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REVIEW ARTICLE

Control and management of *Phytophthora* damage in forestry—A systematic mapping study

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Abstract

Plant pathogens in the genus *Phytophthora* are a severe threat to forest plantations, ecosystems and tree nurseries. Especially in forests and natural ecosystems, there is a lack of effective measures to control and manage these pathogens. In this study, we conducted a systematic mapping review to collate evidence regarding the control and management of forest *Phytophthora* in different production settings and ecosystems. The study aimed to reveal possible knowledge gaps, thus guiding future research priorities. We extracted information from nine databases, limiting the search to studies published during the time period from January 2010 to December 2022. The articles were shared between three reviewers who classified the reports using a set of inclusion/exclusion criteria. A total of 561 articles were included and mapped in a database using pre-defined coding, and critically appraised for relevance and reliability. The analysis showed that biological or bio-based measures were the most studied interventions, followed by genetics or breeding programmes, whereas chemical and silvicultural management approaches were less studied. Most of the studies were conducted in Europe, North America, Australia and New Zealand. *Phytophthora cinnamomi* has been the most studied species followed by *P. ramorum*. We discuss the current knowledge gaps in the implementation of existing research, likely due to a lack of holistic understanding of the processes over time and space, and suggest future research that is needed to manage *Phytophthora* in forest ecosystems.

KEYWORDS
biocontrol mechanisms, breeding programs, control strategies, oomycetes, pesticides, *Phytophthora* damage

1 | INTRODUCTION

Throughout the world, pathogens in the genus *Phytophthora* (Oomycetes) cause significant yield losses in tree nurseries, natural forests and plantations (Benavent-Celma et al., 2022; Hansen, 2015; Jung et al., 2018; Shamoun et al., 2018). Moreover, these species have been linked to mortality and reduced stability of trees and forests in urban and peri-urban settings (Hansen, 2015; Hayden, Garbelotto, et al., 2013; Jung et al., 2018) and conservation areas (Hansen, 2015; Jung et al., 2018; Štraus et al., 2023). Trees can get infected at any age, with infections leading to the expression of diverse symptoms, such as root and collar rot, necrotic cankers and fine root deterioration, leaf chlorosis and necrosis, crown transparency, bleeding bark cankers and plant death, depending on the specific pathogen and host involved (Erwin & Ribeiro, 1996; Jung et al., 2018). However, infections can also be asymptomatic, especially in young plants, which complicates the detection of *Phytophthora* in plants for planting (Brasier, 2008; Jung et al., 2016, 2018). Trade in living plants and plant products has been identified as the main pathway for the introduction of newly recognized pathogens, and asymptomatic plant transportation can easily escape controls at borders and custom inspections (Benavent-Celma et al., 2022; Brasier, 2008; Jung et al., 2018; Scott, Burgess, & Hardy, 2013; Shamoun et al., 2018). Once established in nature, *Phytophthora* species may become invasive and have major ecological and economic consequences, as is evident from *Phytophthora* introductions that have devastated forests in the United Kingdom, Australia and the United States (Garbelotto et al., 2001; Hee et al., 2013; King et al., 2015; Pérez-Sierra et al., 2022, 2024). In Europe, nursery surveys have detected widespread and almost ubiquitous infestations with more than 20 *Phytophthora* species in field- and container-grown nursery stock of forest trees, ornamental plants and irrigation systems (Jung et al., 2016), further illustrating the extent of the problem.

The lifecycle of *Phytophthora* species makes the control and management of these pathogens highly challenging. The motile zoospores enable rapid infection of new host plants and dormant resting structures (chlamydospores, hyphal aggregations and oospores) allow them to survive unfavourable environmental conditions over long periods (Erwin & Ribeiro, 1996; Judelson & Blanco, 2005; Jung et al., 2018; McCarren et al., 2005). As oomycetes, *Phytophthora* species exhibit resistance to fungicides, especially those designed to target fungal physiology and impact cell structures. This resistance is due to fundamental differences in physiology and biochemistry between oomycetes and fungi (Adomako et al., 2017; Hu et al., 2008; Olson & Benson, 2013), which adds to the difficulty in managing these pathogens in plant production systems. Potential management options include silvicultural measures (Daniels et al., 2022; Goheen et al., 2017; Hansen et al., 2019), chemical treatments (Garbelotto et al., 2009; Hansen et al., 2019; Hardy et al., 2001; Silva et al., 2016), biological or bio-based methods and deployment of genetic resistance genes or resistance breeding (Hayden, Garbelotto, et al., 2013; Jung et al., 2018; Santos et al., 2015). Research evidence showing the applicability and efficiency of these measures has accumulated over several decades, but it comes from different hosts and *Phytophthora* species interactions, experimental settings and continents. A systematic overview of these studies will help in making recommendations for best practices in different situations and identify the possible research gaps where experimental evidence is missing.

Systematic mapping is an evidence collation method that has recently emerged in environmental sciences (James et al., 2016). Systematic mapping (scoping) studies aim to outline the research area by searching, classifying and tallying the available literature on a topic, resulting in an inventory of publications that cover the different categories related to the topic (Petersen et al., 2015). A mapping inventory enables the discovery of research trends, biases and gaps, providing valuable information for a systematic review. The goal and approach of systematic mapping differ from a systematic review: unlike a systematic review, systematic mapping does not attempt to answer specific research questions by evaluating the evidence but instead collates, describes and catalogues available evidence (e.g. primary, secondary, theoretical and economic), aiming at revealing the structure of the research related to the topic or question of interest (James et al., 2016). Importantly, a mapping approach does not necessarily include a quality assessment (Petersen et al., 2015). The method is particularly suitable in cases where systematic review is challenging, for example, due to the heterogeneous quality of the available papers, due to quantitative and qualitative research, and different methodologies and outcomes (James et al., 2016). Here, we used a systematic mapping approach to collate evidence regarding the management of forest Phytophthoras across diverse production settings and ecosystems, including forest nurseries, production forests and natural ecosystems. Our study addressed two questions:

1. Which control or management measures, used in forests and nurseries, have been most thoroughly addressed in original research studies, and which require more investigation?
2. Is the research biased towards specific regions, environments (nursery, plantation, natural forests) or species (host tree and *Phytophthora* species)?

The study aimed to reveal knowledge gaps, providing insights into potential future research priorities.

2 | METHODS

2.1 | Information sources and literature search

We followed the Collaboration for Environmental Evidence guidelines and Standards for Evidence Synthesis in Environmental Management (Version 5.1) (Pullin et al., 2023) to make the process more reliable when setting up the eligibility criteria. These included the PICO framework structure of the review question, details on PICO key elements (Problem or Population, Intervention, Comparison, control or comparator, and Outcomes), as well as formulating the general questions addressed to compile the systematic map report. We used the following databases to find relevant articles: Web of Science Core Collection, BIOSIS Citation Index, CABI CAB Abstracts, Current Contents Connect, Data Citation Index, KCI Korean Journal Database, MEDLINE (gateway.ovid.com), Russian Science Citation Index and SciELO Citation Index. Search results were limited to studies published between January 2010 and December 2022, aiming to focus on recent developments in research that display the latest changes in forest management priorities and legislation up to 2022. This decision aligns with guidance on setting limits in literature searches to ensure focused and timely reviews (Cooper et al., 2018; Helbach et al., 2022). Searches were conducted in March 2023, and the search language was set as Auto.

2.2 | Search strategy and selection process

We included search terms for environments (forest settings), pathogens (*Phytophthora* species), measures (chemical, biological, breeding/genetics, silvicultural) and outcomes (symptoms, disease damage, susceptibility, resistance) in the searches, aiming to obtain a search that is comprehensive enough to adequately cover the topic of interest. The search strings were composed as ((forest*) AND (tree* OR seedling*) AND (*Phytophthora*) AND (manage* OR control* OR measure* OR intervention*) AND (silvicultur* OR chemical* OR natural OR biological OR bio-based OR phosph* OR breeding) AND (symptom* OR disease* OR damage OR susceptib* OR resistance OR protecti*)). The term 'Forest*', was selected to encompass different forest-related environments, including plantations, urban and peri-urban areas, and natural ecosystems. To ensure the inclusion of nurseries, terms like 'tree*' and 'seedling*' were also included in the search. The term '*Phytophthora*' was used to refer to all *Phytophthora* species in the search. Although not fully comprehensive, we believe that a representative collection of the published scientific literature covering management of forest *Phytophthora* in different production settings and ecosystems was captured.

2.3 | Eligibility criteria

To structure and focus the literature retrieval, we used the PICO framework (Schardt et al., 2007) where Population (P) = forest (tree(s) or seedling(s)) and *Phytophthora*; Intervention (I) = management/control, measure(s) or intervention(s): silviculture/silvicultural, chemical(s), natural, phosphite, biological/bio-based, genetic (resistance) or breeding; Comparator (C) = no interventions or variation in them; and Outcomes (O) = symptom(s), disease, damage, susceptible/susceptibility, resistant/resistance or protection/protective.

We defined three inclusion criteria: (1) *Phytophthora* management studies/trials, (2) relevance for forest ecosystems or forestry and (3) inclusion of settings such as forest settings, nurseries, experimental orchards, greenhouses and laboratory facilities. Articles failing to meet at least the first two of the three criteria were excluded. Articles were excluded if they met any of the following exclusion criteria: (1) published in a language other than English; (2) not focused on forest *Phytophthora* management or control measures or (3) not dealing with seedlings, trees or shrubs.

2.4 | Data extraction

Data were collected and extracted by a team of three independent reviewers, and the information was organized in a common file according to 12 coding variables. The results of the literature search, motivations for rejections and the categorization of the studies included are presented as Table S1.

2.5 | Data analysis

We conducted descriptive analyses to summarize characteristics of the studies used in the analyses, including geographic distribution, type of management or control measures executed, study settings or facilities and *Phytophthora* species evaluated. Analyses were performed in R environment v. 4.3.1 (R Core Team, 2022) by grouping studies by outcome categories and examining characteristics of the studies mentioned above. Visualization of the data was done using the ggplot2 package v. 3.4.1 (Wickham et al., 2023).

3 | RESULTS

In total, 561 references passed the initial filtering process. After removing duplicates and papers that did not meet the criteria, a total of 126 papers were included in the final analysis (Dataset S2). The selection of studies is summarized in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram in Figure 1.

3.1 | Distribution of publications across the intervention categories

The most thoroughly addressed management or control measures in original research studies between 2010 and 2022 focused on biological or bio-based measures (32.5%) followed by genetics or breeding programmes (27.8%), chemical control (27%) and finally silvicultural approaches (5.5%). Only a few of the selected studies (7.2%) used more than one approach, for example, a combination of biological or chemical methods with silviculture (Figure 2).

3.2 | Biological or bio-based measures

The studies focusing on biological or bio-based measures discussed approaches such as the use of plant extracts that can enhance host defence responses and tolerance to *Phytophthora* species (Hao et al., 2012) or secondary metabolites produced by the host plant during interactions with endophytic fungi, bacteria or mycoviruses (i.e. viruses that infect fungi) (Lackus et al., 2018; Macías-Rubalcava et al., 2010). These interactions can also initiate the release of volatile compounds and elicitins, which trigger host defence responses and can promote resistance to *Phytophthora* species (Medeira et al., 2012; Poimala et al., 2022; Tellenbach et al., 2013; Xie et al., 2015). Other studies tested the antimicrobial activity of bacterial and fungal extracts against *Phytophthora* species (Lawrence et al., 2019; Lefort et al., 2013;

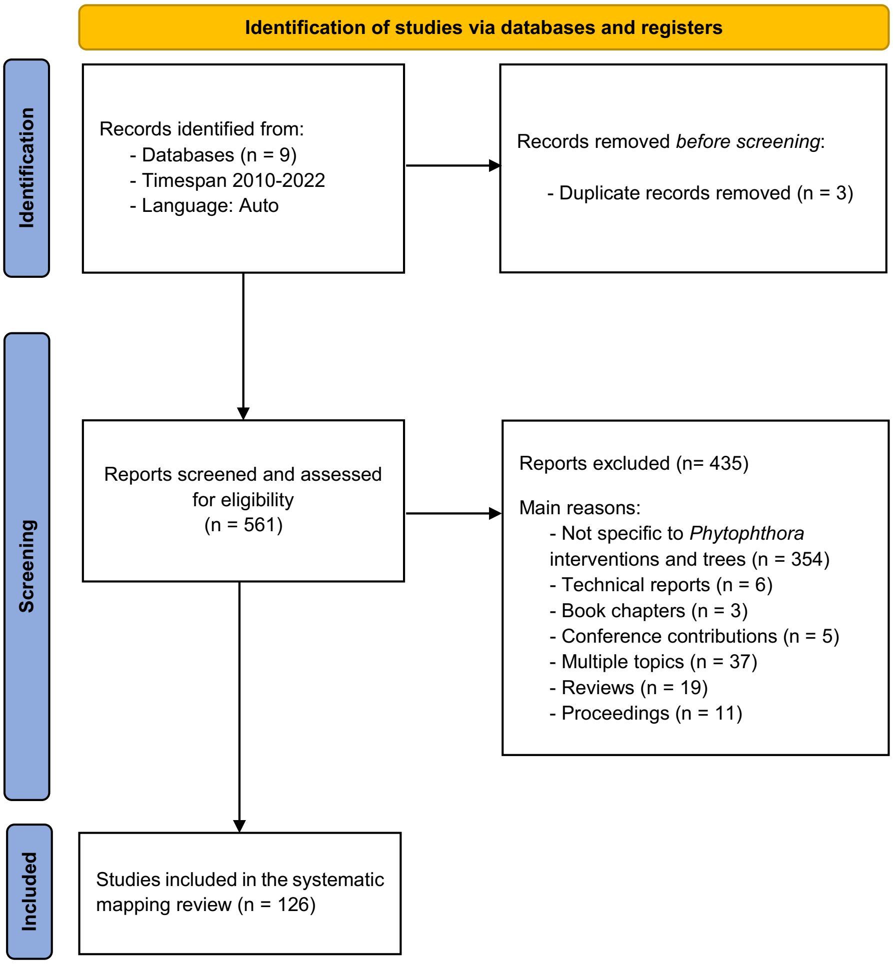

FIGURE 1 PRISMA flow diagram of the study (based on Page et al., 2021).

Masi et al., 2016; Mondol et al., 2016). Finally, some of the articles included the application of bio-fertilizers to reduce plant vulnerability to *Phytophthora* species (López-Sánchez et al., 2022) and bio-fumigation to control vegetative and reproductive structures (Morales-Rodríguez et al., 2016; Ríos et al., 2016, 2017). Specifically, these studies described measures such as inhibition of mycelial growth or sporangia and gametangium (oogonium and antheridia) formation and reducing the motility of zoospores and their germination rate.

3.3 | Genetic or breeding measures

Another common topic was the genetic basis of resistance and plant defence mechanisms against *Phytophthora* (Figure 2). Several of these studies focused on the evaluation and comparison of mechanisms of susceptibility and resistance to *Phytophthora* infections in host trees. To assess these mechanisms, many experiments used an approach based on plant screening by inoculation aiming to identify and select resistant individuals within susceptible taxa. In some cases, genes encoding certain antifungal proteins were introduced to boost resistance (Abraham et al., 2013). For example, the *Raphanus sativus*-antifungal protein 2 (Rs-AFP2) was introduced into *Eucalyptus urophylla* aiming to enhance resistance to *Phytophthora capsici* (Ouyang et al., 2012). Other screening programmes were focused on selecting plants that were most likely to produce active secondary compounds with an anti-*Phytophthora* activity (e.g. Lawrence et al., 2019).

3.4 | Chemical measures

In studies on the use of chemical management approaches, the primary focus was on the evaluation and comparison of direct activities, and effectiveness (Romero et al., 2019) (Horner et al., 2015; Miyake & Nagai, 2017) of agrochemicals to suppress or slow down the development of the disease. The aspects examined included uptake of products (Rolando et al., 2017), phytotoxicity (Horner et al., 2015; Scott et al., 2016; Scott, Dell, et al., 2013), resistance of pathogen species to fungicides (Silva et al., 2016), inhibition of mycelial growth (González et al., 2017; Miyake & Nagai, 2017; Singh et al., 2010), effect on sporangia and oospore formation (Miyake & Nagai, 2017; Serrano et al., 2011) or zoospore germination (Miyake & Nagai, 2017). Whilst studies focusing on tree treatments investigated the efficacy of chemicals to reduce disease incidence and severity (Reglinski et al., 2010), measured as

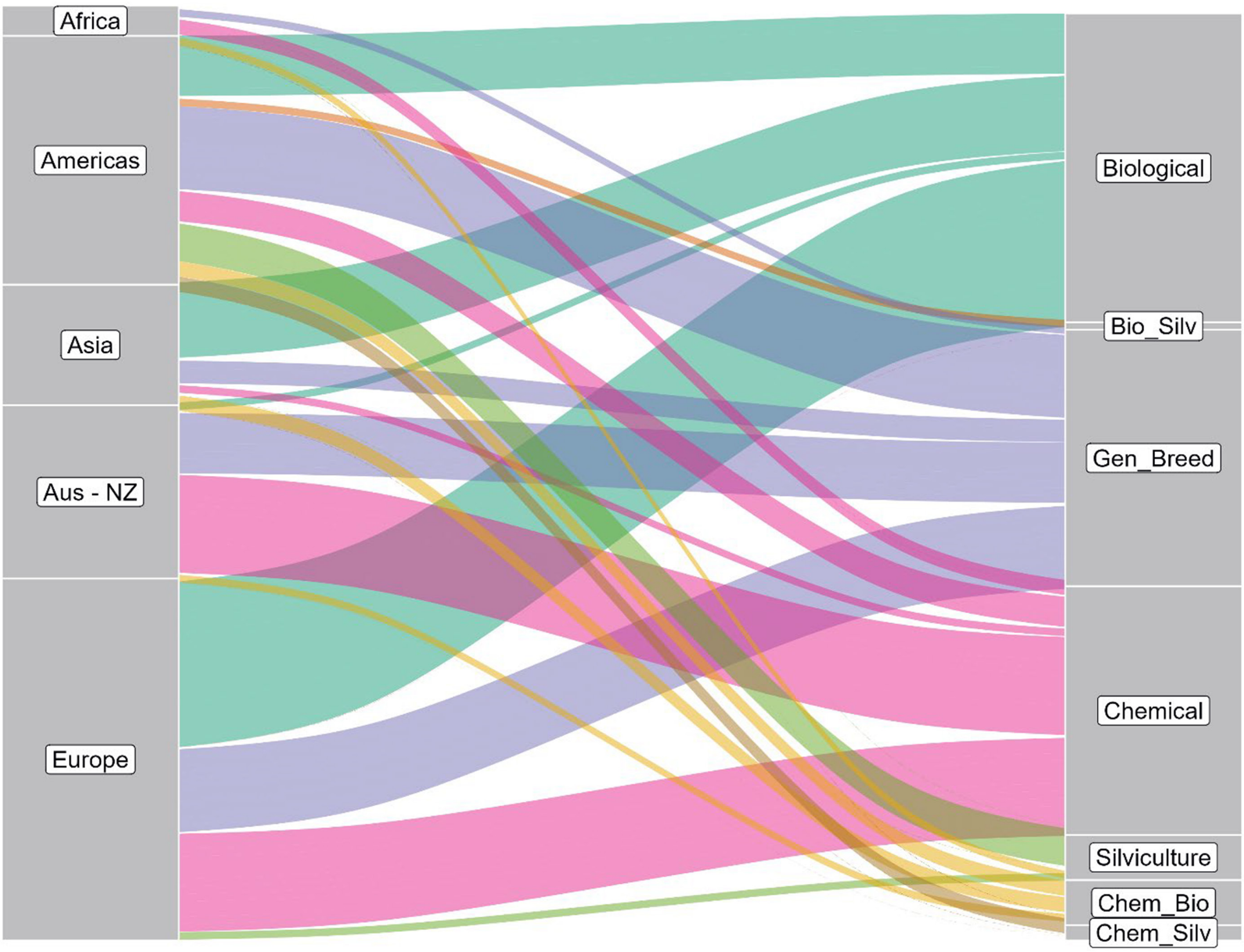

FIGURE 2 The most assessed approaches by geographic distribution are included in the systematic mapping review. Aus – NZ, Australia & New Zealand; Bio_Silv, Biological and Silvicultural; Chem_Bio, Chemical and Biological; Chem_Silv, Chemical and Silvicultural; Gen_Breed, Genetics & Breeding.

the degree of damage (Swiecki & Bernhardt, 2017), root density and infection rates (Oszako et al., 2018), canopy health scores (Horner et al., 2015), *damping-off* severity (Januszek et al., 2014), lesion activity, progression and length (Rolando et al., 2014; Scott et al., 2016), host mortality rates (Stasikowski et al., 2014; Swiecki & Bernhardt, 2017), defence responses and disease progress after treatments (Hansen et al., 2019; Horner et al., 2015; Romero et al., 2019).

Overall, systemic fungicides such as metalaxyl, fosetyl-Al and potassium phosphite were the most frequently utilized, constituting 60% of the included studies, probably because systemic action enables translocation of active ingredients throughout the plant, ensuring effective movement to all host tissues. When applied at low concentrations, some systemic fungicides may activate defence responses (Hardy et al., 2001), making these products highly cost-effective. Tables comprising the most commonly studied chemical products and inorganic amendments have been listed in Appendices 1 and 2.

3.5 | Silvicultural measures

The silvicultural approaches addressed in the analysed publications included strategies such as containment measures to mitigate the chances of spread by limiting access to forests or natural environments and the establishment of quarantine areas (Daniels et al., 2022; Goheen et al., 2017; Valachovic et al., 2017). Early detection methods, encompassing aerial and ground surveys, as well as stream baitings were carried out (Goheen et al., 2017; Kanaskie et al., 2011). Demarcation of infested areas, and eradication treatments involving herbicide applications, uprooting, clear-cutting and burning were also included (Goheen et al., 2017; Swiecki & Bernhardt, 2017). Additionally, the establishment of buffer areas beyond the disease front was recommended, with the removal of host plants in areas where disease spread was likely (Goheen et al., 2017; O'Hanlon et al., 2018; Valachovic et al., 2017). Research and continuous monitoring were also emphasized as crucial components of these comprehensive management strategies (Goheen et al., 2017;

Kanaskie et al., 2011; O'Hanlon et al., 2018; Valachovic et al., 2017). Most of the analysed silvicultural measures aimed to control *P. ramorum*, *P. cinnamomi* or *P. cactorum*.

Under nursery conditions, root pruning has been tested to control *P. cactorum* infection of *Quercus robur* seedlings (Łakomy et al., 2019). Measures studied to control the spread of *P. ramorum* have included physical removal of hosts, herbicide applications, with cutting and burning of hosts within a buffer area of 100 m of a known disease outbreak (Goheen et al., 2017; Valachovic et al., 2017), and monitoring using baitings (i.e. a laboratory technique which consists of soil sample submerged in water with pieces of the bait (tree leaves) floated on the water surface) and, more recently, high resolution digital aerial imagery. Post-treatment monitoring conducted over several years has revealed that, despite elimination of the pathogen from initially affected sites, the spread could continue (Daniels et al., 2022; Goheen et al., 2017; Hansen et al., 2019; Valachovic et al., 2017).

3.6 | Geographic bias among the published studies

Most of the captured studies were carried out in Europe (38.9%), followed by both Americas (26.19%), Australia and New Zealand (19.04%), Asia (12.7%) and Africa (3.17%). The majority of the studies addressing biological or bio-based measures were carried out in Europe (22 studies); chemical treatments were mainly studied in Australia and New Zealand (14 studies) and Europe (13 studies); genetics and breeding in Europe (11 studies) and the Americas (11 studies). While the few studies on silvicultural practices for the control and management of *Phytophthora* were carried out in the Americas (8 studies) and Europe (2 studies).

3.7 | Study environments

The studies selected for this review were carried out in laboratory facilities (31 articles), greenhouses (14 articles), forest nurseries (9 articles), and in the field (19 articles). A total of 53 of the included experiments were accomplished by a combination of two or more facilities such as laboratory and greenhouse or laboratory, greenhouse and field.

3.8 | *Phytophthora* and host tree species or genera in the included studies

The publications included in this work covered a total of 32 *Phytophthora* species. The most commonly studied pathogen species was *P. cinnamomi*, followed by *P. ramorum*, *P. palmivora* and *P. cactorum* (Table 1). Other species were included in fewer than 6% of studies (Table 1).

TABLE 1 Number and percentage of studies on the most representative *Phytophthora* species included in the systematic mapping review.

Phytophthora species	No. studies	Percentage (%)
Phytophthora cinnamomi	56	44.4
Phytophthora ramorum	17	13.5
Phytophthora cactorum; *Phytophthora palmivora*	10	7.9
Phytophthora pluvialis	8	6.3
Phytophthora plurivora	7	5.5
Phytophthora alni; *Phytophthora capsici*; Multiple species	5	4
Phytophthora agathidicida; *Phytophthora parasitica*; *Phytophthora* x *cambivora*	4	3.2

The most common host species of *P. cinnamomi* included in the articles were in the genus *Quercus*, followed by *Eucalyptus* spp., *Banksia* spp., *Castanea* spp. and gymnosperms such as *Agathis australis* (kauri). The host species of *P. ramorum* were most commonly trees in the genus *Notholicarpus*, followed by *Umbellularia californica*, *Quercus agrifolia*, *Quercus kelloggii*, *Rhododendron* spp. and conifers such as *Larix kaempferi*. The host species of *P. palmivora* were most commonly trees in the genus *Hevea*, followed by *Durio* spp., *Ficus* spp., *Acer* spp., *Olea* spp. and conifers such as *Tsuga heterophylla*. The host species of *P. cactorum*, were most commonly trees in the genus *Quercus*, followed by *Fagus sylvatica*, *Acer* spp., *Populus* spp. and conifers such as *Pinus sylvestris*, *Picea abies*, *Abies fraseri* and *Pinus radiata*.

4 | DISCUSSION

The systematic mapping indicated that the most thoroughly studied control or management methods against *Phytophthora* species in forestry settings over the last 12 years have been biological or bio-based measures. The studied solutions include use of bacteria or fungi as biocontrol agents against different *Phytophthora* species, and employing different modes of action (e.g. induction of plant defences, antibiosis or competition). Fungi from the genus *Trichoderma* spp. are considered strong candidates for future integrated pest management (IPM) strategies (Lefort et al., 2013; Oszako et al., 2019; Ruiz-Gómez et al., 2019; Ruiz-Gómez & Miguel-Rojas, 2021). Nevertheless, current research on interactions between beneficial microorganisms and host species is insufficient for evaluating the effectiveness and feasibility of implementing biological control measures in *Phytophthora*-affected forest settings. The majority of the studies selected were conducted in laboratory and greenhouse settings, and rarely in field conditions. Cabrera-Puerto et al. (2023) and Fuller et al. (2023) highlighted the need for additional research to determine effective methods for the use of biological control agents in forest settings and to understand the potential implications, whether positive or negative, of these agents on non-target microbial species in forest ecosystems. More research is needed to, for example, understand the influence of genetic variability within the species on responses to *Trichoderma* spp. and bacterial colonization. There is also a need for more research to clarify the mechanisms of induced plant resistance, including studies at the physiological, biochemical and genetic levels to explain this phenomenon. A comprehensive understanding of how microbial biocontrol agents interact with their host and other microbes at the cellular and molecular levels will facilitate the screening of effective and eco-friendly bioagents (Giachero et al., 2022; Siah et al., 2018; Zehra et al., 2021). An improved understanding of the behaviour of microorganisms in their natural habitat would also improve assessments of environmental and human health risks. Future studies should also assess the long-term sustainability of biocontrol approaches.

We found that a considerable share of research has focused on the genetics of *Phytophthora* resistance in a broad array of economically and ecologically important broadleaf and conifer species (e.g. *Quercus* spp., *Castanea* spp., *Eucalyptus* spp., *Banksia* spp., *Fagus* spp., *Notholicarpus* spp., *Agathis australis*, *Pinus* spp., *Picea abies*, *Abies fraseri*), and the results from these studies should provide good support for resistance breeding programs. The introduction of more resistant tree genotypes is a promising avenue to control *Phytophthora* diseases in planted forests (Miranda-Fontaíña et al., 2007; Santos et al., 2015; Stukely et al., 2007). For example, seedling progeny resistant to *P. lateralis* in the conifer species *Chamaecyparis lawsoniana* (Port-Orford-cedar) have been effectively deployed for restoration and reforestation in the Pacific Northwest region of the United States (Sniezko et al., 2020; Sniezko & Dana Nelson, 2022). Further, Santos et al. (2017) and Zhebentyayeva et al. (2019) developed the first interspecific genetic map for chestnuts, enabling the identification of Quantitative Trait Loci (QTL) for *P. cinnamomi* resistance. These studies provide valuable genomic resources for enhancing resistance in chestnuts. Recent investigations utilizing proteomics techniques have identified disease-related genes in the *P. ramorum*-tanoak and *P. cinnamomi*-cork oak pathosystems (Coelho & Schütz, 2022; Hayden et al., 2014), serving as markers for early detection of host-pathogen interactions. Additionally, they provide valuable insights for subsequent experiments employing novel genome editing tools such as CRISPR-Cas (Koonin & Makarova, 2009), which can be used to target the active genes involved in the infection cycle, aiming to annotate and alter their function. Together with RNA interference (gene silencing) and nanotechnology, CRISPR-Cas hold promise for targeting disease-resistant genes or disrupting susceptible genes in forest settings to enhance resistance against *Phytophthora* species (Javed et al., 2021). CRISPR-Cas genome editing has been successfully used in a limited number of model *Phytophthora* species such as *P. sojae* (Fang et al., 2017; Fang & Tyler, 2016), *P. capsici* (Wang et al., 2018), *P. palmivora* (Gumtow et al., 2018) and *P. agathidicida* (Hayhurst, 2023), to investigate the roles of critical genes. Still, some technical limitations must be overcome, including the long time period needed to select tolerant and resistant tree families. Moreover, the genetic variation in pathogen populations complicates the selection of resistant host families (Eikemo et al., 2004).

A large proportion of the studies analysed here addressed the use of chemical treatments against *Phytophthora* diseases, most likely because the utilization of agrochemicals has proven to be effective even though legislation is shifting to more sustainable approaches (Booker, 2021; EU, 2019, 2023). Several of the studies focused on the application and assessment of potassium phosphite, used as an aerial foliar spray over large areas (Dalio et al., 2014; Hardy et al., 2001; Solla et al., 2021) or as trunk injections (Brandano et al., 2023; Horner et al., 2015; Horner & Hough, 2013; Solla et al., 2021). The use of phosphite treatments to suppress *Phytophthora* infections in forestry has in many cases been complicated by regulations, phosphites have been registered to markets either as fungicides, fertilizers or biostimulants, and for example in Spain, potassium phosphite products registered as fertilizers have been prohibited (González et al., 2017, 2020). The analysed studies also point out concerns regarding phytotoxicity when applied in higher doses (Horner et al., 2015; Manghi et al., 2021). Unlike phosphite, which stimulates plant defence against *Phytophthora* species, most fungicides can have persistent environmental effects. The selected literature revealed a trend of shifting from 'older' fungicides to other chemicals, such as cuprous oxide, metalaxyl-M and copper hydroxide, in combination with some *Trichoderma* spp., as well as the usage of inorganic amendments and Brassica-based biofumigation, seeking to innovate and adapt the chemical treatments to the current legislation (Agbeniyi et al., 2014; Fraser et al., 2022; Morales-Rodríguez et al., 2016; Ríos et al., 2017; Rolando et al., 2019; Serrano et al., 2011; Singh et al., 2010). Despite the associated risks (Benavent-Celma et al., 2022; Garbelotto et al., 2009; Hayden, Hardy, & Garbelotto, 2013; Horner et al., 2015; Manghi et al., 2021), these treatments have proven effective in controlling diseases caused by *Phytophthora*. Considering the newly imposed regulations, silicate-based mulch could prove to be a valuable alternative (Dann & Le, 2017). New fungicides such as ethaboxam, fluopicolide, mandipropamid and oxathiapiprolin have been proven effective in reducing *P. cinnamomi* in avocados (Belisle et al., 2019) and oxathiapiprolin was very effective against *P. agathidicida* in *Agathis* (Lacey et al., 2021). Moreover, Khdiar et al. (2023) identified calcium chelate as a potential product capable of triggering plant defence responses against plant pathogens, specifically *P. cinnamomi*. Likewise, the use of green pesticides, such as those based on the cinnamate anion and bioactive metabolites produced by fungi, have shown an inhibition rate comparable to certain fungicides against *Phytophthora* species, including *P. cinnamomi* and *P.* × *cambivora*, when applied in controlled chamber conditions (Bugatti et al., 2019; Evidente et al., 2011). Further, antifungal compounds of natural and synthetic origin, such as lipopeptides, sesquiterpenoids and two synthetic derivatives (diol and dicarboxylic acid) of polygodial, have demonstrated effectiveness in targeting multiple life stages of *Phytophthora* species (De Zoysa et al., 2023).

The paucity of research on silvicultural methods to control *Phytophthora* spread may be due to the inefficiency of these methods or the high financial costs involved (Goheen et al., 2017; Hoover & Bates, 2012). Studies of silvicultural methods generally demand long-term field studies, which is challenging when research is organized and funded in short projects. Further, it is plausible that the limited amount of research on silvicultural approaches reflects the exclusion of grey literature, such as Best Management Practices Handbooks, from our analysis. The compiled literature lacks specific studies on silvicultural management of *P. cinnamomi* in Western Australia. However, it is important to briefly mention that implemented strategies include physical removal or herbicide treatment of vegetation, fungicide application to surface and sub-surface areas, and the installation of physical barriers to prevent root-to-root spread (Hayden, Hardy, & Garbelotto, 2013; O'Brien & Hardy, 2014). These measures are considered effective for addressing localized infections that have the potential to spread and become more widespread (O'Brien & Hardy, 2014). While the silviculture utilized to control *P. ramorum* focused on reducing primary infection by limiting forest stand connectivity and treating or removing stumps during site preparation, secondary infection reduction was achieved through planting mixed species forests. Even though these silvicultural methods may be considered drastic, they have demonstrated efficacy in enhancing forest resilience to pathogens (Roberts et al., 2020). In the selected literature, silvicultural approaches were studied to develop effective long-term management strategies to contain *P. ramorum* spread in California and Oregon (Goheen et al., 2017; Hansen et al., 2019; Kanaskie et al., 2011). Complete eradication of the inoculum established in forests is known to be very difficult, but Daniels et al. (2022) confirmed the effectiveness of current treatments in reducing the inoculum in understory plants. The study indicated that while wildfire improved understory treatment, it did not lead to a reduction in infected tanoak trees. Nevertheless, eradication efforts have likely considerably slowed down the epidemic (Daniels et al., 2022). However, further research is needed to understand the potential impacts of the NA1 and EU1 lineages of *P. ramorum* and support appropriate control measures for future introductions of non-native pathogens (Daniels et al., 2022; Goheen et al., 2017; Hansen et al., 2019). In California, recent studies are focused on advancing forest disease and wildfire management goals. Quiroga et al. (2023) demonstrated that utilizing common forest fuels and disease prevention treatments effectively addressed numerous stand-level impacts of sudden oak death without causing significant loss of standing basal area. These results indicated that diverse treatment approaches in various disease contexts have resulted in changes in forest structure and host reduction.

In Ireland and the United Kingdom, O'Hanlon et al. (2018) demonstrated the effectiveness of eradication treatments applied to manage *P. ramorum* and continued surveillance, particularly since the initial discoveries in *Larix kaempferi* forests. Additionally, it emphasizes the importance of drawing lessons from the management program in Oregon and applying them to the situations in Ireland and the United Kingdom. More research is needed to address the long-distance dispersal of *P. ramorum* (Peterson et al., 2015), its ability to asymptomatically infect *L. kaempferi* (Harris & Webber, 2016), and challenges in isolating *P. ramorum* cultures from *L. kaempferi* material (O'Hanlon et al., 2018).

In France, eradication measures were implemented in *L. kaempferi* plantations to limit the spread of the epidemic. Continuous monitoring was conducted on native woody hosts within infected clear-cut larch stands and around seven ornamental nurseries that had previously experienced *P. ramorum* infections. After implementing eradication measures, the pathogen was only detected on rhododendrons and chestnut trees (*Castanea sativa* Mill.) near the outbreak areas, presenting the highest risk for the survival of *P. ramorum* in the region, particularly considering that chestnut trees represent 21%–25% of the forest (Beltran et al., 2024).

The selection of studies revealed a geographic bias in global research activities, with European and North American countries, together with New Zealand and Australia producing most of the research. While these biases may mainly reflect the generally high investments in research in these countries, they may also result from the compelling need to discover new solutions to increasing problems related to introduced and invasive *Phytophthora* species. These problems include sudden oak death caused by *P. ramorum* (Rizzo & Garbelotto, 2003), holm oak decline driven by *P. cinnamomi* (Brasier et al., 1993; Camilo-Alves et al., 2013; Frisullo et al., 2018), red needle cast of pine caused by *P. pluvialis* (Dick et al., 2014) and kauri dieback caused by *P. agathidicida* (Bradshaw et al., 2020). In parallel, the lower number of studies focusing on genetics and breeding programs in Asia may reflect the less urgent problems with *Phytophthora* damage in forests, although more research would be needed to test this hypothesis. Recent population studies indicate that some of the tree-pathogenic *Phytophthora* species, such as *P. cinnamomi* and *P. ramorum*, likely originated in East Asia (Jung et al., 2021; Shakya et al., 2021), suggesting that resistance may have developed in trees through co-evolution. Our research highlights also the lack of investigation into the effectiveness of control methods for *Phytophthora* species in Africa.

The fact that most of the selected studies were focused on *P. cinnamomi* and *P. ramorum* was not surprising, considering that these species are among the most harmful forest *Phytophthora* species (Kamoun et al., 2015) and in many countries, their control is demanded by phytosanitary regulations (DCCEEW, 2023; EU, 2016). While it is important to continue research on these species, new research should also be conducted on methods to control other known forest *Phytophthora* species with potential to influence global forests, such as *P. pluvialis* recently discovered in Europe (Pérez-Sierra et al., 2022; Pirronitto et al., 2024), and previously studied in New Zealand (Dick et al., 2014; Fraser et al., 2022; Gómez-Gallego et al., 2019) and in the Pacific Northwest of North America (Brar et al., 2018; Hansen et al., 2017; Reeser et al., 2013).

Our findings underscore a gap in the implementation of existing research, likely due to the lack of holistic understanding of the processes in time and space. The same gap has also been noted in other studies focusing on biological control agents against *Phytophthora* species in agriculture (de Andrade Lourenço et al., 2022; Giachero et al., 2022). In this regard, the challenge is to develop research strategies that integrate diverse techniques to investigate the collective effects of microbial biocontrol agents on pathogen growth, disease progression, host vigour and environmental dynamics. Overall, more research and development efforts are needed to validate the results from laboratory and greenhouse facilities in field conditions.

5 | CONCLUDING REMARKS

Our systematic mapping of the literature reveals an impressive global research activity focused on the management and control of *Phytophthora* pathogens of forest trees. Future research using advanced technologies will likely result in improved tools for surveillance and management, while progress in understanding epidemiology and host resistance will allow the design of better management strategies and facilitate breeding efforts, although there is still a gap to overcome between research and implementation. Managing *Phytophthora* diseases in forest ecosystems remains challenging due to the lack of field experimental data on control strategies. While field experiments can be resource-intensive, they are crucial for demonstrating the efficacy of experimental treatments for disease control and optimizing their application methods and dosage. Hence, future field experiments are imperative to address knowledge gaps concerning the combined effects of microbial biocontrol agents on pathogen growth, disease progression, host vigour and environmental dynamics to improve our ability to manage *Phytophthora* diseases effectively. Multidisciplinary approaches that combine knowledge from plant pathology, ecology, genetics, climate science and forest management are needed in future research to enable a more holistic understanding of *Phytophthora* diseases and the development of effective control and management strategies.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest to disclose.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX 1

Chemical products utilized in the selected literature to control *Phytophthora* of forest trees, their active ingredients, chemical group and mode of action.

Product and manufacturer	Active ingredient (A. I.)	Chemical group	Mode of action
Cuprofix Disperss® UPL Australia Pty Ltd.	200 g/kg copper (copper sulphate/ calcium hydroxide)	Inorganic	Protectant
AgriFos®600 Key Industries Ltd. (NZ)	600 g/L phosphite	Phosphonate	Systemic
AgriFos®400 Key Industries Ltd. (NZ)	400 g/L phosphite	Phosphonate	Systemic
Algon's Algatac Algon (NZ) Ltd.	40 g/L copper salts 100 g/L benzyl ammonium chloride	Inorganic	Protectant
Ridomil® Gold SL Syngenta	480 g/L metalaxyl-M	Phenylamide	Systemic
Amistar® Syngenta	250 g/L azoxystrobin	Strobilurin	Local systemic and protectant
AGPRO Cupric-hydroxide 350 SC AGPRO (NZ) Ltd.	350 g/L copper hydroxide	Inorganic copper	Protectant
Chemet® American Chemet Corporation, USA	750 g/kg cuprous oxide	Inorganic copper	Protectant
Dithane® Dow AgroSciences Australia Ltd., NSW	750 g/kg mancozeb	Dithiocarbamate	Protectant
Blizzard™ Orion Crop Protection Ltd. (NZ)	500 g/L chlorothalinal	Chloronitrile	Protectant
Polyram® DF BASF	700 g/kg metiram	Dithiocarbamate	Protectant
Sphinx® Agronica (NZ) Ltd.	500 g/L dimethomorph	Cinnamic acid amide	Local systemic and protectant

APPENDIX 1 (Continued)

Product and manufacturer	Active ingredient (A. I.)	Chemical group	Mode of action
Funguran® OH Spiess Urania Chemicals	500 g/kg copper hydroxide	Inorganic copper	Protectant
Avoguard® Nulandis® (A division of AECI Ltd.)	500 g/L potassium phosphonate	Phosphonate	Systemic
Empress® Intrinsic® BASF	23.3% pyraclostrobin	Strobilurin	Systemic and curative
ON-Gard® 5-0-0 BioWorks	5% nitrogen (N)	Fertilizer	Organic biological fertilizer
Orkestra® Intrinsic® BASF	21.26% pyraclostrobin 21.26% fluxapyroxad	Strobilurin, succinate dehydrogenase inhibitor	Protectant
Pageant® Intrinsic® BASF	12.8% pyraclostrobin 25.2% boscalid	Strobilurin, succinate dehydrogenase inhibitor	Protectant
RootShield Plus$^+$ WP BioWorks	1.15% *Trichoderma* harzianum Rifai (T-22) 0.61% T. virens (G-41)	Biofungicide	Protectant
Subdue Maxx® Syngenta	22% mefenoxam	Phenylamide	Systemic
Tartan® Stressgard® Bayer	4.17% trifloxystrobin 20.86% triadimefon	Fungicide	Systemic, preventive and curative
EnerBite® Newpharm©	11% phosphorous pentoxide (P_2O_5) 7.3% potassium oxide (K_2O)	Fertilizer	Systemic
Armetil® 5 G IQV-Mat Holding Group.	5% metalaxil	Phenylamide	Systemic
Aliette® WP 80% Bayer	Fosetyl-Al [Aluminium tris-(ethylphosphonate)]	Organophosphonates	Systemic
Stature® SC BASF	dimethomorph	Cinnamic acid amide	Systemic and preventive
Phyto Fos®-K AMC Chemical – Trichodex	18% soluble potash (K_2O)	Derived from potassium phosphite	Systemic
OTRIA® 5 GR ©Probelte	5% metalaxyl	Phenylamide	Systemic
Zamorph® 50 WP Zagro©	Dimethomorph	Fungicide	Systemic and protective
ZeroTol® 2.0 BioSaf	27.1% hydrogen peroxide 2% peroxyacetic acid	Algaecide, bactericide and fungicide	Systemic
Banol Bayer	600 g/L propamocarb hydrochloride	Carbamate	Systemic, curative and preventative
Thiophanate-Methyl 70 WP Nippon Soda Co. Ltd. Japan	70% thiophanate-methyl	Benzimidazole	Systemic, protective and curative
Pentra-Bark® Quest Products Corp.	99.8% alkylphenol ethoxylate, polysiloxane polyether copolymer, propylene glycol	Synthetic-non-ionic surfactants	Non-ionic wetting agent designed to aid penetration through bark
Actifos® Agropak Sp.J. Poland	10.02% nitrogen (N) 0.02% boron (B) 0.008% copper (Cu) 0.06% iron (Fe) 0.04% manganese (Mn) 0.004% molybdenum (Mo) 0.02% zinc (Zn)	Fertilizer	Systemic
Ridomil® Gold MZ 68 WG Syngenta	64% mancozeb 4% metalaxyl-M	Ethylenebisdithiocarbamate (EBDC) Phenylamide	Systemic and protective
Phosplus® ©Otsuka Chemical Co., Ltd.	605 g/L potassium phosphite	Phosphorous acid	Systemic

APPENDIX 1 (Continued)

Product and manufacturer	Active ingredient (A. I.)	Chemical group	Mode of action
Amistar® Gold Syngenta	125 g/L azoxystrobin 125 g/L difenoconazol	Strobilurins, Triazole	Systemic and translaminar
Daconil® Action™ Syngenta	720 g/L chlorothalonil 2.34 g/L acibenzolar-S-methyl	Chlorinated Benzonitrile	Systemic
Kocide® 2000 DuPont™	53.8% copper hydroxide	Inorganic copper	Protectant
Ranman® Ishihara Sangyo Kaisha, Ltd.	34.5% cyazofamid	Imidazoles	Protectant
Bordeaux WG Grochem Australia Ltd.	200 g/kg tri-basic copper sulphate and lime (calcium hydroxide)	Bactericide and fungicide	Protectant
Kalex® Alba Milagro International S.P.A.	30% phosphoric anhydride 20% potassium oxide	Phosphoric acid	Bio-stimulant
Foli-R-Fos® 400 Bayer	40% mono and di potassium phosphite	Phosphorous acid	Systemic
Ridomil® Gold EC Syngenta	480 g/L metalaxyl-M	Phenylamide	Systemic and protectant
Foschek® 400 Arxada Ltd. (NZ)	400 g/L mono and di potassium phosphite	Phosphorous acid	Systemic
Fosject® 200 Bayer	200 g/L mono and di potassium phosphite	Phosphorous acid	Systemic
Apron® Gold Syngenta	35 g metalaxyl-M	Phenylamide	Systemic and protectant
Actiwett® Etec™ Crop Solutions Ltd. (NZ)	98% alcohol ethoxylate 2% polyethylene glycol	Linear alcohol ethoxylate	Surfactant (adjuvants)
LI-1000® Etec™ Crop Solutions Ltd. (NZ)	100% lecthin, methyl esters of fatty acids and alcohol ethoxylate	Lecithin, methyl esters of fatty acids and alcohol ethoxylate	Surfactant (adjuvants)
Hasten™ BASF	704 g/L ethyl and methyl esters of fatty acids	Derived from food grade canola Oil	Non-ionic surfactants (adjuvants)
Nu-Film-17® Key Industries Ltd. (NZ)	904 g/L di-1-p-menthene (a terpenic non-ionic polymer)	di-1-p-menteno	Adjuvant
Du-Wett Stainless® Etec™ Crop Solutions Ltd. (NZ)	30%–60% alcohol ethoxylate polyalkylene compounds: 10%–30% polyalkylene oxide 10%–30% polyalkyleneoxide silane 1%–5% polyalkyleneoxide	A pH-stable organosilicone polymer containing alcohol ethoxylate and polyalkylene compounds	Non-ionic organosilicone surfactant (adjuvants)
Du-Wett® Etec™ Crop Solutions Ltd. (NZ)	500 g/L trisiloxane ethoxylate	An organosilicone-blend containing siloxane polyalkeneoxide copolymers	Non-ionic organosilicone surfactant (adjuvants)
Du-Wett WeatherMAX® UPL (NZ) Ltd.	60% latex emulsion 30% water 15% siloxane polyalkyleneoxide copolymer	An organosilicone-blend superspreading sticker containing organosilicone and polimer latex	Non-ionic organosilicone surfactant (adjuvants)
Biohumin® Deutschland GmbH, Berlin, Germany	0.5% organic (N) 0.3% (P) 0.5% (S) 1% (Ca) 0.2% (Mg) 0.3% (Fe, Mn, B, Zn) 55% organic substance 20% humic fulvic acids	Composed of leonardite in liquid chelated form	Organic soil fertilizer
Break-Thru® S240 Western Farm Services Inc, Fresno, CA	100% Polyether Modified Trisiloxane	Organomodified trisiloxanes	Systemic Insecticides Fungicides Weedicides

APPENDIX 2

Composition of implants of phosphite, PHOSCAP® and MEDICAP® (Creative Sales, Inc., Fremont, Nebraska, United States of America).

Product and manufacturer	Composition % by weight	Chemical group	Mode of action
MEDICAP MD® Creative Sales, Inc. USA	12% nitrogen (N) 4% phosphate (P_2O_5) 4% soluble potash (k_2O) 4% iron (Fe) 4% manganese (Mn) 4% zinc (Zn)	Derived from potassium nitrate, ammonium phosphate, urea, sulphate of ammonia, ferric ammonium citrate, manganese sulphate and zinc sulphate	Systemic Fertilizer Implants
PHOSCAP® Creative Sales, Inc. USA	50% phosphate (P_2O_5) 30% soluble potash (k_2O) 0.06% magnesium (Mg) 0.02% boron (B) 0.05% copper (Cu) 0.1% iron (Fe) 0.05% manganese (Mn) 0.0005% molybdenum (Mo) 0.05% zinc (Zn)	Derived from mono-potassium phosphite and di-potassium phosphate	Systemic Fertilizer Implants
Zinc – (MEDICAP ZN®) Creative Sales, Inc. USA	30% zinc sulphide	Derived from purified Zinc sulphate	Systemic Fertilizer Implants
Iron – (MEDICAP FE®) Creative Sales, Inc. USA	Ammonium iron (II) citrate about 28% Fe	Derived from Ferric ammonium citrate	Systemic Fertilizer Implants