as well as in decreasing the number of propagules of *Pythium ultimum* in field soil. If wood vinegar is applied at the appropriate concentration, it can also serve as a soil fertilizer.

The application of wood vinegar has been shown to increase root dry weight, promote plant height, enhance ear number, and improve grain yield in rice (Tsuzuki *et al.*, 2000) [47]. Additionally, wood vinegar enhances nitrogen-utilization efficiency when used in conjunction with nitrogen fertilizers.

Wood vinegar has potential for managing cowpea weevil infestations through its egg-laying and piercing effects on seeds. Notably, centrifuged and raw wood vinegar can be produced by individuals in rural areas, making it a promising alternative for sustainable agriculture in terms of plant protection (Chalermsan & Peerapan, 2009) [6].

In crops such as maize, rice, and tomato, wood vinegar has been effective in promoting germination and seedling growth. This is attributed to ethanol, one of the components of wood vinegar, which stimulates germination and cell division.

In tomato plants, wood vinegar has shown slight improvements in total plant dry weight, fruit number, and both fruit fresh and dry weight. It has also significantly improved Total Soluble Solids (TSS) (Mungkunkamchao *et al*., 2013) [29].

In rapeseed, wood vinegar has been effective in reducing the infestation of *Sclerotinia sclerotiorum* and *Peronospora parasitica*, which cause downy mildew (Zhu *et al.*, 2021) [55]. Studies indicate that wood vinegar diluted 300 times can increase yield and protein content, improve rice quality, and significantly enhance photosynthesis, panicle number, and effective tiller count (Simma *et al.*, 2017) [39]. Additionally, soaking seeds in wood vinegar diluted 600 times has been shown to promote germination and growth in wheat, increase dry weight, and enhance drought stress tolerance (Wang *et al*., 2019) [50]. Spraying tobacco with a 300-fold dilution of wood vinegar can significantly increase yield and boost antioxidant enzyme activity, as well as soluble protein and potassium content.

Wood vinegar and its compounds have significantly improved the dry and fresh weight of rapeseed at various growth stages. In particular, the accumulation of dry matter increased rapidly during the bud-bolting stage and decreased during the pod stage. Compared to the control group, the biomass of rapeseed treated with wood vinegar increased by an average of 39.56%, 46.45%, 23.09%, and 14.02% at the seedling, bud-bolting, flowering, and pod stages over two years, respectively. These results suggest that the treatments were most effective during the seedling stage and became less effective as the growth period extended (Zhu *et al*., 2021) [55].

Bamboo vinegar, when diluted appropriately, enhances germination and radicle growth in lettuce and chrysanthemum due to the stimulation of hormone-like substances (Mu *et al.*, 2003) [27]. In mulberry, using wood vinegar at a concentration of 2.5% has been shown to reduce whitefly attacks. Similarly, the application of organic wood vinegar can also lessen whitefly infestations in other raw-consumed vegetables and fruits (Dewi *et al*., 2020) [8].

In tomato plants, the use of smoke water can improve growth, yield, and nutritional composition. Specifically, the smoke-water treatment (1:500, by volume) produced the highest plant height, leaf number, and stem thickness from 57 to 78 days after sowing. Additionally, the percentage of plants bearing fruit from 85 to 95 days after sowing was significantly higher with the application of smoke-water and butenolide solution compared to the control group (Kulkarni *et al*., 2008) [21].

Conclusion

Wood vinegar, created by condensing smoke from the pyrolysis of wood, is becoming increasingly recognized as a versatile resource in organic and sustainable agriculture. Its composition and effectiveness depend on the type of wood used and the temperature of pyrolysis. At lower temperatures (250-350 °C), wood vinegar is particularly effective for managing phytopathogenic diseases. In contrast, higher temperatures (350-600 °C) enhance its insecticidal properties.

Additionally, wood vinegar acts as an herbicide, a plant growth regulator, a soil conditioner, and even a wood preservative. These beneficial properties arise from the combined actions of its chemical components, including phenols and organic acids. By reducing the reliance on synthetic agrochemicals, wood vinegar is well-suited for organic crop production.

Its potential applications extend across various fields, including agriculture, horticulture, weed science, forestry, conservation, and ecosystem rehabilitation. Wood vinegar not only promotes crop growth and yield but also enhances resilience to stress. Therefore, further research and application of wood vinegar are essential for advancing sustainable agriculture, improving soil and crop health, and contributing to environmental protection.

References

1. Baimark Y, Threeprom J, Dumrongchai N, Srisuwan Y, Kotsaeng N. Utilization of wood vinegars as sustainable coagulating and antifungal agents in the production of natural rubber sheets. J Environ Sci Technol. 2008;1(4):157-63.
2. Berahim Z, Panhwar QA, Ismail MR, *et al*. Rice yield improvement by foliar application of phytohormone. J Food Agric Environ. 2014;12:399-404.
3. Brown NAC, Van Staden J, Daws MI, Johnson T. Patterns in the seed germination response to smoke in plants from the Cape Floristic Region, South Africa. S Afr J Bot. 2003;69:514-25.
4. Brown NAC. Seed germination in the fynbos fire ephemeral, *Syncarpha vestita* (L) B-Nord is promoted by smoke, aqueous extracts of smoke and charred wood derived from burning the ericoid-leaved shrub, *Passerina vulgaris* Thoday. Int J Wildl Fire. 1993;3(4):203-6.
5. Mattos C, *et al*. Biocidal applications trends of bio-oils from pyrolysis: Characterization of several conditions and biomass - a review. J Anal Appl Pyrolysis. 2019.
6. Chalermsan Y, Peerapan S. Wood vinegar: by-product from rural charcoal kiln and its role in plant protection. Asian J Food Agro-Ind. 2009;2(Special Issue):189-95.
7. Chuaboon W, Ponghirantanachoke N, Athinuwat D. Application of wood vinegar for fungal disease controls in paddy rice. Appl Environ Res. 2016;38(3):77-85.
8. Dewi R, Hastuti N, Nuraeni Y. Utilization of wood vinegar as plant based insecticide in mulberry (*Morus* sp). IOP Conf Ser Mater Sci Eng. 2020;1:12-7.
9. Fanfarillo E, *et al*. Effects of wood distillate on seedling emergence and first-stage growth in five threatened arable plants. Diversity. 2022.
10. El-Fawy MM, Abo-Elyousr KA, Sallam NM, El-Sharkawy RM, Ibrahim YE. Fungicidal effect of guava wood vinegar against *Colletotrichum coccodes* causing black dot disease of potatoes. Horticulturae. 2023;9(6):710.
11. Hashemi SM, Safavi SA, Estaji A. Insecticidal activity of wood vinegar mixed with *Salvia leriifolia* (Benth.) extract against *Lasioderma serricorne* (F.). Biharean Biol. 2014;8(1):5-11.
12. Hossain MM, Scott IM, McGarvey BD, Conn K, Ferrante L, Berruti F, Briens C. Insecticidal and anti-microbial activity of bio-oil derived from fast pyrolysis of lignin, cellulose, and hemicellulose. J Pest Sci. 2015;88:171-9.
13. Hwang Y, Matsushita Y, Sugamoto K, Matsui T. Antimicrobial effect of the wood vinegar from *Cryptomeria japonica* sapwood on plant pathogenic microorganisms. J Microbiol Biotechnol. 2005;15:1106-9.
14. Jeong KW, Kim BS, Ultra JRVU, Chul S. Effects of rhizosphere microorganisms and wood vinegar mixtures on rice growth and soil properties. Korean J Crop Sci. 2015;60(3):355-65.
15. Jothityangkoon D, Koolachart R, Wanapat S, Wongkaew S, Jogloy S. Using wood vinegar in enhancing peanut yield and in controlling the contamination of aflatoxin producing fungus. Int Crop Sci. 2008;4:253.
16. Jung KH. Growth inhibition effect of pyroligneous acid on pathogenic fungus, *Alternaria mali*, the agent of Alternaria blotch of apple. Biotechnol Bioprocess Eng. 2007;12:318-22.
17. Kartal SN, Terzi E, Kose C, Hofmeyr J, Imamura Y. Efficacy of tar oil recovered during slow pyrolysis of macadamia nut shells. Int Biodeterior Biodegradation. 2011;65(2):369-73.
18. Kiarie-Makara MW, Yoon HE, Lee DK. Repellent efficacy of wood vinegar against *Culex pipiens pallens* and *Aedes togoi* (Diptera: Culicidae) under laboratory and semi-field conditions. Entomol Res. 2010;40:97-103.
19. Kim DH, Seo HE, Lee SC, Lee KY. Effects of wood vinegar mixed with insecticides on the mortalities of *Nilaparvata lugens* and *Laodelphax striatellus* (Homoptera: Delphacidae). Anim Cells Syst. 2010;12:47-52.
20. Koç İ, Öğün E, Namlı A, Mendeş M, Kutlu E, Yardim EN. The effects of wood vinegar on some soil microorganisms. Appl Ecol Environ Res. 2019;17(2).
21. Kulkarni MG, Ascough GD, Van Staden J. Smoke-water and a smoke-isolated butenolide improve growth and yield of tomatoes under greenhouse conditions. HortTechnology. 2008;18(3):449-54.
22. Mahmud KN, Yahayu SHM, Sarip MY, Rizan NH, Min CB, Mustafa NF, *et al*. Evaluation on the efficiency of pyroligneous acid from palm kernel shell as antifungal and solid pineapple biomass as an antibacterial and plant growth promoter. Sains Malays. 2016;45(10):1423-34.
23. Masum SM, Malek M, Mandal MSH, Haque MN, Akther Z. Influence of plant-extracted pyroligneous acid on transplanted aman rice. World J Exp Biosci. 2013;4:31-4.
24. Mitsuyoshi Y, Madoka N, Keko H, Tatsuro O, Akira S. Termiticidal activity of wood vinegar, its components and their homologues. J Wood Sci. 2002;48(4):338-42.
25. Mmojieje J, Hornung A. The potential application of pyroligneous acid in the UK agricultural industry. J Crop Improv. 2015;29(2):228-46.
26. Modi AT. Indigenous storage method enhances seed vigour of traditional maize. S Afr J Bot. 2002;98:138-9.
27. Mu J, Uehara T, Furuno T. Effect of bamboo vinegar on the regulation of germination and radicle growth of seed plants. J Wood Sci. 2003;49:262-70.
28. Mu J, Yu ZM, Wu WQ, Wu QL. Preliminary study of application effect of bamboo vinegar on vegetable growth. For Stud China. 2006;8:43-7.
29. Mungkunkamchao T, Kesmala T, Pimratch S, Toomsan B, Jothityangkoon D. Wood vinegar and fermented bioextracts: Natural products to enhance growth and yield of tomato (*Solanum lycopersicum* L.). Sci Hortic. 2013;154:66-72.
30. Nakayama FS, Vinyard SH, Chow P, Bajwa DS, Youngquist JA, Muehl JH, *et al*. Guayule as a wood preservative. Ind Crops Prod. 2001;14:105-11.

31. Nelson DC, Flematti GR, Ghisalberti EL, Dixon KW, Smith SM. Regulation of seed germination and seedling growth by chemical signals from burning vegetation. Annu Rev Plant Biol. 2012;63(1):107-30.
32. Oramahi HA, Yoshimura T. Antifungal and antitermitic activities of wood vinegar from *Vitex pubescens* Vahl. J Wood Sci. 2013;59:344-50.
33. Pangnakorn U, Kanlaya S. Efficiency of wood vinegar mixed with some plant extracts against the housefly (*Musca domestica* L.). Int J Biol Biomol Agric Food Biotechnol Eng. 2014;8(9):1038-42.
34. Prianto AH, Yulizar Y, Simanjuntak P. Wood vinegar as a supporting active ingredient and neem oil dispersant in a nanoemulsion system and their bioactivity. Rasayan J Chem. 2022;15(2).
35. Regnault-Roger C. The potential of botanical essential oils for insect pest control. Integr Pest Manag Rev. 1997;2:25-34. https://doi.org/10.1023/A:1018472227889
36. Mathew S, Zakaria ZA. Pyroligneous acid: the smoky acidic liquid from plant biomass. Appl Microbiol Biotechnol. 2015;99(2):611-22. https://doi.org/10.1007/s00253-014-6242-1
37. Mathew S, *et al*. Pyroligneous acid—the smoky acidic liquid from plant biomass. Appl Microbiol Biotechnol. 2015.
38. Shiny KS, Remadevi OK. Evaluation of termiticidal activity of coconut shell oil and its comparison to commercial wood preservatives. Eur J Wood Wood Prod. 2014;72:139-41.
39. Simma B, Polthanee A, Goggi AS, Siri B, Promkhambut A, Caragea PC. Wood vinegar seed priming improves yield and suppresses weeds in dryland direct-seeding rice under rainfed production. Agron Sustain Dev. 2017;37:1-9.
40. Simma B, Polthanee A, Goggi AS. Wood vinegar seed priming improves yield and suppresses weeds in dryland direct-seeding rice under rainfed production. Agron Sustain Dev. 2017;37:56.
41. Sivaram AK, Panneerselvan L, Mukunthan K, Megharaj M. Effect of pyroligneous acid on the microbial community composition and plant growth-promoting bacteria (PGPB) in soils. Soil Syst. 2022;6(1):10.
42. Spencer DF, Ksander GG. Influence of dilute acetic acid treatments on survival of *Hydrilla* tubers in the Oregon House Canal, California. J Aquat Plant Manage. 1999;37:67-71.
43. Higashino T, *et al*. Basic study for establishing specifications for wood vinegar by distillation I. Study of regulations and reproducibility of compounds contained in distilled wood vinegar. Mokuzai Gakkaishi J Jpn Wood Res Soc. 2005.
44. Theapparat Y, Chandumpai A, Leelasuphakul W, Laemsak N. Pyroligneous acids from carbonisation of wood and bamboo: their components and antifungal activity. J Trop For Sci. 2015:517-26.
45. Tiilikkala K, Fagernäs L, Tiilikkala J. History and use of wood pyrolysis liquids as biocide and plant protection product. 2010.
46. Tsuzuki E, Wakiyama Y, Eto H, Handa H. Effect of pyroligneous acid and mixture of charcoal with pyroligneous acid on the growth and yield of rice plant. Jpn J Crop Sci. 1989;58:592-7.
47. Tsuzuki E, Morimitsu T, Matsui T. Effect of chemical compounds in pyroligneous acid on root growth in rice plant. Rep Kyushu Branch Crop Sci Soc Jpn. 2000;(66):15-6.
48. Van Staden J, Jager AK, Light ME, Burger BV. Isolation of the major germination cue from plant-derived smoke. 2004.
49. Arsyad WOM, *et al*. Termiticidal activity and chemical components of bamboo vinegar against subterranean termites under different pyrolysis temperatures. J Korean Wood Sci Technol. 2020.
50. Wang Y, Qiu L, Song Q, Wang S, Wang Y, Ge Y. Root proteomics reveals the effects of wood vinegar on wheat growth and subsequent tolerance to drought stress. Int J Mol Sci. 2019;20:943.
51. Wei Q, Ma X, Dong J. Preparation, chemical constituents and antimicrobial activity of pyroligneous acids from walnut tree branches. J Anal Appl Pyrolysis. 2010;87(1):24-8.
52. Wititsiri S. Production of wood vinegars from coconut shells and additional materials for control of termite workers, *Odontotermes* sp. and striped mealy bugs, *Ferrisia virgata*. Songklanakarin J Sci Technol. 2011;33(3).
53. Yatagai M, Nishimoto M, Hori K, *et al*. Termiticidal activity of wood vinegar, its components and their homologues. J Wood Sci. 2002;48:338-42.
54. Young-Hee H, Yoh-Ichi M, Kazuhiro S, Takanao M. Antimicrobial effect of the wood vinegar from *Cryptomeria japonica* sapwood on plant pathogenic microorganisms. J Microbiol Biotechnol. 2005;15(5):1106-9.
55. Zhu K, Gu S, Liu J, Luo T, Khan Z, Zhang K, Hu L. Wood vinegar as a complex growth regulator promotes the growth, yield, and quality of rapeseed. Agronomy. 2021;11(3):510.
56. Zulkarami B, Ashrafuzzaman M, Husni Ismail MR. Effect of pyroligneous acid on growth, yield and quality improvement of rock melon in soilless culture. Aust J Crop Sci. 2011;5:1508-14.