Pesticides for fumigation with relevance for animal feed

J.P. van Dijk, C. Liu, H. van Egmond, H. Mol, P. Bikker

WAGENINGEN
UNIVERSITY & RESEARCH

Pesticides for fumigation with relevance for animal feed

J.P. van Dijk, C. Liu, H. van Egmond, H. Mol, P. Bikker

This research has been carried out by Wageningen Food Safety Research, institute within the legal entity Wageningen Research Foundation subsidised by the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature (LVVN) (project number WOT-02-004-013).

Wageningen, 30 May 2025

WFSR Report 2025.007

WAGENINGEN
UNIVERSITY & RESEARCH

Dijk, J.P. van, C. Liu, H. van Egmond, H. Mol, P. Bikker, 2025. *Pesticides for fumigation with relevance for animal feed.* Wageningen, Wageningen Food Safety Research, WFSR Report 2025.007. 36 pp.; 0 fig.; 3 tab.; 246 ref.

Project number: 1227186001
BAPS-code: WOT-02-004-013-WFSR
Project title: Juridische eisen met betrekking tot analyse- en bemonsteringsmethoden gebruikt in het opsporingsonderzoek van diervoeders en diervoedergrondstoffen
Project leader: N.P. Meijer

This report can be downloaded for free at https://doi.org/10.18174/693568 or at www.wur.eu/food-safety-research (under WFSR publications).

P.O. Box 230, 6700 AE Wageningen, The Netherlands, T +31 (0)317 48 02 56, E info.wfsr@wur.nl, www.wur.eu/food-safety-research. WFSR is part of Wageningen University & Research.

WFSR report 2025.007

Contents

Summary

Fumigation is the process of pest control using gaseous pesticides in closed areas. Such pesticides are referred to as fumigants. Pesticides such as fumigants or its residues might have an impact on animal feed safety. In the case of fumigants the gas disperses throughout the animal feed, hence the questions:

- Which fumigants are likely to be present in containers used for shipment, or other means of transport or storage, of feed and feed materials?
- Which of these should be prioritised in the light of animal feed safety?

Apart from looking for authorised or approved fumigants in official databases, also a search for relevant fumigants was performed in scientific literature. Presence of a fumigant in either source was considered as an indication of potential use, and as a result, of a potential presence of residues in feed.

A total of 34 active ingredients was found in pesticides used as fumigants. Eleven of those were found in the Ctgb database (the Dutch Board for the Authorisation of Plant Protection Products), and 23 in scientific literature using specific search criteria. A shortlist was made of 13 fumigants based on considerations such as presence of an EU maximum residue level (which considers both toxicology and good agricultural practice), feed relevance, information on historical or intended use. This shortlist consists of the following substances: aluminium phosphide, magnesium phosphide, sulfurylfluoride, hydrogen cyanide, ethylene oxide methylbromide, 1,3-dichloropropene, metam-sodium, 1,2-dichloroethane (ethylene dichloride), carbon tetrachloride, 1,2-dichloropropane (trimethylene dichloride), 1,2-dibromoethane (ethylene dibromide), and chloropicrin. It is recommended to use this shortlist with high priority regarding animal feed safety, and hence for inclusion in monitoring, after method development where needed.

1 Introduction

Recently there have been a number of incidents in harbours, where people have become unwell when opening containers, due to exposure to fumigants that were still present in air in the container. These incidents are primarily a matter for authorities dealing with safe working conditions, rather than the NVWA. However, if fumigants can be present in container air, this might also lead to residues of these fumigants on animal feed shipped in these containers, which makes it a matter of animal feed safety as well. This lead to the following questions from the NVWA which are addressed in the report:

- which fumigants are likely to be present in containers used for shipment, or other means of transport or storage, of feed and feed materials?
- which of these should be prioritised for monitoring and control in the light of animal feed safety and/or good agricultural practice?

In 2022, the NVWA has drawn attention to the possible presence of residues of approved disinfectants during the transport and storage of feed materials. The use of products for cleaning and disinfection of equipment for storage and transport of animal feed (silos, vessels, trucks, etc.) can result in residues in the feed. The risk of (too) high residue levels is partly determined by the application of the product, such as the amount used, dosage and distribution. The NVWA did not have adequate insight into the substances used, the practical application of the regulations for these substances, and the possible risks involved. It was therefore requested to determine in this project which agents are permitted for cleaning and disinfecting means of transport, which regulations apply to this application, which agents can result in residues in the feed and which critical factors increase the risk of high residue levels.

Within WFSR and in meetings with NVWA, this subject has been discussed in relation to other projects addressing the use of biocides. Biocides are pesticides that are not included in the category of plant protection products (PPP). Biocides include several main groups, such as for disinfection, preservation and pest control[1]. The assumption was that PPPs are mainly used in presence of the feed and thus have a higher chance of presence of residues on the feed, while biocides are mainly used in empty storage or transport facilities. But the use of biocides might also result in residues in the feed, if stored or transported in facilities that have undergone a biocide treatment. Also, from the authorisations of the fumigants investigated in the report it appears that the distinction of application in the presence of absence of feed or food is not that strict.

Some fumigant PPP authorisations allow use in empty spaces (e.g. phosphides and sulfuryl fluoride). On the other hand, biocide authorisations of sulfuryl fluoride products explicitly include the control of insect pests in stored commodities, besides pest control in empty food processing and storage facilities. This shows an overlap in PPP and biocides when it comes to use in presence or absence of commodities. NVWA requested background information for residues of disinfectants, or biocides, in means of transport with initial focus on fumigants.

The first approach to answer this was a study of national and EU authorisations and approvals of these products. Because of the overlap between biocides and PPPs, both categories were reviewed.

NB The terms used in these authorisation need some explanation for better understanding of the results. This concerns the terms authorisation, approval, active substances, and fumigants requires clarification. Active substances of pesticides used as fumigants, liquids or otherwise, are approved or not approved for use in the EU in EU regulations. Following EU approval of the active substance, several different products containing these active substances can be authorised in one or more EU countries. As an example, the active substance aluminium phosphide is approved in the EU under regulation EC 1107/2009 and is present in

[1] Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products.

several products which are authorised in 27 EU countries. In the Netherlands, aluminium phosphide is the active substance in, among others, the product QuickPhos B, authorised as PPP, and in DETIA WM, authorised as biocide. When referring in this report to authorisation(s) of a particular fumigant, this in fact means that authorisation(s) were found for fumigation product(s) either as PPP, biocide, or both, containing this particular approved active substance. Pesticides used as nebuliser, such as formaldehyde, were not considered to be fumigants, and were not included in this report.

The second approach was a search for relevant fumigants in scientific literature. Presence of a fumigant in either source was considered as an indication of potential use, and as a result, of a potential presence of residues in feed. The fumigants derived from both searches and their prioritisation are presented in the results section, while recommendations are presented in the discussion.

2 Material and methods

2.1 Selection of fumigants

The first aim was to provide an overview of fumigants which might be of relevance for animal feed. Fumigants were selected in a stepwise procedure:

1. Fumigants in the Dutch authorisation and approval database of pesticides.
2. Fumigants selected from scientific literature and which are not listed in step 1.

A more detailed description of the steps is provided in the sections 2.1.1 and 2.1.2.

2.1.1 Selection of fumigants in the authorisation and approval databases

The Dutch national competent authority (Ctgb) hosts an online authorisation database[2]. For some fumigants with expired authorisations, information on use is still present in de Ctgb database, while for some older expired authorisations, this information is no longer present. In the latter case, also the European Chemicals Agency (ECHA) website[3] with information on biocides was consulted, regarding either authorisation or methods of use.

Ctgb provides an online database with all pesticides authorised in the Netherlands and a number of pesticides for which the authorisation is expired. The online database does not provide a search option for all entry fields. However the download version of the database allowed a search within Excel. Relevant terms were looked for in the information for the known fumigants 1-methylcyclopropeen, aluminiumfosfide, koolstofdioxide, magnesiumfosfide, sulfurylfluoride (NB search terms are in Dutch). The most relevant search terms appeared to be “fumi” and “gas”. The ECHA database does not provide such a download option, therefore the literature search described in the next section was used to discover fumigants without an EU authorisation or approval that are nonetheless used outside of the EU and that might end up in containers in EU harbours, or in the food or feed commodities shipped in these containers. This was assumed to also cover all fumigants with authorisation in other EU countries, e.g. not listed in Ctgb, which might end up in the Netherlands through containers or bulktrucks, etc. from other Member States.

2.1.2 Selection of fumigants from scientific literature

Apart from looking for authorised or approved fumigants in official databases, a search for relevant fumigants was performed in scientific literature.

A structured review of scientific literature was performed in 2021 and repeated in June 2023 for results published after 2020. Overlapping results from 2021 were removed from the selection. All fumigants from the literature study were checked with the Ctgb and ECHA databases to see if authorisations were missed in the first step. In short, four categories of search terms were combined in a literature search: fumigants, commodities, treatment targets, and location. For each category, a list of search terms was made using e.g. FAO reports, Wikipedia, the EU-MRL database, and a Ctgb permitted fumigant list from the NVWA. The database used for the literature search was Scopus[4], and the search terms were:

#1: Fumigants
fumigant* OR “gaseous pesticide*” OR “aluminium phosphide” OR “ethylene oxide” OR “2-chloroethanol” OR ethylene OR “carbon dioxide” OR CO2 OR “sodium bicarbonate” OR “magnesium phosphide” OR “sulfuryl fluoride” OR “hydrogen cyanide” OR formaldehyde OR paraformaldehyde OR “L-lactic acid” OR “lactic acid”

2 https://pesticidesdatabase.ctgb.nl/en/authorisations
3 https://echa.europa.eu/nl/information-on-chemicals/biocidal-products
4 https://www.scopus.com/search/form.uri?display=basic&zone=header&origin=#basic

OR “peracetic acid” OR “1-methylcyclopropene” OR phosphine OR “methyl bromide” OR “1,2-dichloroethane” OR “1,3-dichloropropene” OR “1,2-dibromoethane” OR dazomet OR “methyl isothiocyanate” OR “methyl isocyanate” OR chloropicrin OR DBCP OR dibromochloropropane OR “1,2-Dibromo-3-chloropropane” OR iodoform OR triiodomethane OR acrylonitrile OR “carbon disulphide” OR “carbon tetrachloride” OR dichlorvos OR DDVP OR “ethylene dibromide” OR “ethylene dichloride” OR “ethyl formate” OR “methyl formate” OR paradichlorobenzene OR “sulphuryl fluoride” OR trichloroethylene OR naphthalene OR malathion OR acetaldebyde OR dichloronitroethane OR “ethylene chlorobromide” OR “methallyl chloride” OR “methylene chloride” OR nicotine OR “propylene dichloride” OR “sulphur dioxide” OR “methyl chloroform”

#2: Commodities
crop* OR seed* OR food OR feed OR cereal* OR grain* OR wheat* OR maize* OR corn* OR flour* OR pasta OR cookie* OR *bean OR *pea OR lentils OR vegetable* OR potato* OR soy* OR meet OR fish OR dairy OR milk OR cheese OR coffee OR chocolate OR cocoa OR sugar OR candy OR sweet OR nut* OR vegetable* OR fruit* OR apple* OR pear* Or *berr* OR *melon* OR oilseed* OR tea OR spice* OR herb* OR chilli* OR pepper* OR pulses

#3: Treatment targets
insect* OR salmonella OR beetle* OR bug* OR butterfl* OR caterpillar* OR worm* OR mite* OR mice OR mouse OR pest*

#4 location
warehouse* OR ship* OR boat* OR vessel* OR container* OR store* OR silo* OR harbor* OR harbour* OR “post-harvest”

A combined search was performed: #1 AND #2 AND #3 AND #4 AND KEY (fumigant* OR fumigation) AND NOT TITLE-ABS-KEY (“essential oil”) AND (LIMIT-TO (LANGUAGE, “English”).

Active substances used as fumigants were retrieved from the resulting literature collection as well as relevant information regarding their use. Additional information of use for specific fumigants was retrieved from the ‘toxic substances portal’ of the American ‘Agency for Toxic Substances and Disease Registry’ (ATSDR)[5]. Noteworthy is that the MRLs listed there are minimal risk levels and as such inherently different from the maximum residue levels used in this report.

2.2 Prioritization of fumigants

The second aim was to make a first prioritisation regarding potential impact on animal feed safety of these fumigants. Prioritisation might have implications for monitoring by companies involved in the transport, trade and use of animal feed and for authorities, as well as for development of analytical methods, if necessary.

Criteria used for prioritisation are:

- Authorisation status
  Fumigants which have or have had an authorisation are more likely to be used in commercial settings than unauthorised fumigants. Fumigants which are still in experimental phase are not prioritized for monitoring.

- Absence of MRL value / GRAS status
  Products for which an MRL is not required are likely to be less harmful than products which do require an MRL. Note that products which are not authorized in EU have a default MRL, indicated by an asterisk in EU pesticide database[6]. Also, products which are generally recognized as safe (GRAS) receive lower priority.

5 https://wwwn.cdc.gov/TSP/MRLS/mrlslisting.aspx
6 https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/start/screen/mrls

- Feed relevance
  If an active substance is authorized for applications not related to feed (e.g. medical use) and /or the active substance is applied to matrixes which are not used as feed substantially (e.g. apples), it is not considered as feed relevant.

The fumigants that are prioritised are listed in a shortlist, with additional details.

- Analytical method availability at WFSR
  Active substances for which WFSR methods are available could easily be included in surveys of animal feed if desired. Expertise is available at WFSR to develop methods if not available yet.

- Toxicological information
  ADI (acceptable daily intake, long term intake) and ARfD (Acute Reference Dose, short term intake) are obtained from EU Pesticide Database under the active substances section. If not available there, the LD50 rat is taken from the PPDB[7] as an indication of oral toxicity.

- Half life
  Substances that have a long half-life are likely to persist in feed material and might end up in animal feed put on the market.
  The typical half-life in soil (DT50) and aqueous hydrolysis is taken from the PPDB, where available.

- Remarks
  In case the active substance of a pesticide is classified according to EU Reg. 1272/2008 with at least one of the terms (Muta. 1A, Muta 1B, Carc. 1A, Carc. 1B, Repr. 1A, Repr. 1B), this is mentioned as different rules apply for notification of MRL exceedances to NVWA. The CRM status of a pesticide is retrieved using the C&L inventory of ECHA database[8].

[7] https://sitem.herts.ac.uk/aeru/ppdb/en/atoz.htm
[8] https://echa.europa.eu/information-on-chemicals/cl-inventory-database

3 Results

3.1 Selection of fumigants

A total of 34 active ingredients were found in pesticides used as fumigants. Eleven of those were found in the Ctgb database, and 23 in scientific literature using specific search criteria (see methods).

Tables 1 and Table 2 provide an overview of these products, together with a number of important aspects regarding feed safety, such as the authorisation status in Ctgb or ECHA, and evaluation of feed relevance. Table 1 also lists maximum residue levels (MRLs), as well as the commodities for which a higher than default MRL value applies, as well as some information of authorisation in EU countries if not authorised in the Netherlands. All MRL values and approval information were retrieved from the EU Pesticide Database. The main difference between tables 1 and 2 is either the commercial or the developmental status of the products listed.

3.1.1 Selection of fumigants in the authorisation and approval databases

Products of seven fumigants were found in the Ctgb database with an active authorisation status (Table 1). Four of those have a clear feed application in either biocide or PPP authorisations, as well as an MRL: two phosphides, sulfuryldifluoride, and hydrogen cyanide. For carbon dioxide, no MRL is required for use in the EU as fumigant[9]. 1-Methylcyclopropene has no feed but only food relevance, as its mode of action is to prevent fruit ripening. As for chlorine dioxide (ClO_2), feed relevance is not obvious from the authorisation's information, nor its use as fumigant. In fact, none of the products that contain ClO_2 are used as fumigant, but for liquid cleaning of various hard surfaces instead, including those that may come into contact with food or feed. ClO_2 is also not authorised as PPP in the EU. In scientific literature, ClO_2 is investigated as a fumigant in stored grains in three papers (Xinyi et al., 2017 and 2018, and Buenavista et al., 2023). ClO_2 may therefore be considered to be still in an experimental or developmental stage, rather than being used as fumigant on a commercial level.

Four fumigants were found with expired Ctgb authorizations, all of which have an MRL. Feed relevance is evident from the authorisations of three of them, metam-sodium, 1,3-dichloropropene, and methyl bromide. Interestingly, for ethylene oxide, feed relevance is not obvious from its authorisations, which deal with industrial sterilisation of medical equipment. It is currently being reviewed for use as a biocide by Norway, again with the intended use: 'Industrial sterilisation of single use medical devices, which cannot be sterilised by other means, before these are made available on the market'. However, ethylene oxide is used outside the EU also as a fumigant biocide for spices and herbs[10,11]used in food, among others. An incident with ethylene oxide occurred in the EU in 2021 with high levels in sesame seeds from India[12,13]. Metam-sodium is still approved in the EU and authorised as PPP in 12 EU countries, 1,3-dichloropropene and methyl bromide are not approved anymore in the EU, and as such also not authorised in any EU country.

3.1.2 Selection of fumigants from scientific literature

The literature review resulted in 247 publications in which 23 fumigants are mentioned that were not previously found in the Ctgb database. Eight of those 23 have been used, are being used, or are going to be used as fumigants in feed. These were therefore added to Table 1, and listed with 'no', regarding Ctgb authorisation. Six of these 'commercial' fumigants have an MRL. None of these six are approved in the EU.

[9] Commission Regulation (EU) 2022/1435 of 26 August 2022 amending Annexes II and IV to Regulation (EC) No 396/2005 of the European Parliament and of the Council as regards maximum residue levels for calcium carbonate, carbon dioxide, cyprodinil and potassium hydrogen carbonate in or on certain products

[10] https://www.foodstandards.gov.au/consumer/chemicals/Pages/Ethylene-oxide.aspx

[11] https://www.epa.gov/ingredients-used-pesticide-products/regulation-ethylene-oxide-eto-under-federal-insecticide

[12] https://food.ec.europa.eu/system/files/2021-01/rasff_ethylene-oxide-incident_crisis-coord_sum.pdf

[13] https://www.europarl.europa.eu/RegData/etudes/ATAG/2021/679077/EPRS_ATA(2021)679077_EN.pdf

Noteworthy is that one of those is ethyl formate, which has the GRAS (generally regarded as safe) status in the USA. Of the other five, only chloropicrin is still used in the USA, the others are no longer used or even banned as a fumigant in the USA (i.e. 1,2-dichloroethane; carbon tetrachloride; 1,2-dichloropropane; 1,2-dibromoethane). These five fumigants have been widely used and might still be used. They are toxic, and, in one documented case, 1,2-dichloroethane (ethylene dichloride was detected in containers shipped to the EU (Budnik et al., 2017).

Two of the eight fumigants with documented (intended) use as fumigant in animal feed do not have an MRL. One is ozone, for which there is an EU approval starting in 1-7-2024[14], and for which MRLs have to be considered for products that may lead to residues in food or feed. Noteworthy, no ozone products have an authorisation yet at this time with Ctgb. The other one is sulfur dioxide, for which ECHA authorisation as a fumigant is under review. However, sulfur dioxide is also part of the group of sulfur dioxide-sulfites (E 220-228), which has an EU food additive registration. An EFSA opinion provides levels for acceptable daily intake (ADI) and margin of exposure (MoE). It is therefore included twice in the table, once as fumigant, and once as food additive.

The other 15 are considered to be still in an experimental, or developmental phase (Table 2). Most of the 15 experimental fumigants resulting from the literature search are bio-based. Some are grouped together in Table 2 as they were described as components of the same plant extract. At present, none of them have been approved for use in the EU, so in principle the default MRL value of 0.01 mg/kg applies. One of these fumigants is registered as a food additive in the USA (octenol), although its use as a fumigant is still experimental. Toxicity for humans has not yet been described for these fumigants in the literature, except for the common remark that bio-based fumigants would be generally more safe than chemical ones.

Table 1 *Fumigants with documented commercial use -historical or intended-, derived from Ctgb authorisations or literature study, grouped by Ctgb authorisation status.*

Active ingredient		**Authorisation Ctgb[1]**	**Information on use from authorisation or literature**	**feed relevant**	**MRL range mg/kg**	**MRLs > LOD apply to:**
aluminiumphosphide	BC/ PPP[2]	active	BC: moles and rabbits, outside PPP: insects, stored edibles PPP: water vole and moles, fruit, vegetables, ornamental, grass and tree horticulture	yes	phosphane generators; 0.01-0.7	tree nuts, herbs and edible flowers, oilseeds, cereals, coffee tea etc., hops, spices
magnesiumphosphide	BC/ PPP	active	BC (expired): insects in stored products in contained spaces and in cargo spaces in ships PPP: insecticide/acaricide, stored (non-) edibles, empty storage facilities	yes	phosphane generators; 0.01-0.7	tree nuts, herbs and edible flowers, oilseeds, cereals, coffee tea etc., hops, spices
sulfuryldifluoride	BC/ PPP	active	BC: Insecticide/acaricide, stored products, empty storage facilities PPP: insecticide/acaricide, stored (non-) edibles, empty storage facilities	yes	0.01-10	tree nuts
hydrogen cyanide	BC	active	BC: Wood-destroying beetles BC: insecticide/acaricide, stored products, empty storage facilities, transport facilities (trains, ships) BC: rodenticide, empty buildings (agriculture)	yes	15, NB, ML[3] range in feed: 10-350	cereals (food); animal feed: feed materials, complete feed
carbondioxide	BC/ PPP	active	BC: killing of caught wild geese BC (expired): mice, inside PPP: insecticide/acaricide, stored (non-) edibles, empty storage facilities	yes	not required	
chlorine dioxide	BC	active	Ctgb not as fumigant, but as solution, in literature use as fumigant (Beunavista 2023)	no	0.01	default, not approved as PPP in EU

[14] COMMISSION IMPLEMENTING REGULATION (EU) 2023/1078 of 2 June 2023.

Active ingredient		Authorisation Ctgb[1]	Information on use from authorisation or literature	feed relevant	MRL range mg/kg	MRLs > LOD apply to:
1-methylcyclopropene	PPP	active	PPP: stored edibles, prevent ripening	no	0.01-0.05	only * levels, authorized in 22 EU countries
ethylene oxide (including 2-chloroethanol as residue definition)	BC	expired, ECHA: assessment in progress	BC: industrial sterilisation of single use medical devices, which cannot be sterilised by other means, before these are made available on the market.	yes	0.02-0.1	only LOD (*) levels, not approved as PPP in EU
methyl bromide	BC/ PPP	expired	insecticide, rodenticide,	yes	bromide ion: 5-400	fruits, tree nuts, vegetables, pulses, oil seeds and fruits, cereals, coffee, tea etc., hops, spices, sugar plants, not approved as PPP in EU
1,3-dichloropropene	PPP	expired	soil disinfectant in the open ground for the cultivation of potatoes, sugar and fodder beets, onions, flower bulbs, strawberries, vegetables, nursery crops, floristry crops and perennials, as well as for the replanting of orchards	yes	0.01-0.05	only LOD (*) levels, not approved as PPP in EU
metam-sodium (carbathion), is metabolised to methyl isothiocyanate (MITC)	PPP	expired	soil fumigation broad spectrum	yes	methyl isothiocyanate : 0.01-0.5	strawberries, other root and tuber vegetables, fruiting vegetables, leafy brassica, lettuces, spinaches, authorized in 12 EU countries
ozone (generated from oxygen)	BC	no; ECHA: approval starts 1-7-2024	use in (among others) food, feed and drinking water	yes	no MRLs yet	
1,2-dichloroethane (ethylene dichloride)		no	still found in container air, Budnik 2017	yes	0.01-0.02	only LOQ (*) levels, not approved as PPP in EU
carbon tetrachloride		no	fumigant in stored grain, carcinogenic. Historically used with carbon disulfide or ethylene dichloride, Daft 1991 a.o.	yes	0.01	LOQ level, only for cereals, not approved as PPP in EU
1,2-dichloropropane (trimethylene dichloride)		no	carcinogenic, Pandey 2018, Kinochita 2019	maybe	0.01	default, only for cereals, not approved as PPP in EU
1,2-dibromoethane (ethylene dibromide)		no	banned in USA in 1983, Daft et al 1991	yes	0.01-0.02	only LOQ (*) levels, not approved as PPP in EU
chloropicrin		no	soil fumigation broad spectrum, dichloronitromethane is a metabolite, Baggio 2022 a.o.	yes	0.005-0.05	only LOQ (*) levels, not approved as PPP in EU
ethyl formate		no	widely used fumigant for stored feed. Occurs also naturally, GRAS status by USDA, 29 scientific papers	yes	0.01	default, not approved as PPP in EU
sulfur dioxide	BC	no; ECHA: under review	BC: antimocrobial, wine barrels (generated from sulfur by combustion, or released from sodium metabisulfite)	maybe		
sulfur dioxide-sulfites (E 220-228), food additives		no	commonly added tot fruit juices and wine, EFSA opinion on ADI and MoE (acceptable daily intake and margin of exposure) https://www.efsa.europa.eu/en/efsajournal/pub/7594	no		

[1] Ctgb authorisation refers to the authorisation status of products containing the active ingredients in the first column.

[2] BC = biocide; PPP = Plant Protection Product.

[3] ML: Maximum content in mg/kg (ppm) relative to a feed with a moisture content of 12% (EC 2002/32).

Table 2 *Fumigants in an experimental or developmental phase, derived from literature review. MRLs are not listed as they are not authorised a default MRL.*

Active ingredient	information on use from literature	feed relevant
1-octen-3-ol (octenol, mushroom alcohol), food additive in USA	wheat and other stored grains, Cui 2021	yes
methyl benzoate	food safe alternative for phosphine resistant insects, Morrison 2019, Mostafiz 2021	maybe
trans-anethole	(synthetic) product from star anise, Wang 2021 a.o.	yes
rhizome powder of Z. officinales	stored cocoa beans, Akinneye 2022	yes
hexane extracts of certain botanicals, Mentha spicata,Vitex negundo	rice, against rice weevil Sitophilus oryzae L., Anandhabhairavi 2022	yes
dihydro-p-coumaric acid	insect pests in stored grain, Devi 2022	yes
nitric oxide	pests in stored grain, Granella 2022, a.o.	yes
estragole	in combination with trans-anethole, less potent, Wang 2021	yes
plant powder fumigants, clove, holy basil, lemongrass, and turmeric powder	Callosobruchus chinensis (L.), stored legumes, Mario 2023	yes
Dennettia tripetala extract	red flour beetle, milled cereal flours, Oyeniyi 2021	yes
cinnamaldehyde	Tribolium castaneum (Herbst) and Sitophilus zeamais Motsch, Huang 1998	maybe
trans-Cinnamaldehyde (TC), benzaldehyde, allyl isothiocyanate (AITC), hexanal	Drosophila suzukii Matsumura, Jabeen, 2021	maybe
diallyl disulfide, citral, eucalyptol, eugenol and menthol	Sitophilus oryzae (weevil), Sahu 2021	yes
methyl salicylate	in combination with ethyl formate, adzuki bean beetle, Chiluwal 2020	yes
volatile constituents from Asari Radix et Rhizoma, δ-3-carene, γ-terpinene, terpinolene, eucarvone, 3,5-dimethoxytoluene, and methyleugenol	potato, Phthorimaea operculella (Zeller), Wu, 2021	maybe

3.2 Prioritisation of fumigants

Following the prioritisation criteria below, a shortlist of 13 fumigants was made (Table 3). Further information was added regarding presence of an analytical method at WFSR, toxicity and half life.

- Authorisation status
  Table 2 contains experimental fumigants. It’s good to be aware of those, and although technically the default MRL of 0.01 mg/kg applies, there seems to be a limited risk of those being used in an industry setting. They have not been authorised for use in the EU. Also, no literature was found describing industrial use. In fact, few were described in more than one paper, contrary to the literature found for fumigants that *are* used in an industrial setting.

- Absence of MRL value / GRAS status
  Table 1 contains two fumigants that do not require an MRL: carbon dioxide (no MRL required) and sulfur dioxide (no MRL likely to be required). Hence, these two substances seem unlikely to hamper feed safety and do not require priority in monitoring.
  The same accounts for ozone (for which MRLs are still to be established) and ethyl formate (USA GRAS status).

- Relevance for feed
  Table 1 contains also fumigants that are less likely to end up in animal feed. 1-Methylcyclopropene is not used for pest control, but to delay fruit ripening. ClO_2 is used in surface disinfection and its use as fumigant is still in an experimental stage.
  Feed relevance is also not obvious from its authorisations for ethylene oxide; however, feed relevance was clear from its illegal use in the EU (@refs to rasff). Illegal use in feed of 1-methylcyclopropene and ClO_2 does not seem likely, given the information above. Therefore, ethylene oxide should receive priority, whereas 1-methylcyclopropene and ClO_2 are of low priority.

Noteworthy is that the EU review report for the active substance sulfurylfluoride (SANCO/10567/2010 - Rev 1 7 December 2016) defines limits for placing products on the market. Any foodstuff present in the structure or storage or any adjoining structures during fumigation shall not be put on the market as food or feed, as defined in art. 3 of Reg. (EC) 178/2002, unless compliance with Regulation (EC) No 396/2005 is proven.

Table 3 *Fumigants prioritised for monitoring for animal feed safety.*

Active ingredient	Authori sation Ctgb	MRL-range (mg/kg)	WFSR method	Toxicological information (mg kg bw/day)	Half life (Days)	Remarks
aluminium phosphide	active	phosphane and phosphane generators (expressed as phosphane) 0.01*-0.7	no	ADI 0.019 ARfD 0.032	0.21-1	very rapid aqueous hydrolysis Only problems expected in case of non-compliance (e.g. active substance used directly in the product, insufficient aeration). Advised as fumigant (MVO)
magnesium phosphide	active	phosphane and phosphane generators (expressed as phosphane) ; 0.01*-0.7	no	ADI: 0.022 ARfD: 0.038	0.21-1 PPDB 0.24 (soil) very rapid (water)	see above. Advised as fumigant (MVO)
sulfurylfluoride	active	sulfuryl fluoride 0.01*-10	yes	LD50: 100 mg/kg	- (soil) 0.25 (hydrolysis)	detection does not necessarily imply illegal use of fumigant as bromide occurs naturally in various products. Used as replacement for methylbromide (PPDB)
hydrogen cyanide	active	hydrogen cyanide (cyanides expressed as hydrogen cyanide) 15	yes	-	-	EU 2002/32 provide limits for hydrogen cyanide (50 for feed materials and 100-250 for specific products such as linseed).
ethylene oxide	expired	ethylene oxide (sum of ethylene oxide and 2-chloro-ethanol expressed as ethylene oxide) 0.02*-0.1*	yes	-	-	CRM substance (Carc. 1B, Muta. 1B, Repr. 1B) Relevant for feed as relevant to food. Incorperated in EU Impl. Reg 2019/1793 regarding import controls for food.
methylbromide	expired	bromide ion 5-400	yes	-	-	detection does not necessarily imply illegal use of fumigant as bromide occurs naturally in various products. EFSA opinion on bromide is expected.
1,3-dichloropropene	expired	0.01*-0.05*	no	ADI 0.0125 ARfD 0.2	10.3 (soil) 4 (hydrolysis)	
metam-sodium	expired	Methyl isothiocyanate (resulting from the use of dazomet or metam) 0.01*-0.4	no	ADI: 0.001 ARfD: 0.1	7 (soil) 2.2 (hydrolysis)	methylisothiocyanate is also a metabolite of dazomet.
1,2-dichloroethane (ethylene dichloride)	no	0.01*-0.1*	no	LD50>413 mg/kg	-	CRM substance (Carc. 1B) The default MRL for products of animal origin (terrestrial origin) is 0.1 mg/kg.
carbon tetrachloride	no	0.01*	no	LD50: 2851 mg/kg	5 (soil) Stable (hydrolysis)	
1,2-dichloropropane (trimethylene dichloride)	no	0.01*	no	LD50: 1947 mg/kg	700 (soil) Stable (hydrolysis)	CRM substance (Carc. 1B)
1,2-dibromoethane (ethylene dibromide)	no	0.01*-0.02*	no	LD50: 108 mg/kg	100 (soil) -(hydrolysis)	CRM substance (Carc.1B)
chloropicrin	no	0.005*-0.05*	no	ADI: 0.001 ARfD: 0.001	4.2 (soil) Stable (hydrolysis)	

4 Discussion and recommendations

For this report the Cgtb database was used as a starting point for fumigant selection. This database only contains fumigants that are approved in the Netherlands. Those authorised in other EU Member States have not been assessed. It was assumed those substances are covered by the literature search, and it is likely that this was indeed the case, as the literature search covered all fumigants found in Ctgb, plus several others, for which no authorisations were present in the Ctgb or ECHA databases. Two fumigants were found in literature with an ECHA but without a Ctgb entry. Further exploration of the ECHA database would require a serious time investment with limited, if any, expected gain.

Out of 34 fumigants found, 13 were prioritized for monitoring or method development. To further assess the risk of these fumigants for animal feed safety, both the probability of occurrence and the adverse effect of the active ingredient must be taken into account, which was outside the scope of this report. It’s hard to predict their occurrence based on known current use, as this, by definition does not include unknown illegal use. Occurrence might be further explored through monitoring or production data, or any steps in between, if available. Also the adverse effect of these fumigants needs to be assessed for further prioritisation. The EU pesticide database contains information on approved and not approved active substances, including toxicity data, some of which were included in this report. Also the American Agency for Toxic Substances and Disease Registry provides information on toxicity, as well as some history on the use of several compounds, including fumigants.

Further information might result from stakeholder consultation on the provided shortlist, to uncover operator experience that is not available in scientific literature. This might involve stakeholders such as Comite van graanhandelaren (EU level: Coceral), MVO (EU level: EFISC), Nevedi (EU level: FEFAC), GMP+ International, Croplife NL, Koninklijke Binnenvaart nl. Additionally, responsible parties for operator safety might provide feedback on the provided shortlist based on their signals on illegal or incompliant use of fumigants in practice. This might guide further prioritisation of fumigants for monitoring and/or method development.

Annex 1 Results of literature research

All 246 results from the structured review of scientific literature are listed here first in alphabetical order by author(s) and secondly by publication date.

Afful, E., A. Cato, M. K. Nayak and T. W. Phillips (2021). "A rapid assay for the detection of resistance to phosphine in the lesser grain borer, Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae)." Journal of Stored Products Research 91.

Afful, E., B. Elliott, M. K. Nayak and T. W. Phillips (2018). "Phosphine Resistance in North American Field Populations of the Lesser Grain Borer, Rhyzopertha Dominica (Coleoptera: Bostrichidae)." Journal of Economic Entomology 111(1): 463-469.

Afful, E., T. M. Tadesse, M. K. Nayak and T. W. Phillips (2020). "High-dose strategies for managing phosphine-resistant populations of Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae)." Pest Management Science 76(5): 1683-1690.

Agrafioti, P., D. L. Brabec, W. R. Morrison, III, J. F. Campbell and C. G. Athanassiou (2021). "Scaling recovery of susceptible and resistant stored product insects after short exposures to phosphine by using automated video-tracking software." Pest Management Science 77(3): 1245-1255.

Agrafioti, P., E. Kaloudis, S. Bantas, V. Sotiroudas and C. G. Athanassiou (2020). "Modeling the distribution of phosphine and insect mortality in cylindrical grain silos with Computational Fluid Dynamics: Validation with field trials." Computers and Electronics in Agriculture 173.

Agyekum, D. V. A., T. Kobayashi, K. M. G. Dastogeer, M. Yasuda, E. Sarkodee-Addo, S. T. N. Ratu, Q. Xu, T. Miki, E. Matsuura and S. Okazaki (2023). "Diversity and function of soybean rhizosphere microbiome under nature farming." Frontiers in Microbiology 14.

Ahmad, A., M. Ahmed, Noorullah, Q. M. Ali, M. Abbas and S. Arif (2013). "Monitoring of resistance against phosphine in stored grain insect pests in Sindh." Middle East Journal of Scientific Research 16(11): 1501-1507.

Ahmad, M. S. and T. Mahmood (1996). "Phosphine fumigation of wheat stored in open bulkhead - A simple method." Pakistan Journal of Zoology 28(1): 35-38.

Ahmed, S. S., M. H. Naroz and M. A. El-Mohandes (2022). "Use of modified atmospheres combined with phosphine in controlling stored date fruit pests, Oryzaephilus surinamensis and Tribolium confusum, and effect on the fruit chemical properties." International Journal of Tropical Insect Science 42(2): 1933-1941.

Ahmedani, M. S. and A. Khaliq (2007). "Overview of psocids: As a new threat to stored grains and scope of thermal treatment for management." International Pest Control 49(4): 128-135.

Akinneye, J. O., S. Akinwotu, F. A. Ologundudu, O. salawu, M. Akinyemi and A. J. Owoeye (2022). "Management of store pest of cocoa Ephestia cautella (lepidioptera:pyralidae) using the powder and ethanolic oil extract of Zingiber officinales." International Journal of Tropical Insect Science 42(2): 1323-1330.

Albright, D. C. (2009). SEM-EDX analysis of an unknown "known" white powder found in a shipping container from Peru. Proceedings of SPIE - The International Society for Optical Engineering.

Allahvaisi, S. (2013). "Controlling Lasioderma serricorne F. (Col.: Anobiidae) by fumigation and packaging." World Applied Sciences Journal 28(12): 1983-1988.

Alnasser, S., S. M. Hussain, T. S. Kirdi and A. Ahmed (2018). "Aluminum phosphide poisoning in Saudi Arabia over a nine-year period." Annals of Saudi Medicine 38(4): 277-283.

Alzahrani, S. M. and P. R. Ebert (2018). "Stress pre-conditioning with temperature, UV and gamma radiation induces tolerance against phosphine toxicity." PLoS ONE 13(4).

Alzahrani, S. M. and P. R. Ebert (2023). "Pesticidal Toxicity of Phosphine and Its Interaction with Other Pest Control Treatments." Current Issues in Molecular Biology 45(3): 2461-2473.

Anandhabhairavi, N., M. Shanthi, C. Chinniah, R. Geetha and S. Vellaikumar (2022). "EFFICACY OF HEXANE EXTRACTS OF SOME PLANTS AGAINST RICE WEEVIL SITOPHILUS ORYZAE (L.) IN STORED MAIZE." Indian Journal of Entomology 84(2): 368-372.

Arora, S., J. Stanley and C. Srivastava (2021). "Temporal dynamics of phosphine fumigation against insect pests in wheat storage." Crop Protection 144.

Arthur, F. H. (2012). "Aerosols and contact insecticides as alternatives to methyl bromide in flour mills, food production facilities, and food warehouses." Journal of Pest Science 85(3): 323-329.

Asimah, H., L. Albert and A. B. Idris (2015). "Application of ethyl formate as a postharvest fumigant for dry cocoa beans under a semi commercial trial." Journal of Entomology 12(2): 55-66.

Athanassiou, C. G., T. W. Phillips, M. J. Aikins, M. M. Hasan and J. E. Throne (2012). "Effectiveness of sulfuryl fluoride for control of different life stages of stored-product psocids (Psocoptera)." Journal of Economic Entomology 105(1): 282-287.

Athanassiou, C. G., C. I. Rumbos, M. Sakka and V. Sotiroudas (2016). "Insecticidal efficacy of phosphine fumigation at low pressure against major stored-product insect species in a commercial dried fig processing facility." Crop Protection 90: 177-185.

Athié, I., R. A. R. Gomes, S. Bolonhezi, S. R. T. Valentini, M. F. Penteado and M. De Castro (1998). "Effects of carbon dioxide and phosphine mixtures on resistant populations of stored-grain insects." Journal of Stored Products Research 34(1): 27-32.

Aulicky, R. and V. Stejskal (2015). "Efficacy and limitations of phosphine "spot-fumigation" against five coleoptera species of stored product pests in wheat in a grain store - Short note." Plant Protection Science 51(1): 33-38.

Austel, N., J. Schubert, S. Gadau, H. Jungnickel, L. T. Budnik and A. Luch (2017). "Influence of fumigants on sunflower seeds: Characteristics of fumigant desorption and changes in volatile profiles." Journal of Hazardous Materials 337: 138-147.

Baggio, J. S., L. G. Cordova, B. F. Toledo, J. W. Noling and N. A. Peres (2022). "A reassessment of the fungicidal efficacy of 1,3-dichloropropene, chloropicrin, and metam potassium against Macrophomina phaseolina in strawberry." Pest Management Science 78(8): 3416-3423.

Bajracharya, N. S., G. P. Opit, J. Talley, S. G. Gautam and M. E. Payton (2016). "Assessment of Fitness Effects Associated with Phosphine Resistance in Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae) and Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae)." African Entomology 24(1): 39-49.

Barakat, D. A., G. Flingelli and C. Reichmuth (2011). "Lethal effect of sulfuryl fluoride on eggs of different age of the Indian meal moth plodia interpunctella (Hübner) - Demonstration of the no constancy of the ct product for control." Journal fur Kulturpflanzen 63(10): 323-332.

Beever, D. J. and C. W. Yearsley (1987). "Kiwifruit: Effect of post-harvest fumigation on fruit quality." New Zealand Journal of Experimental Agriculture 15(2): 185-189.

Bell, C. H. (2000). "Fumigation in the 21st century." Crop Protection 19(8-10): 563-569.

Berck, B. (1974). "Fumigant Residues of Carbon Tetrachloride, Ethylene Dichloride, and Ethylene Dibromide in Wheat, Flour, Bran, Middlings, and Bread." Journal of Agricultural and Food Chemistry 22(6): 977-984.

Berck, B. (1975). "Determination of air movement in stored grain as a factor in dynamic dispersion and distribution patterns of gaseous pesticides (fumigants)." Bulletin of Environmental Contamination and Toxicology 13(5): 527-533.

Bikoba, V. N., F. Pupin, W. V. Biasi, F. U. Rutaganira and E. J. Mitcham (2019). "Use of Ethyl Formate Fumigation to Control Adult Bean Thrips in Navel Oranges." Journal of Economic Entomology 112(2): 591-596.

Blanc, M. P., C. Panighini, F. Gadani and L. Rossi (2004). "Activity of spinosad on stored-tobacco insects and persistence on cured tobacco strips." Pest Management Science 60(11): 1091-1098.

Boopathy, B., A. Rajan and M. Radhakrishnan (2022). "Ozone: An Alternative Fumigant in Controlling the Stored Product Insects and Pests: A Status Report." Ozone: Science and Engineering 44(1): 79-95.

Brabec, D., J. Campbell, F. Arthur, M. Casada, D. Tilley and S. Bantas (2019). "Evaluation of wireless phosphine sensors for monitoring fumigation gas in wheat stored in farm bins." Insects 10(5).

Brabec, D., E. Kaloudis, C. G. Athanassiou, J. Campbell, P. Agrafioti, D. S. Scheff, S. Bantas and V. Sotiroudas (2022). "Fumigation Monitoring and Modeling of Hopper-Bottom Railcars Loaded with Corn Grits." Journal of Biosystems Engineering 47(3): 358-369.

Buckman, K. A., J. F. Campbell and B. Subramanyam (2013). "Tribolium castaneum (Coleoptera: Tenebrionidae) associated with rice mills: Fumigation efficacy and population rebound." Journal of Economic Entomology 106(1): 499-512.

Budnik, L. T., N. Austel, S. Gadau, S. Kloth, J. Schubert, H. Jungnickel and A. Luch (2017). "Experimental outgassing of toxic chemicals to simulate the characteristics of hazards tainting globally shipped products." PLOS ONE 12(5): e0177363.

Buenavista, R. M., X. E, B. Subramanyam, J. L. Rivera, M. Casada and K. Siliveru (2023). "Evaluation of wheat kernel and flour quality as influenced by chlorine dioxide gas treatment." Journal of Stored Products Research 102.
Castro, M. F. P. M., A. C. B. Rezende, E. A. Benato, S. R. T. Valentini, R. P. Z. Furlani and S. A. V. Tfouni (2011). "Studies on the effects of phosphine on Salmonella enterica serotype enteritidis in culture medium and in black pepper (Piper nigrum)." Journal of Food Protection 74(4): 665-671.
Cato, A. J., B. Elliott, M. K. Nayak and T. W. Phillips (2017). "Geographic Variation in Phosphine Resistance among North American Populations of the Red Flour Beetle (Coleoptera: Tenebrionidae)." Journal of Economic Entomology 110(3): 1359-1365.
Chaudhary, P. (2020). "Efficacy of fumigation in management of rodents in rice shellers in District Kaithal, India." International Journal of Current Research and Review 12(24): 130-134.
Chayaprasert, W. (2022). "A review of current fumigation practices in Thailand." Agriculture and Natural Resources 56(6): 1233-1248.
Chidemo, S. C., R. Musundire and N. Mashavakure (2023). "Higher dosage of phosphine is required to control resistant strains of pests in outdoor grain storage systems: Evidence from Zimbabwe." Journal of Stored Products Research 100.
Chigoverah, A. A., B. M. Mvumi, C. Muchechemera and J. V. Dator (2018). "Are GrainPro Cocoons™ an effective alternative to conventional phosphine fumigation in large-scale control of stored-maize insect pests?" Journal of Pest Science 91(4): 1393-1406.
Chiluwal, K., B. H. Lee, T. H. Kwon, J. Kim, S. D. Bae, G. H. Roh, Y. Ren, B. Li and C. G. Park (2020). "Synergistic effect of fumigation with ethyl formate and methyl salicylate on mortality of life stages of adzuki bean beetle, Callosobruchus chinensis (L.)." Journal of Asia-Pacific Entomology 23(2): 483-491.
Chiluwal, K., B. H. Lee, T. H. Kwon, J. Kim and C. G. Park (2023). "Post-fumigation sub-lethal activities of phosphine and ethyl formate on survivorship, fertility and female sex pheromone production of Callosobruchus chinensis (L.)." Scientific Reports 13(1).
Corrêa, A. S., H. V. V. Tomé, L. S. Braga, G. F. Martins, L. O. De Oliveira and R. N. C. Guedes (2014). "Are mitochondrial lineages, mitochondrial lysis and respiration rate associated with phosphine susceptibility in the maize weevil Sitophilus zeamais ?" Annals of Applied Biology 165(1): 137-146.
Cottrell, T. E., M. J. Aikins, E. M. Thoms and T. W. Phillips (2020). "Efficacy of Sulfuryl Fluoride against Fourth-Instar Pecan Weevil (Coleoptera: Curculionidae) in Pecans for Quarantine Security." Journal of Economic Entomology 113(3): 1152-1157.
Cui, K., S. Yang, N. Zou, L. He, T. Zhang, F. Liu and W. Mu (2021). "Residual behavior of the potential grain fumigant 1-octen-3-ol in wheat during fumigation and ventilation processes." Pest Management Science 77(6): 2933-2938.
Cui, K., L. Zhang, L. He, Z. Zhang, T. Zhang, W. Mu, J. Lin and F. Liu (2021). "Toxicological effects of the fungal volatile compound 1-octen-3-ol against the red flour beetle, Tribolium castaneum (Herbst)." Ecotoxicology and Environmental Safety 208.
Daft, J. L. (1983). "Evaluation of a mixed-phase column packing for the GC determination of fumigant residues in grains." Bulletin of Environmental Contamination and Toxicology 30(1): 492-496.
Daft, J. L. (1991). "Fumigants and related chemicals in foods: Review of residue findings, contamination sources, and analytical methods." Science of the Total Environment, The 100(C): 501-518.
Daglish, G. J., P. J. Collins, H. Pavic and R. A. Kopittke (2002). "Effects of time and concentration on mortality of phosphine-resistant Sitophilus oryzae (L) fumigated with phosphine." Pest Management Science 58(10): 1015-1021.
Daglish, G. J., M. K. Nayak and H. Pavic (2014). "Phosphine resistance in Sitophilus oryzae (L.) from eastern Australia: Inheritance, fitness and prevalence." Journal of Stored Products Research 59: 237e244-244.
Daglish, G. J., M. K. Nayak, H. Pavic and L. W. Smith (2015). "Prevalence and potential fitness cost of weak phosphine resistance in tribolium castaneum (Herbst) in eastern Australia." Journal of Stored Products Research 61: 54-58.
Daglish, G. J. and H. Pavic (2008). "Effect of phosphine dose on sorption in wheat." Pest Management Science 64(5): 513-518.
Daglish, G. J. and H. Pavic (2009). "Changes in phosphine sorption in wheat after storage at two temperatures." Pest Management Science 65(11): 1228-1232.
Damcevski, K. A. and P. C. Annis (2006). "Influence of grain and relative humidity on the mortality of Sitophilus oryzae (L.) adults exposed to ethyl formate vapour." Journal of Stored Products Research 42(1): 61-74.

Damcevski, K. A., G. Dojchinov, J. D. Woodman and V. S. Haritos (2010). "Efficacy of vaporised ethyl formate/carbon dioxide formulation against stored-grain insects: Effect of fumigant concentration, exposure time and two grain temperatures." Pest Management Science 66(4): 432-438.

Danso, J. K., G. P. Opit, B. H. Noden and K. L. Giles (2022). "Estimating discriminating doses of phosphine for adults of eight species of psocids of genera Liposcelis (Psocodea: Liposcelididae) and Lepinotus (Psocodea: Trogiidae)." Journal of Stored Products Research 99.

De Lima, C. P. F. (2015). Maintaining table grape quality by applying quarantine treatments during cooling. Acta Horticulturae. 1091: 55-62.

Deer, H. M., C. E. McJilton and P. K. Harein (1987). "Respiratory Exposure of Grain Inspection Workers to Carbon Tetrachloride Fumigant." American Industrial Hygiene Association Journal 48(6): 586-593.

Desmarchelier, J. M., F. M. Johnston and V. Le Trang (1999). "Ethyl formate, formic acid and ethanol in air, wheat, barley and sultanas: Analysis of natural levels and fumigant residues." Pesticide Science 55(8): 815-824.

Devi, T. B., V. Raina and Y. Rajashekar (2022). "A novel biofumigant from Tithonia diversifolia (Hemsl.) A. Gray for control of stored grain insect pests." Pesticide Biochemistry and Physiology 184.

Dojchinov, G., K. A. Damcevski, J. D. Woodman and V. S. Haritos (2010). "Field evaluation of vaporised ethyl formate and carbon dioxide for fumigation of stored wheat." Pest Management Science 66(4): 417-424.

Dong, X., M. Agarwal, Y. Xiao, Y. Ren, G. Maker and X. Yu (2022). "Ozone Efficiency on Two Coleopteran Insect Pests and Its Effect on Quality and Germination of Barley." Insects 13(4).

Ebert, P. R., N. S. Nath, I. Bhattacharya, A. G. Tuck and D. I. Schlipalius (2011). "Mechanisms of phosphine toxicity." Journal of Toxicology 2011.

Edde, P. A. (2019). "Biology, Ecology, and Control of Lasioderma serricorne (F.) (Coleoptera: Anobiidae): A Review." Journal of Economic Entomology 112(3): 1011-1031.

Elsayed, S., M. E. Casada, R. G. Maghirang and M. Wei (2021). "Evolution of phosphine from aluminum phosphide pellets." Transactions of the ASABE 64(2): 615-624.

El-Shafie, H. (2017). "Alternatives to methyl bromide for disinfesting date moth, Cadra Cautella, in stored dates." Outlooks on Pest Management 28(1): 17-20.

Ertürk, S., F. Sen, M. Alkan and M. Olçülu (2018). "Effect of different phosphine gas concentrations against Frankliniella occidentalis (Pergande, 1895) (Thysanoptera: Thripidae) on tomato and green pepper fruit, and determination of fruit quality after application under low-temperature storage conditions." Turkiye Entomoloji Dergisi 42(2): 85-92.

Fields, P. G. and N. D. G. White (2002). Alternatives to methyl bromide treatments for stored-product and quarantine insects. Annual Review of Entomology. 47: 331-359.

Fleurat-Lessard, F. (2015). Stored-Grain Pest Management. Encyclopedia of Food Grains: Second Edition. 4-4: 126-139.

Flingelli, G., M. Schöller, D. W. Klementz and C. Reichmuth (2014). "Influence of temperature and exposure time on the mortality of Tribolium castaneum eggs at fumigation with sulfuryl fluoride with regard to the progressive egg development." Journal fur Kulturpflanzen 66(1): 7-14.

Flinn, P. W., D. W. Hagstrum, C. Reed and T. W. Phillips (2003). "United States Department of Agriculture-Agricultural Research Service stored-grain areawide integrated pest management program." Pest Management Science 59(6-7): 614-618.

Flora, J. W., L. E. Byers, S. E. Plunkett and D. L. Faustini (2006). "Residue formations of phosphorus hydride polymers and phosphorus oxyacids during phosphine gas fumigations of stored products." Journal of Agricultural and Food Chemistry 54(1): 107-111.

Friedemann, A. E. R., L. Andernach, H. Jungnickel, D. W. Borchmann, D. Baltaci, P. Laux, H. Schulz and A. Luch (2020). "Phosphine fumigation – Time dependent changes in the volatile profile of table grapes." Journal of Hazardous Materials 393.

Gad, H. A., T. M. Sileem, R. S. Hassan and S. A. M. Abdelgaleil (2021). "Toxicity of gaseous ozone to the different life stages of cowpea beetle, Callosobruchus maculatus (Coleoptera: Bruchidae), under laboratory conditions." Hellenic Plant Protection Journal 14(1): 31-38.

Garry, V. F., P. F. Good, J. C. Manivel and D. P. Perl (1993). "Investigation of a fatality from nonoccupational aluminum phosphide exposure: Measurement of aluminum in tissue and body fluids as a marker of exposure." The Journal of Laboratory and Clinical Medicine 122(6): 739-747.

Gautam, S. G., G. P. Opit and E. Hosoda (2016). "Phosphine resistance in adult and immature life stages of Tribolium castaneum (Coleoptera: Tenebrionidae) and Plodia interpunctella (Lepidoptera: Pyralidae) populations in California." Journal of Economic Entomology 109(6): 2525-2533.
Gautam, S. G., G. P. Opit, C. Konemann, K. Shakya and E. Hosoda (2020). "Phosphine resistance in saw-toothed grain beetle, Oryzaephilus surinamensis in the United States." Journal of Stored Products Research 89.
Gourgouta, M., P. Agrafioti and C. G. Athanassiou (2021). "Insecticidal effect of phosphine for the control of different life stages of the khapra beetle, Trogoderma granarium (Coleoptera: Dermestidae)." Crop Protection 140.
Granella, S. J., T. R. Bechlin, D. Christ and S. R. M. Coelho (2022). "A potential role of nitric oxide in postharvest pest control: A review." Journal of the Saudi Society of Agricultural Sciences 21(7): 452-459.
Guru, P. N., D. Mridula, A. S. Dukare, B. M. Ghodki, A. U. Paschapur, I. Samal, M. Nikhil Raj, V. K. Padala, M. Rajashekhar and A. R. N. S. Subbanna (2022). "A comprehensive review on advances in storage pest management: Current scenario and future prospects." Frontiers in Sustainable Food Systems 6.
Haritos, V. S., K. A. Damcevski and G. Dojchinov (2006). "Improved efficacy of ethyl formate against stored grain insects by combination with carbon dioxide in a 'dynamic' application." Pest Management Science 62(4): 325-333.
Hasan, M. M., M. J. Aikins, M. W. Schilling, T. W. Phillips and R. Mahroof (2020). "Comparison of Methyl Bromide and Phosphine for Fumigation of Necrobia rufipes (Coleoptera: Cleridae) and Tyrophagus putrescentiae (Sarcoptiformes: Acaridae), Pests of High-Value Stored Products." Journal of Economic Entomology 113(2): 1008-1014.
Hinz, R., A. Mannetje, B. Glass, D. McLean and J. Douwes (2022). "Airborne Fumigants and Residual Chemicals in Shipping Containers Arriving in New Zealand." Annals of Work Exposures and Health 66(4): 481-494.
Holloway, J. C., M. G. Falk, R. N. Emery, P. J. Collins and M. K. Nayak (2016). "Resistance to phosphine in Sitophilus oryzae in Australia: A national analysis of trends and frequencies over time and geographical spread." Journal of Stored Products Research 69: 129-137.
Hong, T. K., S. H. Lee, J. S. Shin, K. H. Jang, E. S. Na, C. S. Park, C. H. Kim, J. R. Kim, S. R. Balusamy and H. Perumalsamy (2023). "Toxicological and molecular adverse effect of Illicium verum fruit constituents toward Bradysia procera." Pest Management Science 79(3): 1131-1139.
Hooper, J. L., J. M. Desmarchelier, Y. Ren and S. E. Allen (2003). "Toxicity of cyanogen to insects of stored grain." Pest Management Science 59(3): 353-357.
Horn, P., F. Horn, J. Tumambing and M. Rogers (2010). Studies and commercial application of VAPORPH3OS phosphine fumigant for disinfestation of exported fruits and vegetables in South America. Acta Horticulturae. 880: 407-414.
Howe, R. W. (1974). "Problems in the laboratory investigation of the toxicity of phosphine to stored product insects." Journal of Stored Products Research 10(3-4): 167-181.
Huang, Y. and S. H. Ho (1998). "Toxicity and antifeedant activities of cinnamaldehyde against the grain storage insects, Tribolium castaneum (Herbst) and Sitophilus zeamais Motsch." Journal of Stored Products Research 34(1): 11-17.
Huang, Y., F. Li, M. Liu, Y. Wang, F. Shen and P. Tang (2019). "Susceptibility of Tribolium castaneum to phosphine in China and functions of cytochrome P450s in phosphine resistance." Journal of Pest Science 92(3): 1239-1248.
Imamura, T., S. Todoriki, A. Miyanoshita, A. K. Horigane, M. Yoshida and T. Hayashi (2009). "Efficacy of soft-electron (low-energy electron) treatment for disinfestation of brown rice containing different ages of the maize weevil, Sitophilus zeamais Motschulsky." Radiation Physics and Chemistry 78(7-8): 627-630.
Isa, Z. M., T. W. Farrell, G. R. Fulford and N. A. Kelson (2016). "Mathematical modelling and numerical simulation of phosphine flow during grain fumigation in leaky cylindrical silos." Journal of Stored Products Research 67: 28-40.
Isa, Z. M., G. R. Fulford, N. A. Kelson and T. W. Farrell (2016). "Flow field and traverse times for fan forced injection of fumigant via circular or annular inlet into stored grain." Applied Mathematical Modelling 40(15-16): 7156-7163.
Isa, Z. M., M. D. Nazri and A. Idris (2022). "Numerical Simulation of Gas Flow through a Cylindrical Grain Storage." Malaysian Journal of Fundamental and Applied Sciences 18(5): 584-591.

Jabeen, A., A. Zaitoon, L. T. Lim and C. Scott-Dupree (2021). "Toxicity of Five Plant Volatiles to Adult and Egg Stages of Drosophila suzukii Matsumura (Diptera: Drosophilidae), the Spotted-Wing Drosophila." Journal of Agricultural and Food Chemistry 69(33): 9511-9519.

Jagadeesan, R. and M. K. Nayak (2017). "Phosphine resistance does not confer cross-resistance to sulfuryl fluoride in four major stored grain insect pests." Pest Management Science 73(7): 1391-1401.

Jagadeesan, R., M. K. Nayak, H. Pavic, K. Chandra and P. J. Collins (2015). "Susceptibility to sulfuryl fluoride and lack of cross-resistance to phosphine in developmental stages of the red flour beetle, Tribolium castaneum (Coleoptera: Tenebrionidae)." Pest Management Science 71(10): 1379-1386.

Jagadeesan, R., D. I. Schlipalius, V. T. Singarayan, N. S. Nath, M. K. Nayak and P. R. Ebert (2021). "Unique genetic variants in dihydrolipoamide dehydrogenase (dld) gene confer strong resistance to phosphine in the rusty grain beetle, Cryptolestes ferrugineus (Stephens)." Pesticide Biochemistry and Physiology 171.

Jagadeesan, R., V. T. Singarayan, K. Chandra, P. R. Ebert and M. K. Nayak (2018). "Potential of Co-Fumigation with Phosphine (PH 3) and Sulfuryl Fluoride (SO 2 F 2) for the Management of Strongly Phosphine-Resistant Insect Pests of Stored Grain." Journal of Economic Entomology 111(6): 2956-2965.

Jamieson, L. E., N. E. M. Page-Weir, M. J. Griffin, S. P. Redpath, A. Chhagan and P. G. Connolly (2016). "Efficacy of ethyl formate As a disinfestation treatment for codling moth (Cydia pomonella) in apples." New Zealand Plant Protection 69: 167-175.

Jones, A. T., R. C. Jones and E. O. Longley (1964). "Environmental and Clinical Aspects of Bulk Wheat Fumigation with Aluminum Phosphide." American Industrial Hygiene Association Journal 25(4): 376-379.

Kailappan, R., S. K. Aleksha Kudos, S. Mohan and V. V. Sreenarayanan (1999). "Effect of field infestation on post-harvest losses in pulses." Pestology 23(8): 9-10.

Karthik, S. K., D. Kumari, B. M. Nagaraj, G. Jayaprakash and J. Mohana Velu (2015). "Aluminium phosphide poisoning - A case report." Indian Journal of Forensic Medicine and Toxicology 9(2): 13-15.

Kaur, R., E. V. Daniels, M. K. Nayak, P. R. Ebert and D. I. Schlipalius (2013). "Determining changes in the distribution and abundance of a Rhyzopertha dominica phosphine resistance allele in farm grain storages using a DNA marker." Pest Management Science 69(6): 685-688.

Kaur, R. and M. K. Nayak (2015). "Developing effective fumigation protocols to manage strongly phosphine-resistant Cryptolestes ferrugineus (Stephens) (Coleoptera: Laemophloeidae)." Pest Management Science 71(9): 1297-1302.

Kaur, R., D. I. Schlipalius, P. J. Collins, A. J. Swain and P. R. Ebert (2012). "Inheritance and relative dominance, expressed as toxicity response and delayed development, of phosphine resistance in immature stages of Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae)." Journal of Stored Products Research 51: 74-80.

Kaur, R., M. Subbarayalu, R. Jagadeesan, G. J. Daglish, M. K. Nayak, H. R. Naik, S. Ramasamy, C. Subramanian, P. R. Ebert and D. I. Schlipalius (2015). "Phosphine resistance in India is characterised by a dihydrolipoamide dehydrogenase variant that is otherwise unobserved in eukaryotes." Heredity 115(3): 188-194.

Kinoshita, M., Y. Sato, H. Nebiki, Y. Tamamori, N. Ishii, T. Inoue, G. Hamano, A. Kanazawa and S. Kubo (2019). "Occupational cholangiocarcinoma diagnosed 18 years after the end of exposure to 1,2-dichloropropane and dichloromethane at a printing company: a case report." Surgical Case Reports 5(1): 65.

Konemann, C. E., Z. Hubhachen, G. P. Opit, S. Gautam and N. S. Bajracharya (2017). "Phosphine Resistance in Cryptolestes ferrugineus (Coleoptera: Laemophloeidae) Collected from Grain Storage Facilities in Oklahoma, USA." Journal of Economic Entomology 110(3): 1377-1383.

Kumar, P., T. R. Chauhan, R. Gera and N. Kumar (2008). "Analysis of natural levels of ethyl formate in freshly harvested feed commodities using gas chromatography." Indian Journal of Animal Sciences 78(6): 642-644.

Kumar, S., D. Mohapatra, N. Kotwaliwale and K. K. Singh (2017). "Vacuum Hermetic Fumigation: A review." Journal of Stored Products Research 71: 47-56.

Kumar, S., D. Mohapatra, N. Kotwaliwale and K. K. Singh (2020). "Efficacy of sensor assisted vacuum hermetic storage against chemical fumigated wheat." Journal of Stored Products Research 88.

Lawrence, L. (2005). "Vapormate™ - An environmentally friendly fumigant." Outlooks on Pest Management 16(3): 114-115.

Lee, B. H., W. Huh, Y. Ren, D. Mahon and W. S. Choi (2007). "New Formulations of Ethyl Formate to Control Internal Stages of Sitophilus oryzae." Journal of Asia-Pacific Entomology 10(4): 369-374.

Lee, H. K., G. Jeong, H. K. Kim, B. S. Kim, J. O. Yang, H. N. Koo and G. H. Kim (2020). "Fumigation activity against phosphine-resistant Tribolium castaneum (Coleoptera: Tenebrionidae) using carbonyl sulfide." Insects 11(11): 1-12.

Lilford, K., G. R. Fulford, D. Schlipalius and A. Ridley (2009). Fumigation of stored-grain insects - a two locus model of phosphine resistance. 18th World IMACS Congress and MODSIM 2009 - International Congress on Modelling and Simulation: Interfacing Modelling and Simulation with Mathematical and Computational Sciences, Proceedings.

Liu, T., L. Li, B. Li, F. Zhang and Y. Wang (2012). "Proteomic analysis of peach fruit moth larvae treated with phosphine." Frontiers in Bioscience - Elite 4 E(5): 1780-1786.

Liu, Y. B. (2008). "Low temperature phosphine fumigation for postharvest control of western flower thrips (Thysanoptera: Thripidae) on lettuce, broccoli, asparagus, and strawberry." Journal of Economic Entomology 101(6): 1786-1791.

Loddé, B., D. Lucas, J. M. Letort, D. Jegaden, R. Pougnet and J. D. Dewitte (2015). "Acute phosphine poisoning on board a bulk carrier: Analysis of factors leading to a fatal case." Journal of Occupational Medicine and Toxicology 10(1).

Lucas, D., G. Mauguen, P. Lesné, E. Polard and D. Jegaden (2018). "Exposure to phosphine in maritime transport: A real and important occupational risk: A report of three cases." International Maritime Health 69(3): 181-183.

Mahroof, R. M., B. A. Amoah and J. Wrighton (2018). "Efficacy of ozone against the life stages of oryzaephilus mercator (Coleoptera: Silvanidae)." Journal of Economic Entomology 111(1): 470-481.

Mair, A. and A. I. El-Kadi (2013). "Logistic regression modeling to assess groundwater vulnerability to contamination in Hawaii, USA." Journal of Contaminant Hydrology 153: 1-23.

Malekpour, R., P. A. Arnold, M. A. Rafter, G. J. Daglish and G. H. Walter (2020). "Effects of sublethal phosphine exposure on respiration rate and dispersal propensity of adult females of Tribolium castaneum." Journal of Pest Science 93(1): 149-157.

Mangoba, M. A. A. and D. G. Alvindia (2019). "Response of Suidasia pontifica (Acaridida: Suidasiidae) to phosphine fumigation." Experimental and Applied Acarology 79(3-4): 377-386.

Mario, M. B., L. P. Astuti, J. L. Hsu, L. Kafle and I. Fernando (2023). "Bioefficacy of eight different plant powders applied as fumigants against the adzuki bean weevil, Callosobruchus chinensis." Crop Protection 167.

Mau, Y. S., P. J. Collins, G. J. Daglish, M. K. Nayak, H. Pavic and P. R. Ebert (2012). "The rph1 gene is a common contributor to the evolution of phosphine resistance in independent field isolates of rhyzopertha dominica." PLoS ONE 7(2).

McCulloch, G. A., S. Mohankumar, S. Subramanian, T. S. Rajan, C. Rahul, R. Surendran, R. Gaurav, S. Chandrasekaran, G. J. Daglish and G. H. Walter (2019). "Contrasting patterns of phylogeographic structuring in two key beetle pests of stored grain in India and Australia." Journal of Pest Science 92(3): 1249-1259.

Misra, U. K., S. K. Bhargava, D. Nag, M. M. Kidwai and M. M. Lal (1988). "Occupational phosphine exposure in Indian workers." Toxicology Letters 42(3): 257-263.

Morrison, W. R., III, F. H. Arthur, C. G. Athanassiou, E. Lampiri, L. T. Wilson, Y. Yang and J. Wang (2022). "Modeling of Sitophilus oryzae (L.) (Coleoptera: Curculionidae) based on historical weather data indicates aeration is effective for management of wheat stored in Greece." Computers and Electronics in Agriculture 197.

Morrison, W. R., III, F. H. Arthur and A. Bruce (2021). "Characterizing and predicting sublethal shifts in mobility by multiple stored product insects over time to an old and novel contact insecticide in three key stored commodities." Pest Management Science 77(4): 1990-2006.

Morrison, W. R., III, D. Brabec, A. Bruce, F. H. Arthur and C. G. Athanassiou (2023). "Immediate and delayed movement of resistant and susceptible adults of Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae) after short exposures to phosphine." Pest Management Science 79(6): 2066-2074.

Morrison, W. R., N. L. Larson, D. Brabec, A. Zhang and R. Mahroof (2019). "Methyl Benzoate as a Putative Alternative, Environmentally Friendly Fumigant for the Control of Stored Product Insects." Journal of Economic Entomology 112(5): 2458-2468.

Morrison, W. R., III, E. D. Scully and J. F. Campbell (2021). "Towards developing areawide semiochemical-mediated, behaviorally-based integrated pest management programs for stored product insects." Pest Management Science 77(6): 2667-2682.

Mostafiz, M. M., E. Hassan, R. Acharya, J. K. Shim and K. Y. Lee (2021). "Methyl benzoate is superior to other natural fumigants for controlling the Indian meal moth (Plodia interpunctella)." Insects 12(1): 1-11.
Nayak, M. K. (2006). "Management of mould mite Tyrophagus putrescentiae (Schrank) (Acarina: Acaridae): A case study in stored animal feed." International Pest Control 48(3): 128-130.
Nayak, M. K. and P. J. Collins (2008). "Influence of concentration, temperature and humidity on the toxicity of phosphine to the strongly phosphine-resistant psocid Liposcelis bostrychophila Badonnel (Psocoptera: Liposcelididae)." Pest Management Science 64(9): 971-976.
Nayak, M. K., P. J. Collins and H. Pavic (2002). "Long-term effectiveness of grain protectants and structural treatments against Liposcelis decolor (Pearman) (Psocoptera: Liposcelididae), a pest of stored products." Pest Management Science 58(12): 1223-1228.
Nayak, M. K., G. J. Daglish and T. W. Phillips (2015). "Managing resistance to chemical treatments in stored products pests." Stewart Postharvest Review 11(1): 1-6.
Nayak, M. K., G. J. Daglish, T. W. Phillips and P. R. Ebert (2020). Resistance to the fumigant phosphine and its management in insect pests of stored products: A global perspective. Annual Review of Entomology. 65: 333-350.
Nayak, M. K., J. C. Holloway, R. N. Emery, H. Pavic, J. Bartlet and P. J. Collins (2013). "Strong resistance to phosphine in the rusty grain beetle, Cryptolestes ferrugineus (Stephens) (Coleoptera: Laemophloeidae): Its characterisation, a rapid assay for diagnosis and its distribution in Australia." Pest Management Science 69(1): 48-53.
Nayak, M. K., R. Kaur, R. Jagadeesan, H. Pavic, T. W. Phillips and G. J. Daglish (2019). "Development of a Quick Knockdown Test for Diagnosing Resistance to Phosphine in Sitophilus oryzae (Coleoptera: Curculionidae), a Major Pest of Stored Products." Journal of Economic Entomology 112(4): 1975-1982.
Nguyen, T. T., P. J. Collins and P. R. Ebert (2015). "Inheritance and characterization of strong resistance to phosphine in Sitophilus oryzae (L.)." PLoS ONE 10(4).
Nguyen, T. T., R. Kaur, D. I. Schlipalius, P. J. Collins and P. R. Ebert (2016). "Effect of diet on phosphine toxicity, rate of development and reproduction of the rice weevil Sitophilus oryzae (Linnaeus)." Journal of Stored Products Research 69: 221-226.
Ntalli, N., A. Skourti, E. P. Nika, M. C. Boukouvala and N. G. Kavallieratos (2021). "Five natural compounds of botanical origin as wheat protectants against adults and larvae of Tenebrio molitor L. and Trogoderma granarium Everts." Environmental Science and Pollution Research 28(31): 42763-42775.
Opit, G. P., T. W. Phillips, M. J. Aikins and M. M. Hasan (2012). "Phosphine resistance in tribolium castaneum and rhyzopertha dominica from stored wheat in Oklahoma." Journal of Economic Entomology 105(4): 1107-1114.
Opit, G. P., E. Thoms, T. W. Phillips and M. E. Payton (2016). "Effectiveness of sulfuryl fluoride fumigation for the control of phosphine-resistant grain insects infesting stored wheat." Journal of Economic Entomology 109(2): 930-941.
Oppert, B., R. N. C. Guedes, M. J. Aikins, L. Perkin, Z. Chen, T. W. Phillips, K. Y. Zhu, G. P. Opit, K. Hoon, Y. Sun, G. Meredith, K. Bramlett, N. S. Hernandez, B. Sanderson, M. W. Taylor, D. Dhingra, B. Blakey, M. Lorenzen, F. Adedipe and F. Arthur (2015). "Genes related to mitochondrial functions are differentially expressed in phosphine-resistant and -susceptible Tribolium castaneum." BMC Genomics 16(1).
Oppert, B., A. Muszewska, K. Steczkiewicz, E. Šatović-Vukšić, M. Plohl, J. A. Fabrick, K. S. Vinokurov, I. Koloniuk, J. S. Johnston, T. P. L. Smith, R. N. C. Guedes, W. R. Terra, C. Ferreira, R. O. Dias, K. A. Chaply, E. N. Elpidina, V. F. Tereshchenkova, R. F. Mitchell, A. J. Jenson, R. McKay, T. Shan, X. Cao, Z. Miao, C. Xiong, H. Jiang, W. R. Morrison, III, S. Koren, D. Schlipalius, M. D. Lorenzen, R. Bansal, Y. H. Wang, L. Perkin, M. Poelchau, K. Friesen, M. L. Olmstead, E. Scully and J. F. Campbell (2022). "The Genome of Rhyzopertha dominica (Fab.) (Coleoptera: Bostrichidae): Adaptation for Success." Genes 13(3).
Otitodun, G. O., M. O. Ogundare, S. K. Ajao, S. I. Nwaubani, G. I. Abel, G. P. Opit, G. Bingham and M. O. Omobowale (2019). "Efficacy of phosphine and insect penetration ability in ZeroFly® bags." Journal of Stored Products Research 82: 81-90.
Oyeniyi, E. A., J. A. Adeyemi and O. T. Omotoso (2021). "The interaction between strain and food type influences biological parameters of Tribolium castaneum and its susceptibility to Dennettia tripetala extract." Entomologia Experimentalis et Applicata 169(10): 899-910.
Pandey, P. and R. Yadav (2018). "A review on volatile organic compounds (VOCs) as environmental pollutants: fate and distribution." International Journal of Plant and Environment 4(2).

Pant, H. and S. Tripathi (2012). "Evaluation of aluminum phosphide against wood-destroying insects." Journal of Economic Entomology 105(1): 135-139.

Park, D. S., C. Peterson, S. Zhao and J. R. Coats (2004). "Fumigation toxicity of volatile natural and synthetic cyanohydrins to stored-product pests and activity as soil fumigants." Pest Management Science 60(8): 833-838.

Park, M. G., B. H. Lee, J. O. Yang, B. S. Kim, G. H. Roh, P. E. Kendra and D. H. Cha (2021). "Ethyl Formate as a Methyl Bromide Alternative for Fumigation of Citrus: Efficacy, Fruit Quality, and Workplace Safety." Journal of Economic Entomology 114(6): 2290-2296.

Phillips, T. W., A. Cato, E. Afful and M. K. Nayak (2019). "Evaluation of knockdown bioassay methods to assess phosphine resistance in the red flour beetle, tribolium castaneum (herbst) (coleoptera: Tenebrionidae)." Insects 10(5).

Pidakala, P. P. B., K. Esfandi, S. Afsar, C. Baldassarre, G. I. Ortiz, N. Page-Weir, A. Najar-Rodriguez, K. O'Donnell, L. E. Jamieson and A. B. Woolf (2022). "Effects of phosphine (ECO2FUME®) on 'Hass' avocado fruit quality and target pest mortality." New Zealand Journal of Crop and Horticultural Science.

Pidakala, P. P. B., R. T. Wilkinson, A. Nangul, D. E. Hartnett, N. E. M. Page-Weir, A. J. Hawthorne, L. E. Jamieson and A. B. Woolf (2018). "Potential use of ethyl formate treatment to control surface pests of 'Hass' avocado fruit." New Zealand Plant Protection 71: 121-128.

Pike, V. (1994). "Laboratory assessment of the efficacy of phosphine and methyl bromide fumigation against all life stages of Liposcelis entomophilus (Enderlein)." Crop Protection 13(2): 141-145.

Pimentel, M. A. G., L. R. A. Faroni, A. S. Corrêa and R. N. C. Guedes (2012). "Phosphine-induced walking response of the lesser grain borer (Rhyzopertha dominica)." Pest Management Science 68(10): 1368-1373.

Pimentel, M. A. G., L. R. D. Faroni, M. R. Tótola and R. N. C. Guedes (2007). "Phosphine resistance, respiration rate and fitness consequences in stored-product insects." Pest Management Science 63(9): 876-881.

Plumier, B. M. and D. E. Maier (2018). "Sensitivity analysis of a fumigant movement and loss model for bulk stored grain to predict effects of environmental conditions and operational variables on fumigation efficacy." Journal of Stored Products Research 78: 18-26.

Plumier, B. M., M. Schramm and D. E. Maier (2018). "Developing and verifying a fumigant loss model for bulk stored grain to predict phosphine concentrations by taking into account fumigant leakage and sorption." Journal of Stored Products Research 77: 197-204.

Plumier, B. M., M. Schramm, Y. Ren and D. E. Maier (2020). "Modeling post-fumigation desorption of phosphine in bulk stored grain." Journal of Stored Products Research 85.

Porter, I., M. Pizano, M. Besri, S. W. Mattner and P. Fraser (2010). Progress in the global phase out of methyl bromide and the relative effectiveness of soil disinfestation strategies. Acta Horticulturae. 883: 59-66.

Pourmirza, A. A. and M. Tajbakhsh (2008). "Studies on the toxicity of acetone, acrolein and carbon dioxide on stored-product insects and wheat seed." Pakistan Journal of Biological Sciences 11(7): 953-963.

Pratt, S. J. (2003). "A new measure of uptake: Desorption of unreacted phosphine from susceptible and resistant strains of Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae)." Journal of Stored Products Research 39(5): 507-520.

Prider, J. and A. Williams (2014). "Using dazomet to reduce broomrape seed banks in soils with low moisture content." Crop Protection 59: 43-50.

Pupin, F., V. Bikoba, W. B. Biasi, G. M. Pedroso, Y. Ouyang, E. E. Grafton-Cardwell and E. J. Mitcham (2013). "Postharvest control of western flower thrips (Thysanoptera: Thripidae) and California red scale (Hemiptera: Diaspididae) with ethyl formate and its impact on citrus fruit quality." Journal of Economic Entomology 106(6): 2341-2348.

Pura Naik, J., B. S. Ramesh and K. N. Gurudutt (2005). "Fumigation studies on cured large cardamom (Amomum subulatum Roxb.) capsules." Journal of Food Science and Technology 42(6): 531-533.

Qasim, M. U., M. W. Hassan, J. J. Wang, M. Jamil, J. Iqbal and M. Ul-Hasan (2013). "Management of tribolium castaneum (coleoptera: Tenebrionidae) with phosphine fumigation in relation to packaging materials and food types." Pakistan Journal of Zoology 45(6): 1639-1645.

Qiao, K., H. Zhang, H. Wang, X. Ji and K. Wang (2011). "Efficacy of aluminium phosphide as a soil fumigant against nematode and weed in tomato crop." Scientia Horticulturae 130(3): 570-574.

Rajashekar, Y., P. V. Reddy, K. Begum, B. C. Leelaja and S. Rajendran (2006). "Studies on aluminium phosphide tablet formulation." Pestology 30(4): 41-45.

Rajendran, S. and H. S. C. Devi (2004). "Oilseeds - Storage and insect pest control." Journal of Food Science and Technology 41(4): 359-367.
Rajendran, S. and K. M. Hajira Parveen (2005). "Insect infestation in stored animal products." Journal of Stored Products Research 41(1): 1-30.
Rajendran, S. and N. Muralidharan (2000). "Control failure due to insect resistance in whole-store fumigation of milled rice with phosphine." Pestology 24(10): 29-35.
Rajendran, S., H. Parveen, K. Begum and R. Chethana (2004). "Influence of phosphine on hatching of Cryptolestes ferrugineus (Coleoptera: Cucujidae), Lasioderma serricorne (Coleoptera: Anobiidae) and Oryzaephilus surinamensis (Coleoptera: Silvanidae)." Pest Management Science 60(11): 1114-1118.
Rajendran, S. and V. R. Sriranjini (2007). "Use of fumigation for managing grain quality." Stewart Postharvest Review 3(6).
Ramadan, G. R. M., K. Y. Zhu, S. A. M. Abdelgaleil, M. S. Shawir, A. S. El-Bakary, P. A. Edde and T. W. Phillips (2020). "Ethanedinitrile as a Fumigant for Lasioderma serricorne (Coleoptera: Anobiidae), and Rhyzopertha Dominica (Coleoptera: Bostrichidae): Toxicity and Mode of Action." Journal of Economic Entomology 113(3): 1519-1527.
Ramya, R. S., C. Srivastava, S. Subramanian and M. Ranjith (2023). "Inheritance pattern and expression of resistance to phosphine in larval stage of Tribolium castaneum (Coleoptera: Tenebrionidae)." Journal of Asia-Pacific Entomology 26(1).
Reddy, P. V., Y. Rajashekar, K. Begum, B. C. Leelaja and S. Rajendran (2007). "The relation between phosphine sorption and terminal gas concentrations in successful fumigation of food commodities." Pest Management Science 63(1): 96-103.
Redlinger, L. M., J. L. Zettler, J. G. Leesch, H. B. Gillenwater, R. Davis and J. M. Zehner (1979). "In-transit shipboard fumigation of wheat." Journal of economic entomology 72(4): 642-647.
Regmi, H. and J. Desaeger (2020). "Integrated management of root-knot nematode (Meloidogyne spp.) in Florida tomatoes combining host resistance and nematicides." Crop Protection 134.
Ren, Y., B. Lee, D. Mahon, N. I. Xin, M. Head and R. Reid (2008). "Fumigation of wheat using liquid ethyl formate plus methyl isothiocyanate in 50-tonne farm bins." Journal of Economic Entomology 101(2): 623-630.
Ren, Y., B. Lee, B. Padovan and L. Cai (2012). "Ethyl formate plus methyl isothiocyanate-a potential liquid fumigant for stored grains." Pest Management Science 68(2): 194-201.
Ren, Y. and D. Mahon (2006). "Fumigation trials on the application of ethyl formate to wheat, split faba beans and sorghum in small metal bins." Journal of Stored Products Research 42(3): 277-289.
Ren, Y. L., J. Demarchelier and P. Healy (2011). "Effect of carbonyl sulphide (COS), ethyl formate (EF) and carbon disulphide (CS2) on the malting quality of barley and the flavour profile of beer." Journal of the Institute of Brewing 117(4): 593-599.
Rezanejad, S., M. M. Fazel, A. Kavusi and J. P. Michaud (2022). "Curing raisins with sulfur dioxide suppresses population growth of Indian meal moth, Plodia interpunctella (Hubner) (Lepidoptera: Pyralidae)." Journal of Asia-Pacific Entomology 25(1).
Riaz, T., F. R. Shakoori and S. S. Ali (2017). "Effect of phosphine on esterases of larvae and adult beetles of phosphine-exposed populations of stored grain pest, Trogoderma granarium collected from different godowns of Punjab." Pakistan Journal of Zoology 49(3): 819-824.
Ridley, A. W., S. Magabe, D. I. Schlipalius, M. A. Rafter and P. J. Collins (2012). "Sublethal Exposure to Phosphine Decreases Offspring Production in Strongly Phosphine Resistant Female Red Flour Beetles, Tribolium castaneum (Herbst)." PLoS ONE 7(12).
Rocchi, R., R. Rosato, M. Bellocci, G. Migliorati and R. Scarpone (2022). "Ion Chromatography–High-Resolution Mass Spectrometry Method for the Determination of Bromide Ions in Cereals and Legumes: New Scenario for Global Food Security." Foods 11(16).
Rulon, R. A., D. E. Maier and M. D. Boehlje (1997). Post-harvest IPM economic model to evaluate new pest control technologies. Paper - American Society of Agricultural Engineers.
Sadeghi, G. R., A. A. Pourmirza and M. H. Safaralizade (2011). "Effects of nitrogen and Phosphine mixtures on storedproduct insects' mortality." African Journal of Biotechnology 10(32): 6133-6144.
Sahu, U., S. S. Ibrahim and S. Ezhil Vendan (2021). "Persistence and ingestion characteristics of phytochemical volatiles as bio-fumigants in Sitophilus oryzae adults." Ecotoxicology and Environmental Safety 210.

Sakka, M. K., D. Romano, C. Stefanini, A. Canale, G. Benelli and C. G. Athanassiou (2020). "Mobility parameters of Tribolium castaneum and Rhyzopertha dominica populations with different susceptibility to phosphine." Journal of Stored Products Research 87.

Salha, H., I. Kalinović, M. Ivezić, V. Rozman and A. Liška (2009). Application of low temperatures for pests control in stored maize. Proceedings of 5th International Congress FLOUR-BREAD 2009 - 7th Croatian Congress of Cereal Technologists.

Sankar, R., T. K. Ghosh, H. Ray, A. Ghosh, S. Saha, D. Ghosh and N. Bhattacharyya (2022). Detection of Optimum Fumigation in Grain Storage Using FUMON. Lecture Notes in Networks and Systems. 191: 967-975.

Savage, B. A., S. Masten, H. Chung and M. Grieshop (2022). "Exploring the Insecticidal Potential of Gaseous and Aqueous Ozone to Control Spotted-Wing Drosophila, Drosophila suzukii (Diptera: Drosophilidae)." Journal of Economic Entomology 115(4): 1203-1212.

Schlipalius, D., P. J. Collins, Y. Mau and P. R. Ebert (2006). "New tools for management of phosphine resistance." Outlooks on Pest Management 17(2): 52-56.

Schlipalius, D. I., W. Chen, P. J. Collins, T. Nguyen, P. E. B. Reilly and P. R. Ebert (2008). "Gene interactions constrain the course of evolution of phosphine resistance in the lesser grain borer, Rhyzopertha dominica." Heredity 100(5): 506-516.

Schlipalius, D. I., A. G. Tuck, R. Jagadeesan, T. Nguyen, R. Kaur, S. Subramanian, R. Barrero, M. Nayak and P. R. Ebert (2018). "Variant linkage analysis using de Novo transcriptome sequencing identifies a conserved phosphine resistance gene in insects." Genetics 209(1): 281-290.

Schlipalius, D. I., A. G. Tuck, H. Pavic, G. J. Daglish, M. K. Nayak and P. R. Ebert (2019). "A high-throughput system used to determine frequency and distribution of phosphine resistance across large geographical regions." Pest Management Science 75(4): 1091-1098.

Shi, M., P. J. Collins, T. J. Ridsdill-Smith, R. N. Emery and M. Renton (2013). "Dosage consistency is the key factor in avoiding evolution of resistance to phosphine and population increase in stored-grain pests." Pest Management Science 69(9): 1049-1060.

Shi, M. and M. Renton (2013). "Modelling mortality of a stored grain insect pest with fumigation: Probit, logistic or Cauchy model?" Mathematical Biosciences 243(2): 137-146.

Sivakumar, D., L. A. Terry and L. Korsten (2010). "An overview on litchi fruit quality and alternative postharvest treatments to replace sulfur dioxide fumigation." Food Reviews International 26(2): 162-188.

Small, G. (2009). "Evaluation of the impact of sulfuryl fluoride fumigation and heat treatment on stored-product insect populations in UK flour mills." International Pest Control 51(1): 43-46.

Small, G. J. (2007). "A comparison between the impact of sulfuryl fluoride and methyl bromide fumigations on stored-product insect populations in UK flour mills." Journal of Stored Products Research 43(4): 410-416.

Solanki, M. K., A. Abdelfattah, M. Britzi, V. Zakin, M. Wisniewski, S. Droby and E. Sionov (2019). "Shifts in the composition of the microbiota of stored wheat grains in response to fumigation." Frontiers in Microbiology 10(MAY).

Sousa, A. H., L. R. A. Faroni, G. N. Silva and R. N. C. Guedes (2012). "Ozone toxicity and walking response of populations of sitophilus zeamais (Coleoptera: Curculionidae)." Journal of Economic Entomology 105(6): 2187-2195.

Sousa, A. H., L. R. D. Faroni, R. N. C. Guedes, M. R. Tótola and W. I. Urruchi (2008). "Ozone as a management alternative against phosphine-resistant insect pests of stored products." Journal of Stored Products Research 44(4): 379-385.

Sousa, A. H., L. R. D. A. Faroni, M. A. G. Pimentel and R. N. C. Guedes (2009). "Developmental and population growth rates of phosphine-resistant and -susceptible populations of stored-product insect pests." Journal of Stored Products Research 45(4): 241-246.

Srinath, D., M. Muthu, A. N. Ragunathan and S. K. Majumder (1974). "Effect of fumigants on the internal microflora of insect pests of stored products." Indian Journal of Microbiology 14(1): 7-12.

Sriranjini, V. and S. Rajendran (2008). "Efficacy of sulfuryl fluoride against insect pests of stored food commodities." Pestology 32(6): 32-38.

Sriranjini, V. R. and S. Rajendran (2008). "Sorption of sulfuryl fluoride by food commodities." Pest Management Science 64(8): 873-879.

Subekti, N. and M. A. Syahadan (2021). Comparison the effectiveness of the fumigants sulfuryl fluoride and phosphine in controlling warehouse pest insects. Journal of Physics: Conference Series.

Subekti, N., M. A. Syahadan and A. K. Mahsusoh (2021). Comparison the effectiveness of the fumigant phosphine to control warehouse pest insects in soybean seed and bird feed commodities. Journal of Physics: Conference Series.

Tao, L., W. Qin, Z. Wei, X. Li and H. Zhang (2022). "Effects of small-scale storage on the cooking property and fatty acid profile of sea rice paddy." Applied Food Research 2(2).

Taylor, R. W. D. (1994). "Methyl bromide-Is there any future for this noteworthy fumigant?" Journal of Stored Products Research 30(4): 253-260.

Thabit, T. M. A. M. and D. I. H. Elgeddawy (2018). "Determination of phosphine residues in wheat and yellow corn with a new developed method using headspace and SIM mode GC-MS." Journal of AOAC International 101(1): 288-292.

Vélez, M., R. C. Bernardes, W. F. Barbosa, J. C. Santos and R. N. C. Guedes (2019). "Walking activity and dispersal on deltamethrin- and spinosad-treated grains by the maize weevil Sitophilus zeamais." Crop Protection 118: 50-56.

Venkidusamy, M., R. Jagadeesan, M. K. Nayak, M. Subbarayalu, C. Subramaniam and P. J. Collins (2018). "Relative tolerance and expression of resistance to phosphine in life stages of the rusty grain beetle, Cryptolestes ferrugineus." Journal of Pest Science 91(1): 277-286.

Waheed, H. W., M. W. Hassan, G. Sarwar and M. Jamil (2022). "Laboratory Evaluation of Storage Bags for Infestations in Wheat Caused by Rhyzopertha dominica F. (Coleoptera: Bostrichidae) and Trogoderma granarium Everts (Coleoptera: Dermestidae) and Their Control Using Phosphine Fumigation." Insects 13(10).

Wang, D. and P. J. Collins (2003). "Effectiveness of closed-loop systems for phosphine fumigation of large scale grain storages in China." International Pest Control 45(6): 325-328.

Wang, Z., Y. Xie, M. Sabier, T. Zhang, J. Deng, X. Song, Z. Liao, Q. Li, S. Yang, Y. Cao, X. Liu and G. Zhou (2021). "Trans-anethole is a potent toxic fumigant that partially inhibits rusty grain beetle (Cryptolestes ferrugineus) acetylcholinesterase activity." Industrial Crops and Products 161.

Williams, P., P. J. Nickson, M. F. Braby and A. P. Henderson (1996). "Phosphine fumigations of wheat in 2500 m3 steel bins without recirculation facilities." Journal of Stored Products Research 32(2): 153-162.

Wu, G., T. Chen, Y. Ha, D. Shen, H. Feng and Y. Long (2018). "Study of aluminum phosphide levels in waste fumigants from food shipments following simple immersion treatment." Environment Protection Engineering 44(1): 19-27.

Wu, G., T. Chen, Y. Jia, D. Shen, H. Feng and Y. Long (2018). "Study of aluminum phosphide levels in waste fumigants from food shipments following simple immersion treatment." Environment Protection Engineering 44(1): 19-27.

Wu, H., G. A. Zhang, S. Zeng and K. C. Lin (2009). "Extraction of allyl isothiocyanate from horseradish (Armoracia rusticana) and its fumigant insecticidal activity on four stored-product pests of paddy." Pest Management Science 65(9): 1003-1008.

Wu, M., Y. Xiong, R. Han, W. Dong and C. Xiao (2021). "Fumigant Toxicity and Oviposition Deterrent Activity of Volatile Constituents from Asari Radix et Rhizoma against Phthorimaea operculella (Lepidoptera: Gelechiidae)." Journal of Insect Science 20(6).

Xiao, Y., T. Liu, C. Gu, J. Yu, M. Agarwal, C. Shan and Y. Ren (2019). "Physical, chemical and biological behaviour of fumigants on cottonseed." Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes 54(1): 41-48.

Xinyi, E., B. Li and B. Subramanyam (2018). "Toxicity of chlorine dioxide gas to phosphine-susceptible and -resistant adults of five stored-product insect species: Influence of temperature and food during gas exposure." Journal of Economic Entomology 111(4): 1947-1957.

Xinyi, E., B. Subramanyam and B. Li (2017). "Efficacy of ozone against phosphine susceptible and resistant strains of four stored-product insect species." Insects 8(2).

Xinyi, E., B. Subramanyam and B. Li (2017). "Responses of phosphine susceptible and resistant strains of five stored-product insect species to chlorine dioxide." Journal of Stored Products Research 72: 21-27.

Yan, H., H. Chen, Z. Li, M. Shen, X. Zhuo, H. Wu and P. Xiang (2018). "Phosphine analysis in postmortem specimens following inhalation of phosphine: Fatal aluminum phosphide poisoning in children." Journal of Analytical Toxicology 42(5): 330-336.

Yang, X., Y. B. Liu, G. Simmons, D. Light and R. Haff (2021). "Nitric oxide fumigation for control of navel orangeworm, Amyelois transitella, on walnut." Journal of Applied Entomology 145(3): 270-276.

Yokoyama, V. Y. (2011). "Approved quarantine treatment for hessian fly (Diptera: Cecidomyiidae) in large-size hay bales and hessian fly and cereal leaf beetle (Coleoptera: Chrysomelidae) control by bale compression." Journal of Economic Entomology 104(3): 792-798.

Yokoyama, V. Y. (2014). "Multiple quarantine treatment using bale compression and a three-day fumigation to control hessian fly (Diptera: Cecidomyiidae) in exported hay." Journal of Economic Entomology 107(3): 981-986.

Yokoyama, V. Y. and G. T. Miller (2002). "Bale compression and hydrogen phosphide fumigation to control cereal leaf beetle (Coleoptera: Chrysomelidae) in exported rye straw." Journal of economic entomology 95(2): 513-519.

Young, P., A. Luch and P. Laux (2023). "Impact of phosphine and of sulfuryl fluoride fumigation on walnut quality." Journal of Stored Products Research 100.

Zhang, C., Z. Ma, X. Zhang and H. Wu (2017). "Transcriptomic alterations in Sitophilus zeamais in response to allyl isothiocyanate fumigation." Pesticide Biochemistry and Physiology 137: 62-70.

Ziaee, M., A. Ebadollahi and W. Wakil (2021). "Integrating inert dusts with other technologies in stored products protection." Toxin Reviews 40(4): 404-419.

Wageningen Food Safety Research
P.O. Box 230
6700 AE Wageningen
The Netherlands
T +31 (0)317 48 02 56
wur.eu/food-safety-research

WFSR Report 2025.007

The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

To explore the potential of nature to improve the quality of life

Wageningen Food Safety Research
P.O. Box 230
6700 AE Wageningen
The Netherlands
T +31 (0) 317 48 02 56
wur.eu/food-safety-research

WFSR report 2025.007

The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.