Nematicidal potential of Agro-Industrial byproducts and wastes

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Abstract. The widespread use of synthetic pesticides in agriculture has raised significant concerns due to their adverse effects on human health and the environment, driving the need for safer and more sustainable alternatives. Agro-industrial wastes have recently emerged as promising sources of bioactive compounds for the development of natural biopesticides within a circular economy framework. This review examines the nematicidal potential of two main types of processing-derived residues: essential oil hydrolates and biochar obtained from biomass pyrolysis. Hydrolates are aqueous by-products of essential oil distillation containing bioactive constituents such as terpenoids, phenolics, and sulfur compounds. Studies have demonstrated their effectiveness against plant-parasitic nematodes, particularly *Meloidogyne* species, by inducing juvenile mortality, inhibiting egg hatching, and reducing infection and reproduction in host plants. However, their large-scale application is limited by challenges related to standardization and reproducibility. Biochar, produced through thermochemical conversion of biomass, also exhibits potential for nematode control. Its effects depend on the feedstock and production conditions, acting through both direct toxicity and indirect mechanisms, including improved soil properties, enhanced plant growth, and activation of plant defense responses. Overall, the valorization of these residues offers a sustainable alternative to synthetic nematicides, although further research is needed to optimize their application and ensure consistent efficacy.

1 Introduction

Plant-parasitic nematodes represent a major constraint to global agriculture, causing substantial yield losses and threatening the sustainability of crop production worldwide. It is estimated that plant-parasitic nematodes are responsible for billions of dollars in annual crop losses globally, affecting key staples and high-value crops alike. Their wide distribution, broad host range, and ability to survive in soil for extended periods make them particularly difficult to control.

Traditionally, plant-parasitic nematodes have been controlled using chemical nematicides, but it is proven that the widespread use of chemical pesticides in crop protection poses significant long-term risks to human health and the environment due to their persistence and harmful side effects [1].

In this context, the development of environmentally friendly alternatives, such as biopesticides and, more specifically, bionematicides, has become a major challenge and priority for sustainable agriculture [2]. Natural product–based biopesticides can be sourced from a wide range of origins, including microorganisms and plants. Among these, agricultural and agro-industrial wastes have gained increasing attention as abundant, low-cost, and renewable sources of bioactive compounds [3]. Their valorization not only contributes to pest management strategies but also supports circular economy approaches [4].

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These by-products can be exploited for the production of bioenergy or as sources of high-value compounds through extraction or biotransformation processes. Recent studies have highlighted agro-industrial wastes as promising sources of natural antioxidants, antimicrobial agents, and biopesticides, with demonstrated activity against a wide range of plant pathogens and pests [5]. Additionally, more recent research has reinforced their potential in sustainable pest management, particularly within integrated pest management (IPM) frameworks [6].

A wide variety of agroforestry residues have been reported to exhibit biopesticidal activity. These materials are rich in secondary metabolites such as phenolics, terpenoids, and alkaloids, which are often responsible for their biological activity. Among these residues, lignocellulosic biomass derived from wood-processing industries and agricultural by-products represents one of the largest waste fractions. These materials can be further processed (e.g., via pyrolysis) to generate value-added products rich in bioactive compounds [7]. In Mediterranean regions, although generated on a smaller scale, residues from the essential oil industry—such as hydrolates and distillation by-products—have emerged as promising sources of biologically active natural compounds [8].

This review focuses on the nematicidal potential of selected processing-derived wastes, including essential oil hydrolates and biomass pyrolysis products, for the control of plant-parasitic nematodes.

2 Nematicidal properties of hydrolates: by-products of essential oil distillation

Hydrolates, also known as hydrosols, represent a promising yet underutilized byproduct of essential oil (EO) extraction. These aqueous solutions contain a complex mixture of trace amounts of essential oils and water-soluble compounds, which confer notable biological activity. Some of these aromatic waters are used as food preservatives, as well as in cosmetics and perfumery [9]. Their antioxidant and antimicrobial properties have also been reported [8]. In agriculture, the antifungal and herbicidal effects of hydrolates have been widely documented [10]; however, studies addressing their nematicidal properties remain limited.

Artemisia absinthium (Candial®) hydrolate demonstrated strong effects against the root-knot nematode *Meloidogyne javanica*, including high juvenile mortality, inhibition of egg hatching, reduction of juvenile penetration into roots, and significant suppression of nematode reproduction in potted tomato plants [11]. The active constituents were primarily associated with the organic fraction of the hydrolate, with (5Z)-2,6-dimethylocta-5,7-diene-2,3-diol identified as the major compound. Subsequently, the nematicidal activity in vitro and in vivo of hydrolate by-products obtained from semi-industrial steam distillation of selected aromatic plants from Spain against *M. javanica* was investigated [12]. Hydrolates from *Lavandula × intermedia* (var. Super), *L. luisieri*, *Thymus vulgaris*, and *T. zygis*, exhibited strong in vitro activity, including high second-stage juvenile mortality and inhibition of egg hatching. In *Thymus* species, the active compounds were located in the organic fraction, characterized by thymol as the major component. In contrast, the nematicidal activity of *L. × intermedia* and *L. luisieri* was associated with their aqueous fractions. In vivo assays on tomato seedlings treated with undiluted hydrolates or their organic fractions showed a significant reduction in nematode infectivity. Furthermore, pot experiments demonstrated that all tested hydrolates markedly reduced infection frequency and the reproductive rate of the nematode population [12]. Additionally, hydrolate obtained from the industrial extraction of Spanish purple garlic essential oil was evaluated against *M. javanica* [13], [14]. Both, the hydrolate and its organic fraction caused high juvenile mortality, inhibited egg hatching, and reduced nematode infection and reproduction in tomato plants. The nematicidal activity was attributed to sulfur-containing compounds, mainly diallyl disulfide and diallyl trisulfide, as well as a group of novel compounds known as garlicinins.

Hydrolates from Greek aromatic plant species have also been tested against *M. incognita* and *M. javanica* [15], [16], [17]. Hydrolates from *Origanum vulgare* and *Satureja hellenica*, rich in carvacrol and thymol, exhibited strong in vitro activity against both nematode species, whereas *Cuminum cyminum* hydrolate showed significant activity associated with γ-terpinen-7-al, cuminaldehyde, and α-terpinen-7-al as its main constituents. These studies have focused on aqueous extracts obtained by conventional hydrodistillation (e.g., using a Clevenger apparatus) without further fractionation, which hinders standardization and reproducibility. Therefore, further extraction of hydrolates to obtain organic fractions is essential for proper chemical characterization and reproducibility. In this context, bio-guided chromatographic approaches enable the identification of active compounds and the establishment of chemical markers and fingerprints for batch standardization [18].

3 Nematicidal properties of biochar: pyrolysis products from agroindustrial wastes

In recent years, thermochemical conversion technologies, particularly pyrolysis, have gained considerable attention as effective methods for the valorization of diverse waste biomass streams. Pyrolysis is an efficient and controlled process conducted under an inert atmosphere at elevated temperatures (~300–700 °C), generating solid (biochar), liquid (bio-oil and pyroligneous extracts), and gaseous products with variable composition and yields [19]. Beyond reducing waste volume, this process also produces valuable by-products with potential applications as biopesticides [18].

Biochar has shown considerable potential in the management of plant-parasitic nematodes, although its effectiveness varies depending on feedstock type and pyrolysis conditions [20]. Field and experimental studies demonstrate that biochar applications can reduce nematode populations and limit their impact through both direct and indirect mechanisms. For example, rice husk biochar applied at 10 t/ha reduced *Heterodera glycines* in soybean [21], while various plant waste-derived biochars have been reported to suppress root-knot nematodes by improving crop growth, yield, and photosynthetic performance and enhancing antioxidant defenses, physiological activity, and reduced ROS accumulation [22]. Similarly, biochars derived from rice husk and wheat straw, rich in silica, strengthen systemic resistance and limit *Meloidogyne incognita* root penetration [23]. Other studies highlight the suppression of *Pratylenchus coffeae* [24] in banana and coffee systems by wood-derived biochar, and reduced infection by *P. penetrans* in carrot following application of softwood or husk biochars [25]. In addition, different biochar (bitter leaves, cassava peels and sawdust) applications can impair nematode reproduction in *Vigna radiata* [26].

Notably, some biochars that do not exhibit direct nematicidal activity can nonetheless negatively affect plant-parasitic nematodes through indirect mechanisms. These include enhanced nutrient solubilization and uptake, which promote plant growth and increase resistance to pathogen-related stress, as well as the induction of plant defense responses [27]. For instance, a microcosm study showed that wheat-straw biochar increased the abundance of fungivorous nematodes while reducing populations of plant-parasitic nematodes [28], confirming that the addition of biochar, a porous and carbon-stable material, has the potential to provide a favorable habitat for fungi [29]. Similarly, the suppression of *M. incognita* in rice following the incorporation of oak wood biochar into the potting substrate was associated with localized H_2O_2 accumulation and the upregulation of ethylene-related genes involved in plant defense [30]. Experimental evidence also indicates that, although aqueous extracts derived from grape pomace biochar did not show toxic effects in vitro on the infectious stage of *M. javanica*, the infectivity and reproductive traits of the nematode population in tomato were significantly reduced in biochar-treated soils in pots, probably due to induction of plant defenses [31]. Moreover, even a biologically inactive maize-straw biochar exhibited synergistic and enhancing effects when combined with furfural in formulations against *M. incognita* in tomato [32]. These results highlight the potential of biochar as a functional additive in the development and formulation of biopesticides [18]. In general, these studies demonstrate the wide variability in the impact of biochar on plant-parasitic nematodes, which depends largely on the type of agro-industrial raw material used and the pyrolysis process conditions during its production.

4 Conclusions and Perspectives

Agro-industrial processing wastes, such as essential oil hydrolates and biomass-derived biochar, represent promising and sustainable alternatives to synthetic nematicides for the management of plant-parasitic nematodes. Hydrolates, particularly those rich in bioactive compounds such as thymol, carvacrol, sulfur-containing molecules, and specific terpenoids, have demonstrated strong nematicidal activity both in vitro and in vivo against root-knot nematode species. Biochar-derived products exhibit a more complex mode of action, contributing to nematode suppression through both direct and indirect mechanisms, including improvements in soil health, stimulation of plant defense responses, and modulation of soil microbiota.

The variability in efficacy observed across studies highlights the importance of feedstock selection, processing conditions, and chemical characterization to ensure reproducibility and optimize performance. In the case of hydrolates, the differences between the chemotypes of aromatic plants and the essential oil extraction technique must be considered, as both can generate substantial variations in their chemical composition, hindering standardization and consistent use. Therefore, it will be necessary to focus more on identifying the compounds responsible for nematicidal activity to determine reliable chemical markers and develop formulations with reproducible effects.

In the case of biochar, the type of raw material and the pyrolysis conditions determine its physicochemical properties, making it difficult to predict its nematicidal activity in different soils or cropping systems. Future studies should focus on its mechanisms of action, specifically the indirect ones, determining how its effects on soil microbiota and the activation of plant defense pathways contribute to the suppression of plant-parasitic nematodes. These indirect effects could be as important as direct toxicity. Furthermore, biochar can offer added value as a carrier material in the formulation of biopesticides.

In the context of a circular economy, the reuse and valorization of agro-industrial byproducts and wastes represents not only an environmentally sustainable option for nematode control, but also an opportunity to improve resource efficiency. Although further research is needed, hydrolates and biochar have clear potential to be incorporated into future sustainable strategies for the control of plant-parasitic nematodes.

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