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Phosphine as a possible alternative to methyl bromide for the phytosanitary treatment of wood products

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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

Phosphine (PH_3) has gained momentum as a phytosanitary treatment to control quarantine pests in exported wood products. Originally used as a grain fumigant, its use increased after methyl bromide was banned for its ozone-depleting properties. While the effectiveness of PH_3 against grain pests is well-established, its efficacy for wood products requires review due to growing adoption. We observed insufficient evidence supporting PH_3 as a broad-spectrum quarantine treatment for wood products from peer-reviewed/gray literature and international groups. We assessed 41 research articles covering 29 insect species, 1 nematode, and 11 fungi, and observed that while PH_3 is effective against some forest insects, it generally fails to meet quarantine treatment standards and is ineffective against nematodes and fungi. Our analysis highlights concerns over the effectiveness of PH_3 as a broad-spectrum treatment for wood products. Many studies lack the quality needed to meet contemporary standards. We strongly recommend that National Plant Protection Organizations review the efficacy data supporting PH_3 use for wood products to strengthen biosecurity systems.

1. Introduction

Since humans first began storing grain in mudbrick and straw structures (Rees, 2004; Roberts, 1976), various insect species have threatened these supplies for thousands of years. Despite advances in industrialization and the development of modern storage facilities made from steel, concrete, and durable fabrics, infestations from storage pests continue to jeopardize the biosecurity of grain and its products (Reed, 1992). These pests, primarily from three insect orders, include the following families: Order Coleoptera (Anobiidae, Anthribidae, Bostrichidae, Bruchidae, Chrysomelidae, Cleridae, Cryptophagidae, Curculionidae, Dermestidae, Histeridae, Laemophloeidae, Latridiidae, Lophocateridae, Mycetophagidae, Nitidulidae, Ptinidae, Silvanidae, Tenebrionidae and Trogossitidae); Order Lepidoptera (Gelechiidae, Oecophoridae, Pyralidae, Tineidae and Tortricidae); and Order Psocoptera (Lachesillidae, Liposcelididae, Psyllipsocidae and Trogiidae).

Insect infestations in stored products result in significant economic losses due to physical damage, quality degradation, market rejection, workplace health and safety (WHS) concerns, and management costs (Nayak and Daglish, 2018; Nayak et al., 2020). Effective pest management in stored products requires an integrated approach, including regular inspections, hygiene, drying, cooling, heat treatment, controlled atmospheres, and insecticide treatments (Daglish et al., 2018). Among these methods, insecticide treatments—comprising contact chemicals and fumigants—are particularly effective, meeting the logistical demands of storage operators. These treatments are applied for non-quarantine and pre-shipment (non-QPS) purposes, such as protecting commodities during storage (e.g., direct application as

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protectants or structural treatments) or for quarantine and pre-shipment (QPS) uses to reduce the risk of pest transfer between regions or countries.

Among various fumigants tested for stored product pests, methyl bromide (MB) and phosphine (PH_3) have been the most successful (Nayak et al., 2020). However, the effectiveness of MB was overshadowed by its classification as an ozone-depleting substance, leading to its phased reduction in non-QPS applications (UNEP, 1992). With the restricted use of MB and the regulatory withdrawal of several contact insecticides over the past two decades, PH_3 has emerged as the preferred fumigant for grains and durable commodities globally (Chadda, 2016; Nayak et al., 2020). PH_3 was first chemically described by Philippe Gengembre in 1783 as a product of heating elemental phosphorous in a potassium carbonate solution (Gengembre, 1783). Key factors contributing to the success of PH_3 include its residue-free nature, affordability, ease of application in various forms (e.g., tablets, blankets, and cylinderized gas), suitability for a range of storage structures (e.g., silos, bag stacks, bunkers, shipping containers, and ship holds), compatibility with grain handling logistics (e.g., WHS and excellent grain penetration), and its effectiveness against all life stages of major grain storage pests (Nayak et al., 2020).

Although several alternative treatments have been developed and tested for controlling grain pests, none have matched the comprehensive benefits of PH_3. Notable alternatives include nitrogen (low oxygen (O_2)) and carbon dioxide (CO_2; Fields and White, 2002), propylene oxide (Navarro et al., 2004), carbonyl sulfide (Bartholomaeus and Haritos, 2005), ethyl formate (Ren et al., 2012), sulfuryl fluoride (SF; Nayak et al., 2016), ozone (Velasquez et al., 2017), chlorine dioxide (Xinyi et al., 2018), ethanedinitrile (Ramadan et al., 2020), and nitric oxide (Liu, 2020). Given these considerations, PH_3 is expected to remain the primary fumigant in the grain industry for the foreseeable future.

The grain industry's global push to adopt alternatives to MB was mirrored across agricultural systems and exported commodities reliant on MB for non-QPS and QPS uses. The United Nations Environment Programme (UNEP) imposed stricter regulations on non-QPS uses, accounting for most of the global MB consumption in the mid-90s. By 2024, only one critical use exemption (CUE) for 3.9 tons per year was granted (UNEP, 2024a). This milestone highlights the success of identifying and commercializing alternative pest management strategies for various scenarios.

In contrast, QPS uses of MB remain unregulated, leading to relatively stable global consumption over the past 29 years. Countries can use unlimited amounts of MB for QPS purposes and are only required to self-report their annual consumption to UNEP, with no financial or reputational disincentives for countries that increase their MB consumption. For example, recent significant increases in QPS MB use have been reported in India and Pakistan (UNEP, 2024b). Approximately 50 % of the global QPS consumption of MB relates to the treatment of wood products (MBTOC, 2022).

Many chemical and physical treatments have been explored as alternatives to MB fumigation to control forest pests. Armstrong et al. (2014a) comprehensively reviewed fumigants and disinfestation strategies for wood products. Alternatives tested include carbonyl sulfide (Gan et al., 2005; Ren et al., 1997), chloropicrin (Hutchinson et al., 2000; Schmidt and Christopherson, 1997), ethanedinitrile (Najar-Rodriguez et al., 2020a; Park et al., 2021; Uzunovic et al., 2022), methyl iodide (Naito et al., 2003; Shamilov, 2012; Tubajika and Barak, 2008), PH_3 (Armstrong et al., 2014b; Devitt, 2021), and SF (Bonifácio et al., 2014; Jeffers et al., 2012; Ren et al., 2011; Schmidt et al., 1997). PH_3 and SF emerged as the most promising chemical alternatives for treating wood products (Armstrong et al., 2014a; Dwinell et al., 2003; Leesch et al., 1989; Soma et al., 2001; Zhang, 2006), as these fumigants were already registered for other commodities and use patterns.

Global pests of concern for wood packaging material (WPM) and logs include insect families Bostrichidae, Buprestidae, Cerambycidae, and Siricidae, along with two pathogen genera, *Ceratocystis* spp. and *Heterobasidion* spp., and the pine wood nematode (PWN; *Bursaphelenchus xylophilus*) (Ormsby, 2022). Therefore, to meet modern quarantine standards, wood products require broad-spectrum phytosanitary treatments capable of controlling insects, pathogens, and nematodes.

In this review, we described the historical and scientific links between the use of PH_3 to treat stored products and the development and use of PH_3 to treat wood products. We concentrated on PH_3 as a phytosanitary treatment for wood, its efficacy against a broad range of forest pests (particularly those identified by Ormsby (2022), existing and rescinded phytosanitary approvals, and strategies to enhance the effectiveness of PH_3.

2. Phosphine as a fumigant for grain products

2.1. Key characteristics

Food storage, a long-standing technique to preserve food for winter and non-harvest seasons, poses challenges, particularly for grains and stored commodities. Biological agents such as insects, rodents, and mold can contaminate stored food (Rees, 2004), leading to significant losses (Manandhar et al., 2018; Nayak et al., 2014). While various pest control methods are utilized for stored product protection, fumigation remains the predominant practice.

Historically, MB and PH_3 have been the primary fumigants to combat these pests and minimize losses in stored grains. Over the past three decades, PH_3 has emerged as the preferred choice due to its favorable attributes, including low cost, ease of application, versatility, and effectiveness against different pest life stages while leaving no or minimal residues. The widespread use of PH_3 is facilitated by its global registration, availability, cost-effectiveness, and acceptance as a clean, residue-free or clean grain in all markets. Its rapid dispersal within grain enclosures eliminates the need for additional fumigation equipment. Furthermore, PH_3 can be safely transported in its original packaging and does not adversely affect seed germination (Chadda, 2016; Chaudhry, 2000; Nayak et al., 2020).

2.2. Mode of action

Fumigants, whether gases or highly volatile liquids that vaporize at ambient temperatures, primarily enter exposed animals through the respiratory system. The uptake of a fumigant is generally proportional to the respiration rate of the exposed animal. Factors that increase respiratory activity heighten the uptake and toxicity of the fumigant (Chaudhry, 1997). For PH_3, O_2 plays a pivotal role in its mode of action, underscoring its significance in the toxicity of PH_3 (Bond et al., 1969; Nath et al., 2011; Nayak et al., 2020). Additionally, temperature can exacerbate PH_3 intoxication in insects, likely due to higher metabolic rates and increased O_2 consumption (i.e., respiration rate), further amplifying the intoxicating effects of PH_3 (Bond et al., 1969; Chaudhry, 1997).

PH_3 disrupts vital respiratory functions in various pest species, including rats (Dua and Gill, 2004; Nakakita et al., 1971), insects (Chefurka et al., 1976; Nakakita, 1976), mites (Jian et al., 2000), and nematodes (Zuryn et al., 2008). It affects cellular processes by directly targeting mitochondria. Specifically, mitochondria generate adenosine triphosphate through aerobic respiration, a process in which the enzyme cytochrome *c* oxidase, also known as complex IV, plays a central role. This enzyme facilitates the final step of electron transport, coupling O_2 reduction with water production.

PH_3 disrupts this pathway by inhibiting the activity of cytochrome *c* oxidase, its primary site of action, thereby impeding electron flow (Nath et al., 2011). Consequently, the ability of cells to utilize O_2 is compromised, creating a cascade of metabolic dysfunctions. Furthermore, PH_3 exposure generates reactive oxygen species within cells, exacerbating cellular damage and oxidative stress (Hsu et al., 2002; Shen et al., 2023; Zuryn et al., 2008). These highly reactive molecules, such as superoxide radicals and hydrogen peroxide, damage cellular components (Chaudhry and Price, 1992; Hsu et al., 2002; Shen et al., 2023; Valmas et al., 2008), contributing to cellular dysfunction and potential pest mortality (Nath et al., 2011).

The inhibition of the catalase enzyme is another significant aspect of the mode of action of PH_3. Research has shown that PH_3 can inhibit or reduce insect catalase activity (Bond, 1963; Price et al., 1982). The inhibition often increases with incubation time, suggesting an irreversible or only slowly reversible binding of the fumigant to the enzyme. Hobbs and Bond (1989) showed that enzyme levels remained low for at least two weeks after a single treatment with a sublethal dose of PH_3. This finding indicates long-term inhibition of catalase function and the possibility of prolonged impairment of the enzyme's function.

2.3. Phosphine formulations

Phosphine is available in two widely used formulations: solid and gaseous. The solid formulation primarily consists of aluminum phosphide (AlP) with ammonium carbamate, which regulates water absorption and fumigant release. When this formulation reacts with water, the heat generated releases CO_2 and ammonia, reducing flammability by diluting the generated PH_3 gas. Commercial formulations are available under various trade names and forms, including tablets, pellets, sachets, belts, chains, and blankets, and produce a predetermined quantity of PH_3 gas. Additionally, plates containing magnesium phosphide (Mg_3P_2) provide a faster release of PH_3, even at temperatures below 20 °C, making them suitable for colder climates. PH_3 can be generated directly from gas generators and cylinderized formulations. Gas generators facilitate the rapid release of PH_3 gas from solid formulations like Mg_3P_2, while cylinderized formulations enable more rapid and controlled release, allowing for shorter exposure times. The two cylinderized PH_3 formulations are pure compressed gas and a mixture of 2 % PH_3 with 98 % CO_2 (Chadda, 2016; Ryan and De Lima, 2013).

2.4. Typical use patterns

PH_3 applications for disinfestation are commonly conducted in warehouses, shipping containers, tarpaulins, ship holds, and silos (Agrafioti et al., 2020, 2021; Collins, 2010). Studies have investigated both the application methods and the concentrations and distribution of PH_3 within these treated spaces to assess the effectiveness of the fumigant. In warehouses, PH_3 applications often involve low concentrations and short durations, resulting in ineffective pest control. Poor sealing in warehouses, silos, and ship holds further diminishes the efficacy of fumigation efforts. Shipping containers have emerged as optimal structures for PH_3 application due to their tighter seals, which help maintain the required fumigant concentration. Research suggests that fumigating containers can eradicate all insect life stages of grain pests, including certain resistant populations (Agrafioti et al., 2020).

2.5. Typical treatment conditions

Several decades of research have established that numerous biological and non-biological factors can influence PH_3 efficacy. Key considerations critical for the safe and effective use of PH_3 are outlined below.

A fundamental requirement for successful fumigation is the ability of the storage structure to retain the gas concentration over the necessary exposure period for complete pest control. In Australia, for instance, storage operators are advised to use sealable silos that meet Standard AS2628, with half-life pressure testing recommended before initiating fumigation (Collins, 2009).

Active re-circulation is recommended for larger treatment volumes, such as silos, to achieve rapid and uniform distribution of the fumigant throughout the grain mass. Where re-circulation is impractical (e.g., in bunkers), additional time should be allowed for fumigant distribution. Grain moisture content (MC) and temperature should be assessed before fumigation, as these factors impact the recommended dosage rates.

Fumigants should be applied by a trained professional following label directions for correct dosages, application rates, and exposure periods. Gas concentrations must be monitored throughout the fumigation period using commercially available equipment (Nayak et al., 2020). Post-fumigation ventilation should adhere to label and industry guidelines as part of the WHS procedure to ensure that gas concentrations in the grain mass meet the legal limits at the delivery point (Collins, 2009).

2.5.1. Relationship between concentration and time

Two key non-biological factors that considerably influence PH_3 efficacy are concentration (C) and exposure time (t). The dosage, or **Ct** (concentration x time) product, achieved in a particular situation for a given quantity of fumigant is largely determined by the rate of fumigant loss during the decay phase. Without additional fumigant added during this phase, C decays exponentially with t, as described by the equation: $\mathbf{C} = \mathbf{C_0}\, e^{-k(t - t_0)}$, where **C** is the concentration at any time **t**, $\mathbf{C_0}$ is the concentration at time $\mathbf{t_0}$, **k** is the decay rate constant in units of (time^{-1}), such as "per day," and ***e*** is the base of natural logarithms. The value of **k** can be obtained from the slope of the semilogarithmic graph of concentration against time. This equation has been simplified to reflect a more general relationship in the form of $\mathbf{C^n} \times \mathbf{t} = \mathbf{K}$, where **K** is a constant equaling the dosage for a specified level of response, such as the LD_{99} (lethal dose for 99 % of the pest population present) and **n** is known as the toxicity index and is a specified value that describes the toxicity relationship between a fumigant and the developmental stage of a species. Under constant environmental conditions, this **Ct** relationship remains linear for most of the exposure period (Bell, 1979, 1992; Daglish et al., 2022; Winks and Waterford, 1986). Recent research has been focused on developing fumigation protocols targeting all life stages of resistant pest populations under field-mimicking conditions (Collins et al., 2005; Kaur and Nayak, 2015; Nayak and Collins, 2008). These studies have demonstrated that increasing either "C" or "t" enhances PH_3 efficacy against strongly resistant pests, although "t" often plays a more critical role than "C."

2.5.2. Fumigation temperature and moisture content of grain

Application labels for solid formulations of PH_3 (i.e., AlP) indicate that the minimum ideal conditions for the reaction of phosphide salts to yield PH_3 gas are temperatures of 25–32 °C and relative humidity of 70 % and grain MC between 9 and 12 % (Phillips et al., 2012). Gaseous fumigants, including PH_3, vaporize and diffuse slowly at low temperatures, and insect activity and metabolism diminish under such conditions (Bond, 1984). Since insects absorb fumigants through their respiratory systems, temperature directly influences fumigant uptake and toxicity. PH_3 toxicity increases at higher temperatures due to heightened insect respiratory activity (Fytizas and Katsoyannos, 1979; May, 1989).

High grain MC raises quality concerns and makes the grain more sorptive to PH_3, potentially undermining fumigation efficacy (Daglish and Pavic, 2008, 2009; Reddy et al., 2007). Reduced insect respiration at low temperatures, combined with decreased fumigant uptake and high grain MC, can jeopardize successful fumigation. To address this, efforts should be made to reduce MC content to an acceptable level in highly moist grain before fumigation, either by blending with dry grain or using aeration-drying techniques (Phillips et al., 2012). These principles have guided the development of fumigation protocols for managing PH_3-resistant pests in grain storages (Kaur and Nayak, 2015; Nayak and Collins, 2008). Current guidelines recommend conducting PH_3 fumigations at temperatures $\geq$15 °C, with optimal results at 25–35 °C.

Another critical factor affecting PH_3 efficacy is sorption by commodities, which leads to gas loss from the treated space and reduces fumigant effectiveness. Laboratory (Daglish and Pavic, 2008, 2009; Reddy et al., 2007) and field research (Plumier et al., 2018, 2020; Rajendran and Muralidharan, 2001) have extensively documented PH_3

sorption and desorption in various stored products. These studies have shown that PH_3 sorption increases with higher grain temperature and MC (Darby, 2011; Dumas, 1980; Reed and Pan, 2000; Sato and Suwanai, 1974). Elevated temperatures accelerate PH_3 sorption in cereals (Banks, 1986; Sato and Suwanai, 1974).

PH_3 desorbs slowly due to chemical interactions with the commodity, and not all gas sorbed is released, leaving behind a fixed residue. If significant amounts of sorbed gas remain after ventilation, unacceptable residue levels can accumulate, affecting commodity quality (Banks, 1986). Therefore, fumigation strategies must account for the sorption characteristics of commodities to ensure efficient treatment while adhering to WHS guidelines and limiting exposure to fumigators and bystanders.

2.6. Workplace health and safety considerations

Following fumigation, ventilation of storages must be conducted to allow PH_3 gas to escape into the atmosphere, ensuring that the grain can be delivered free of harmful gas residues. The recommended ventilation period ranges from 2 to 5 days, depending on storage capacity and the availability of a throughflow system. In Australia, according to the label directions for solid PH_3 formulations, ventilation is considered complete only when PH_3 concentrations measured at appropriate locations in the enclosure and work areas are below the Threshold Limit Value-Time Weighted Average (TLV-TWA) exposure standard of 0.3 ppm. However, a new TWA for PH_3, effective December 2026, will be 0.05 ppm (SWA, 2024). This TLV-TWA is based on an 8-h working day and a 40-h working week, during which a worker may be repeatedly exposed without adverse health effects. Several commercially available devices can monitor PH_3 concentrations inside and outside the grain mass. Personal PH_3 monitors are available, which are easy to use by clipping onto an operator's collar or top pocket (near their nose and mouth). According to current label recommendations, grain should be held for an additional two days after the ventilation period before being delivered or used for human consumption or animal feed.

2.7. Limitations

Due to its highly corrosive nature, PH_3 is restricted from use in certain metal storage structures and those with metal fittings, including gold, silver, and copper (Phillips et al., 2012). Electrical appliances, wiring, lighting, and electronic equipment with integrated circuits, computer chips, and other devices containing copper and electrical conductors are at risk of damage during PH_3 fumigation. This is the main factor restricting PH_3 use in buildings such as flour mills, food plants, climate-controlled warehouses, and other structures with extensive electrical wiring, telephones, and electrically powered equipment susceptible to gas damage.

PH_3 can pose hazardous situations due to spontaneous ignition if concentrations exceed 18,000 ppm (or 25.7 g/m^3) (Phillips et al., 2012). This can occur if large quantities of AlP or Mg_3P_2 pellets or tablets are piled in a small space. Dangerous high-concentration situations are more likely when cylinderized pure PH_3 gas is not adequately mixed with a diluting gas. Phosphide pellets and tablets are prone to smoldering, and ignition or fires may occur if stacked in piles, especially when the pellets touch or when standing water is present. Fire hazards from "piling" can be avoided with proper application.

Over-reliance on PH_3 without suitable alternatives to MB has led to resistance development in major storage pest species worldwide, as comprehensively covered in a recent review (Nayak et al., 2020). For fumigants, resistance evolves as a heritable trait in storage insects through selection pressure from treatments. This develops via inheritance and fitness costs for individuals carrying resistance genes in a population (Nayak et al., 2020). Repeated fumigation of the same grain or commodity parcel to control surviving populations in leaky storage structures is a typical example of resistance selection (Collins, 2009; Nayak et al., 2020). Modern molecular tools have enabled researchers to confirm that resistance to PH_3 can result from multiple resistance gene variants. Genetic and molecular research on key grain insect pests identified two genes, *rph1* and *rph2*, conferring resistance to PH_3 (Schlipalius et al., 2012, 2018). Both genes are inherited in an incompletely recessive manner and, in homozygous isolation, confer weak resistance (20 times for *rph1* and 12.5 times for *rph2*). However, when both genes are present in an individual insect, they interact synergistically to confer very high resistance (strong, >250 times). Although resistance continues to threaten the future viability of PH_3, early detection of resistance in field populations and characterization of its strength has enabled researchers to develop modified fumigation protocols, adjusting concentrations and exposure times to manage resistance (Aulicky et al., 2019; Kaur and Nayak, 2015; Lorini et al., 2007; Nayak et al., 2013).

3. Phosphine as a fumigant for wood products

On September 16, 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was negotiated by forty-seven parties (UN, 1987). Since then, the treaty has been ratified by all 197 parties, making it the only global environmental treaty (UNEP, 2024c). This landmark agreement regulates the global production and consumption of ozone-depleting substances. In 1992, the fumigant MB was added to the list of ozone-depleting substances (Allen et al., 2017; UNEP, 1992). These events had significant global implications due to the widespread use of MB (Backstrom, 2002; Ferguson and Yee, 1997; Yücel et al., 2007). For example, in the mid-90s, approximately 45,000 tons/year of MB were used for non-QPS purposes, while approximately 10,000 tons/year were used for QPS (MBTOC, 2006; UNEP, 2024d). This resulted in an urgent search for alternatives to MB to maintain agricultural productivity and the integrity of biosecurity systems to support international trade. Several working groups and forums were established to gather and share information. For example, in 1994, the Methyl Bromide Technical Options Committee (MBTOC) presented its first technical report (MBTOC, 1995), and the first Methyl Bromide Alternatives Outreach (MBAO) conference was held in the USA (MBAO, 1994). PH_3 and SF were the most researched chemical alternatives for treating wood products (Armstrong et al., 2014a; Dwinell et al., 2003; Leesch et al., 1989; Soma et al., 2001; Zhang, 2006), as both were widely registered and used in other applications, facilitating their adoption for wood product treatment.

For the last 30 years, MBTOC has reported to the UNEP on scientific, technical, and economic matters related to the global use of MB and its alternatives. Every four years, MBTOC releases a comprehensive report that includes recent scientific developments on MB alternatives. Our analysis of these reports showed that PH_3 was frequently mentioned but rarely discussed in the context of QPS treatment for wood products. For example, PH_3 (keywords phosphine and phosphide) was mentioned 1185 times in the eight reports released since 1994 (MBTOC, 1995, 1998, 2002, 2006, 2010, 2014, 2018, 2022), but only 77 times in relation to wood products. PH_3 was more commonly referenced for treating grain commodities, durable goods, and empty structures. MBTOC reported the commercial use of PH_3 for treating pine logs exported from New Zealand to China (MBTOC, 2006) and logs exported from Ecuador to India (MBTOC, 2018). In 2014, MBTOC reported that Indonesia was developing a PH_3 schedule for wood chips (MBTOC, 2014; Tumambing and Dikin, 2013). However, we could not determine whether a treatment schedule was developed and adopted. MBTOC cited five peer-reviewed sources (Kawakami, 1999; Leesch et al., 1989; Oogita et al., 1997; Rajendran and Kumar, 2008; Schmidt and Christopherson, 1997) and 11 unpublished sources (Dwinell, 2001; Frontline Biosecurity, 2003a, 2005; Hosking, 2005; Hosking and Goss, 2005; Spiers, 2003; Tumambing and Dikin, 2013; Zhang, 2003, 2004a, 2004b; Zhang and van Epenhuijsen, 2005) relating to the use of PH_3 for wood products.

The MBAO conference is an annual event in the USA dedicated to sharing information on current research into MB alternatives. Our analysis shows that, over the past 30 years, 70 presentations and 3 posters were associated with PH_3 as an alternative to MB. Of these, only three presentations discussed PH_3 as a treatment for wood products (Brash et al., 2008a; Glassey et al., 2005; Tumambing and Dikin, 2013).

Since 2004, the International Forestry Quarantine Research Group (IFQRG) has supported the International Plant Protection Convention (IPPC) community by addressing critical forestry quarantine issues. Over the past 20 years, IFQRG has held twenty meetings, including four online symposia (IPPC, 2024). Our analysis of meeting reports and proceedings indicates that PH_3 was rarely discussed. When mentioned, it was typically in the context of research updates (IFQRG, 2005, 2008, 2009, 2010, 2011, 2018) or statements about the ineffectiveness of PH_3 against pathogens and nematodes (IFQRG, 2014, 2017). The only commercial uses mentioned include the in-hold fumigation of pine logs exported from New Zealand to China (IFQRG, 2011, 2017) and wood chips exported from Canada to Turkey (IFQRG, 2023).

In 2005, the IPPC Technical Panel on Phytosanitary Treatments (TPPT) identified PH_3 as an alternative to MB for treating logs (IPPC, 2005). In 2006, the New Zealand Ministry for Primary Industries (MPI; formerly the Ministry of Agriculture and Forestry) applied for PH_3 approval under International Standards for Phytosanitary Measures (ISPM) 15 (IPPC, 2006; submission number 2006-TPPT-112). In 2007, TPPT concluded that the PH_3 submission did not provide sufficient scientific data to demonstrate the effectiveness of the treatment schedule for wood (IPPC, 2007). Our analysis has identified that several references, presumably available then, were omitted from the submission (Baker et al., 2003a, 2003b; Brash and Page, 2009; Cavasin et al., 2006; Davis et al., 1987; Dwinell, 2001, 2004; Frontline Biosecurity, 2003a, 2003b, 2005; Hosking, 2005; Hosking and Goss, 2005; Kawakami, 1999; Morrell, 1995; Tumambing, 2005; Zhang, 2004a, 2004b; Zhang and van Epenhuijsen, 2005; Zhang et al., 2004, 2006). The reason for the omission of this information in the submission remains unclear, as most of these studies were conducted in New Zealand. In November 2007, MPI resubmitted the application (Glassey, 2007; IPPC, 2007; submission number 2007-TPPT-115). In 2008, TPPT requested additional information (IPPC, 2009), and three references were provided (Brash et al., 2008b; Zhang et al., 2004, 2006). However, several new references were omitted despite this being an active research period in New Zealand (Hosking and Burridge, 2008; Rajendran and Kumar, 2008; Tumambing, 2007; Wimalaratne et al., 2008; Zhang and Brash, 2007; Zhang et al., 2007). TPPT concluded that PH_3 fumigation was not equivalent to MB. In 2010, no additional information was received, and the matter was removed from the work schedule of TPPT (IPPC, 2010). Consequently, PH_3 was not approved under ISPM 15 due to insufficient scientific data supporting the effectiveness of the proposed treatment, i.e., $\geq$200 ppm for 10 days at temperatures $\geq$15 °C.

Based on our analysis, the scientific evidence to support PH_3 as a broad-spectrum quarantine treatment for wood products has not been presented through relevant international groups and forums, particularly regarding the ISPM 15 submission (and by default, ISPM 28) and the decision of TPPT. In the next section, we will analyze PH_3 efficacy against forestry pests.

3.1. *Phosphine efficacy against forestry pests*

Trees are natural habitats for many organisms, including insects, nematodes, and pathogens (e.g., fungi, bacteria, viruses, and mycoplasma). Their potential presence in wood products moved between countries or regions necessitates risk mitigation measures, such as phytosanitary treatments, to limit their spread (Allen et al., 2017; IPPC, 2017).

Historically, efficacy data for phytosanitary treatments used for wood products (i.e., MB, SF, and PH_3) primarily focused on eradicating insects, except data on PWN for SF and dielectric heating, required for submissions under ISPM 15 and 28—Annex 23. In the early 2000s, no standardized testing methods existed, leading to diverse approaches (e.g., in vitro or in vivo studies, different test materials naturally or artificially infested, and different pest numbers and replication). Consequently, these studies may produce confounded and imprecise results (Noseworthy et al., 2024) and may not meet contemporary standards for quality and repeatability.

The IPPC recently developed a standardized approach for evaluating phytosanitary treatments for wood products (IPPC, 2023). This approach requires documenting various factors, including experimental design, efficacy under laboratory and operational conditions, and statistical analysis (IPPC, 2016). Pests must be consistently killed to a specific confidence level to prevent survivors from forming viable breeding populations. The LD_{99} level is typically not accepted for quarantine treatments, as survivors are likely to recuperate and establish. Probit-9 has historically been used to measure efficacy based on fruit fly control in the USA (Ormsby, 2022). It requires a treatment sample size of 93,613 individuals with no survivors or 94,587 individuals with few survivors, achieving 99.9968 % mortality ($LD_{99.9968}$). However, Haack et al. (2011) and Schortemeyer et al. (2011) summarized arguments suggesting that this level of confidence may not be suitable for forest pests. They proposed alternative approaches for evaluating the efficacy of treatments for WPM (Ormsby, 2022) and expressed confidence in using treatments with smaller sample sizes.

Our analysis of the PH_3 efficacy dataset encompassed all available materials, including peer-reviewed publications ($n = 18$) and gray literature ($n = 23$). We separated the data into in vitro (Table S1) and in vivo (Table S2) studies for insects ($n = 29$), nematode ($n = 1$), and fungi ($n = 11$) species. The supplementary materials (Tables S1 and S2) summarize key information such as pest family, genus, species, life stage, experimental conditions, treatment success, and the confidence level based on sample size.

The dataset was dominated by insect pests, with the Burnt Pine Longhorn (*Arhopalus ferus*), representing over 40 % of the studies (17/41 efficacy studies; Tables S1 and S2). While PH_3 efficacy data exists for 29 insect species, the dataset was insufficient to meet ISPM 15 standards. *A. ferus*, a minor global forestry pest, is found in New Zealand, Central Europe, and the Near East (GBIF, 2024). Its life cycle spans 1–2 years, with larvae and pupae being the primary life stages likely to be found in wood products. However, the PH_3 efficacy data focused on eggs ($n = 10$), adults ($n = 9$), and larvae ($n = 5$), with no studies on pupae.

The data quality was generally good for *A. ferus*, with reasonable sample sizes and replication. However, inconsistent results were observed between in vitro and in vivo studies. Studies, such as those by Hosking (2005), Zhang and van Epenhuijsen (2005), Baker et al. (2003a), Zhang et al. (2006), and Tumambing (2007), reported that PH_3 did not kill all *A. ferus* insects, while other studies reported that PH_3 was effective (Tables S1 and S2). As some studies showed efficacy while others did not, these discrepancies are likely due to experimental design issues rather than the tolerance of insects to PH_3.

Many studies failed to report critical parameters like insect numbers, replication, and treatment temperature (refer to the IPPC (2023) checklist, page 142), compromising the quality of the dataset. As mentioned earlier, PH_3 fumigations should occur at temperatures >15 °C for efficacy and compliance with product labels. Most studies conducted at temperatures above this threshold align with the recommendation. Choi et al. (2014) showed that fumigant activity for the Japanese Termite (*Reticulitermes speratus*) was considerably reduced at 5 °C compared to 15 °C.

In vitro studies generally used shorter treatment times and lower doses, whereas in vivo studies had longer treatment times and higher doses (Tables S1 and S2). Earlier PH_3 studies are considered lower quality due to missing critical parameters or inadequate experimental design (e.g., Frontline Biosecurity (2003a,b), Hosking (2005), and Hosking and Goss (2005)). More recent research tends to be of higher quality, e.g., Armstrong et al. (2014b), Devitt (2021), and Seabright et al. (2020).

Insects can colonize wet and relatively dry wood, while nematodes and fungi typically thrive in wetter conditions. Higher moisture content may reduce fumigant penetration and increase sorption (Hall and Adlam, 2023; Ren et al., 2011). PH_3 penetration through the bark of logs is poor, especially at higher temperatures, with penetration rates up to three times lower at 25 °C than at 15 °C (Hall et al., 2018). Fungi and nematodes, often located deeper inside wood tissues, including the heartwood (Bari et al., 2019; Son et al., 2010; Zhao et al., 2009), may be out of reach of the fumigant and/or have survival mechanisms that hinder fumigant efficacy, such as chlamydospores, cysts, or the JIII stage of PWN.

Different pest life stages have varying tolerances to fumigants, particularly where active respiration is required for effective control. If gases are not inhaled due to dormancy or other factors (e.g., high CO_2 and/or low O_2 levels or closure of gas exchange organs), fumigant efficacy may be greatly reduced. Armstrong et al. (2014b) demonstrated that a low O_2 atmosphere considerably affects PH_3 effectiveness. For example, a PH_3 dose of 1000 ppm for 240 h at 20 °C in a normal atmosphere resulted in 100 % mortality of *A. ferus* eggs. However, the same treatment in a low O_2 atmosphere (<1.6 %) achieved only 90.4 % mortality, while the low O_2 atmosphere without PH_3 caused 78.7 % mortality. Under these conditions, simulating a low O_2 atmosphere due to log respiration (Adlam et al., 2018; Devitt et al., 2020; Feng et al., 2015; Hall et al., 2016a, 2016b), PH_3 was ineffective in controlling *A. ferus* eggs. The modified atmosphere caused approximately 87 % of the mortality, while PH_3 contributed only approximately 13 % (Armstrong et al., 2014b; Table S1).

Testing all possible pests that can occur on wood products is unviable. Over the last 13 years, IFQRG and TPPT have developed an approach for evaluating the efficacy of new treatments for WPM under ISPM 15. Universal treatments must be effective against various pests that may be present in various wood species used for wood packaging. Ormsby (2022) summarized an evaluation approach, indicating that research for a universal WPM treatment should include at least one species from five insect families (Bostrichidae, Buprestidae, Cerambycidae, Scolytinae, and Siricidae), two pathogens (*Ceratocystis* spp., *Heterobasidion* spp.), and one nematode (PWN) to confirm the efficacy of treatment (Table 1). These pests are significant in their association with WPM and other wood products, including logs (MBTOC, 2018). After laboratory evaluation, the most tolerant species and life stage should be tested under operational conditions with proper insect numbers and replication to ensure reliable data. Najar-Rodriguez et al. (2020a,b) provide contemporary examples of this approach.

Based on Ormsby's (2022) and MBTOC's (2018) pest groupings, available PH_3 efficacy data is summarized in Table 1. As seen in Table 1, PH_3 cannot be considered an effective broad-spectrum treatment for controlling insect, pathogen, and nematode pests in wood products. No efficacy studies have shown success for the insect pest families Buprestidae and Siricidae, the pathogen families Bondarzewiaceae and Ceratocystidaceae, or the nematode family Aphelenchoididae. Efficacy data is available for four species within the Bostrichidae family, but this includes only three studies (Rajendran and Kumar, 2008; Remadevi and Deepthi, 2018; Remadevi et al., 2013), and results for species in the Cerambycidae and Curculionidae families were inconsistent.

Based on the available data, our analysis strongly indicates that PH_3 is not an effective broad-spectrum chemical treatment for controlling forest pests. However, in specific circumstances, it may be possible—such as treating surface pests at high temperatures on low MC products, where there is mutual agreement on the effectiveness of the treatment schedule. Our conclusion agrees with the findings of TPPT, which indicated insufficient scientific data to support the efficacy of PH_3. Additionally, no accepted PH_3 treatment exists for any individual pest species under ISPM 28. This analysis has demonstrated that the scientific evidence to support the efficacy of PH_3 as a quarantine treatment for wood products has not been offered through peer-reviewed or gray literature. The historical and current commercial uses of PH_3 to treat wood products will be discussed in the next section.

3.2. Development and status of wood product treatment schedules

The US Department of Agriculture's Agricultural Research Services laboratory in Savannah, Georgia, was the first research group to use PH_3 to treat wood products (Leesch et al., 1989). They initially developed the in-transit PH_3 schedule for grain crops (Davis, 1982; Leesch et al., 1978, 1986; Redlinger et al., 1979, 1982; Zettler et al., 1982, 1984) and explored its potential for treating wood chips. In 1986, the first trial shipment of PH_3-fumigated wood chips was exported from the USA to Sweden (Davis et al., 1987; Leesch et al., 1989). However, by the mid-90s, PH_3 had not been widely adopted in the USA for in-transit treatment of exported wood chips (Dwinell, 1997). Currently, China is the only country that accepts PH_3-treated wood chips from the USA (USDA, 2024, Table 2). However, in 2022, China restricted the use of AlP for treating debarked southern yellow pine wood chips, making trade unviable (F. Peeples Jr., personal communication, May 9, 2024). Limited adoption of PH_3 is attributed to efficacy issues, increased enforcement for PWN, and high treatment costs due to demurrage charges (T. Jones, personal communication, April 19, 2024).

Malaysia accepts PH_3 treatment for all imported wood products from any country (DOA, 2014, Table 2). No temperature restrictions, minimum concentration, or CT value requirements exist for treatment acceptance (F. Samsudin, personal communication, March 19, 2024). Despite this, PH_3 is not commonly used; most of Malaysia's imported wood products are processed wooden items treated under ISPM 15 (FAO, 2017; Healey et al., 2021), and approximately 75 % of imported logs are from Australia and fumigated with MB (DAFF, 2024b; R. Elson, personal communication, May 9, 2024).

In 2013, Indonesia was developing a PH_3 schedule for wood chips (MBTOC, 2014; Tumambing and Dikin, 2013). However, we cannot confirm whether a treatment schedule for wood chips was developed and adopted. Similarly, in 2021, AlP was approved under an emergency permit for in-transit fumigation of wood pellets exported from Australia (APVMA, 2021, Table 2), though its current usage status is unknown.

Canada has exported PH_3-treated wood chips to Turkey (IFQRG, 2023). The Canadian National Plant Protection Organization (NPPO) confirmed that Turkey is the only market where PH_3 is used, with fewer than two shipments exported in the last four years (M. Noseworthy, personal communication, May 11, 2024). As PH_3 is not regularly used in Canada, the wood chip treatment schedule remains unknown (Table 2).

The USA (USDA-APHIS, 2024a,b), Australia (DAFF, 2024c,d), and Canada (GOC, 2010, 2016, 2017, 2023) do not accept PH_3 treatment for imported wood products (Fig. 1).

In 2001, China granted New Zealand an experimental permit to fumigate exported pine (*Pinus radiata*) logs with PH_3 (EPA, 2012). The adopted fumigation schedule was based on Australia's grain treatment schedule (MBTOC, 2006), requiring >200 ppm for 10 days at 15–25 °C (GRDC, 2013). This approval seemed to have been based solely on PH_3 effectiveness against stored product pests, as research into forestry pests did not commence in New Zealand until 2003 (i.e., Baker et al., 2003a,b; Frontline Biosecurity, 2003a,b; Spiers, 2003; Zhang, 2003). Logs are fumigated with AlP at a dose of 3.5 g/m^3 for 10 days, with a minimum concentration requirement of >200 ppm (MPI, 2024a, Table 2). An initial dose of 2.0 g/m^3 is applied before the vessel sails, followed by a top-up dose of 1.5 g/m^3 after five days by an in-transit technician (Adlam et al., 2018; Hall et al., 2016a, 2016b). Despite the presence of the critical forestry pest, the Golden-Haired Bark Beetle (*Hylurgus ligniperda*) in China, originating from New Zealand (Lili et al., 2021; Lin et al., 2021), the experimental approval continues. A critical issue in New Zealand is the treatment temperature, as the largest port for wood exports, the Port of Tauranga, falls below 15 °C for eight months of the year (Fig. S1). Ship holds are not currently heated, and temperatures inside the hold only increase modestly during the voyage (Adlam et al.,

Table 1
Summary of phosphine (PH_3) efficacy against wood pest groups that present a phytosanitary risk in the international movement of wood products.

Type	Family	Species	Reference	Summary[a]
Insect	Bostrichidae	*Dinoderus minutus*	Remadevi et al. (2013)	In vitro fumigations of $\geq$350 ppm for 96 h controlled eggs, larvae, and adults. A few key parameters, such as insect count per replicate and treatment temperature, were not reported.
		Dinoderus ocellaris	Rajendran and Kumar (2008)	In vivo fumigations with concentrations $\geq$1400 ppm for 96 h controlled this species. A few key parameters, such as low or no replication, and insect numbers and life stages, were not reported.
		Sinoxylon anale	Remadevi and Deepthi (2018)	In vitro fumigations of adults at 200 ppm for 96 h controlled this species. However, control was not achieved for in vivo fumigations of mixed life stages in naturally infested wood.
		Sinoxylon sp.	Rajendran and Kumar (2008)	In vivo fumigations of $\geq$1400 ppm for 96 h controlled this undefined species within the *Sinoxylon* genera. Low or no replication, insect numbers, and life stages were not reported, which impacted the findings of this research.
	Buprestidae	Nil	Nil	–
	Cerambycidae	*Anoplophora chinensis*	Lee et al. (2018),[b]	In vitro fumigations of >1400 ppm for 24–168 h controlled eggs and larvae of this species, including one replicate at a very low treatment temperature of −1.3 °C. However, certain treatments for larvae were unreplicated, and control mortality for the −1.3 °C treatment was not reported.
		Anoplophora glabripennis	Lee et al. (2018),[b]	Very low-temperature treatments of −1.3 °C and 1.5 °C. Certain treatments for larvae were unreplicated, and control mortality was not reported for low-temperature treatments.
		Anoplophora nobilis	Wang et al. (2003),[b]	Larvae and pupae were controlled under the conditions tested despite the concentration of PH3 dropping below 3 % of the initial concentration after 96 h.
		Arhopalus ferus	Armstrong et al. (2014b) Baker et al. (2003a,b) Brash et al. (2008) Frontline Biosecurity (2003a,b) Hosking (2005) Hosking and Goss (2005) Hosking and Burridge (2008) Tumambing (2005, 2007) Zhang (2003, 2004a,b) Zhang and van Epenhuijsen (2005) Zhang et al. (2006, 2007)	Many in vitro and in vivo studies for this species (n = 17) exist. A few studies did not report key experimental factors or had inadequate experimental designs to provide confidence in the results, i.e., the treatment temperature, no replication, low insect number (3–5 insects per replicate), and high control mortality (up to 74 %). Overall, inconsistent results were reported for this species, with a few studies reporting that PH3 is effective at controlling the different life stages, while others report that PH_3 is ineffective (i.e., Baker et al. (2003a); Hosking (2005); Zhang and van Epenhuijsen (2005); Zhang et al. (2006); Tumambing (2007)).
		Callidiellum rufipenne	Oogita et al. (1997),[b]	Control was not achieved under the conditions tested.
		Monochamus alternatus	Lee et al. (2018),[b] Oogita et al. (1997),[b]	In vitro fumigations of 1400 ppm for $\geq$120 h controlled eggs and larvae of this species. Oogita et al. (1997),[b] did not report on the number of replicates, size of the fumigation chamber, or control mortality.

(continued on next page)

Table 1 (*continued*)

Type	Family	Species	Reference	Summary[a]
		Prionoplus reticularis	Frontline Biosecurity (2003a)	
Hosking and Goss (2005) Zhang et al. (2006)	All three studies are considered unreliable. For example, the treatment temperature was not reported, there was no treatment replication, and the control mortality was 40 %.			
		Semanotus japonicus	Oogita et al. (1997),[b]	Control was not achieved under the conditions tested.
Insect	Curculionidae	*Cryphalus fulvus*	Cho et al. (2019),[b]	
Oogita et al. (1997),[b]	Higher mortality of PH_3 was shown at 25 °C than at 15 °C for eggs, pupae, and adults. Larvae were not controlled under the conditions tested. Key factors were not reported, e.g., control mortality, number of replicates, and volume of the fumigation chamber.			
		Hylastes ater	Brash et al. (2008b)	
Frontline biosecurity (2003a,b) Hosking and Goss (2005) Zhang (2003) Zhang et al. (2004, 2006, 2007)	In vitro studies were able to control larvae and adult life stages. However, Brash et al. (2008b) reported a control mortality of 57–76 %. In vivo studies reported inconsistent PH3 efficacy results for insects fumigated within infested logs.			
		Hylurgus ligniperda	Armstrong et al. (2014b)	
Baker et al. (2003a,b) Brash et al. (2008b) Devitt (2021) Esfandi et al. (2022, 2023) Frontline Biosecurity (2003a,b) Hosking and Goss (2005) Zhang et al. (2007)	Many in vitro and in vivo studies for this species (n = 11) exist. Earlier studies are typically considered to be of poorer quality due to inadequate experimental designs. In contrast, the experimental design of newer studies provides statistically valid conclusions about the efficacy of PH3, i.e., Armstrong et al. (2014b) and Devitt (2021). In vivo studies reported inconsistent PH3 efficacy results for insects fumigated within infested logs.			
		Phloeosinus perlatus	Oogita et al. (1997),[b]	All life stages could not be controlled under the conditions tested.
		Platypus calamus	Oogita et al. (1997),[b]	All life stages could not be controlled under the conditions tested.
		Platypus koryoensis	Cho et al. (2019),[b]	Adults were controlled by the highest dose of 862.7 ppm for 24 h for in vitro fumigations. Control mortality was not reported.
		Platypus quercivorus	Oogita et al. (1997),[b]	All life stages could not be controlled under the conditions tested.
		Xyleborus pfeili	Oogita et al. (1997),[b]	Higher mortality of PH3 was shown at 25 °C than at 15 °C for all life stages. Under the conditions tested, eggs, larvae, and pupae were not controlled at 15 °C. Key factors were not reported, e.g., control mortality, number of replicates, and volume of the fumigation chamber.
		Xyleborus mutilatus	Cho et al. (2019),[b]	Adults were controlled by the treatment conditions. Control mortality was not reported.
	Siricidae	*Sirex noctilio*	Wimalaratne et al. (2008)	Control was not achieved under the conditions tested.
Nematode	Aphelenchoididae	*Bursaphelenchus xylophilus*	Leesch et al. (1989)	
Seabright et al. (2020) Uzunovic and Coelho (2012)				

(*continued on next page*)

Table 1 (*continued*)

Type	Family	Species	Reference	Summary[a]
Uzunovic et al. (2009, 2010)	Control was not achieved under the conditions tested.			
Fungi	Bondarzewiaceae	Heterobasidion spp. (*Heterobasidion annosum*)	Uzunovic and Coelho (2012)	Control was not achieved under the conditions tested.
	Ceratocystidaceae	Ceratocystis spp. (*Bretziella fagacearum*)	Schmidt and Christopherson (1997)	Control was not achieved under the conditions tested.

[a] Refer to supplementary material for more information (Tables S1 and S2).

[b] Manuscript translated to English using Google Translate. https://translate.google.com/?hl=en&tab=TT. Where possible, authors were contacted to ensure the accuracy of the details provided in the table.

2018; Hall et al., 2016a, 2016b). In addition, most chemical labels in New Zealand do not permit fumigation at temperatures below 15 °C (ACVM, 2024a,b,c,d,e,f,g,h), presumably due to the absence of efficacy data and the suboptimal release of AlP. Based on historical export volumes, we estimate that this situation accounts for ~90 % of the global use of PH_3 to treat wood products.

In 2018, Uruguay started using PH_3 to treat pine logs exported to China (MGAP, 2018). A single dose of 5 g/m^3 is applied for 10 days, maintaining a minimum concentration of >200 ppm (Table 2). Uruguay uses PH_3 to fumigate sawn timber exported to Malaysia and Vietnam (Table 2; P. Canabez, personal communication, February 25, 2024). The Vietnamese NPPO has not approved specific treatments; they only require consignments to be free of live pests. Like New Zealand, the minimum treatment temperature falls <15 °C at the largest port for wood exports, Port of Montevideo, for eight months of the year (Fig. S2).

Suriname voluntarily phased out MB for QPS uses in 2020 (UNEP, 2024e). In 2023, they requested India's NPPO to accept a PH_3 dose of 2.5 g/m^3 for log treatment (Y. Rokadji, personal communication, March 15, 2024). However, India does not currently accept PH_3 for Suriname's logs exports.

New Zealand (MPI, 2023, 2024b,c) does not accept PH_3 as a treatment for imported wood products, except for miscellaneous items such as pine cones and wood shavings (Table S3). In contrast, Uruguay accepts PH_3 for imported wood products (Fig. 1).

Many countries, including Azerbaijan, Mongolia, Mozambique, Paraguay, and Zimbabwe, accept PH_3 fumigation for imported wood products. However, they do not specify a treatment schedule and only require documentation of treatment conditions on the phytosanitary certificate. For more information on the requirements of individual countries, please refer to supplementary materials (Table S3). However, whether PH_3 is routinely used in these countries to treat imported wood products remains unclear. Based on correspondence with NPPOs, our opinion is that PH_3 is not widely used to treat wood products, as MB remains the predominant treatment globally.

3.3. Limitations for wood products

As demonstrated, PH_3 is generally ineffective or partially effective against wood-damaging fungi and nematodes (Leesch et al., 1989; Uzunovic et al., 2010; Table S2). Unlike insects confined to tunnel galleries within the wood, where the gas is accessible, nematodes and fungi are located deep within the wood cell matrix and are less exposed. Additionally, they thrive in wet wood and often possess complex survival mechanisms or resistant structures, further reducing fumigant efficacy (Uzunovic and Stirling, 2015). While PH_3 is non-phytotoxic and does not affect parenchyma viability, even at high treatment levels (Schmidt and Christopherson, 1997), controlling fungi and nematodes may require extended treatment times and very high concentrations (Seabright et al., 2020; Pant and Tripathi, 2011; Tables S1 and S2). However, we hypothesized that such conditions could trigger dormancy in insects, reducing the effectiveness of PH_3 treatment for them.

Freshly harvested logs with high MC pose additional challenges due to increased sorption, which accelerates the depletion of PH_3 in the treated space and diminishes its effectiveness (Daglish and Pavic, 2008; Reddy et al., 2007). Thus, treating logs appears more challenging than other dry wood materials (Uzunovic and Stirling, 2015), such as sawn timber and plywood. More gas is needed to counter the solubility of PH_3 when treating high MC wood products (CYTEC, 2024). Barked logs exhibit a higher rate of PH_3 depletion compared to debarked logs or wood chips (Seabright et al., 2020; Zhang and Brash, 2007), which explains the success of PH_3 in eliminating PWN on low-MC wood chips but not on higher-MC wood products (Seabright et al., 2020).

The high respiration rate of recently harvested logs causes rapid changes in atmospheric conditions, creating hypercapnic (high CO_2) and hypoxic (low O_2) environments (Devitt et al., 2020). Low O_2 levels during fumigation reduce pest respiration and PH_3 uptake, undermining pest control. Hypoxic conditions, commonly encountered in the middle and end stages of in-transit fumigations (Adlam et al., 2018; Armstrong et al., 2014b; Feng et al., 2015; Hall et al., 2016a, 2016b; Devitt et al., 2020), are not conducive to successful pest control with PH_3. For example, Armstrong et al. (2014b) reported that in low-O_2 conditions (<1.6 %), most *A. ferus* egg mortality (~87 %) was due to oxygen deprivation, while PH_3 contributed only ~13 % to mortality (Table S1).

A major disadvantage of PH_3 fumigation is the long exposure time, typically 7–10 days (CYTEC, 2024; Zhang et al., 2004). Logs may need to be treated quickly, such as at the point of export or import. PH_3 fumigation alone is challenging to incorporate into quarantine treatments since short-term treatments, even at high doses and temperatures, cannot completely control many forest pests (Oogita et al., 1997). In certain cases, the time constraint can be addressed by PH_3 for in-transit fumigation, where voyage duration allows extended exposure. PH_3 is more effective at high temperatures, with successful control of many forest pests achievable only at >15 °C (Brash and Page, 2009; Wang et al., 2003) and preferably >25 °C. Unfortunately, such conditions are uncommon for log exports from New Zealand and Uruguay for most of the year (Figs. S1 and S2), and ship holds are not currently heated to optimize treatment efficacy. Under these conditions, Mg_3P_2 may be preferable to AlP, though PH_3 still faces challenges in meeting quarantine treatment requirements.

Solid formulations of PH_3 are relatively safe, as gas generation occurs upon contact with atmospheric moisture and is released gradually through dilution with surrounding air. However, PH_3 becomes flammable at concentrations >18,000 ppm. Using AlP in ships poses a fire and explosion hazard if the lower flammability limit is exceeded and an ignition source is present (Tumambing et al., 2018). Solid metal phosphide formulations require the safe deactivation and disposal of unspent powder residues. Extensive PH_3 leakage through hatch covers can create hazardous situations for workers. Zettler et al. (1982, 1986) reported PH_3 levels exceeding the TLV during in-transit shipboard fumigation due to leaking hatch covers and cracked bulkheads.

3.4. Options to improve phosphine efficacy for wood products

The toxicity of PH_3 increases when combined with 5–35 % CO_2

Table 2
Summary of the phytosanitary uses of phosphine (PH_3) to treat wood products in international trade.

Exporting country	Importing country	Wood product	Species	Status[a]	Treatment schedule[b]
Chile	China	Logs	*Pinus radiata*	Active	Chambers, shipping containers or tarpaulins: 2872 ppm (or 4 g/m^3) PH_3 gas for 7 days. The minimum concentration after 7 days must be > 250 ppm (SAG, 2024) 5 g/m^3 aluminum phosphide (AlP) for 7 days at temperatures of >4.5 °C maintaining a minimum concentration of >400 ppm (SAG, 2024) 5 g/m^3 magnesium phosphide (MgP) for 7 days at temperatures of >6.2 °C maintaining a minimum concentration of >400 ppm (SAG, 2024) In-transit: 3600 ppm (or 5 g/m^3) PH_3 gas during transit for up to 5 days before arrival (SAG, 2024) 5 g/m^3 AlP at temperatures of >4.5 °C during transit for up to 5 days before arrival (SAG, 2024) 5 g/m^3 MgP at temperatures of >6.2 °C during transit for up to 5 days before arrival (SAG, 2024)
			Pinus ponderosa *Pinus sylvestris* *Pseudotzuga menziesii*	Active	2872 ppm (or 4 g/m^3) PH_3 gas for 7 days in a chamber, shipping container, or tarpaulin. The minimum concentration after 7 days must be > 250 ppm (SAG, 2024) 3600 ppm (or 5 g/m^3) PH_3 gas during transit for up to 5 days before arrival (SAG, 2024)
New Zealand	China	Logs	*Pinus radiata*	Active	3.5 g/m^3 for 10 days, maintaining a minimum concentration of >200 ppm (MPI, 2024a)
Uruguay	China	Logs	*Pinus* spp.	Not active	5 g/m^3 for 10 days, maintaining a minimum concentration of >200 ppm (MGAP, 2018)
All countries	Malaysia	Logs	All – no restrictions	Not active	5 g/m^3 for 5 days (DOA, 2014)
Chile	Bolivia	Sawn timber	*Pinus radiata* *Weinmannia trichosperma*	Active	10 g/m^3 for 7 days at ambient temperatures of >10 °C (SAG, 2024)
Ecuador	India	Sawn timber	*Tectona grandis*	Not renewed	3 g/m^3 for 7 days (MBTOC, 2018)[c]
All countries	Malaysia	Sawn timber	All – no restrictions	Not active	5 g/m^3 for 5 days (DOA, 2014)
Chile	Perú	Sawn timber	*Pinus radiata*	Active	2 g/m^3 for 3 days at ambient temperatures of >20 °C (SAG, 2024) 3 g/m^3 for 4 days at ambient temperature between 4 and 19 °C (SAG, 2024)
Chile	Perú	Sawn timber	*Eucalyptus globulus* *Eucalyptus nitens* *Eucalyptus regnans*	Active	5 g/m^3 for 4 days at ambient temperatures between 15.6 and 20 °C (SAG, 2024) 5 g/m^3 for 5 days at ambient temperatures between 12.2 and 15 °C (SAG, 2024) 5 g/m^3 for 10 days at ambient temperatures between 4.4 and 11.7 °C (SAG, 2024)
Uruguay	Vietnam	Sawn timber	*Pinus* spp.	Not active	5 g/m^3 for 6 days, or 3600 ppm/m^3 (5 g/m^3) for 5 days - Horn Diluphos System (HDS)
Chile	Bolivia	Rods	*Salix viminalis*	Active	3 g/m^3 for 5 days at ambient temperatures of >10 °C (SAG, 2024)
Chile	México	Rods	*Salix viminalis* *Chusquea culeou*	Active	1.16 g/m^3 for 2 days at ambient temperatures of >21 °C (SAG, 2024)
Chile	Perú	Rods	*Chusquea culeou*	Active	5 g/m^3 for 3 days at ambient temperatures of >21 °C (SAG, 2024) 5 g/m^3 for 4 days at ambient temperatures between 16 and 20 °C (SAG, 2024) 5 g/m^3 for 5 days at ambient temperatures between 11 and 15 °C (SAG, 2024) 5 g/m^3 for 10 days at ambient temperatures between 5 and 10 °C (SAG, 2024)
Chile	Venezuela	Rods	*Salix viminalis*	Active	3 g/m^3 for 5 days at ambient temperatures of >10 °C (SAG, 2024)
All countries	New Zealand	Wooden items	All – no restrictions	Not active	>200 ppm for 9 days at ambient temperatures between 21 and 25 °C (MPI, 2024b) >200 ppm for 12 days at ambient temperatures between 16 and 20 °C (MPI, 2024b) >200 ppm for 15 days at ambient temperatures between 10 and 15 °C (MPI, 2024b)
United States of America	China	Wood chips	*Abies* spp. *Picea* spp. *Pinus* spp. *Pseudotsuga* spp.	Not active	4 g/m^3[d] for 3 days at ambient temperatures of >20 °C[e] (USDA, 2024) 4 g/m^3[d] for 4 days at ambient temperatures between 15.6 and 20 °C[e] (USDA, 2024) 4 g/m^3[d] for 5 days at ambient temperatures between 12.2 and 15 °C[e] (USDA, 2024) 4 g/m^3[d] for 10 days at ambient temperatures between 4.4 and 11.7 °C[e] (USDA, 2024)
All countries	Malaysia	Wood chips	All – no restrictions	Not active	5 g/m^3 for 5 days (DOA, 2014)
Canada	Turkey	Wood chips	Unknown	Not active	Unknown (IFQRG, 2023)
Australia	Unknown	Wood pellets	Unknown	Unknown	3 g/m^3 for an undefined period (APVMA, 2021)
Indonesia	Unknown	Wood chips	Unknown	Unknown	Unknown (MBTOC, 2014; Tumambing and Dikin, 2013)
All countries	New Zealand	Wood packaging material	All – no restrictions	Rescinded	Unknown (DAFF, 2024a; MPI, 2023, 2024b)
All countries	Samoa	Wood packaging material	All – no restrictions	Rescinded	1.41 g/m^3 for 3 days at a minimum ambient temperature of 10 °C and maximum of 30 °C. Filleted to 300 mm maximum (DAFF, 2024a)
All countries	United States of America	Wood packaging material	All – no restrictions	Rescinded	Unknown

[a] Status definitions: active – the treatment is currently regularly used; not active – the treatment is approved but not widely used; not renewed – the exporting country did not renew a prior approval; unknown – the status of the treatment could not be determined; rescinded – the treatment was previously approved but is no longer accepted by the importing country.
[b] Refer to supplementary material for more information (Table S3).
[c] This reference incorrectly stated that teak logs were exported from Ecuador to India. We confirmed with the Ecuadorian NPPO that this approval was for sawn timber only.
[d] Values converted from 115 tables per 1000 ft^3 to g/m^3.
[e] Values converted from °F to °C.

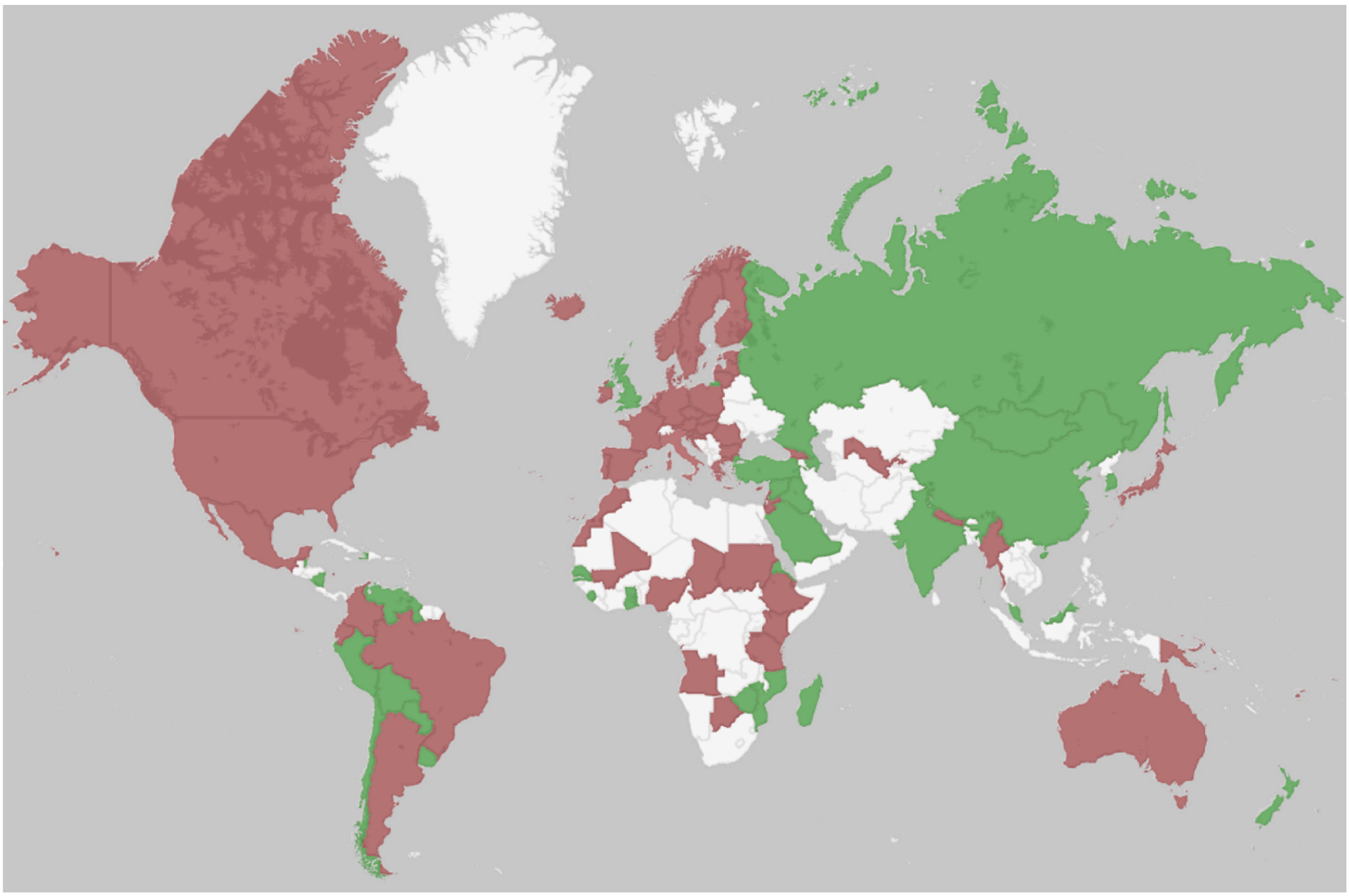

Fig. 1. Summary of countries that currently accept phosphine (PH_3) fumigation as a phytosanitary treatment of imported wood products (green shading) and countries that do not accept PH_3 for this use pattern (red shading). The status of PH_3's approval in unshaded countries is currently unknown. Refer to supplementary material for more information (Table S3).

(Page, 2011), with a significant enhancement observed when CO_2 levels exceed 20 % (Tumambing, 2007). However, this response needs validation across a range of wood pests, as CO_2 concentrations above 35 % can have a narcotic effect on insects, reducing respiration and gas uptake (Ren et al., 1994). CO_2 facilitates PH_3 penetration and distribution of the gas in fumigated substrates (Leesch, 1992). Successful trials have demonstrated that combining PH_3 with CO_2 improves pest control. For instance, PH_3 with 94 % CO_2 at normal atmospheric pressure for 120 h achieved 100 % mortality of fig moth and fig mite (Şen et al., 2009). ECO2FUME® has proven effective against all life stages of numerous stored-product insects at 26.7 °C (Hartsell et al., 2005). Certain fumigant combinations can enhance treatment efficacy compared to single fumigants. For example, a mix of 2 g/m^3 PH_3 and 50 g/m^3 SF for 48 h at 15 °C resulted in 100 % mortality of the egg stage of various pest species, including *Callidiellum rufipenne* (eggs on paper), *Monochamus alternatus* (eggs under bark), *Cryphalus fulvus* (eggs under bark), *Ips cembrae* (eggs under bark), *Phloeosinu perlatus* (eggs under bark), *Pissodes nitidus* (eggs under bark), *Semanotus japonicus* (eggs), *Xyleborus validus* (all stages in xylem), and *Scolytoplatypus tycon* (all stages in xylem) (Soma et al., 1999). Thus, mixed gas fumigation with PH_3 and SF could be an alternative to MB for log and timber disinfection.

A unique feature of PH_3 is its dependency on O_2 within the treated space for effective uptake by insect pests (Chefurka et al., 1976). Increasing O_2 levels to >40 % during PH_3 application enhances pest respiration and gas uptake, which can dramatically increase efficacy compared to ambient O_2 levels (Liu, 2011; 21 %) or O_2 levels modified by respiring logs during treatment (Adlam et al., 2018; Feng et al., 2015; Hall et al., 2016a, 2016b; Devitt et al., 2020). For fumigation temperatures below 15 °C, heating is essential to ensure effectiveness unless efficacy data supports PH_3 use at lower temperatures. Heating the treatment space and mechanically circulating the fumigant/air mixture should be mandatory practices for larger treatment volumes (>100 m^3) to ensure success (DAFF, 2023; ICCBA, 2018; USDA-APHIS, 2016).

When PH_3 is produced from solid metal phosphides, it may take up to 24 h to reach target concentrations (Rajendran and Kumar, 2008; Remadevi and Deepthi, 2018). Cylindered gas formulations address this issue by allowing rapid, precise dosage application, eliminating the risk of spontaneous flammability, ensuring better distribution, and enabling controlled flow for extended periods (Ryan and De Lima, 2013). Application methods influence PH_3 effectiveness. The multi-layer application of phosphide tablets in log stacks provides more uniform and faster gas distribution than surface application (Remadevi and Deepthi, 2018). Currently, AlP is applied only at two locations within ship holds (hatch covers), with no heating or circulation to optimize outcomes. Gas monitoring is typically limited to areas near AlP blankets, with no comprehensive monitoring of PH_3 concentrations throughout the hold (Adlam et al., 2018; Hall et al., 2016a, 2016b). Challenges in treating freshly harvested logs with high MC could be mitigated by drying logs for 4–6 weeks at suitable temperatures before fumigation (Feng et al., 2015).

4. Future prospects and recommendations

Although we have shown that the scientific evidence to support the use of PH_3 as a broad-spectrum treatment of wood products is non-existent, the evaluation was understandable, given the urgent need to find alternatives to MB and the various benefits offered by PH_3. The PH_3 efficacy dataset does not currently provide the statistical confidence required by modern quarantine standards for any insect, pathogen, or nematode species (Tables S1 and S2). Therefore, future research should provide scientific evidence of the effectiveness of PH_3 against a specific pest or pest groups. This specificity is necessary because the PH_3 efficacy data for grain pests cannot be used to support the efficaciousness of this fumigant against forest pests since pest families, MC, sorption rates, and respiration rates of materials can differ. If efficacy data for stored product pests were to support the use of PH_3 as a treatment for forestry pests, caution should be exercised when extrapolating this information.

New efficacy research should adopt a methodical approach similar to that outlined by Najar-Rodriguez et al. (2020a,b). This involves evaluating a range of pests under small-scale laboratory conditions, followed by assessing the most PH_3-tolerant species and life stages under large-scale commercial conditions. This process should include appropriate insect numbers and replication to ensure statistical confidence in the effectiveness of the PH_3 treatment schedule.

Based on available information, the best chances for successful PH_3 fumigations of wood products rely on conducting fumigations at temperatures above 15 °C, preferably exceeding 25 °C, to facilitate PH_3 gas generation from AlP and ensure effective diffusion throughout the treated space. Maintaining the treated space at temperatures above 15 °C requires appropriate heating sources. Mg_3P_2 or pure PH_3 gas, offers advantages over AlP, particularly in colder climates like New Zealand and Uruguay (Figs. S1 and S2). Re-circulating the fumigant/air mixture during the fumigation period is essential, especially for larger treatment volumes exceeding 100 m^3 (DAFF, 2023; ICCBA, 2018; USDA-APHIS, 2016), as is standard practice with other fumigants. Recently harvested logs respire during the 10-day fumigation period, depleting O_2 and generating CO_2, which reduces PH_3 efficacy. Maintaining O_2 concentrations above a defined threshold (yet to be determined by research) ensures optimal results.

This research approach should target specific insect pests in wood products, such as sawn timber, plywood, and wood chips from countries free of the PWN. Developing PH_3 treatment schedules for surface pests of low-MC wood products should focus on utilizing PH_3 as a standalone treatment or in combination with supplementary measures, such as other fumigants (i.e., SF) or gases (i.e., O_2), to enhance efficacy and address specific pest control challenges. Significant challenges associated with treating high-MC logs suggest limited potential for pursuing PH_3 research as an alternative to MB for this type of wood product.

CRediT authorship contribution statement

Matthew K.D. Hall: Writing – review & editing, Writing – original draft, Conceptualization. **Laura M. Machuca-Mesa:** Writing – review & editing, Writing – original draft, Conceptualization. **Adnan Uzunovic:** Writing – review & editing, Writing – original draft, Conceptualization. **Sunil K. Yadav:** Writing – review & editing, Writing – original draft, Conceptualization. **Dongwoon Lee:** Writing – review & editing, Writing – original draft, Conceptualization. **Manoj K. Nayak:** Writing – review & editing, Writing – original draft, Conceptualization.

Compliance with ethical standards

Conflict of Interest All authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent The article does not contain any studies with human or animal subjects performed by any of the authors.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matthew Hall is employed by Draslovka Agricultural Solutions Pty Ltd (Australia), a company owned by Draslovka s.a. (Czech Republic), which manufactures fumigants, including ethanedinitrile (EDN™) and hydrogen cyanide (BLUEFUME™). Draslovka s.a. owns a group of service companies, the Intreso Group (Belgium, the Netherlands, and Slovenia), where all commonly used fumigants, including phosphine (PH_3), are routinely used to disinfest materials. It is the authors' opinion that this perceived competing interest has had no impact on this review. All other authors declare no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jspr.2025.102672.

Data availability

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

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