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Mini Review

Peroxyacetic Acid: A Potential Sustainable Alternative to Conventional Fumigants

Stephen F Hanson*

Department of Entomology, Plant Pathology, and Weed Science, New Mexico State University, 945 College Ave, Las Cruces, USA

***Corresponding author:** Stephen F Hanson, Department of Entomology, Plant Pathology, and Weed Science, New Mexico State University, 945 College Ave, Las Cruces, NM 88001, USA.

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Abstract

Traditional fumigants such as methyl bromide, potassium N-methyldithiocarbamate (KPAM), and sodium N-methyldithiocarbamate (VAPAM) have historically provided broad-spectrum control of soilborne pests and pathogens but pose substantial environmental and human health risks. The global phase-out of methyl bromide under the Montreal Protocol and increasing restrictions on methyl isothiocyanate (MITC)–based fumigants have intensified the need for sustainable alternatives. Peroxyacetic acid (PAA) is a promising replacement due to its broad-spectrum antimicrobial activity, rapid decomposition into non-toxic byproducts, and comparatively low occupational risk. This review summarizes the historical use and limitations of conventional fumigants, describes the chemical and biological properties of PAA, and evaluates current research on its potential as a soil treatment. Continued research on field-scale performance, soil and microbiome interactions, crop safety, and integration into integrated pest management programs will be essential to determine whether PAA may serve as a reliable and sustainable alternative for high-value crop production systems.

Keywords: Peroxyacetic acid; Soil fumigation; Fumigant alternatives; Soilborne pathogens; Sustainable agriculture

Introduction

Soil fumigants have long been used to reduce populations of pests, pathogens, and weed propagules in agricultural soils. Although effective, fumigant use has declined over recent decades due to increasing environmental and human health concerns. Traditional fumigants such as methyl bromide, potassium N-methyldithiocarbamate (KPAM; metam sodium), and sodium N-methyldithiocarbamate (VAPAM) were widely adopted because of their broad-spectrum efficacy and rapid action [1,2]. However, these compounds have been associated with ozone depletion, groundwater contamination, and acute and chronic toxicity to applicators and bystanders [3,4]. Regulatory actions, including the Montreal Protocol, have resulted in the withdrawal or restriction of many fumigants worldwide [5,6].

Methyl bromide was among the first fumigants widely deployed in agriculture. Its volatility and non-specific biocidal activity enabled deep soil penetration and effective control of a broad range of soilborne fungi, nematodes, and weed seeds [1]. Methyl bromide use was associated with improved yields in high-value crops such as strawberries, tomatoes, and peppers [7]. Despite these benefits, methyl bromide is a potent ozone-depleting substance with sufficient atmospheric persistence to reach the stratosphere, where it catalyzes ozone destruction [6]. Human health concerns include acute toxicity via inhalation and dermal exposure, resulting in neurological, respiratory, and systemic effects, as well as chronic neurological and reproductive impacts following occupational exposure [3,8]. These concerns led to its global phase-out, with only limited critical-use exemptions remaining.

As methyl bromide use declined, alternative fumigants such as KPAM and VAPAM were adopted. These water-soluble dithiocarbamate salts generate methyl isothiocyanate (MITC) in soil following hydrolysis, providing broad-spectrum control of nematodes, fungi, and some weed species [9,10]. Their solubility allows application through drip irrigation or shank injection systems. However, MITC persistence and mobility in soil can lead to volatilization and groundwater contamination, and degradation byproducts such as carbon disulfide and methylamine pose additional environmental risks [11,12]. Occupational exposure to MITC has been associated with irritation of the eyes, skin, and respiratory tract, as well as potential neurotoxicity at high exposure levels [4,7]. As a result, MITC-based fumigants are subject to increasing regulatory restrictions in many regions.

In response to these limitations, research has focused on alternative approaches that reduce environmental and human health risks while maintaining effective pest suppression. Physical and biological methods such as soil solarization [13,14], biofumigation using organic amendments [15], and anaerobic soil disinfestation [16] have shown promise but may provide inconsistent control depending on climate, soil type, and cropping system. This review focuses on peroxyacetic acid as a potential chemical alternative to conventional soil fumigants.

Peroxyacetic acid (PAA; CH_3CO_3H) is a strong oxidizing agent formed by the equilibrium reaction of acetic acid and hydrogen peroxide in aqueous solution. PAA exhibits broad-spectrum antimicrobial activity against bacteria, fungi, viruses, and spores through oxidative damage to cellular membranes, proteins, and nucleic acids [17,18]. Importantly, PAA rapidly decomposes into acetic acid, oxygen, and water, leaving no persistent or halogenated residues in the environment [19]. Several commercial PAA formulations are approved for use in organic production systems.

Relative to conventional fumigants, PAA exhibits a more favorable environmental and safety profile, largely due to its rapid degradation and lack of persistent residues [17,20]. Occupational hazards are primarily limited to irritant effects on skin and mucous membranes, which can be managed through standard handling and application precautions [18].

Experimental studies indicate that PAA can suppress a range of soilborne pests and pathogens, including root-knot nematodes (Meloidogyne spp.), fungal pathogens such as Fusarium oxysporum and Verticillium dahliae, and bacterial pathogens such as Ralstonia solanacearum [19-21]. Greenhouse trials have demonstrated that soil drenches with PAA can reduce nematode populations at levels comparable to reduced rates of metam sodium while minimizing phytotoxic effects when applied at appropriate concentrations and timings [21].

Despite these promising results, PAA performance is influenced by soil properties such as pH, organic matter content, and moisture. Its high reactivity and short persistence require precise application timing and, in some cases, repeated treatments to maintain efficacy against soilborne pathogens [20]. Careful management is also required to avoid crop injury, as plant sensitivity to PAA varies by species and developmental stage.

Because PAA acts as a fast-acting, short-lived general biocide, its effects on soil microbial communities warrant further investigation. Preliminary, unpublished observations suggest that total culturable soil bacterial populations decline immediately following PAA application but recover to near pre-treatment levels within 48 hours.

Whether PAA induces longer-term shifts in microbial community composition or selectively affects beneficial organisms remains unknown and warrants further study. In addition to soil applications, PAA has been widely used for foliar disease management and post-harvest sanitation of fruits and vegetables, where it reduces microbial contamination without adversely affecting product quality [17,22].

Peroxyacetic acid represents a promising alternative to conventional soil fumigants, offering broad-spectrum pest suppression with reduced environmental persistence and lower human health risks. However, additional field-scale research is needed to define application strategies that balance efficacy and crop safety, determine economic feasibility, and characterize short- and long-term effects on soil microbial communities. With continued research and refinement, PAA may become a valuable component of sustainable soil pest management programs, particularly in high value cropping systems where fumigant options are increasingly limited [23,24].

Acknowledgement

None.

Conflict of Interest

No conflict of interest.

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