# Post-Harvest Commodity Fumigation in California

Roundtable Convening Proceedings

Held November 6–7, 2025 in Sacramento, California

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# Post-Harvest Commodity Fumigation in California

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**CCST**

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## Appendix D. Post-harvest Commodity Fumigation: Use Trends

# Introduction

On November 6 and 7, 2025, the California Council on Science and Technology (CCST) convened a diverse cohort of experts on post-harvest commodity fumigation to discuss the current state of post-harvest fumigation, advances in developing alternatives, barriers to adopting alternatives, and possible steps California can take to overcome those barriers. The event was organized to fulfill, in part, a California Department of Pesticide Regulation (DPR) contract (#23-C0081) for CCST to review fumigant use in the state and assess available alternatives.

Over five sessions spread across the 1.5-day convening, 11 participants from academia and industry, with expertise in post-harvest commodity fumigants, alternative treatments, commodities, international trade and regulation, public health, and environmental justice, explored the themes introduced above (see ***Appendix A***). Sessions covered the fumigants themselves (including current drivers of fumigant use), strategies for mitigating fumigant-related emissions and community exposure to these emissions, currently available and emerging alternatives to traditional post-harvest fumigants, barriers preventing the adoption of those alternatives, and current research gaps (see ***Appendix B***). The roundtable was conducted per Chatham House Rules.

This document synthesizes the discussions that took place during the roundtable, covering the current state of post-harvest commodity fumigation in California, including current fumigants and alternatives, mitigation strategies, and research gaps. The summaries reflect the range of views expressed by participants and do not represent consensus positions or the endorsement of any individual or institution. Some of the statements were verified with peer-reviewed documents including papers and reports; par-enthetical citations indicate where this was done. Uncited statements reflect participant perspectives that have not been independently validated.

In preparing these proceedings, CCST has endeavored to preserve participants' own language and framing wherever possible. Content has been lightly edited for clarity and organization, and external sources were added where participants requested additional context for readers. These proceedings have not been formally peer-reviewed.

Discussions surfaced the challenges observed and encountered by the expert participants in their work with fumigants, identifying several important questions and research gaps that need to be addressed as alternatives are considered. Participants acknowledged the critical role of fumigants in the post-harvest commodities sector, particularly given the numerous stakeholders and regulations at local, state, national, and international levels. They also identified the need to clarify stakeholder roles, especially at the state level, to enable stronger, more consistent enforcement of regulations. Moreover, mitigating emissions requires investment in developing new technology. Participants also called attention to tradeoffs between societal costs and benefits of further regulating and restricting fumigant use, including implications for the availability of goods, food wastage, trade considerations, health impacts, and implementation costs.

Supplementary information is included at the end of this document to contextualize discussions. This includes backgrounders on the human health impacts of each of the four fumigants (***Appendix C***) and an analysis of use trends of the four fumigants in California over the last 10 years (***Appendix D***). Participants were not involved in the preparation and review of these documents. The human health backgrounders underwent peer review and were revised to satisfy reviewer comments. The rest of the document was edited by CCST staff, together with a technical editor, in response to Roundtable attendees' comments.

# Background for Readers

Fumigants are universally toxic, non-specific pesticides that exist as gases or vapors or are capable of being changed into one of these states.[1] Fumigants can also be available as solids that release the gas form on reaction with water. They are highly effective (99.99% with quarantine) when compared to conventional pesticides (50-75% when sprayed in the field). They are very effective at disrupting biological processes in pests primarily due to their gaseous property, which allows the chemical to diffuse and penetrate commodities. Consequently, during application, fumigants can be rapidly absorbed through workers' respiratory systems, gastrointestinal tracts, and skin, thus requiring specialized training and equipment to protect exposed workers during application. During post-harvest commodity fumigation, fumigants are used in confined, enclosed, or sealed environments such as silos, shipping containers, railroad hopper cars, and storage areas.[1] These enclosed spaces enable greater control and concentration maintenance for longer periods, unlike the settings for pre-plant and structural fumigation.

***Chapter 1 begins on the next page.***

1 Zuckerman, M. (2017). Fumigants. In: Brent, J., et al. Critical Care Toxicology. Springer, Cham. https://doi.org/10.1007/978-3-319-17900-1_140

Chapter I

# Post-Harvest Commodity Fumigants

## Session Goals and Structure

The goal of this session was to focus on the four main post-harvest fumigants—methyl bromide, sulfuryl fluoride, phosphine, and propylene oxide—and to build a shared understanding of how each fumigant is used in California. The guiding objectives for the session included:

1. Define the context and situations in which each of the four post-harvest commodity fumigants are used in California.
2. Describe the drivers behind the use of each of these fumigants, including how their usage has changed over time.

The session began with a group discussion to set the context for post-harvest commodity fumigation in California. Participants discussed three questions for each of the four fumigants:

1. What commodities or products are commonly treated with this fumigant?
2. Where in the supply chain does fumigation occur? What types of facilities use this fumigant?
3. What conditions trigger the use of this fumigant?

Following brief discussion, participants were paired to answer the three questions and brainstorm the drivers behind the use of each fumigant, including the characteristics that make them preferred for different use cases. All groups had the opportunity to review, comment on, and add to other's points. The session closed with a full group discussion to summarize their insights.

## Session Summary

Twelve key drivers emerged from the conversation about current use of post-harvest fumigants in California. Participants were then asked to identify which drivers they believed to be most important in shaping post-harvest fumigant use in California (***Table 1***).

**Table 1.** Drivers of post-harvest fumigant use in California identified by participants, including the number of votes cast by participants for those deemed most important (via dot voting).

| Driver | Votes† |
|---|---|
| Trade Requirements (including Import and Export) | 9 |
| Invasive Pests | 7 |
| Food Safety | 1 |
| Consumer Expectations (Affordable, Pest-free, Access to Varied and Quality Produce) | 3 |
| Regulations | 1 |
| Industry Norms | |
| Cost (To Growers/Producers and to Consumers) | 2 |
| Lack of Drop-in Replacement | |
| Existing Supply Chain / Inertia | |
| Storage (For Food Security and to Guard Against Market Volatility) | 4 |
| Lack of Training (and People to Provide it) | |
| Post-harvest Food Loss** | |

†Each participant was given three "dots" to allocate among the drivers they deemed most important. Some participants did not use all their dots during voting.
**Added after voting had been completed.

Relatedly, participants wished to emphasize two critical societal/ecological benefits of post-harvest fumigants (associated with two of the drivers above):

1. Preventing food loss following harvest.
2. Preventing the spread of pest species during domestic and international trade.

**Preventing post-harvest food loss**. Fumigants are used in post-harvest settings to protect food supplies, such as grains stored for many years, from pests that can infest, consume, and contaminate stored products. They help reduce food loss after harvest. Globally, post-harvest food loss is a significant concern, with roughly 40% of food produced lost before consumption. In the United States, post-harvest losses account for roughly 20–25% of total food production. The ability to store food for extended periods of time enhances society's resilience to cycles of feast and famine. Minimizing these losses is increasingly important because projected global population growth, combined with limited arable land, reduced water availability, and climate-related stresses, will require large gains in agricultural productivity without significantly expanding farmland.

Moreover, consumers expect, and the Food Safety Modernization Act (2011) requires, a certain standard of quality from food products, with unadulterated food—i.e., pure, undiluted, uncontaminated, and without anything added that alters its original quality or composition—being the standard. Fumigation prevents adulteration in consumer food products because pests can directly contaminate food and damage stored products, making them more susceptible to issues such as mold. For example, tree nuts damaged by pests during storage could develop mold growth and mycotoxin contamination, which are serious food safety concerns. Food adulteration standards drive fumigant use; fumigant treatment is mandated when insect presence in a food product exceeds U.S. Food and Drug Administration (FDA) thresholds. Importantly, fumigants are typically effective against a range of insect pests with a single treatment, targeting eggs, larvae, pupae, and adults.

**Preventing the spread of pests.** Participants identified the prevention of new pest introductions as a critical societal and ecological benefit provided by post-harvest fumigants. Countries can impose import-export requirements, mandate fumigation regardless of confirmed pest presence or absence, or refuse to accept goods in transit or on their shores without fumigation. For example, India requires either phosphine (as aluminum or magnesium phosphide) or methyl bromide treatment of post-harvest commodities. Other countries, such as Australia and New Zealand, also mandate fumigation of imported goods as precautionary measures to prevent pest infestation.

The US Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) also requires fumigant treatments for certain imported food items and logs, among other commodities. Where this fumigation occurs, whether prior to export or on US shores, depends on whether or not they are fresh or perishable, as with treatment of Chilean grapes with methyl bromide in Long Beach. The need for compliance with business and government standards underscores that fumigation is mandated for trade and the exchange of goods both domestically and internationally. For example, although almonds can be stored for later processing, harvesters, shellers, and handlers (sellers) must fumigate before storing the nuts because of business-to-business expectations. Additionally, consumer expectations for the availability of a variety of fruits and vegetables, regardless of peak season or country of origin, drive fumigant use.

Fumigation is also employed in quarantine situations within the US. In California, the Asian citrus psyllid (ACP) pest, which affects citrus trees, requires quarantine and insecticide treatment to prevent its spread from one county to another. During fruit fly outbreaks, fruit cannot be moved out of affected areas unless treated, with methyl bromide often the only acceptable option due to regulations mandated by the US Department of Agriculture (USDA). The need to reduce microbial load in crops also drives fumigant use. The discovery of two salmonella outbreaks in almonds in 2001 and 2004 led to a requirement for pasteurization of almonds sold in North America, for which one of the acceptable treatments is propylene oxide.

Participants noted that fumigant use is complementary, with different fumigants applied for different purposes or at different points in production. Following harvest, aluminum phosphide tablets are typically used under tarps for almonds, while phosphine is preferred on the farm, or in storage/processing facilities. Additionally, propylene oxide may be used for sterilization. Fumigants can act in a complementary manner, targeting different pest life stages. For example, while sulfuryl fluoride targets adult pests, propylene oxide may target eggs, allowing both together to substitute for methyl bromide.

Participants also mentioned other applications for fumigants, such as treating wood pallets used to transport commodities and using ethylene oxide to treat medical equipment; however, these applications were beyond the scope of the convening.

## Characteristics of the Four Main Fumigants

During the initial small group activity, participants were invited to describe the properties of the four post-harvest fumigants used in California and reasons for their use.

1. **Sulfuryl fluoride.** Currently only used on low moisture commodities such as label-listed and approved dried fruits, tree nuts, grains, legumes, and cocoa beans, due to its phytotoxic effects (damage) on some fresh fruit and vegetables. Because sulfuryl fluoride treatments are relatively quick, this fumigant offers flexibility in turnaround times. It is non-flammable and non-reactive, with a substantial list of commodities for which it is approved for use. There is no known resistance to sulfuryl fluoride, and it is used in cases where there is pesticide resistance to phosphine. Unique among post-harvest fumigants, it has industry-leading stewardship requirements and programs for its use, including effective enforcement of regulations, training, and availability of safety equipment. A maximum cumulative dosage limitation dictated by the fumigant label prevents its repeated use on the same product, limiting its use for long-term storage. Even though its residue, fluoride, is ubiquitous in nature, fluoride residues left after fumigation with sulfuryl fluoride are highly regulated in the U.S.
2. **Methyl bromide.** Primarily used for quarantine and pre-shipment (QPS) treatments due to international ozone layer protection regulations (The Montreal Protocol). Methyl bromide usage is driven by export (market) and import (USDA) requirements. For many commodities or target/quarantine pests, the only approved treatment is methyl bromide, at or near points of entry to the U.S. It is typically recommended for a single application with fresh fruit, including citrus, fresh cherries, strawberries, and grapes, because it reduces shelf life. However, dried commodities can undergo multiple quarantine fumigation rounds with methyl bromide, provided that the residue tolerance is not exceeded. Due to its limited use, methyl bromide is becoming increasingly costly, and U.S. production may be set to end in 2026, although production in other countries will continue. Methyl bromide dissipates quickly into the atmosphere after application (EPA, 2026).

3. **Phosphine.** This fumigant can be used on both fresh and dried commodities. Although widely used, participants noted its high reactivity with metals, including silver, brass, copper, copper alloys, and gold, which prevents its use with valuable electrical equipment. Phosphine offers many advantages, including being the only fumigant allowed during transit (e.g., with grains on ships, railcars, or truck trailers piggybacked on railcars); flexibility and ease of use (available in various formulations such as pellets and tablets, making it easier to fumigate smaller spaces such as almond bins); and minimal costs as it is inexpensive to produce compared to other fumigants. However, fumigating larger spaces that require cylinderized phosphine gas can be expensive, and treatment requires several days to be effective. Pest resistance to phosphine is established and its pyrophoricity (capacity for spontaneous combustion at high temperatures) raises the risk of explosions and complicates disposal and safe storage of the metal phosphide formulations in partially-filled containers.

4. **Propylene oxide.** Primarily used for dried fruit, nut, and seasoning commodities, propylene oxide is valued for its antimicrobial properties, including against human pathogens. It effectively controls insects, larvae, and eggs on commodity surfaces, especially when methyl bromide or other fumigants cannot be used and a quick treatment is necessary. However, propylene oxide is not used commonly for bulk-stored grains or long-term stored dry nuts. Regulatory and business-to-business requirements for reducing microbial loads drive its use. However, it requires a complex system for application—specifically, a vacuum fumigation chamber—making it less common. Nonetheless, managing propylene oxide emissions using a scrubber is relatively straightforward. It is most commonly used for almonds, walnuts, and other tree nuts for which it is registered, as well as commodities such as spices and cocoa (although spices and cocoa are not typically treated in California). While propylene oxide constitutes a small portion of fumigant use for these crops, it may sometimes be the only available option.

Chapter II

# Exposure and Emissions Mitigation

## Session Goals and Structure

The goal of this session was to discuss measures currently being implemented to limit fumigant emissions in communities and explore opportunities for improving these measures. The main guiding questions for the session were:

1. What fumigant exposure mitigation measures are in practice?
2. How effective are they?
3. What more can be done?

The session began with a context-setting presentation by a roundtable participant, followed by a group discussion on current mitigation practices. The discussion focused on the following questions:

1. What does fumigation with [this fumigant] look like in practice?
2. What emission or exposure mitigation measures are required or are standard in California today?
3. Are there any pitfalls associated with these mitigation measures?

Lastly, the session concluded with a discussion on emerging solutions and future directions, addressing the following questions:

1. For which fumigant(s) would this method be applicable?
2. What improvements would this have over the status quo?
3. What challenges remain with this method?
4. What might limit the deployment of this new method?

## Session Summary

The context-setting discussion that opened the session highlighted the community impacts of post-harvest commodity fumigation, using recent West Long Beach air monitoring levels as an example. The California Air Resources Board (CARB) installed air quality monitors 200 feet from the facilities between January 2023 and April 2024 (CARB, 2025). Over those 15 months, data revealed elevated methyl bromide levels (average total concentration = 2.1 ppb), exceeding California Office of Environmental Health Hazard Assessment (OEHHA) chronic reference exposure limits (REL). Two measured hourly peak levels approached the acute REL of 1,000 ppb. Data collection for this project was prompted by fenceline community members, who raised concerns about adverse effects on children from methyl bromide emitted by a facility located near a school. Four other facilities in Los Angeles County are under investigation to obtain more comprehensive air toxic emissions data.

In 2025, the LA County Agricultural Commissioner updated the permit conditions for the two facilities to decrease community exposure to methyl bromide (South Coast AQMD, 2025). These conditions included:

- No fumigation during school hours
- Increased stack heights to reduce exposure to methyl bromide at ground level
- Coordination of fumigation activities such that both facilities are not releasing fumigants at the same time
- Additional leak prevention measures

## Points of Consideration on Fumigation Emission Mitigation

There was some disagreement during the conversation on fumigation emission mitigation. Some participants thought that current mitigation regulations are stringent enough and expressed surprise that such high concentrations of methyl bromide could have occurred unless the regulations were not followed or poorly implemented. Others thought increased mitigation measures needed to be in place and enforced to ensure community protection. While this was a point of disagreement, some participants also expressed concern that the research could lead to more stringent regulations and raised several points regarding current emissions regulations:

1. **Complicated regulatory landscape.** Participants expressed that multiple government agencies, including CARB, OEHHA, DPR, and the California Division of Occupational Safety and Health (Cal OSHA), as well as the USDA, are involved in discussions surrounding fumigants. However, from the perspective of external parties there is no clear delineation of responsibilities or communication about roles among them. This multitude of agencies, without coordinated efforts, has resulted in conflicting exposure limits, complicating matters further. For methyl bromide, while Cal OSHA has set a 1 ppm limit for an 8-hour time-weighted average concentration of exposure, OEHHA established a 1 part per billion (ppb) target air concentration, which is consistent with the U.S. Environmental Protection Agency's (EPA) target concentration (Cal OSHA; OEHHA, 1993). While methyl bromide's toxicity is widely understood, it is important to note that there are differences in the agencies' risk and exposure limits, mainly due to the different population groups that are the focus of the agencies. OEHHA focuses on regulating general health risks, while Cal OSHA's work centers on worker risks. DPR uses the EPA's risk assessments (in addition to its own rigorous assessments) to guide its regulatory work, primarily determining the quantity of fumigants used in the state within a given time period. State Air Districts are also involved in regulation conversation due to their role in providing permits and regulating air quality.
2. **Data gaps.** Participants noted a lack of recent health-related studies (beyond the 1990s) on post-harvest commodity fumigation, with most studies limited to toxicology. While older data is not bad data, it was pointed out that most studies were conducted with workers and are not directly applicable to children and other residents not directly involved in fumigation, raising concerns about the applicability of recommendations for these groups. Furthermore, the current reliance on self-reporting of fumigant emissions hampers assessment of the impacts of these facilities using fumigants to fenceline communities, as the data are often unreliable. Another data gap involves access to facility-level fumigant use information. Currently, access to pesticide applications data through the Pesticide Use Registry for non-agricultural applications is only available at the county-level and at monthly-intervals. Data on emissions is available from the California Emissions

Inventory Data Analysis and Reporting System only at the facility level and at yearly-intervals for facilities with an active permit The lack of daily facility-level data limits more robust data assessments.

3. **Regulation Enforcement.** Clarifying the roles of various state agencies involved in monitoring and regulating fumigant use would allow for stronger enforcement of regulations. Participants expressed a desire for state agencies, local air quality management districts, and County Agricultural Commissioners to communicate better with each other to ensure effective regulatory enforcement and reduce exposure levels. They noted that enforcement represents low-hanging fruit for decreasing exposures, emphasizing that new rules would not resolve the issue if existing rules are not being followed.

## Mitigation of Fumigant Emissions

Participants emphasized the importance of outlining the full landscape of available mitigation options, including their feasibility, implementation strategies, potential health impacts to workers and residents, and the difficulty or ease of execution.

Participants believed that there could be more opportunities for capturing off-gassing post-fumigation. While practices for doing so already exist for some fumigants, costs vary, indicating a need for further research. Scrubbers exist for capturing the offgas of both propylene oxide and methyl bromide, but their complexity and cost affect their practicality and viability. For sulfuryl fluoride, research lab-scale processes have been identified that capture the gas and break it down into its minor components, but scaling these options remains challenging. Phosphine gas can be captured using a scrubber. Participants expressed doubt that companies would be willing to invest in developing better means of mitigating methyl bromide emissions given the perception that its use will not continue long into the future.

Capturing emissions immediately following fumigation is relatively easy compared to attempting to capture any slow off-gassing of fumigants from commodities themselves post-fumigation (due in part to the differences in concentration). Additionally, for fumigants like methyl bromide,  major issues include the proper management or disposal of recaptured gas and the carbon bed.

Participants discussed available tools for decreasing worker exposure to fumigant emissions, including traditional personal protective equipment (PPE), monitoring badges, and Draeger tube monitoring, which are recommended by EPA. The EPA has implemented regulations to mitigate applicator and bystander exposures as part of fumigant labels and fumigation management plans, aiming to increase safety practices among fumigant users.

***Chapter 3 begins on the next page.***

Chapter III

# Fumigant Alternatives

## Session Goal and Structure

The goal of this session was to collaboratively generate a list of available and emerging fumigant alternatives, including descriptions of how they work and their strengths and limitations. The main guiding objectives for the session were to:

1. Identify alternatives currently in practice and those on the horizon.
2. Identify advantages and disadvantages of each alternative.
3. Categorize the alternatives based on characteristics.
4. Begin to delineate the barriers to their adoption.

The session began with context setting to ensure the group was starting with roughly the same baseline knowledge. Discussions then focused on surfacing existing practices and emerging innovations and identifying areas of alignment, uncertainty, and disagreement. Participants discussed all non-fumigant alternatives they were aware of for post-harvest pest management (both chemical and nonchemical). The alternatives were then categorized as either chemical, physical, biological/behavioral, or other. Participants were asked to describe the alternatives based on their target pests and commodities, their mechanisms of action, current knowledge about their efficacy and the extent of use, and their advantages and disadvantages.

## Session Summary

Discussions began with the acknowledgment that alternatives can be used only where allowed by regulation, and they might not be a viable option in practice due to current regulatory requirements. Participants noted that many fumigants are used for their curative attributes, while alternatives may be either curative or preventive. They identified time, cost, and trade requirements as key barriers to implementation of fumigant alternatives.

**Chemical alternatives** include combinations of fumigants that allow for lower concentrations of each to be used with comparable efficacy, for example, propylene oxide/sulfuryl fluoride, or phosphine/sulfuryl fluoride combinations. Also, methyl iodide, ethyl formate, ethanedinitrile (EDN), hydrogen cyanide (HCN), sulfur dioxide, DDVP (dichlorvos), carbon dioxide, and ozone are other chemical alternatives with varying efficacies and registration statuses. Although promising as an alternative, methyl iodide's toxic secondary metabolite was raised as a concern.

Participants communicated that chemical alternatives can be useful as part of a systems approach, giving some control and reducing, not eliminating, the amount of fumigation needed, albeit while generating residues. Although they may take up to months to be effective, residual sprays or insect growth regulators, such as hydroprene and methoprene, can also be part of an integrated or multipronged approach, decreasing reliance on fumigant use. Naturally occurring compounds such as pyrethrin (derived from chrysanthemums), spinosad (derived from a soil bacterium), and pyrethroids can also be used, although there are restrictions on their use. Pyrethroid netting, fogging agents, and combinations (e.g., dichlorvos, pyrethrins, pyrethroids with synergists) of these compounds can also be used to reduce the use of fumigants.

**Physical alternatives** include modified and controlled atmospheres, irradiation, temperature changes, diatomaceous earth, lighting, traps (e.g., sticky or rodent), and modified insect-proof packaging. Heat treatments are on the decline due to impacts on commodities' integrity, as it is difficult to prevent damage to goods. Heat treatment is mostly used for empty structures and logs. Participants suggested that heat could work for spices and dried fruit, but not grains. Diatomaceous earth acts as a desiccant and is used in grain storage areas to reduce insect populations by placing on surfaces that insects cross over.

**Biological alternatives** included mating disruption for control, pheromones for detecting and monitoring pest populations, and natural enemies such as parasitoids and predators to reduce insect populations. The options in this class of alternatives do not require EPA registration and are allowed by FDA for food safety. Mating disruption uses the biology of the pest to inhibit mating, thus reducing future populations of specific insects such as Indianmeal moths (*Plodia interpunctella*). Participants acknowledged that biological alternatives can be incredibly effective at controlling target insect pests, but these methods of control are species-specific and have only been developed for select pests. Further research would be needed to develop biological alternatives for other pests currently targeted with fumigation. Natural enemies include parasitoids, predators, and pathogens. They may require APHIS approval in addition to the EPA & DPR to avoid the introduction of a new pest.

**Other alternatives** include systems approaches that incorporate inspections, orchard surveys, monitoring, integrated pest management practices, and sanitation in a way that addresses the culture of the workplace. Systems approaches involve layering multiple approaches to achieve the desired level of control. Approaches that can be layered include mating disruption and sanitation, among others. Participants raised questions about ways to standardize the systems approach and make it more workable in the regulatory world, as although there are examples where systems approaches have been approved for use by importing countries as alternatives to fumigation treatments, the approval process can be burdensome.

Participants collectively identified **six alternatives** as priorities for further discussion. These include:

1. **Irradiation.** Irradiation treatment involves exposure of the commodity, under controlled conditions, to gamma-rays (from Cobalt-60 or Cesium-137) or to electron beams (as produced by linear accelerators) (USDA-APHIS 1997). This is a non-chemical, physical alternative that does not leave residue on the commodity. It is quick to implement and has the potential to be effective against most pests. International trade texts list irradiation as an alternative to fumigation, however, not all trading partners accept this alternative.

| Advantages | Disadvantages |
|---|---|
| • Familiar to many countries and for which specific crops have approved protocols.<br>• Can be implemented quickly, for example as a rapid response to an outbreak.<br>• Not a chemical treatment, so it leaves no residue. | • Considerable logistical hurdles limit its practicality as an alternative to methyl bromide.<br>• A low throughput alternative (i.e., it cannot quickly treat large volumes of commodities). As penetration is an issue, and the amount of surface area needed to reach is usually high, it therefore requires a low load factor.<br>• More effective for fresh fruits than dried fruit, particularly tropical fruits and spices.<br>• Requires crop-by-crop assessment of appropriate dosage and impacts to fruit and vegetable quality and shelf-life.<br>• Limited studies on the organoleptic properties of irradiation (its impact on taste and flavor).<br>• Public perception hurdle/low consumer acceptance due to fears of radioactivity of irradiated foods.<br>• No facilities with this capability in California, and participants believed the general difficulty of building new facilities in California would limit its viability.<br>• Safety concerns for staff and community. |

2. **Controlled atmosphere.** This approach involves regulating the levels of gases, such as carbon dioxide ($CO_2$), nitrogen ($N_2$), and oxygen ($O_2$), during storage. While $CO_2$ has been registered and approved as a fumigant for organic use, $N_2$ has not yet been registered. Participants were wary about whether any entities would find the registration process for $N_2$ worthwhile. This approach is distinct from modified atmospheres.

| Advantages | Disadvantages |
|---|---|
| • Low oxygen results in higher quality products.<br>• Lower risk of rancidity for tree nuts.<br>• Safer for communities due to the low toxicities of the gases. | • Slower process with lower flexibility. Treatment involves using 60% $CO_2$ for 4 days or 99% $N_2$ at 98 degrees Fahrenheit for 14 days.<br>• Containing the gas can be difficult, especially at larger scales.<br>• Can also be expensive due to the materials used, e.g., super sacks.<br>• Requires a lot of manual labor to monitor gas levels.<br>• Worker safety is a major concern due to risks these gases pose when used at high concentrations (e.g., asphyxia).<br>• Not approved for phytosanitary treatments in most markets. |

### 3. Multi-pronged Approach

***Systems Approach:*** The definition of systems approach for fumigation and whether it is an alternative was a subject of debate among participants. Systems approach is a federally regulated term that is allowed as an alternative for certain commodities and trading partners. It is considered a term used between the USDA and trading partners for a specific commodity. A systems approach includes a series of actions that reduce the chances of the presence of a pest. In this context, a pesticide is required to be used either in the field or as a post-harvest treatment, regardless of presence of the relevant pest.

| Advantages | Disadvantages |
|---|---|
| • Decreases the need for fumigant use. | • Expensive to implement.<br>• Not currently widely accepted as a replacement for fumigation and must be negotiated between trading partners. |

***Integrated Pest Management/Good Agricultural Practices/Good Manufacturing Practices (IPM/GAP/GMP):*** These approaches to pest management require the identification of the presence of pests for its application.

| Advantages | Disadvantages |
|---|---|
| • Cost-savings in the long term.<br>• Increased safety.<br>• Better quality assurance.<br>• Increased sanitation.<br>• Decreased insect pressure. | • Complex to implement: Approaches require a massive overhaul of existing infrastructure and company operations.<br>• Approaches can also be expensive, based on infrastructure needs, tremendous amounts of labor, record-keeping, and tracking.<br>• Many points for potential failure. |

The practices are more applicable to those businesses that do not have field-related obligations and where systems approach does not apply, such as bakeries.

4. **Pheromones/mating disruption.** These are biologically-based and species-specific chemical attractants that exploit the natural sex attractants of a given pest to target insect hormones and reproduction. Mating disruption is very insect species-specific, requiring a tailored approach for different pest species. For example, very effective alternatives have been developed for the moths, while beetles have pheromones identified, but still require better targeting products. Therefore, it is unclear whether it would be applicable to a wide spectrum of insects. There is, however, an opportunity to integrate mating disruption of moth pests into existing systems approaches, such as sanitation, surface sprays, and trapping mechanisms. Currently, pheromones are approved for mating disruption of the Indianmeal moth, one of the foremost pests for dried stored commodities.

| Advantages | Disadvantages |
|---|---|
| • Deployment can be rapid.<br>• Safe to use.<br>• Can use different formulations, including spray and fog.<br>• Use of pheromones may decrease the need for structural fumigants. | • Extreme specificity required for each insect pest makes it difficult to apply pheromones or mating disruption to all relevant insect pests.<br>• Lack of knowledge about or available deployable forms of pheromones for most storage insect pests.<br>• Takes time to acquire this knowledge and deploy. |

5. **Cold/freeze.** This offers a physical alternative to fumigants. There are currently no domestic regulatory issues, however, it is not a silver bullet for market access, nor do participants believe it is a drop-in for fumigation.

| Advantages | Disadvantages |
|---|---|
| ***Cold*** | ***Cold*** |
| • Slows pest development.<br>• Can be applied at a large scale in many cases.<br>• For places with naturally extremely cold environments, the weather can be relied on, making it an extremely cost-effective approach to pest management. | • Takes a long time for efficacy.<br>• Not suitable for all fresh commodities because of the amount of time needed.<br>• May be expensive based on the size and type of structure.<br>• Has a high risk of failure if the cold temperature is not maintained.<br>• Can be difficult to demonstrate maintenance of the cold chain in the supply chain. |
| ***Freezing*** | ***Freezing*** |
| • Effective, organic, and curative for insects.<br>• Carries low safety risk for humans. | • Damages fresh commodities<br>• High energy costs<br>• Complicates logistics scaling issues |

6. **Ethyl formate.** A chemical alternative that produces degradants (namely formic acid and ethanol) that are generally regarded as safe (GRAS). Ethyl formate is currently registered with EPA for three commodities: citrus, kiwi, and table grapes. However, it is not registered for use in California. It is also not registered for use on stored products.

| Advantages | Disadvantages |
|---|---|
| • Does not damage fresh fruit, although regulatory approval is required for its use in this case.<br>• Treats surface pests and works on the calyx of citrus, allowing it to go into tight spaces such as between the calyx and skin of citrus because of its gaseous property.<br>• Curative and can be viewed as a propylene oxide alternative, and the same facilities can be used for both chemicals.<br>• Fast to implement.<br>» Treatment time is measured in hours, not days.<br>» Novel in-field application techniques, including bins and tarps enable ergonomic support for workers.<br>• One of the degradation products is ethanol which volatilizes over time, resulting in low emissions. | • Flammable and requires $CO_2$ in the formulation to address this.<br>• Has high sorption and low volatility when it is used in pallets, which has to be accounted for.<br>• Worker safety is a remaining concern, for example off gassing of the chemical.<br>• Efficacy depends on the pests and more information is needed on assessment of risks, pests, and efficacy.<br>• Unclear whether this chemical can be used at large scales, especially if there is a need for heat during the operation. |

# Issues and Concerns with Alternatives

Several issues with alternatives were discussed over the course of the session, including:

1. **General concerns**

   a. *Knowledge gaps:* Gaps include the effects of alternatives on the quality and shelf-life of various fruits and vegetables. Participants highlighted the sheer diversity of crops and pests that makes it difficult to develop alternatives that are as broadly effective as current fumigants. Crops would need to be tested individually (and in some cases, according to variety and pest species) to ascertain whether the alternatives are viable options for treating them. As a solution, participants proffered use cases as a way to systematically adopt alternatives, given that a universal response will be hard to achieve.

   b. *Human health implications:* Participants were wary about the potential human health implications of chemical alternatives; they called for gaps in understanding about potential impacts to be addressed to ensure that issues from previous fumigants are not replicated. For example, the secondary metabolite toxicity of methyl iodide was not understood until many years after use. Most of the available risk assessments for fumigants focus on occupational exposure, not community, children, or bystander exposure/effects, groups that may be more vulnerable to adverse impacts from exposures. However, such studies can be resource intensive.

2. **Adoption concerns**

   a. *Education gap:* Participants identified as a challenge the current lack of education and outreach on post-harvest fumigation alternatives to stakeholders involved in the sector. Participants mentioned that there is currently no University of California Extension program for this type of fumigant use (as opposed to the use of fumigants in pre-plant applications, for example). Furthermore, researchers with extensive experience in commodity pest management have begun to retire, reducing the expertise in this field.

b. *Awareness gap:* Knowledge of the available tools and technologies beyond traditional fumigants was another topic of discussion. Participants questioned whether end users have the tools needed to better monitor for and assess the degree of pest pressures and how to approach solving them. Users also need to know what to look for as they become aware of available pest prevention tools.

3. **Economic concerns**

a. *Costs:* The high costs of implementing fumigant alternatives was discussed extensively. Participants mentioned the amount of labor, maintenance, and replacement costs were particularly high in implementing alternatives to fumigation of post-harvest commodities. Participants argued that maintaining the status quo is more cost-effective. Labor costs would be particularly high for a transition to fumigant alternatives compared to anticipated material costs. Given consumer preference for less costly food and the competitiveness of the global market, net impacts to consumer prices are a significant factor in the calculation industry makes when considering alternatives. Some participants expressed that cost calculations also include the costs of fumigant use to the health of workers and surrounding residents.

b. *Brand Reputation:* Food manufacturing companies have to protect their brand reputation, and when food safety issues happen, that reputation is at stake. Thus, they seek products that are proven to work all the time to ensure success. This decreases the chance that alternatives that might not be as effective are utilized in established production systems.

Chapter IV

# Barriers to Adoption of Alternatives

## Session Goals and Structure

The goal of this session was to better understand what could theoretically reduce post-harvest commodity fumigant use in practice and to explore options for increasing the adoption of alternatives. The main objectives were:

1. Identify which drivers of fumigant use are amenable to intervention and describe how they could be influenced.
2. Delineate the barriers that currently prevent the adoption of promising alternatives and brainstorm solutions for those barriers.

The session focused on identifying the drivers of fumigant use, examining fixed constraints, and determining which constraints can be addressed—whether technical, policy, training, or market-based—to realistically reduce reliance on fumigants. The group revisited the barriers limiting the adoption of alternatives and explored what was needed to overcome these barriers, including research, pilot programs, incentives, infrastructure, and coordination across the supply chain.

## Session Summary

The discussion began by revisiting the drivers of post-harvest commodity fumigant use identified on Day 1. Participants were asked to identify which of the twelve drivers of fumigant use they believed to be amenable to intervention by California regulators. Of the twelve, the following were identified by at least one participant as actionable:

1. Consumer expectations
2. Costs
3. Lack of drop-in replacements
4. Lack of training

Notably, these four drivers were not among those participants had previously identified as most important in driving fumigant use in the state.

Following this exercise, facilitators shifted the discussion toward barriers to adopting fumigant alternatives and the steps needed to decrease reliance on commodity fumigants. Participants ranked these barriers and the most significant was lack of regulatory status, followed by the diversity of crops and pests that require treatment, the high costs of adopting alternatives, low throughput of alternatives, and lack of data (*Table 2*).

**Table 2.** Barriers to adoption of alternative fumigants in post-harvest commodity settings in California identified by participants, including the number of votes cast by participants for those deemed most important (via dot voting).

| Barrier | Number of Votes |
|---|---|
| Lack of regulatory status [political will and responses to interventions, APHIS, other countries, time required]** | 9 |
| Sheer diversity of crops + needs + pests + life stages** | 6 |
| High cost** | 5 |
| Low throughput/scaling issues/duration of treatment | 4 |
| Lack of data/long timelines to prove out** | 3 |
| Increased labor requirements | |
| Low market incentive** | |
| Lack of prescribed system application** | |
| California building challenges** | |
| Consumer acceptance | |
| Increased energy intensity | |
| Chain of custody | |

**At least one participant identified this barrier as one they believed could be addressed or ameliorated by state regulators.

# Barriers and Potential Solutions

1. **Lack of Regulatory Status.** A significant barrier that was discussed concerned Animal and Plant Health Inspection Service (APHIS) oversight and acceptance of fumigant alternatives, as well as the inflexibility of trade-based fumigation requirements. Participants felt that fumigant specifications are treated as political negotiations by APHIS rather than being evaluated based on effectiveness or safety. This lack of regulatory status stems from a deficit of political will, not merely lack of data. Additionally, concerns regarding invasive species and blight lead to strict and inflexible fumigation requirements for commodities at various governance levels (that is, from local to international levels).

   *Potential Solutions:*

   Given the regulatory challenges surrounding fumigants, participants proposed the following solutions:

   a. Global and interagency coordination, standardized risk assessment processes, and increased flexibility in fumigation requirements if alternatives are proven safe and effective.
   b. Prioritization of alternatives requiring EPA and DPR registration, as well as additional uses for alternatives with existing registrations, such as ethyl formate.
   c. Streamlining permitting for aeration mitigation and ensuring the regulatory process accounts for gases.
   d. Collaborating with APHIS and industry representatives to identify market access priorities and the data needed to create a strategic plan.

2. **Diversity of Crops and Pests.** Each potential fumigant alternative, whether chemical, physical, or biological, must be tested on all crops exported from and imported to the United States. The fumigant or alternative technology must demonstrate effectiveness against all pests and each developmental stage. Many alternatives to the traditional four fumigants are most effective against specific pest species or commodities. For example, cold treatment

and irradiation have clear limitations regarding their efficacy against a range of pests and their application on commodities such as lettuce and fresh fruit. Participants expressed skepticism that any alternatives would meet Probit 9, the standard for treatment effectiveness that requires a mortality rate of 99.9968% and total control of all pest life stages (i.e., eggs, larvae, pupae, and adults).

*Potential Solutions:*

a. Significant increase in research capacity and funding to assess how well various alternatives work for various crops and pest combinations.

b. Invest in developing the data needed for APHIS to present to other governments to get approval for the alternative approaches.

3. **High Cost of Alternatives Adoption.** Several alternatives to standard commodity fumigation necessitate investment in additional infrastructure, an increased workforce, and/or more time. Each of these factors would raise costs for growers, producers, and handlers, which could ultimately be passed to consumers. Additionally, consumers expect affordability, variety, and quality from their food options, which growers must meet. Without subsidies or financial incentives, it would be challenging for growers to adopt potential alternatives without incurring significant financial burdens or raising consumer costs, risking their competitiveness in the market.

   *Potential Solutions:*

   a. The state subsidize the development of high-cost infrastructure for alternatives, prioritize adequate funding, reduce regulatory cost burdens, and improve cost estimation for implementing these alternatives.

   b. Creating new markets that target domestic consumers and emphasized the need for increased enforcement to ensure successful adoption of alternatives once available.

c. Rather than focusing solely on costs, participants urged DPR to consider the societal benefits of alternatives and seek to balance costs with benefits.

4. **Low Throughput.** Once approved, implementation often encounters scaling issues due to logistical complexities and treatment duration. For several of the available fumigant alternatives, the time required for efficacy is typically longer than what fits into standard business timelines. For example, while methyl bromide and sulfuryl fluoride might take 24-48 hours to treat commodities, many alternatives require significantly more time to be effective.

   *Potential Solutions:*

   Participants were unable to offer many solutions to this limitation to alternative adoption. Alternatives with low throughput can be used in the niche in which they are applicable, i.e., on commodities with longer shelf lives like nuts, grains, and dried fruits. Otherwise, the time scale for treatment may be a true limitation to the adoption of some of the alternatives.

5. **Availability of Resources (Data).** Participants noted a general lack of public data in the post-harvest commodity fumigant sector, which compounds the low data availability for alternatives in the management of post-harvest pests. Other data needs include how best to monitor, identify, avoid, and minimize pests, and determine treatment thresholds and the efficacy of different approaches. Throughout the discussions, the need for clear communication of oversight structures and clarity of responsibilities was emphasized, alongside the need for interagency coordination and data sharing. Specifically,

regarding the adoption of alternatives, participants cited the long timelines required to validate alternatives. There is also a shortage of post-harvest pest management research experts. Due to a lack of UC Agriculture and Natural Resources (UCANR) resources, a lower prioritization of this sector in research, and insufficient regulatory side knowledge, industry representatives often serve as the knowledge experts.

*Potential Solutions:*

- **a.** For alternative pest management data needs, participants discussed the need for heightened investment in focused research funding to meet regulatory data needs, enhanced visibility and cross-validation of existing data, and workforce training programs.
- **b.** Participants called for increased data sharing and interagency coordination, publicly accessible organizational charts to delineate responsibilities and oversight authorities, increased transparency in air monitoring, worker and public health, grower data, daily facility usage, and mitigation data.

6. **Other Barriers.** In addition to the barriers listed in this section, participants mentioned several other potential barriers to the adoption of alternatives, including land use, consumer acceptance, increased energy intensity, the practical application of control technology, and the reputational risks associated with adopting new technologies that could potentially lead to food safety issues or recalls. They were then asked to rank the barriers to adoption of alternatives that they believed were most actionable. In order, they identified the lack of data, lack of training, low market incentives/cost, and regulatory status as promising areas for progress.

Chapter V

# Research Gaps

# Session Goals and Structure

The goal of this session was for participants to discuss research needs and information gaps related to post-harvest commodity fumigants. The main guiding questions were:

1. What are the significant knowledge gaps and research opportunities?
2. Why are these gaps important?
3. What research is needed to address these gaps?

The session began with a review of the significant knowledge gaps and research opportunities that had emerged over the course of the two-day workshop. Participants then identified any additional gaps and conducted a short prioritization exercise (via dot voting). Next, based on the prioritized gaps, the large group was divided into smaller groups of people focused on identifying research needs in these areas and the types of answers that would facilitate progress in policy and practice. The session concluded with small-group report-outs and group discussion.

# Session Summary

Thirteen unique research gaps and information needs were identified (***Table 3***).

**Table 3.** Research gaps and information needs raised by participants throughout the roundtable convening.

| Research Gaps and Information Needs | High Priority Votes | Lower Priority Votes |
|---|---|---|
| Efficacy of Alternatives on Different Pests | 5 | 1 |
| [Health] Impacts of Offsite Movement | 2 | 2 |
| Emission Control & Disposal of Spent Material | 1 | 3 |
| Ultimate Cost Impacts and Ways to Reduce | | 4 |
| Efficacy of Fumigants on Emerging Pests | 1 | 2 |
| Health Impacts of Chemical Alternatives on Worker Safety | | 2 |
| Increased Air Monitoring Sites and Offsite Movement | | 2 |
| Clear Accounting of Tradeoffs | | 1 |
| Impacts of Irradiation on Fruit | | |
| Applicable Commodities for Freezing | | |
| Regulatory Jurisdictions [Clarified] | | |
| End Target of Mitigation | | |
| New Downstream Monitoring Methods | | |

Note: Participants were invited to identify 1 high priority item and up to 2 lower tier priority items (via dot voting).

## Session Themes

The group discussion centered around five themes:

1. The importance of learning from previous efforts;
2. The need for more research on the efficacy of fumigant alternatives;
3. Methods for reducing the cost impacts of alternatives;
4. The culture of post-harvest commodity fumigation and the need for stakeholder buy-in; and
5. The need for a clear-eyed evaluation of the tradeoffs (monetary and non-monetary) between the continued use of post-harvest fumigants and the implementation of alternatives.

1. **Learning from Previous Efforts.** When discussing research gaps, participants encouraged learning from past experiences. They noted the outsized historical role of methyl bromide and the promising search for viable alternatives. The methyl bromide phase-out process offers valuable lessons for approaching any phase out or alternative implementation. Considerable effort was dedicated to the 10-year phase out of methyl bromide for non-quarantine and pre-shipment uses, which required federal and international investment and funding to succeed.

2. **Efficacy of Fumigant Alternatives.** There was agreement that additional information on the efficacy of fumigant alternatives is needed, particularly regarding the concentration and duration of exposure. Participants suggested further investigation of alternatives' efficacy on the three major pest species in the state, including cigarette beetles, Tribolium species (flour beetles), and Indianmeal moth, while acknowledging that there are more insect pests that impact nuts, grains, and dried fruit that also need further research.

   Participants highlighted the need for awareness of existing data on specific pests and crops, as well as a catalog of pests and crops lacking efficacy information. Participants underscored the need to differentiate between the data needs of California-specific users and those related to export markets. Given the importance of commodity fumigation in trade, any decisions regarding alternatives must consider whether they meet export requirements.

Participants acknowledged that meeting this need will be complex. For example, the type of research needed differs between dried and stored goods and foods and fresh produce. For dried products, efficacy of treatment for 5 to 10 different pests is usually needed, while fresh produce typically have more targeted pests but require consideration for treatment impact to quality and shelf life.

3. **Ultimate Cost and Ways to Reduce.** Participants discussed the ultimate cost impacts of transitioning to fumigant alternatives and the mechanisms available for reducing those costs. Stewardship and training requirements, for example, made sulfuryl fluoride adoption more viable as a methyl bromide alternative. Cost considerations include infrastructure for alternatives, labor, costs borne by users and producers, and ultimately, costs passed on to consumers. Participants argued that cost reduction strategies must be built into the implementation of alternatives from the outset.
4. **Culture and Stakeholder Buy-in.** An important consideration discussed was the culture surrounding commodity fumigation and the drivers behind its use. As previously mentioned, a key reason for fumigant use is to minimize pest exposure, which is based on sound pest management practices rather than regulatory requirements. Therefore, stakeholders including growers, processors, storage facilities, workers, fenceline communities, and sellers must understand and agree on the need for alternatives before any transition could succeed.
5. **Clear Accounting for Tradeoffs.** Participants emphasized the importance of understanding the tradeoffs between using post-harvest commodity fumigants versus their alternatives. Cost and efficacy tradeoffs for alternatives and their impact on quality were highlighted during the discussion. Additionally, because many alternatives are not direct substitutes for fumigants, the tradeoffs in efficacy must also be evaluated. Meanwhile, health impacts to communities should also be considered.

# Central Message

At the end of the session, participants were asked to highlight the key messages they hoped readers of the proceedings would take away. They discussed the following:

- *Context:* Stakeholders and regulators must understand the context of the roles fumigants in agriculture, particularly in post-harvest commodities, and recognize the effort and funding required to find replacements. Furthermore, most fumigants are part of an all-tools-in-the-toolbox approach, used complementarily with selective deployment when necessary.
- *Complexity:* Fumigant use regulation and emissions mitigation are more convoluted and complex than commonly understood, and there is no one-size-fits-all solution. This complexity arises from the diverse stakeholders and interest groups involved, as motivations, end goals, and usage patterns vary, as discussed in Chapter II. There are more opportunities to mitigate off-site movement of fumigants during the aeration process in post-harvest fumigation than in other fumigant uses such as for pre-plant use and structures.

As previously stated, a critical part of the solution is appreciating the tradeoffs between fumigants and their alternatives. Determining priorities, whether through science-based decision-making or values-based judgments, will be essential. Ultimately, the future sustainability of these practices must also be considered.

Appendix A

# Roundtable Selection Process and Attendee Biographies

## Selection Process

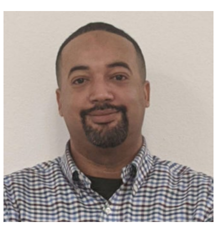
CCST issued a Call for Nominations to find individuals with the necessary expertise who would be willing to participate in this Roundtable Discussion. CCST staff reviewed all nominations through a multi-step process designed to support a constructive, balanced, and independent roundtable discussion. Initial assessments were based on the information provided in the nomination form, including the nominee's statement of interest, relevant expertise, and professional background.

In selecting participants, CCST strove to achieve a diversity of perspectives and experiences across disciplines, sectors, and fumigant-related roles. Nominees whose expertise and background aligned with the roundtable's goals were invited to participate in a brief exploratory conversation with CCST staff. These conversations helped CCST to better understand each individual's interest in the topic, relevant experience, and commitment to collaborative, good-faith engagement with others who may hold differing viewpoints. All final decisions regarding participation rested with CCST.

To support transparency and objectivity, all confirmed participants underwent a conflict-of-interest (COI) review. While a potential COI did not automatically disqualify someone from participating, CCST ensured that such circumstances were appropriately disclosed and managed.

# Attendee Biographies

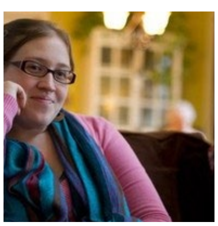
**Dr. James Adaskaveg** is a plant pathologist at UC Riverside. He received a PhD in plant pathology from the University of Arizona, and, following time as a lecturer at UC Davis, joined the faculty of the Department of Plant Pathology at UC Riverside, where he is currently professor of plant pathology with statewide responsibilities in tree fruit and nut pathology. Dr. Adaskaveg is recognized nationally and internationally for his outstanding contributions on the biology, epidemiology, and management of tree pathogens, including post-harvest fruit decays. His research focuses on diseases of tree crops grown in California, specifically on the biology, epidemiology, and management of pre- and post-harvest foliar and root diseases caused by fungal and bacterial pathogens. This includes studies on mycology, the ultra-structure of host-pathogen relationships, the biology of wood decay fungi, and biological and molecular techniques for the detection and identification of pathogens, as well as development of disease forecasting programs and innovative management practices. His research on disease management has resulted in the registration of new pre- and post-harvest fungicides and aided the certification of fruit exports to international markets.



**Dr. Wiley A. Hall IV** obtained a PhD in analytical chemistry from the University of Delaware and is experienced in the detection of toxic chemicals in the atmosphere. Dr. Hall conducts applied chemistry to address issues in global agricultural trade. He possesses particular expertise in fumigant analysis, from the point of application through environmental monitoring for exposures. This expertise is evidenced by numerous published methods regarding gas phase and food stuff analyses as well as fumigant registration activities with USDA-APHIS and EPA. Dr. Hall is uniquely positioned to understand commercial and regulatory perspectives associated with fumigant use and analyses.

**Ed Hosoda** is a consultant in the agricultural fumigation and pest management industry and recent retiree as vice president of Cardinal Professional Products. During his tenure with Cardinal, Mr. Hosoda served both on the Board of Directors and as vice president for over 45 years with a focus on post-harvest fumigation, structural/residential fumigation, and other related pest management and safety products. Before his retirement and throughout his career, Mr. Hosoda was a DPR-licensed pest control adviser (categories ABCDEF), held a qualified applicator license (categories ABCDHI), and was a structural pest control operator in fumigation and general pest control. Mr. Hosoda has various publications related to a variety of fumigant materials and alternatives that are significant to various agricultural commodities, and associated emissions and control techniques.

*Conflict of Interest Statement:* Mr. Hosoda was identified as having a possible financial conflict of interest due to his position as a former vice president and stockholder at Cardinal Professional Products, which sells fumigants and is working on developing fumigant alternatives. However, it was determined that such potential conflict of interest would not affect their ability to participate in the roundtable. Additionally, CCST maintains that it is essential for the roundtable to reflect a diversity of perspectives, and that this potential conflict of interest does not outweigh the unique insights Mr. Hosoda may contribute to the discussions.



**Dr. Jill Johnston** is an exposure scientist and environmental epidemiologist with extensive experience in community-based research and engagement methods. She is currently an associate professor in the Department of Environmental and Occupational Health at UC Irvine. Dr. Johnston's background in health disparities, public policy, community engagement, and environmental justice provide a unique perspective to understanding the impacts of fumigation and its alternatives. She has two decades of experience inside and outside of academia in characterizing industrial exposures in environmental justice settings, evaluating health effects, and conducting community-based participatory research. She has also worked extensively with communities in Southern California impacted by freight transport. Recently, Dr. Johnston has engaged in reviewing fumigation facilities in Los Angeles and understanding the use of methyl bromide for non-agricultural fumigation and completing an extensive literature review on the topic. She is interested in using this data to inform collaborative discussions about the use of commodity fumigants and bring not only a public health but also an environmental justice perspective. Dr. Johnston holds a PhD in environmental sciences and engineering from the University of North Carolina at Chapel Hill and completed a postdoctoral fellowship in environmental epidemiology focused on industrial agriculture.

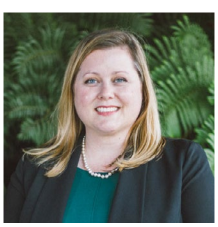
**Dr. Gabriele Ludwig** is the director of environmental policy at the Almond Board of California (ABC). Dr. Ludwig brings a broad background on pest management, regulations at state, federal and international levels, including for post-harvest requirements. At ABC she managed the environmental research program that created the California Almond Stewardship platform. She is currently on the board for the nonprofit Coalition for Urban/Rural Environmental Stewardship and has served on several government agency advisory committees, including the workgroup for the Sustainable Pest Management Roadmap. Before joining the Almond Board, she worked for the consulting firm Schramm, Williams & Associates in Washington, DC. She received her PhD in plant physiology from the University of California, Davis, and her BA in biology from Wellesley College.

*Conflict of Interest Statement:* Dr. Ludwig was identified as having a potential conflict of interest by serving as a member of the Pest Management Advisory Committee (PMAC) for the California Department of Pesticide Regulation. It was determined that such potential conflict of interest would not affect their ability to participate in the roundtable. Additionally, CCST maintains that it is essential for the roundtable to reflect a diversity of perspectives, and that this potential conflict of interest does not outweigh the unique insights Dr. Ludwig may contribute to the discussions.

**Dr. Tom Phillips** is the Donald Wilbur Endowed Professor for Stored Product Protection at Kansas State University. He obtained a PhD in biology with an entomology concentration from the State University of New York's College of Environmental Science and Forestry and in his career has served as a research entomologist with the USDA Agricultural Research Service's Stored Product Insect Research Unit in Madison, Wisconsin, and has served as an associate or full professor of entomology at various universities, including University of Wisconsin, Oklahoma State University, and Kansas State University. Dr. Phillips' research focuses on the biology and management of pests infesting post-harvest agricultural products, insect chemical ecology, and alternative control measures and integrated pest management, including alternatives to methyl bromide fumigation.

**Dr. Suresh Prabhakaran** is the chief technology officer at Douglas Products, LLC. In addition to a PhD in entomology, Dr. Prabhakaran has over 30 years of professional experience in crop protection, post-harvest pest management, pesticide regulation, and toxicology. His work has focused on developing a commodity fumigant as a methyl bromide alternative, while evaluating chemical and non-chemical methods for managing stored product pests. He has also been involved in international, federal, and state-level policy development, applied research, and regulatory science, among other works. In his current role at Douglas Products, he leads the global research and development, regulatory, and business development teams. Dr. Prabhakaran has published, presented, and consulted on topics such as integrated pest management, fumigant alternatives, and regulatory frameworks. He has a strong understanding of the challenges and tradeoffs associated with transitioning away from traditional fumigants, including regulatory barriers, efficacy considerations, and market pressures.

*Conflict of Interest Statement:* Dr. Prabhakaran has been noted as having a potential conflict of interest due to his role as Chief Technology Officer at Douglas Products. In this capacity, Dr. Prabhakaran is responsible for overseeing all technology-related aspects of fumigant development, including global research and development as well as regulatory matters. Additionally, his compensation structure and incentives are directly linked to the performance of Douglas Products' portfolio. However, it was determined that such potential conflict of interest would not affect their ability to participate in the roundtable. Additionally, CCST maintains that it is essential for the roundtable to reflect a diversity of perspectives, and that this potential conflict of interest does not outweigh the unique insights Dr. Prabhakaran may contribute to the discussions.



**Caroline Stringer** joined the California Fresh Fruit Association (CFFA) as director of trade in 2020. Ms. Stringer oversees the California stone fruit phytosanitary export programs, international market development activities, and marketing programs. Ms. Stringer serves on the USDA Agricultural Technical Advisory Committee and as the Minor Crop Farmer Alliance's Secretary. Since joining CFFA, Ms. Stringer has led the stone fruit industry initiatives for new market access for plums into Japan (2022) and nectarines and peaches into Vietnam (2024) and is currently working on market access for nectarines to South Korea (anticipated 2026). She has worked for a variety of food and agricultural organizations, including as an international agricultural intern at FAS Lima in 2008. Ms. Stringer holds a BA in international relations from San Francisco State University and a MA in international trade policy from the Monterey Institute of International Studies.

**Dr. Yoshira "Yoshi" Ornelas Van Horne** is an exposure scientist and environmental justice scholar. She is assistant director of the Agents of Change in Environmental Justice Fellowship, which trains early career scientists in science communications. She currently serves as the Deputy Director of the Environmental heAlth sciences Research for Teachers and High school students (EARTH) program which is funded by the National Institute for Environmental Health Sciences. The EARTH Program is a structured summer environmental health sciences research program for high school students and teachers from three Native communities in the Northern Plains. Her research is currently funded by the JPB Environmental Health Fellowship through Harvard T.H. Chan School of Public Health, the HEI Rosenblith New Investigator award, and the Centers for Disease Control and Prevention.

Her research focuses on addressing unequal *exposures* to harmful contaminants that affect structurally marginalized communities. Her active projects focus on using novel methods for source apportionment of air pollution, characterizing exposures to volatile organic compounds with community partners in Louisiana, and evaluating the impact of federal environmental settlements on population exposures and health outcomes. She is committed to building health equity through community-driven research and is passionate about research translation and communication. To this end, her work not only characterizes inequities in cumulative exposures but also supports community-driven solutions and training efforts. Dr. Ornelas Van Horne serves as the co-chair of the General Scientific Meetings Committee for the International Society of Exposure Science.

**Darren Van Steenwyk** is a consultant at VS Pest Consultants. His expertise spans post-harvest pest management techniques and commodity preservation, paired with a solid understanding of fumigant alternatives that are critical to transitioning away from conventional fumigants, such as controlled atmospheres, irradiation, and integrated pest management. By bridging practical insights into pest management with policy and regulatory awareness, he aims to help shape actionable recommendations that inform both the California Department of Pesticide Regulation and stakeholders across the supply chain. His goal is to advance effective, safe, and scalable post-harvest strategies that support both trade and environmental health.

Appendix B

# Agenda and Discussion Questions

| Day | Time | Agenda Item |
|---|---|---|
| Nov 5 | 5:30–7:00 pm | Group Dinner (Optional) |
| Nov 6 | 9:00–9:30 am | Check-in & Breakfast<br>CCST Welcome & Overview<br>Eric Chu |
| | 9:30–9:45 am | Introductions<br>Eric Chu/Rhianna Hohbein |
| | 9:45–11:15 am | Focus 1: Post-Harvest Commodity Fumigants<br>Facilitator: Rhianna Hohbein<br>Context-setter: Dr. James Adaskaveg |
| | 11:15 am–12:15 pm | Lunch Break |
| | 12:15–3:15 pm | Focus 2: Fumigant Alternatives<br>Facilitator: Rhianna Hohbein |
| | 3:15–5:00 pm | Focus 3: Post-Harvest Commodity Fumigants: Exposure and Emission Mitigation Measures<br>Facilitator: Eric Chu<br>Context-setter: Dr. Jill Johnston |
| | 6:30–8:00 pm | Group Dinner (Optional) |
| Fri, Nov 7 | 8:30–9:00 am | Breakfast<br>Group Recap<br>Facilitator: Eric Chu |
| | 9:00–11:00 am | Focus 4: Barriers to Alternatives<br>Facilitator: Eric Chu |
| | 11:00 am–12:00 pm | Outstanding Gaps<br>Facilitator: Rhianna Hohbein |
| | 12:00–12:30 pm | Group Recap |
| | 12:30–1:30 pm | Light Lunch |

Location: 3rd Floor Conference Room, UC Center Sacramento, 1115 11th St., Sacramento, CA 95814

# Discussion Questions

1. **Post-Harvest Commodity Fumigant Use Drivers:** What drives the use of each of these post-harvest commodity fumigants?
    a. Policies/laws/regulations
    b. Pests
    c. Trade and international usage/regulations
    d. Location methodology and alternatives
    e. Knowledge gaps and research opportunities
2. **Post-Harvest Commodity Fumigant Alternatives:** What alternatives currently exist, and which are on the horizon?
    a. How effective is each in turn?
    b. What is the extent of their use?
    c. Why aren't they [commonly] used right now?
    d. Knowledge gaps and Research opportunities?
3. **Post-Harvest Commodity Fumigant Alternative Barriers:** What would it take to reduce our reliance on commodity fumigants? What barriers prevent the development and deployment of alternatives?
4. **Post-Harvest Commodity Fumigant Exposure and Emission Mitigation:** What fumigant exposure and emission mitigation measures are in use? What emission reduction measures exist? How effective are they? What more can be done?

Appendix C

# Human Health Impacts of Fumigants

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*Peer review:*
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Select staff, California Office of Environmental Health Hazard Assessment

## Human Health Impacts of Phosphine ($PH_3$)

**Appendix Table 1.** Phosphine ($PH_3$) summary

| Category | Description |
|---|---|
| Other names | Hydrogen phosphide |
| Trade name(s) | $ECO_2FUME$®, $VaporPH_3OS$®, U-phos® |
| Properties | Gas at room temperature or solid phosphides that generate gas, flammable, reactive, colorless, odorless |
| Primary use in post-harvest applications | Pest control for stored food and non-food commodities. Applied in enclosed spaces, including storage facilities, warehouses, bins, silos, shipping containers, railcars, and within sealed tents/tarps. |
| Primary exposure routes | Inhalation |
| Acute effects | Respiratory distress, headaches, dizziness, numbness, cardiotoxic, chest pain |
| Chronic effects | Genotoxic potential (DNA damage), neurotoxic, cardiotoxic |
| Air monitoring notes | Insufficient protective threshold for workers and nearby residents for certain fumigation activities and scenarios |
| Regulatory status | Restricted Use Pesticide, Hazardous Air Pollutant, Toxic Air Contaminant |

**A. Background.** Phosphine is a broad-spectrum fumigant used to control insects and rodents in food storage facilities, including grain elevators, farm bins, warehouses, railcars, ships, and shipping containers. It is applied to both foodstuff (e.g., grains, nuts, processed foods, animal feed) and nonfood products (e.g., paper, wood, leather, clothing, natural fibers). Phosphine is available as both a compressed gas and a solid product that generates phosphine gas on contact with moisture. These dry solid phosphides include metal-containing tablets, pellets, or granules with aluminum phosphide or magnesium phosphide as the active ingredients. Metal phosphides are odorless; upon reacting with moisture, phosphine gas is released. Phosphine gas forms impurities that are attributed to the characteristic garlic or fish odor. Phosphine gas is highly flammable and can ignite spontaneously in air (at concentrations of 18,000 ppm or higher). Under certain conditions, it may also react with oxygen, halogens, and certain extinguishing agents. Some formulations include the addition of carbon dioxide to reduce its flammability.

**B. Exposure Pathways.** Human exposure to phosphine primarily occurs through inhalation. Oral exposure from ingestion of residues on treated food is possible, but unlikely according to regulators.[1] Fumigators and commodity workers (e.g., loaders, transporters) are at risk of inhalation exposure during application and post-fumigation when phosphine gas is aerated from treated commodities in structures and cargos. Pure formulations of phosphine gas are odorless but may produce an odor if impurities are present. When phosphine gas forms, it may be associated with a garlic or fish odor. Odor detection may occur at or near occupational exposure limits; however, odor is not a reliable indicator of phosphine presence or exposure, due to individual differences and sensitivity to smell.[1] Phosphine gas is slightly denser than air and has potential to pool at ground level in confined spaces. Proper monitoring and aeration practices are essential to reduce the occupational risk from potentially prolonged emissions and gradual release from solid phosphides. Nearby residents may be exposed to phosphine through leaks from facilities. Pure phosphine's high flammability means that leaks and spills create a fire hazard, further increasing the risk of ambient exposure for nearby communities and emergency responders; however, the formulations used for post-harvest commodity fumigations are mixtures that include carbon dioxide to decrease flammability.[2] Emergency responders may also have an increased risk of acute secondary exposure to phosphine gas released from the clothing and bodies of people who intentionally ingest phosphide solids for self-harm. This off-gassing can occur rapidly, requiring specialized decontamination. Because fumigation with either form of phosphine can last a few days up to a month—depending on the treated structure and local climate—community-wide exposure is a concern.[3]

**C. Health Effects.** Phosphine gas is highly toxic when inhaled, and solid phosphides are poisonous if swallowed because they release phosphine gas in the stomach. Acute exposure from toxicological studies and human exposure injury incidents (both unintentional and intentional) demonstrate that phosphine induces systemic toxicity, posing a serious risk of death.[1] The mechanism of phosphine toxicity is not fully understood. It has been attributed, in part, to its nucleophilicity and reducing capabilities, which disrupt enzyme activity and cellular processes and contribute to oxidative stress. Upon inhalation, it is quickly absorbed by the lungs, where it is then widely distributed to the heart, brain, and liver. Its toxicity is attributed to its high reactivity from extra electrons that it readily donates to other molecules. Phosphine can interact with cell structures such as mitochondria that are important for energy production.[4] Phosphine can cause oxidative stress, a process where unstable molecules (reactive oxygen species) trigger chain reactions that damage cell walls, proteins, and DNA.[1] While acute effects are well-described, there is limited research on the human health effects of continuous, low-dose phosphine exposure.

Acute health effects. Short-term exposure harms the respiratory, nervous, and cardiovascular systems. In humans, inhalation can cause respiratory irritation of the nose, throat, and lungs, leading to coughing, shortness of breath, chest tightness, rales (lung crackles), and in severe cases, pulmonary edema (fluid in lungs). Neurological symptoms include headaches, dizziness, numbness, and confusion. Low blood pressure and irregular heartbeats have also been reported in humans.[5,6] In animals, inhalation exposure caused liver and kidney tissue damage.[1] From 1992–2022, approximately 60% (n=151) of all pesticide-related illnesses and injuries from phosphine or metal phosphide generators in California occurred from post-harvest fumigations (n=253).[7] Over half (54%, n=82) were attributed to aluminum phosphide (***Appendix Table 2***). Among post-harvest exposures, 85 case reports involved facility workers (e.g., sorters, graders, processors, forklift operators) handling nuts, grains, and fruits.

**Appendix Table 2.** California Pesticide Injury Surveillance Program reports of phosphine, aluminum phosphide, and magnesium phosphide-related incidents from post-harvest commodity fumigations (1992–2022)

| Activity types | Phosphine | Aluminum Phosphide | Magnesium Phosphide | Total |
|---|---|---|---|---|
| Applicator/Handler | 8 | 15 | 0 | 23 |
| Post-harvest facility workers (e.g., sorter, packers) | 52 | 30 | 3 | 85 |
| Bystander workers (e.g., maintenance, inspectors) | 4 | 37 | 2 | 43 |
| **Total** | **64** | **82** | **5** | **151** |

*Chronic health effects.* Research on long-term phosphine exposure in fumigators and animals shows that the lungs, brain, and heart are the primary target organs. Phosphine poisoning can lead to chronic heart complications, such as irregular heartbeats and congestive heart failure.[6] In rodents, repeated and low-dose inhalation exposure slowed respiration and caused sleepiness.[1] Long-term exposure studies in humans are limited, but occupational exposure to aluminum phosphide and phosphine gas has been linked to depression[8], cancer,[9,10] shortness of breath (dyspnea),[11] pulmonary obstructive disease,[12] and nerve damage (peripheral neuropathy).[12] Additionally, chronic, low-dose exposure has been associated with anemia, bronchitis, kidney failure, and neurological impairment to speech and movement.[13] Some studies of fumigators suggest that phosphine exposure damages DNA.[14] In a follow-up study, fumigators who only applied products generating phosphine gas had higher risk of changes in chromosome structures (i.e., potential for genotoxicity) compared to other fumigators who worked with a mix of pesticides, other workers, or residents.[15] Other studies reported no associations between phosphine exposure and genotoxicity among workers.[16,17] Laboratory tests on genetic material and animal studies have also produced mixed results.[18–21] A study of rats exposed to phosphine gas over a 2-year period reported no evidence of cancer.[22] No known studies have assessed dermal or reproductive toxicity of phosphine.

**D. Air Monitoring.** To date, comprehensive, statewide air monitoring of phosphine gas concentrations in California are limited. Phosphine is not on the list of pesticides being monitored by the Department of Pesticide Regulation's (DPR) Air Monitoring Network.[3] An exposure assessment conducted by DPR monitored phosphine levels from several fumigation activities by structure type for various occupational and community settings.[1,3,23] An updated report to this assessment concurred with their findings that highlighted several exposure scenarios for fumigators, handlers, and bystanders that may be of concern, while noting that people who live or spend time farther away from fumigation sites, not those living very close to fumigation sites are at minimal risk of exposure from ambient drift.[3]

**E. Regulatory Context. Cylinderized** phosphine was registered in 1999, decades after metal phosphide generators, aluminium and magnesium, were registered in 1958 and 1979, respectively.[24] Phosphine is federally classified as a Restricted Use Pesticide and only handled by certified applicators. As a federally classified Hazardous Air Pollutant, phosphine is subject to emission regulations in accordance with the U.S. Clean Air Act. In California, phosphine is also classified as a Toxic Air Contaminant. Short-term exposure to phosphine gas via inhalation is well-characterized in animal studies and human case reports. Based on its high toxicity, use patterns, and low potential for dermal and ingestion exposure, data waivers were granted for certain toxicity study requirements due to limited relevance and feasibility. However, epidemiological data on the chronic, low-dose exposures, specifically among fumigation workers, is limited and the long-term effects are less understood. Homes near fumigated commodity facilities in California are not protected by buffer zones, which may have public health implications for susceptible populations that work or reside near treated commodities. More research is needed to characterize phosphine exposure from post-harvest commodity fumigations in California among workers and those close to fumigated structures.

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# Human Health Impacts of Propylene Oxide ($C_3H_6O$)

**Appendix Table 3.** Propylene Oxide ($C_3H_6O$) Summary

| Category | Description |
|---|---|
| Other names | 1,2-epoxypropane; 1,2-propylene oxide; methyloxirane; propene oxide; methyl ethylene oxide |
| Trade name(s) | Propoxide 892® |
| Properties | Volatile liquid at room temperature evaporates as a gas, flammable, reactive, colorless, sweet odor |
| Primary Use in post-harvest applications | Pest control and sterilant in stored high-value food and non-food commodities. Applied in airtight chambers, shipping containers, and within sealed tents/tarps. |
| Primary exposure route | Inhalation |
| Acute effects | Eye and respiratory irritation, difficulty breathing, neurotoxicity |
| Chronic effects | Genotoxic potential (DNA damage); tumors observed in animals, likely human carcinogen; respiratory |
| Air monitoring notes | Workplace exposures slightly increase with certain tasks (e.g., unloading sterilization chambers); more data needed on exposure for nearby residents |
| Regulatory status | Restricted Use Pesticide, Hazardous Air Pollutant, Toxic Air Contaminant, Proposition 65 (cancer causing) |

**A. Background.** Propylene oxide is a broad-spectrum fumigant used to control bacteria, fungi, mold, and insects in dry food commodities (e.g., dried fruits, nuts, spices, animal feed). It is also applied in railcars, shipping containers, sealed tarps in warehouses, and other structures used for processing, storing, and transporting food commodities. Propylene oxide is also registered for sterilization of food, cosmetics, and pharmaceuticals to prevent microbial spoilage.[1] Propylene oxide is typically applied as a gas from pressurized containers. Some formulations include carbon dioxide to reduce flammability. In California, approximately 30% of total propylene oxide use from 2013 to 2017 was for commodity fumigation of nuts.[2]

**B. Exposure Pathways.** Human exposure to propylene oxide primarily occurs through inhalation. Oral exposure from ingestion of residues on food is possible but expected to be minimal. Upon fumigation, propylene oxide may react with chloride ions in plant-based commodities (e.g., spices, herbs), forming propylene chlorohydrin.[1–3] Propylene chlorohydrin does not pose an inhalation risk, but it is known to be toxic when ingested at high levels, causing DNA and organ damage in animals. For this reason, regulatory agencies consider dietary residues of propylene chlorohydrin in their propylene oxide risk assessments. Fumigators and commodity workers (e.g., handlers, loaders, transporters) are at risk of inhalation exposure during the application phase. Although propylene oxide dissipates rapidly at room temperature, it is unknown whether concentrations post-fumigation (e.g., when propylene oxide is aerated or off gasses from treated commodities or structures) pose a risk to workers, due to limited pesticide data at the time of its registration.[3] Nearby residents may also be exposed through unintentional propylene oxide leaks from facilities, and during aeration or venting following fumigation.

**C. Health Effects.** Propylene oxide is a highly toxic fumigant that primarily impacts the respiratory and nervous systems. Propylene oxide's toxicity is largely attributed to its highly reactive three-membered epoxide structure, which enables attachment or covalent binding to nucleophilic sites on macromolecules, such as proteins and DNA, leading to cellular dysfunction. Propylene oxide exposure is genotoxic through (1) directly binding to DNA, leading to mutations, and (2) oxidative stress, a process where unstable molecules (reactive oxygen species) trigger chain reactions that cause genetic damage. Upon inhalation, propylene oxide is first absorbed by the nose, throat, and lungs and then distributed to the liver.[3] In humans, propylene oxide is broken down and excreted in urine as 2-HPMA, which serves as a biomarker of exposure.[4] Animal studies show that propylene oxide mainly affects the portals of entry where it firsts contacts the body (e.g., nose, mouth), and long-term exposure may cause cancer.[1–3] Laboratory assays of genetic material show that propylene oxide can bind directly to DNA and hemoglobin, in studies from exposed animals and petrochemical workers, which may lead to genetic mutations.[5,6]

*Acute health effects.* Short-term exposure harms the respiratory system, causing inflammation, nasal discharge, labored breathing, and gasping.[1] In rodents, inhaling high concentrations resulted in neurological symptoms such as slowed motor activity and poor muscle control. Injury case reports reveal dermal contact results in severe eye and skin damage.[7–9] From 1993 to 2022, there have been two reports of propylene oxide-related injuries and illness in California, which occurred from almond fumigations.[10] Those workers reported respiratory and neurological symptoms, such as coughing, breathing problems, headaches, lightheadedness, and fainting. One applicator also reported sores on their face and scalp.[10]

*Chronic health effects.* Emerging research from human studies links continuous, low-dose ambient exposure of propylene oxide, a volatile organic compound (VOC), with several adverse health outcomes. In rodents, studies of prolonged inhalation exposure (103–124 weeks) to propylene oxide caused respiratory tract irritation and lesions.[11,12] While epidemiologic evidence is limited, cross-sectional studies of a large-scale national sample found that higher urinary concentrations of propylene oxide biomarker 2-HPMA were associated with pediatric asthma,[13] as well as reduced lung function in adults[14] and children,[15] along with mixtures of other VOCs. Higher concentrations of biomarker 2-HPMA have been linked to diabetes,[16] cardiovascular disease,[17] kidney stones,[18] and chronic kidney disease.[19] Studies of ambient propylene oxide exposure in Kansas found an elevated risk of liver injury for smokers, especially female smokers.[20,21] Propylene oxide exposure may also have negative developmental and reproductive effects. Rats exposed to high concentrations of propylene oxide in-utero exhibited reduced body weight and fetal skeletal rib deformities.[12] In humans, a higher urinary 2-HPMA biomarker was also linked to reduced female fertility.[22,23]

*Cancer.* Propylene oxide is mutagenic and binds (i.e., forms adducts) with proteins and DNA.[5,6] Propylene oxide has been evaluated by several international and U.S. public health and regulatory agencies, concluding probable carcinogenicity (***Appendix Table 4***). In rodents, long-term inhalation exposure led to tumors in the nose, forestomach, and mammary glands.[1,24,25] Higher urinary 2-HPMA levels were associated with higher cancer mortality in the U.S.[26] A 15-year study of California teachers found that those living in areas with moderate levels of ambient propylene oxide exposure had a higher risk of developing breast cancer,[27] but a nationwide study of nurses found no such association.[28] Early studies of manufacturing workers exposed to a mix of chemicals, including propylene oxide, found no associations with cancer.[29–34] However, research on commodity fumigation workers and nearby residential ambient exposures are limited.

**Appendix Table 4.** Cancer classifications of propylene oxide

| Regulatory Body | Agency | Classification |
|---|---|---|
| **International** | World Health Organization, International Agency for Research on Cancer (IARC)[35] | Possibly carcinogenic to humans (Group 2B) |
| **USA** | U.S. Department of Human and Health Services, National Toxicology Program (NTP)[36] | Reasonably anticipated to be a human carcinogen |
| | U.S. EPA, Integrated Risk Information System (IRIS)[37] | Probable human carcinogen (Group B2) |
| **California** | Cal EPA, Office of Environmental Health and Human Hazard (OEHHA)[38] | Proposition 65 (cancer causing) |

**D. Air Monitoring.** While fumigations are often conducted in sealed structures and chambers, propylene oxide can be released into the air as a VOC, potentially contributing to air pollution. Despite widespread use as an industrial chemical and post-harvest fumigant, data on ambient propylene oxide concentrations are limited, including for California. The U.S. Environmental Protection Agency (EPA) has outlined several key data gaps, including air monitoring data for workers and residents.[3] Registrant-submitted data to EPA assessed outdoor almond worker's exposure to propylene oxide in California.[1] Exposures were estimated using personal monitor badges worn for a typical 8-hour workday. On average, exposures were below safety limits set by the U.S. Occupational Safety and Health Administration (OSHA), with levels slightly rising with certain tasks (e.g., unloading sterilization chambers). These exposure estimates are largely influenced by factors such as climate and ventilation. More studies are needed to characterize risk of both outdoor and indoor fumigation scenarios, including for residents near treated facilities. Early air modeling indicated fugitive emissions from treated chambers were a risk to nearby residents, but that buffer zones would reduce this risk.[1] An updated model for areas with high propylene oxide use concluded that community exposures to ambient propylene oxide were unlikely to exceed regulatory reference levels.[3]

**E. Regulatory Context.** Propylene oxide was first registered in the 1990s and is federally classified as a Restricted Use Pesticide and only handled by certified applicators due to inhalation toxicity. Under the U.S. Clean Air Act, chemicals classified as Hazardous Air Pollutants, including propylene oxide, are subject to federal emission limits designed to protect the environment and public health. In California, propylene oxide is also regulated as a Toxic Air Contaminant and listed as a Proposition 65 chemical known to cause cancer. Propylene oxide is not included in the list of pesticides being monitored by DPR's Air Monitoring Network. In 2020, EPA identified gaps in registrant data, including inhalation exposure for applicators, post-fumigation exposures for workers and residents, gas emissions from treated commodities, and air concentrations near treated facilities.[2] Buffer zones are variable for post-harvest fumigations (i.e., requisite distances tailored to application method, fumigation type, and label requirements). Given limited data, buffer zones are essential for reducing unintentional worker and community exposures to propylene oxide in California.

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# Human Health Impacts of Sulfuryl Fluoride ($SO_2F_2$)

**Appendix Table 5.** Sulfuryl Fluoride ($SO_2F_2$) summary

| Category | Description |
|---|---|
| Other names | Sulfuryl difluoride |
| Trade name(s) | ProFume® |
| Properties | Gas at room temperature, non-flammable, colorless, odorless |
| Primary use in post-harvest applications | Pest control for stored food commodities (e.g., grains, nuts, and dried fruit) and nonfood commodities (e.g., logs). Applied in enclosed spaces, including storage facilities, warehouses, bins, silos, shipping containers, railcars, and within sealed tents/tarps. |
| Primary exposure route | Inhalation |
| Acute effects | Respiratory irritation, brain vacuoles, muscle twitching, seizures |
| Chronic effects | Dental fluorosis, inflammation of respiratory tissue, brain vacuoles, neurotoxicity |
| Air monitoring notes | Southern coastal regions of Los Angeles, Orange, and San Diego counties have the highest concentrations where commodity and structural fumigations are concentrated. |
| Regulatory status | Restricted Use Pesticide, Toxic Air Contaminant |

**A. Background.** Sulfuryl fluoride is a broad-spectrum fumigant used to control pests that infest post-harvest food commodities, including beetles, moths, weevils, and others. Sulfuryl fluoride is approved for the direct fumigation of certain food commodities (e.g., rice, grains, nuts, dried fruit) and nonfood items (e.g., logs, furniture). Its use is approved for food processing and storage facilities (e.g., grain mills, warehouses, shipping containers). Sulfuryl fluoride is an effective fumigant of stored commodities primarily due to its stability as a gas at room temperature, high vapor pressure, and low molecular weight that allow it to diffuse rapidly and penetrate porous materials. Sulfuryl fluoride was first registered in the United States in 1959. However, its use greatly expanded in post-harvest applications following the phaseout of methyl bromide in 2005. Sulfuryl fluoride has become the primary alternative to methyl bromide for treating post-harvest durable foodstuff in export and import trade.[1]

**B. Exposure Pathways**. Human exposure to sulfuryl fluoride from commodity fumigation primarily occurs through inhalation and, to a lesser extent, ingestion of fluoride residues on treated food. Studies measuring ambient sulfuryl fluoride concentrations after commodity fumigations are limited. In a laboratory-based study, 12% of fumigated commodities absorbed or retained high levels of sulfuryl fluoride.[2] Post-harvest studies measuring sulfuryl fluoride residues following commodity fumigations show that minimal levels can persist after treatment and aeration.[3] Thus, residue tolerances have been established to minimize dietary exposure from eating fumigated foods. Fumigators and commodity workers who handle, store, and apply sulfuryl fluoride face the greatest risk of acute or chronic health effects, especially if safety protocols are inadequately followed. No warning agents are used in tandem with commodity fumigations using sulfuryl fluoride. The fumigant is heavier than air, meaning it can pool at ground level in enclosed spaces. Ventilation (e.g., fans, ventilation pipes) is essential to reduce occupational exposures. Sulfuryl fluoride can penetrate porous materials including bulk commodities and packaging material. During aeration, off-gassing can pose an occupational inhalation risk. Nearby residents may also be exposed through sulfuryl fluoride leaks from facilities during fumigations and from aeration events immediately following.[4,5]

**C. Health Effects:** Sulfuryl fluoride is a toxic fumigant with documented adverse neurotoxic and respiratory effects, and laboratory tests of genetic material suggest it may damage DNA.[4] The mechanism of toxicity of sulfuryl fluoride is not fully understood. Upon inhalation, sulfuryl fluoride is rapidly absorbed and hydrolyzed to fluorosulfate, sulfate, and fluoride in rats' lungs.[4] At sufficiently high levels, fluoride ions can inhibit key cellular enzymes such as enolase, disrupting cellular energy production from glucose (i.e., glycolysis) and cellular energy production.[6] Fluoride has been shown to induce oxidative stress in toxicological studies at high concentration (greater than 100 ppm), though this has not been demonstrated for sulfuryl fluoride.[7] Most evidence of the adverse health conditions from sulfuryl fluoride exposure comes from toxicological studies, registrant data, and case reports of injuries and illnesses.

*Acute health effects*. Inhaling high concentrations of sulfuryl fluoride can cause a range of immediate health effects, including death.[11] In California, approximately 12 cases of sulfuryl fluoride-related injuries and accidents were reported from post-harvest fumigations between 1992–2022.[8] Symptoms following exposure included headache, dizziness, nausea, vomiting, increased palpitations, and irritation of eyes and throat.[8] Other reports suggest that severe symptoms from acute poisoning include pulmonary edema (fluid in lungs) and pneumonia, as well as neurological issues such as headaches, dizziness, muscle twitching, seizures, slurred speech, or confusion.[9–11] Animal studies have demonstrated respiratory effects, including inflammation in nasal passages, trachea, and bronchi in rabbits and dogs; neurotoxicity (tremors, lethargy) in rodents, rabbits, and dogs; cerebral lesions (vacuolation, malacia, and demyelination) in rabbits and mice; and renal effects (papillary necrosis and degeneration and regeneration of the collecting and proximal tubules) in rats.[12–13]

*Chronic health effects*. Chronic inhalation studies in rodents and dogs have shown that sulfuryl fluoride exposure can affect multiple organ systems. In animals and humans, the brain and respiratory tract are the main targets of prolonged exposure, with neurological changes (vacuoles, lesions) and respiratory tract inflammation.[4] Renal effects, such as lesions and progressive glomerular nephrosis have been reported in rats.[4] Dental fluorosis (tooth discoloration and enamel damage), reported in rat and dog studies, is consistent with accumulation of fluoride ions in calcified tissues.[4] Data on occupational studies of sulfuryl fluoride inhalation exposure from post-harvest fumigations are limited. However, among structural fumigation workers exposed to both sulfuryl fluoride and methyl bromide, high sulfuryl fluoride exposure the prior year was linked with poorer memory, and a trend of worse performance was observed with increasing lifetime sulfuryl fluoride exposure. Workers with high sulfuryl fluoride exposure also exhibited decreased olfactory function (sense of smell), suggesting subclinical elevations of sulfuryl fluoride may act on the central nervous system.[15] Sulfuryl fluoride is a respiratory irritant, and individuals with underlying respiratory conditions are highly susceptible to lung damage from chronic exposure to sulfuryl fluoride.[4] Some laboratory studies of genetic material suggest that sulfuryl fluoride may cause DNA damage at high doses, with speculation that fluoride ions play a role in mediating its damage.[3,4] However, studies of chronic exposure in humans are lacking, and more research on its potential genotoxicity are necessary to confirm this.

**D. Air Monitoring**. Nationally, California is the largest known emitter of sulfuryl fluoride, releasing approximately 573,000 pounds (0.26 gigagrams) annually, mostly from structural fumigations.[16] The emissions from post-harvest commodity fumigations are poorly understood. Sulfuryl fluoride exposure in the environment varies by season, timing of fumigation, and location. The southern coastal regions of Los Angeles, Orange, and San Diego Counties, where both commodity and structural fumigations are heavily concentrated, have the highest concentrations of ambient sulfuryl fluoride.[16] While coarse studies on ambient sulfuryl fluoride concentrations provide valuable insight, there are few studies that have reported sulfuryl fluoride levels within or adjacent to food processing and storage facilities. Sulfuryl fluoride is not included in the list of pesticides being monitored by the California Department of Pesticide Regulation's Air Monitoring Network, although it is heavily used as a structural and commodity fumigant in California. More workplace and environmental monitoring would help determine whether local ambient concentrations pose a health risk, especially for susceptible populations in Southern California.

**E. Regulatory Context.** Sulfuryl fluoride is federally classified as a Restricted Use Pesticide, and only certified applicators may handle sulfuryl fluoride. In California, sulfuryl fluoride is designated a Toxic Air Contaminant due to its potential for human health risks. However, it is not federally recognized as a Hazardous Air Pollutant, excluding it from the U.S. Clean Air Act emission regulations. In July 2024, the U.S. Environmental Protection Agency updated product labels for Vikane, the structural fumigant, with additional safety measures for certified applicators, including expanded worker training, longer aeration procedures, fumigation logs, and no-entry warning signs. Regulatory agencies have established residue tolerance levels for foods fumigated with sulfuryl fluoride to ensure foodstuffs are within safety margins.[3] Additional data on the potential effects of sulfuryl fluoride on post-harvest workers are lacking, as their exposures may differ in volume, concentration and duration. Populations living or working near fumigated sites may also be exposed to sulfuryl fluoride via off-gassing and drift. Limited air monitoring data around fumigation facilities highlight the need to further evaluate potential risks.

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# Human Health Impacts of Methyl Bromide ($CH_3Br$)

**Appendix Table 6.** Methyl Bromide ($CH_3Br$) summary

| Category | Description |
|---|---|
| Other names | Bromomethane |
| Trade name(s) | Meth-O-Gas®, Metabrom® |
| Properties | Gas at room temperature, non-flammable, colorless, odorless |
| Primary use in post-harvest applications | Quarantine and pre-shipment (QPS) for imported and exported food and nonfood commodities. Applied in enclosed spaces, including storage facilities, warehouses, bins, silos, shipping containers, railcars, and within sealed tents/tarps. |
| Primary exposure route | Inhalation |
| Acute effects | Respiratory irritation, loss of muscle control, seizures |
| Chronic effects | Chronic bronchitis, brain tissue lesions and atrophy, reproductive/developmental toxicity; inconclusive evidence of carcinogenicity |
| Air monitoring notes | Ambient levels exceeded health-protective thresholds for community bystanders in Southern California |
| Regulatory status | QPS exemption (per Montreal Protocol), Restricted Use Pesticide, Hazardous Air Pollutant, Toxic Air Contaminant, Proposition 65 (developmental toxicant) |

**A. Background.** Methyl bromide is a broad-spectrum fumigant used to control a wide range of pests including fungi, weeds, insects, roundworms, snakes, and rodents. In California, methyl bromide is applied to imported and exported fresh produce, dried foodstuff, and nonfood items (e.g., wood, textiles) during storage, shipping, or for quarantine treatment. Nuts, dried fruit, and produce may be fumigated in warehouses or at ports to meet quarantine and trade requirements. Methyl bromide is a colorless, odorless gas with low molecular weight and high volatility. These properties enable the gas to readily diffuse into and out of stored commodities and buildings to reach pests.[1,2] Methyl bromide was widely used for decades across pre-plant, post-harvest, and structural applications until 2005, when its use was largely phased out under the Montreal Protocol due to its ozone-depleting properties. Limited applications for post-harvest commodities have continued through QPS exemptions—all other applications have been eliminated. In California, methyl bromide usage has declined from 17 million pounds in 1992 to about 1.5 million pounds in 2023 for agricultural (pre-plant) uses, which still accounts for over half of total agricultural applications. QPS uses, considered non-agricultural, contributed an additional 200,000 pounds in 2023, bringing the total statewide use to roughly 1.7 million pounds.

**B. Exposure Pathways**. Human exposure to methyl bromide primarily occurs through inhalation.[1] During and immediately after fumigation, treated commodities can release methyl bromide into the surrounding air, but residues on treated commodities dissipate rapidly following aeration.[2] Oral exposure from ingestion of residues on treated food is possible, but generally considered low and within regulatory limits.[3] Fumigators and commodity workers (e.g., loaders, transporters) who handle, store, and apply methyl bromide are at risk of inhalation exposure during the application phase and post-fumigation, when the gas is aerated from treated commodities in structures and cargos. Methyl bromide is heavier than air, meaning it can pool at ground level in enclosed spaces. Ventilation (e.g., fans, ventilation pipes) is essential to reduce occupational exposures.[3] Nearby residents may also be exposed through methyl bromide leaks from facilities during fumigation and from aeration events following fumigations. Ambient air modeling suggests that residential bystander inhalation from methyl bromide depends on several factors, such as meteorological conditions, application rates, and volumes.[2] Air modeling also found that for many scenarios, health-based air benchmarks were not achieved at the facility boundary, suggesting the potential for the methyl bromide to drift.[2]

**C. Health Effects:** Methyl bromide is a highly toxic fumigant with neurological, respiratory, developmental, and reproductive effects, as well as potential carcinogenicity.[4–6] Upon inhalation, methyl bromide is quickly absorbed where it can then spread to fat tissue and ultimately reach the brain (crossing the blood-brain barrier).[5] Methyl bromide is also transported to organs such as the liver, where it is broken down into bromide ions and other compounds.[7] Proposed mechanisms of toxicity include (1) systemic and intracellular effects of bromide ions; (2) formation of reactive methanol metabolites; and (3) alkylating activity, in which methyl bromide transfers alkyl groups (carbon and hydrogen atoms) to other molecules, potentially damaging DNA and causing genetic mutations.[4,6,7] Research in both animals and humans indicate that inhalation exposure to methyl bromide is associated with adverse effects mainly on the nervous and respiratory systems.[1,4]

*Acute health effects.* Inhaling sufficiently high doses of methyl bromide can cause a range of immediate health effects, including death.[8] In California, there were 48 methyl bromide-related injuries and illnesses from post-harvest fumigation between 1992–2022 (***Appendix Table 7***).[9] The majority of these post-harvest fumigations involved facility workers (n=23). Neurological symptoms in humans may include headaches, dizziness, loss of muscle control, visual and speech impairment, and seizures.[5,10–13] Neurological symptoms may appear 30 minutes after exposure, while more severe acute toxicity can develop within 48 hours.[5] Respiratory symptoms include cough, throat irritation, shortness of breath, and pulmonary edema (fluid in lungs).[10–13] Gastrointestinal symptoms include nausea, vomiting, and stomach pain. Toxicological studies show similar neurological and respiratory distress in rodents, dogs, and rabbits, including hyperactivity, convulsions, and nasal inflammation.[1,3]

**Appendix Table 7.** California Pesticide Injury Surveillance Program reports of methyl bromide pesticide-related incidents from post-harvest commodity fumigations (1992–2022)

| Activity types | Methyl Bromide |
|---|---|
| Applicator/Handler | 16 |
| Post-harvest facility workers (e.g., sorter, packers) | 23 |
| Bystander workers (e.g., maintenance, inspectors) | 9 |
| **Total** | **48** |

*Chronic health effects*. Most research on chronic health effects of methyl bromide come from studies of pre-plant use, rather than post-harvest commodity fumigation; nevertheless, they share similar health effects. From the limited studies of inhalation exposure among commodity fumigators, neurological effects were observed.[5,14,15] Occupational studies also indicate that higher levels of urinary biomarkers of bromine ion are linked to cardiovascular effects.[16,17] Studies in agricultural communities in California found prenatal exposures in mothers exposed to methyl bromide were associated with adverse neurological outcomes for their offspring, such as reduced IQ at age 7[18] and autism with intellectual disabilities.[19] Additional evidence suggests exposure is associated with reduced lung function[20] and pediatric asthma.[21] In rodents, chronic inhalation exposure was associated with nasal and cerebral tissue damage and atrophy.[22,23] Reproductive and developmental studies on animals have documented testicular damage in rodents[24,25] and skeletal malformations (e.g., fused sternum) in prenatally exposed rabbit pups.[26] In humans, prenatal exposure was associated with reduced fetal growth, including low-birth weight.[27,28]

*Cancer.* According to regulatory agencies, methyl bromide is not classified as a carcinogen for humans due to limited scientific evidence.[4] Yet, laboratory tests on genetic material suggest that methyl bromide can cause genetic mutations and DNA damage, although studies on animals are mixed.[4] One study found that high oral and inhalation exposure induced tumor formation in the stomach of rats.[29] A study of farmworkers also reported higher odds of gastric cancer,[30] while studies of prostate cancer in occupational cohorts had inconsistent results.[31–34] A study in California of pediatric cancer found that children living within 0.5 miles of agricultural applications of fumigants (including methyl bromide, 1,3-dichloropropene, chloropicrin, metam-sodium, and oxythioquinox) had higher odds of acute lymphoblastic leukemia, among those with moderate lifetime exposure to fumigants.[35] While these cancer studies focus on preplant fumigations rather than post-harvest fumigation, they raise concern that methyl bromide has potential to cause cancer, particularly from repeated or chronic exposure.

**D. Air Monitoring**. The California Air Resources Board (CARB) and California Department of Pesticide Regulation (DPR) both conduct air monitoring to track ambient concentrations of key pollutants and pesticides. Concentrations are compared against reference levels for exposure—levels below which no human health impacts are expected. The California Office of Environmental Health Hazard Assessment (OEHHA) has set reference levels for methyl bromide at 1,000 ppb and 1 ppb for acute and chronic exposures, respectively. Los Angeles County's use of methyl bromide dominates in California, accounting for nearly half (46%) of all commodity fumigation usage from 2016 to 2022.[36] Despite regulatory safeguards, residents of Los Angeles County raised concerns that methyl bromide emissions from commodity fumigations were reaching harmful levels in nearby communities.[37,38] Ambient methyl bromide concentrations have exceeded regulatory thresholds, suggesting that communities in close proximity to fumigated post-harvest commodity facilities are subject to continuous, low-dose exposures from ambient drift.

- ***MATES V study (2018-2019).*** Over 100 air toxins, including methyl bromide, were monitored in Southern California from August 2018 to April 2019.[39] Ten air monitors were placed in residential and commercial sites throughout the Los Angeles Basin and Coachella Valley. The highest average methyl bromide levels (1.14 ppb), which exceeded OEHHA's reference level, were found in the West Long Beach/Hudson area, an urban residential area with schools and childcare centers near a freeway. Emissions were traced to two fumigation facilities across the freeway.
- ***CARB Air Monitoring (2023).*** Following the MATES V study, additional air sampling was conducted in West Long Beach/Hudson from January 2023 to April 2024. An air monitor was placed 1,000 feet from the two fumigation facilities. Over 16 months, the average concentration was 2.1 ppb, twice the chronic reference level set by OEHHA. Two hourly measurements of 983 and 966 ppb recorded in February and March 2024 approached OEHHA's acute reference level of 1,000 ppb (***Appendix Table 8***). DPR used climatic and environmental conditions to model methyl bromide drift, concluding that concentrations were within health-protective levels.

**Appendix Table 8.** Air monitoring results of methyl bromide commodity fumigation levels in West Long Beach/Hudson, California

| Exposure | CARB (08/2023–04/2024) | MATES V (01/2018–04/2019) | OEHHA Reference |
|---|---|---|---|
| Acute (typically 1-hour) | 983 ppb, 966 ppb | Not reported | 1,000 ppb |
| Chronic (typically annual average) | 2.10 ppb | 1.14 ppb | 1 ppb |
| Chronic Hazard Index[a] | Not reported | 1.5–1.6 | > 1 |

[a] Chronic Hazard Index > 1 increases the risk of developing an adverse health outcome.

In January 2025, new rules were implemented to reduce community exposure in the area, including stricter emission control to prevent leaks, limited operations during school hours, additional fans and taller stacks, and reduction of daily usage from 1,000 to 200 pounds. Local air authorities have continued to monitor air quality, including at four other commodity fumigation facilities in Los Angeles County with higher methyl bromide usage than for those at West Long Beach/Hudson.[39]

**E. Regulatory Context.** There is extensive federal and state regulatory oversight of methyl bromide applications in agricultural and commodity settings due to the Montreal Protocol. Regulatory tolerances for residues on treated food commodities have been established to ensure that methyl bromide residues on foodstuff are within safety margins. As a federally classified Hazardous Air Pollutant, methyl bromide is subject to emission regulations in accordance with the U.S. Clean Air Act. In California, methyl bromide is also considered a Toxic Air Contaminant. Under Proposition 65, methyl bromide is also listed as a developmental toxicant. Proposition 65 warnings are not legally required for its current use as a QPS treatment. Gaps remain in our understanding of the potential health effects upon workers and communities living near commodity fumigation facilities and ports. Further research is warranted to evaluate cancer risk and to characterize ambient drift in vulnerable populations as those in Los Angeles County.

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Appendix D

# Post-harvest Commodity Fumigation: Use Trends

Prepared by CCST for the Roundtable Convening on
Post-Harvest Commodity Fumigation

Table of Contents for Appendix D



## About this Document

This backgrounder provides an overview of post-harvest fumigant use in California over the last decade. It summarizes data available from the California Department of Pesticide Regulation's Pesticide Use Report (PUR) database, focusing on the following four active ingredients used in post-harvest applications: methyl bromide, sulfuryl fluoride, propylene oxide, and phosphine.

The purpose of this document is to describe recent use trends, including total pounds applied, number of applications, seasonal variation, commodities treated, and counties where these fumigants are most commonly used.

This backgrounder is intended as a reference to support and provide context for the Roundtable Convening on Post-harvest Commodity Fumigation, scheduled for November 6 and November 7, 2025.

# Background

California instituted full pesticide use reporting in the 1990s. County Agricultural Commissioners (CACs) are the local regulatory authorities for pesticide use enforcement which includes pesticide use reporting. All growers, pest control applicators, and agricultural chemical service providers must work with CACs to report their pesticide use.

The California Department of Pesticide Regulation (DPR) collates these data, checks them for accuracy, and releases them through an online portal as well as in an annual Pesticide Use Report (PUR). For the purposes of this convening, DPR provided the California Council on Science and Technology (CCST) with all PUR data through 2023 (the most recent year for which error-checked data were available) for methyl bromide, sulfuryl fluoride, propylene oxide, and phosphine.

These data included every application of any product that contained one of these four active ingredients, including the pounds of active ingredient applied, pounds of product applied, the name of the product, the target commodities (or "sites"), spatial tags of the applications, dates of application, and whether the applications were coded as either "agricultural" or "non-agricultural" applications. Only applications for agricultural *production* are coded as "agricultural;" all other applications for which reporting is still legally required are coded as "non-agricultural."

# Methods

The PUR data for each of these four active ingredients were imported into the statistical package R (R Core Team, 2024) for graphing and trend analyses. Data were filtered to cover the last ten years available (2014–2023). For each active ingredient, total pounds of active ingredient used (LBS_CHM_USED) were aggregated by month, year, county, and commodity (SITE_NAME) (refer to the following sections for commodities/sites). We also calculated the total number of applications based on the number of unique application identifiers (USE_NO) included in the dataset.

Each of the active ingredients had uses recorded in the PUR beyond post-harvest applications, which needed to be filtered out of the dataset.

# Methyl Bromide

In California, methyl bromide continues to be used as a pre-plant soil fumigant through limited Quarantine and Pre-shipment allocations. These pre-plant applications are typically categorized as "agricultural production uses" in the PUR (all else is coded as "non-agricultural"). To focus on post-harvest applications, all entries categorized as agricultural were removed.

# Sulfuryl Fluoride

The majority of sulfuryl fluoride used in California is for structural applications in residential areas rather than post-harvest commodity uses (81.6% total pounds of active ingredient across 2014–2023 and 74.6% in 2023). To focus on post-harvest applications, entries where the site was "Structural Pest Control" were removed from the analysis. These were almost exclusively applications of Vikane and Zythor (85.7% and 14.1% of total pounds of active ingredient applied in 2023, respectively). ProFume—the only sulfuryl fluoride-containing product which is approved for use on foodstuff—was the product used for nearly all other remaining applications (97.5%).

# Propylene Oxide and Phosphine

Both propylene oxide and phosphine have some limited non-post-harvest uses recorded in the PUR. To focus on post-harvest applications, we removed the following sites from the dataset: "Rights of Way," "Research Commodity," and "Landscape Maintenance." Some applications were coded as "agricultural," but because these fumigants are not used for agricultural production, DPR communicated to CCST that these were likely mis-reported and are actually post-harvest applications. As such, these were not removed.

# Pesticide Use Report Site Definitions

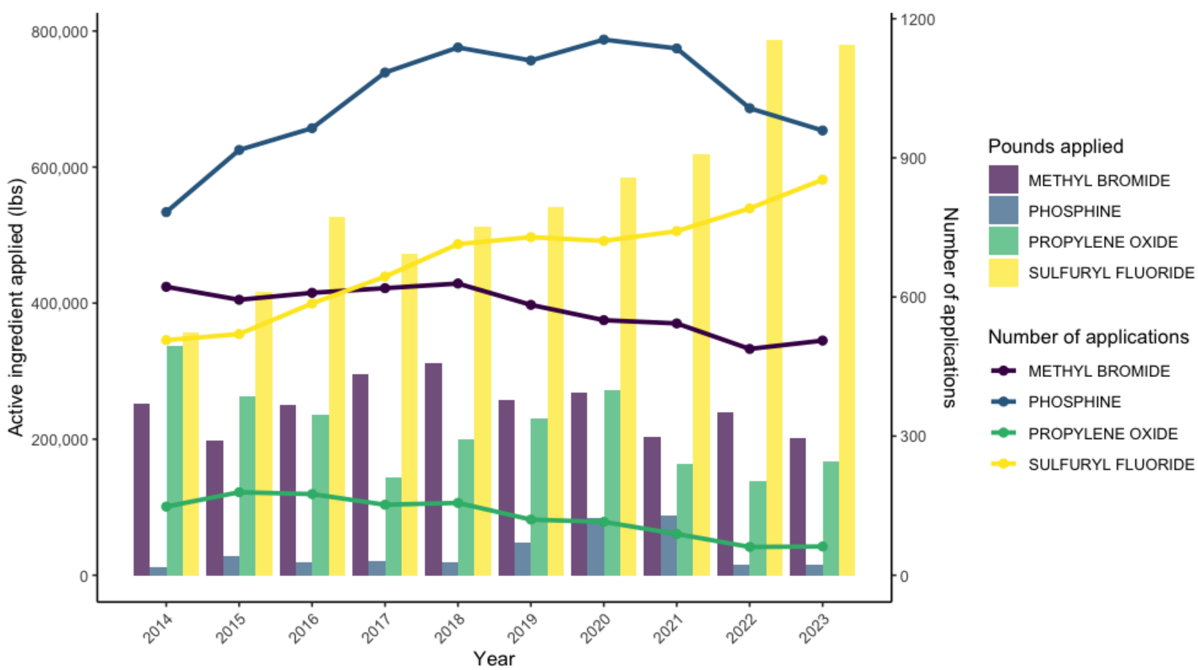
In many cases, the PUR lists the specific commodity treated, but the majority of post-harvest applications include only generic site names. DPR provided CCST with definitions for site names and general site codes. ***Appendix Table 9*** lists those relevant to this document and where the meaning may not be otherwise apparent. See ***Appendix Table 11*** for a list of unique SITE_NAME and SITE_CODE identifiers relevant to this document.

**Appendix Table 9.** Definitions of select site codes included in the Pesticide Use Report.

| Code | Definition |
|---|---|
| SITE_NAME | Identifies the name of the site (e.g., strawberries, wine grapes, tomatoes). Also known as commodity name, although there are non-agricultural sites as well. |
| COMMODITY FUMIGATION | Fumigation of food commodities. |
| FUMIGATION, OTHER | Includes fumigation of nonfood/nonfeed commodities, e.g. pallets, dunnage, furniture, and burlap bags. |
| REGULATORY PEST CONTROL | Includes any pest control work performed by public employees or contractors in the control of regulated pests. |
| STRUCTURAL PEST CONTROL | Includes any pest control work performed within or on buildings and other structures. |

# Overview

Of the four active ingredients, sulfuryl fluoride accounts for the greatest total pounds used for post-harvest applications, with a collective 5.6 million pounds applied from 2014 to 2023 (***Appendix Table 10***). Methyl bromide and propylene oxide had intermediate totals, 2.48 million pounds and 2.15 million pounds, respectively, while phosphine had the lowest total use among the four at 352,000 pounds. However, in terms of the number of applications, phosphine is the most frequently used post-harvest commodity fumigant, followed by sulfuryl fluoride, methyl bromide, and then propylene oxide (***Appendix Figure 1***). The discrepancy is explained by the differences in the average amounts of active ingredient applied per fumigation (***Appendix Table 10***).



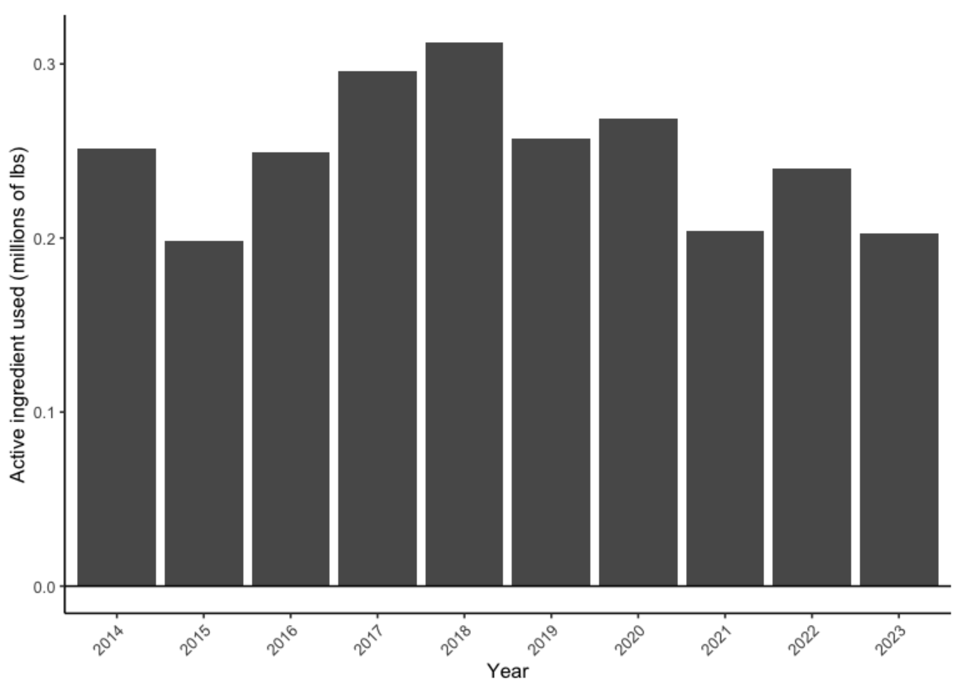

**Appendix Figure 1.** Annual reported use of four fumigants applied in post-harvest commodity fumigation settings in California (2014–2023). Bars show total pounds of active ingredient applied per year, while lines indicate the corresponding total number of applications.

**Appendix Table 10.** Total pounds of active ingredient and total number of applications for each post-harvest fumigant applied during 2014–2023, with a calculated average pound of active ingredient per application.

| Active ingredient | Total pounds | Applications | Pounds per application |
|---|---|---|---|
| Methyl bromide | 2,479,346 | 5,743 | 431.72 |
| Phosphine | 352,003 | 10,253 | 34.33 |
| Propylene oxide | 2,148,042 | 1,257 | 1,708.86 |
| Sulfuryl fluoride | 5,602,049 | 6,807 | 822.98 |

# Methyl Bromide

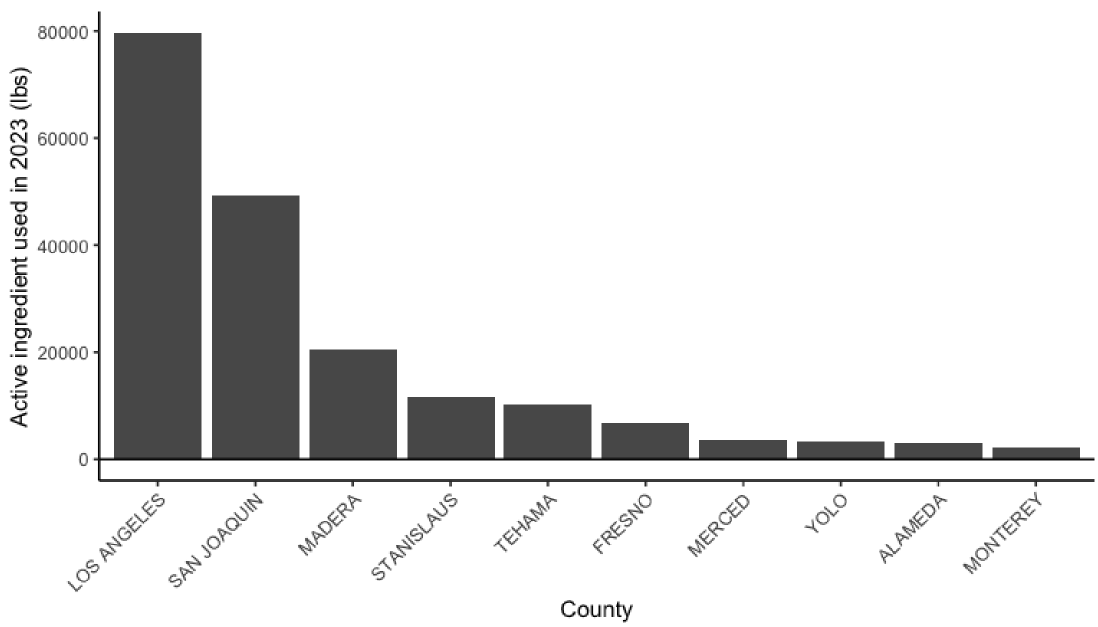
Over the 10-year period examined, reported methyl bromide use in post-harvest applications has been relatively consistent in California, with an average of about 250,000 pounds per year (***Appendix Figure 2***).



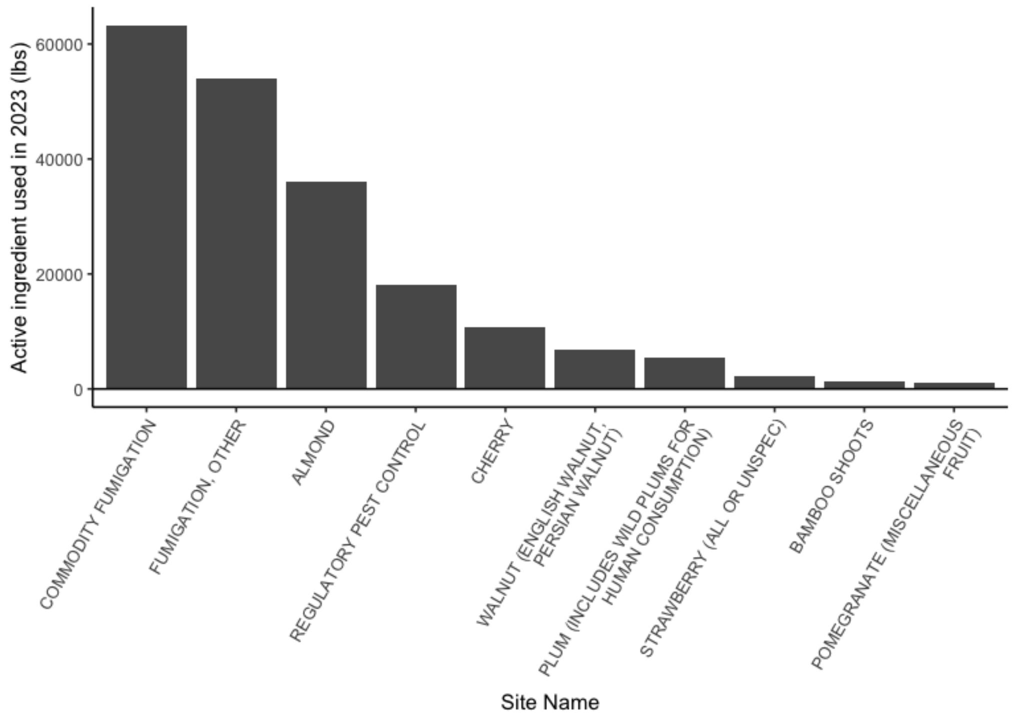

**Appendix Figure 2.** "Non-agricultural" post-harvest applications of methyl bromide in terms of millions of pounds of active ingredient.

In 2023, Los Angeles and San Joaquin Counties together accounted for more than half of the post-harvest commodity applications of methyl bromide, in terms of pounds of active ingredient applied (39.4% and 24.3%, respectively) (***Appendix Figure 3***).

Most post-harvest applications of methyl bromide are coded for "Commodity Fumigation" or "Fumigation, Other," but almonds, cherries, walnuts, and plums account for the third, fifth, sixth and seventh greatest amount of methyl bromide applications in terms of pounds of active ingredient applied in 2023 (***Appendix Figure 4***).

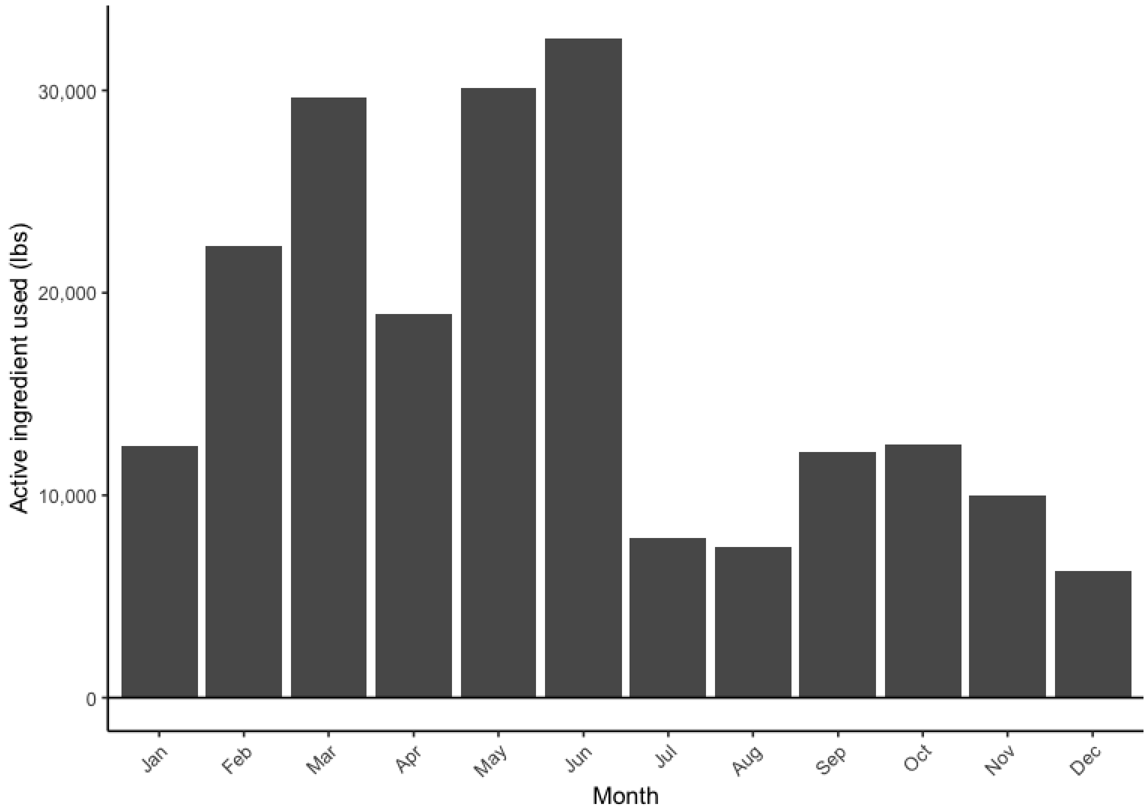



**Appendix Figure 3.** Pounds of methyl bromide active ingredient applied in 2023 for the 10 counties accounting for the greatest total use of "non-agricultural" post-harvest applications.




**Appendix Figure 4.** Pounds of methyl bromide active ingredient applied in 2023 for the 10 "sites" (commodities) accounting for the greatest total use of "non-agricultural" post-harvest applications.

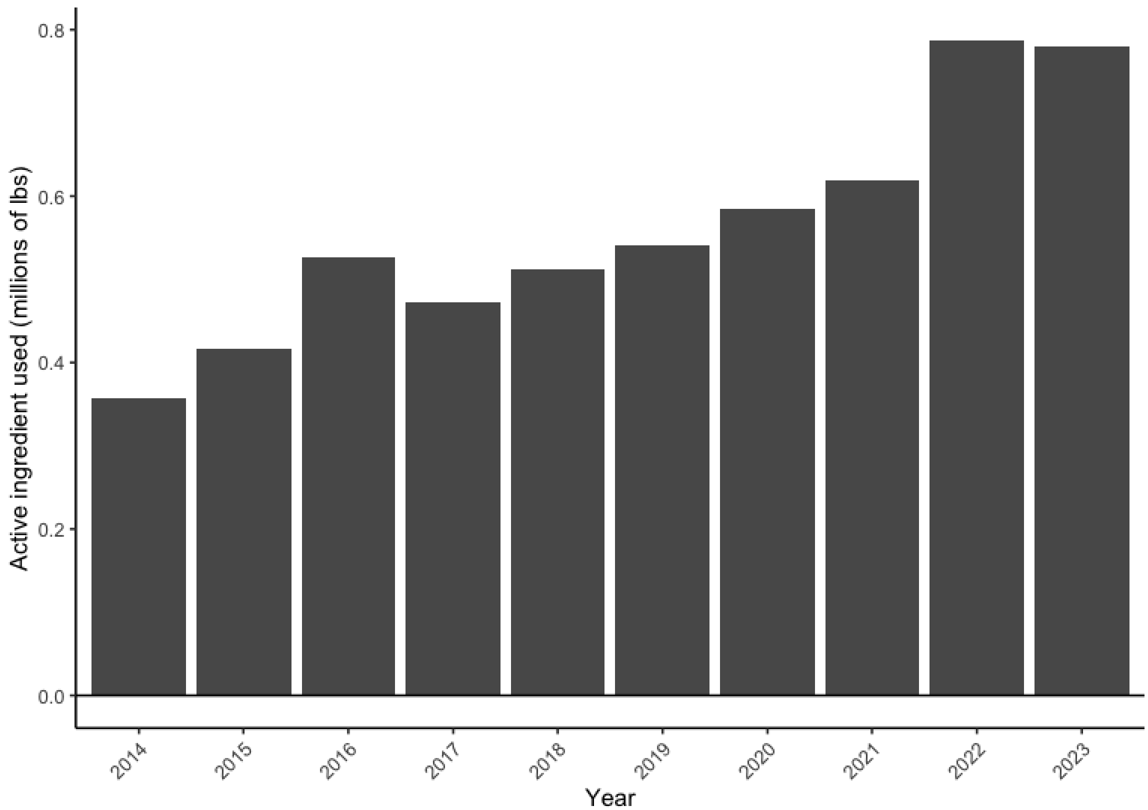
In 2023, applications of methyl bromide for post-harvest commodities showed relatively high month-to-month variability, with a high of 32,576 pounds applied in June and only 6,290 pounds in December (***Appendix Figure 5***).




**Appendix Figure 5.** Pounds of methyl bromide active ingredient applied by month in 2023.

# Sulfuryl Fluoride

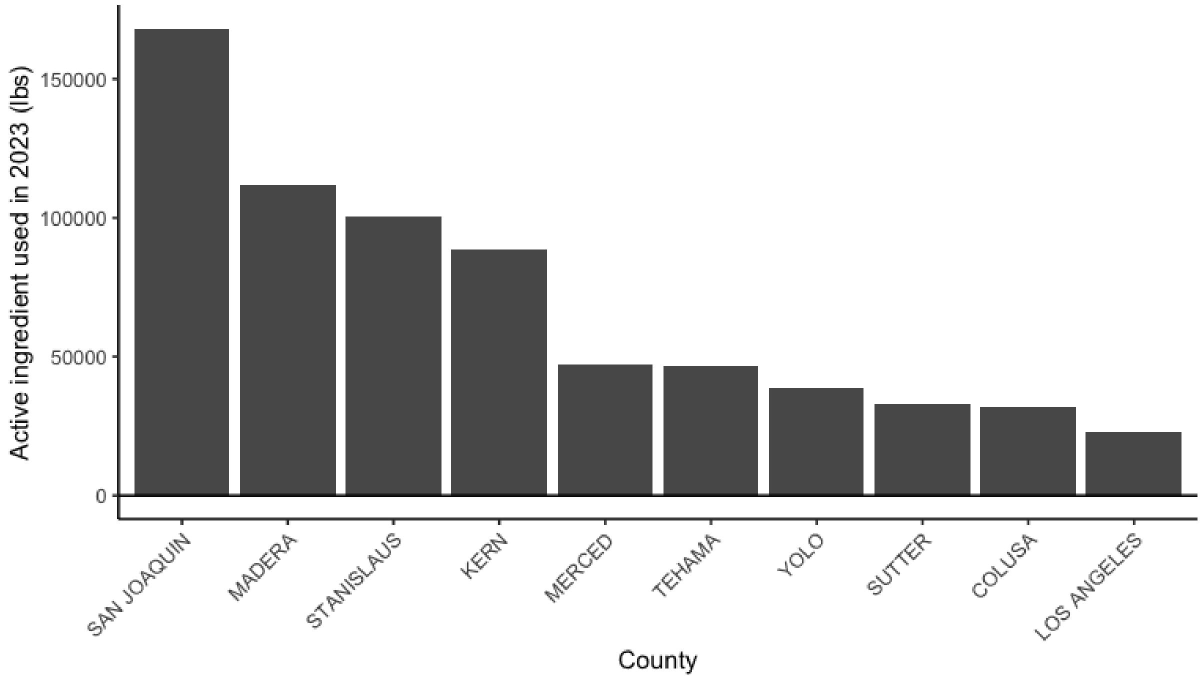
The use of sulfuryl fluoride for post-harvest applications has been steadily increasing in California since 2014, with an average of about 560,000 pounds per year and roughly a 9% year-over-year increase during the 10-year period (*Appendix Figure 6*).



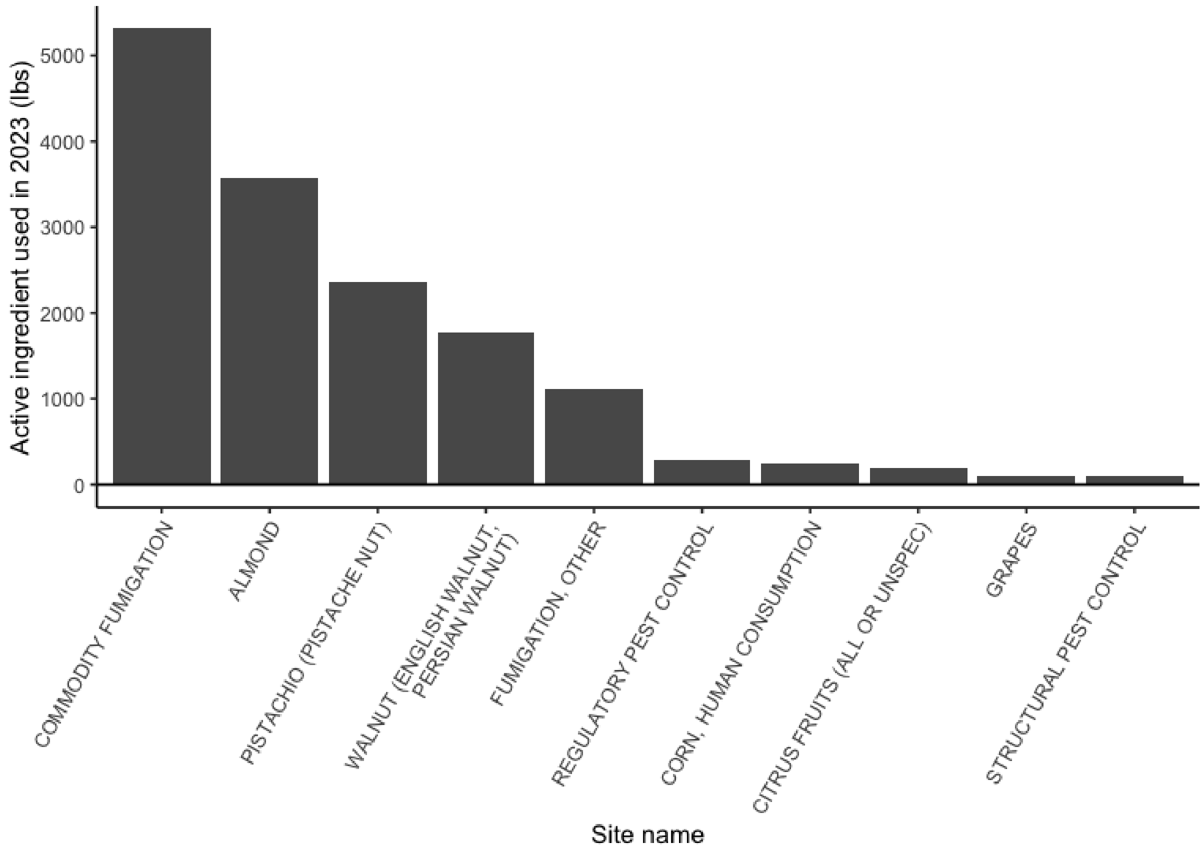

**Appendix Figure 6.** Post-harvest applications of sulfuryl fluoride in terms of millions of pounds of active ingredient.

In 2023, San Joaquin County received the most sulfuryl fluoride for post-harvest applications, in terms of pounds of active ingredient applied (21.6% of total). Madera (14.4%), Stanislaus (12.9%), and Kern (11.4%) Counties were not far behind (*Appendix Figure 7*).

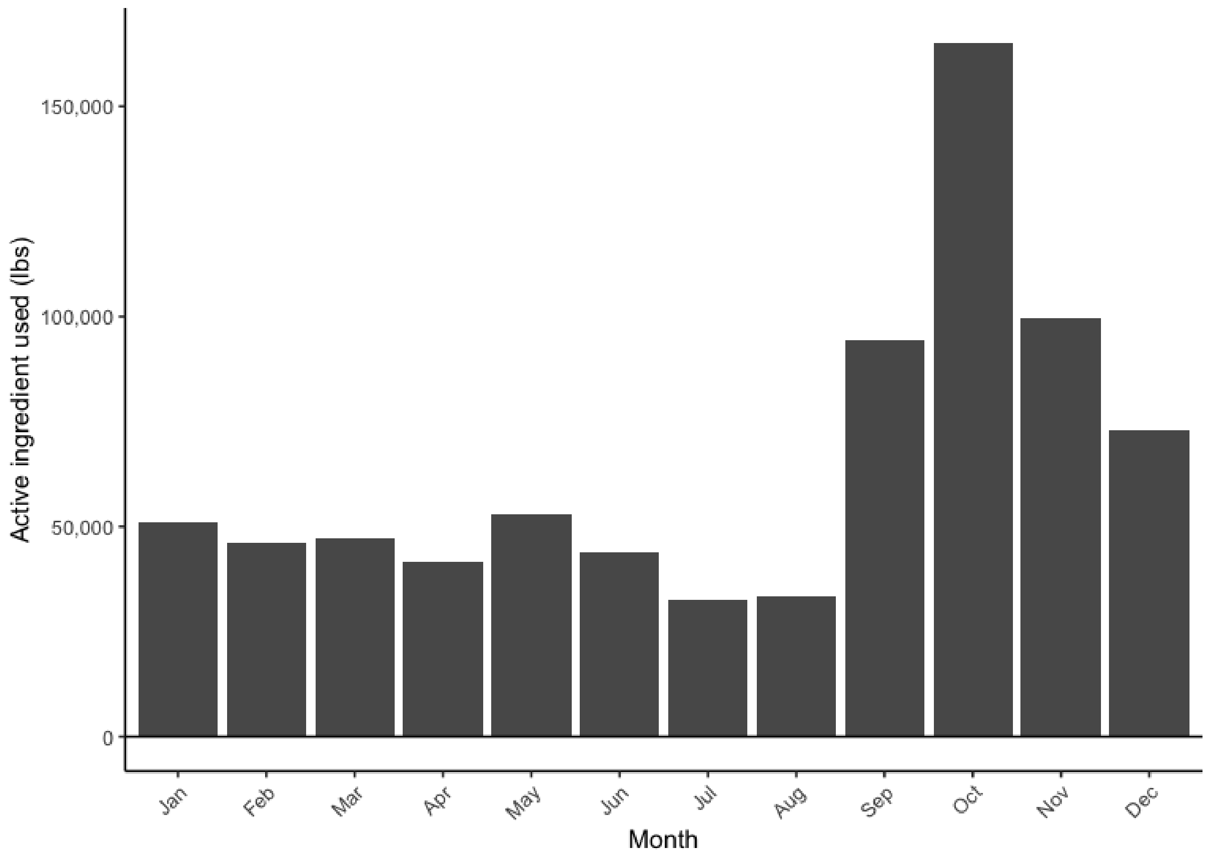
Post-harvest applications of sulfuryl fluoride are primarily used to treat nuts, including almonds, walnuts, and pistachios (*Appendix Figure 8*).




**Appendix Figure 7.** Pounds of sulfuryl fluoride active ingredient applied in 2023 for the 10 counties accounting for the greatest total use of post-harvest applications.



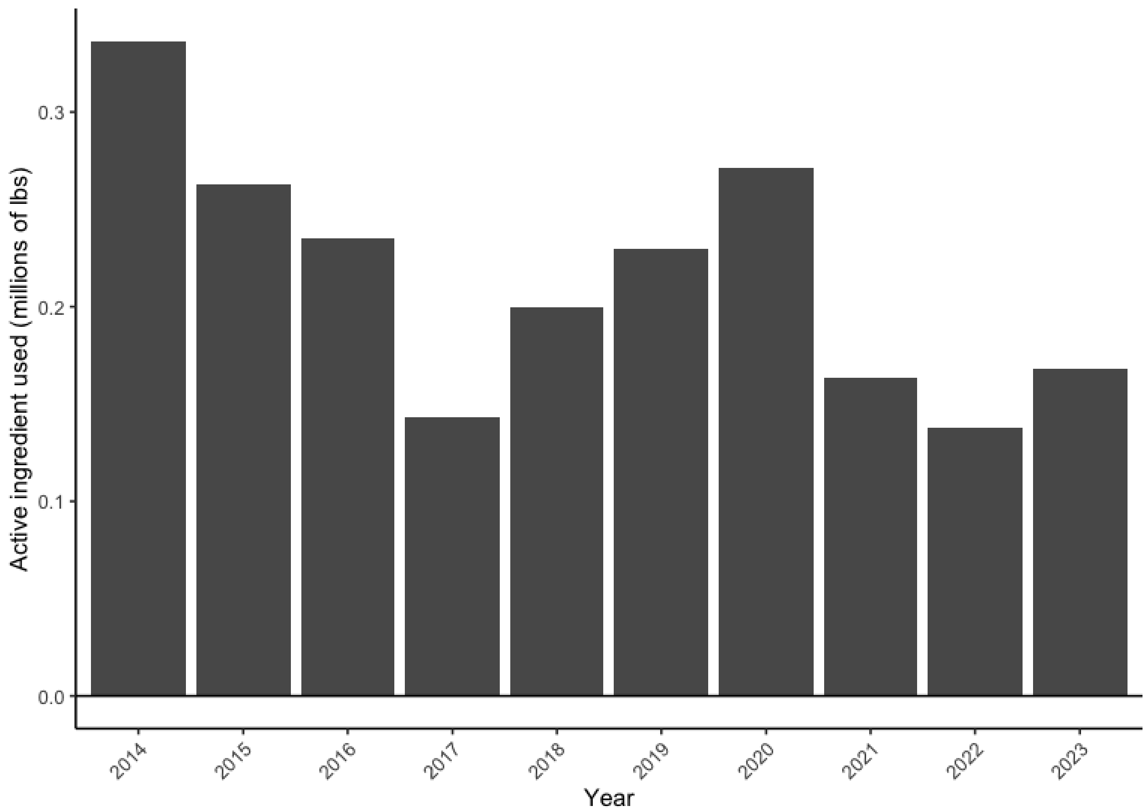

**Appendix Figure 8.** Pounds of sulfuryl fluoride active ingredient applied in 2023 for the 10 "sites" (commodities) accounting for the greatest total use of post-harvest applications. Sulfuryl fluoride use in post-harvest applications in 2023 shows strong seasonal variation. Applications were relatively steady from January to June (about 47,000 pounds per month) before declining slightly to their lowest levels in July and August. Use then rose sharply in the fall, peaking in October at over 165,000 pounds—more than three times the early-year average—before declining again in November and December.




**Appendix Figure 9.** Pounds of sulfuryl fluoride active ingredient applied by month in 2023.

# Propylene Oxide

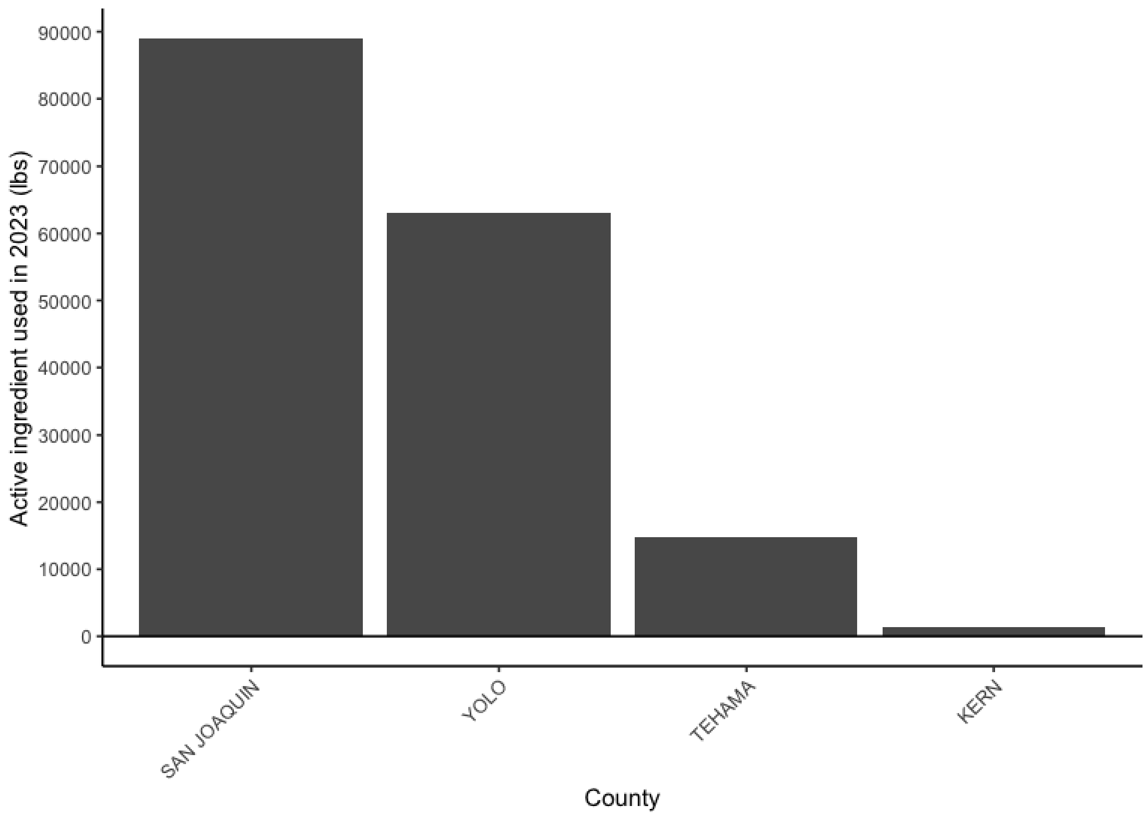
The use of propylene oxide for post-harvest applications demonstrates considerable annual variation during the 2014–2023 period, with a high of ~336,000 pounds in 2014 and a low of approximately 138,000 pounds in 2022, and an overall annual average of 214,800 pounds. Overall, no long-term upward or downward trend is apparent (***Appendix Figure 10***).



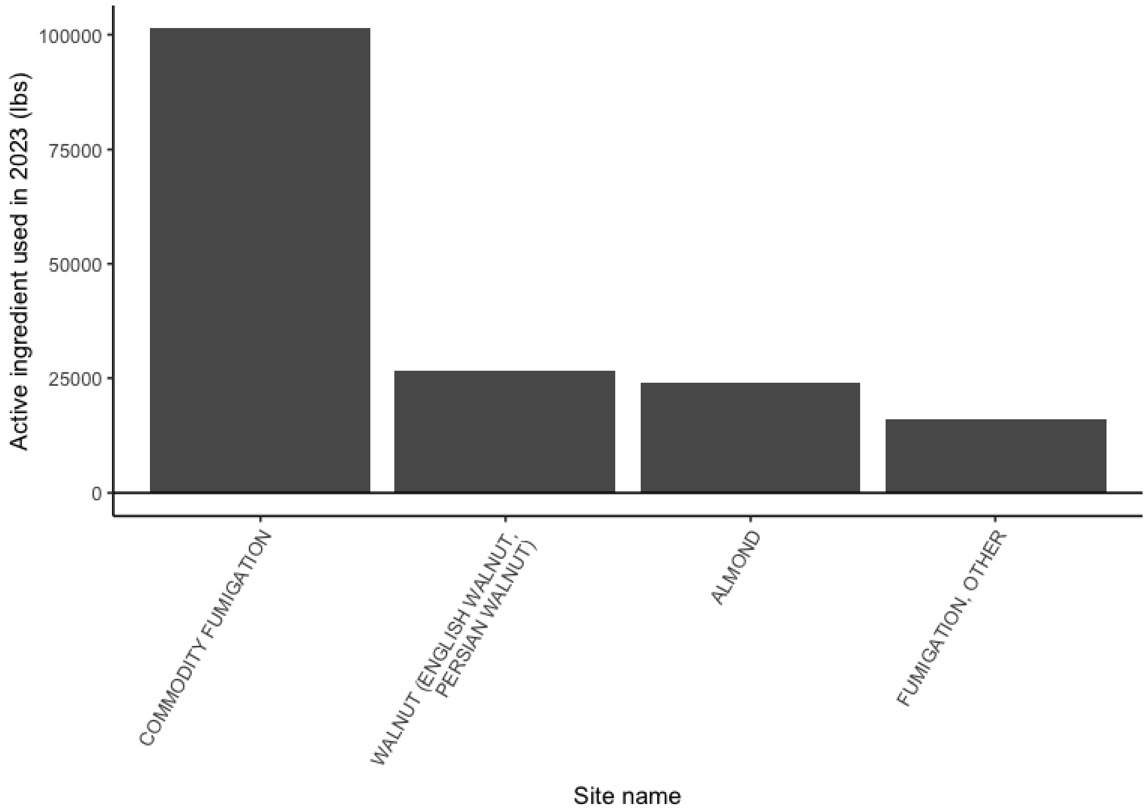

**Appendix Figure 10.** Annual post-harvest applications of propylene oxide in terms of millions of pounds of active ingredient.

In 2023, the use of propylene oxide was relatively geographically constrained, with only four counties reporting use: San Joaquin, Yolo, Tehama, and Kern (***Appendix Figure 11***).

Only 2 unique "sites" (or commodities) were reported for propylene oxide: walnuts and almonds. All other applications were coded as "Commodity Fumigation" or "Fumigation, Other" (***Appendix Figure 12***).

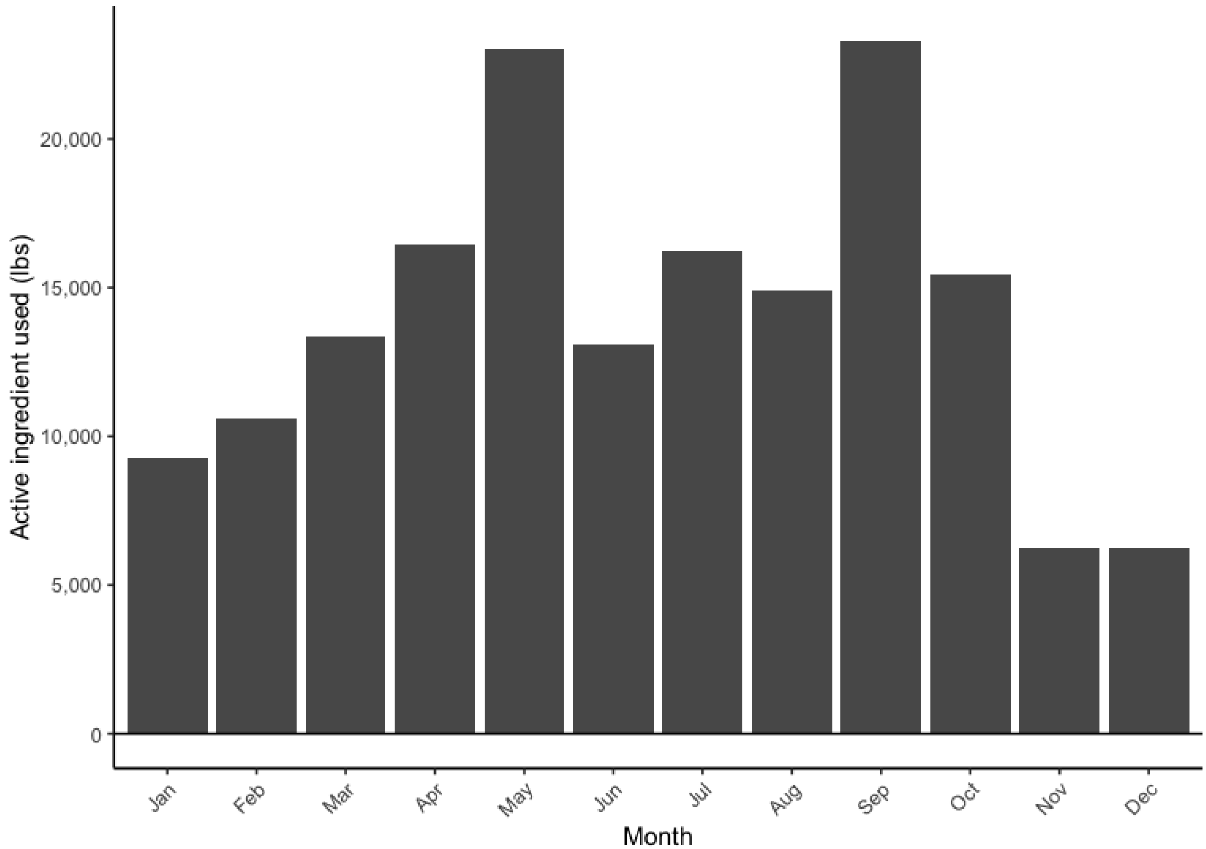



**Appendix Figure 11.** Pounds of propylene oxide applied in 2023 for the only four counties reporting use of the active ingredient for post-harvest applications.




**Appendix Figure 12.** Pounds of propylene oxide active ingredient applied per "site" (or commodity) in 2023.

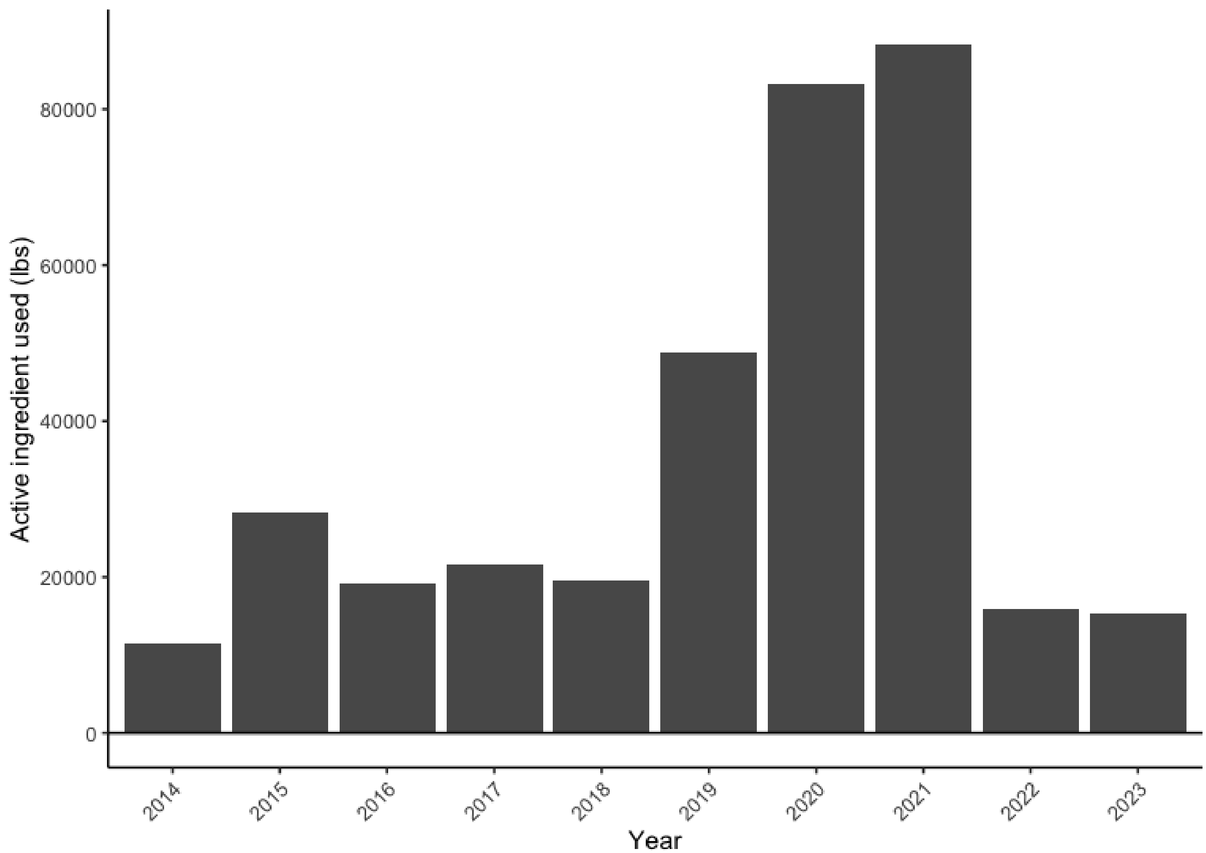
Monthly use of propylene oxide shows seasonal variability in 2023, with peaks in May and September, moderate use through the spring and summer, and the lowest applications occurring in November and December (***Appendix Figure 13***).




**Appendix Figure 13.** Pounds of propylene oxide active ingredient applied by month in 2023.

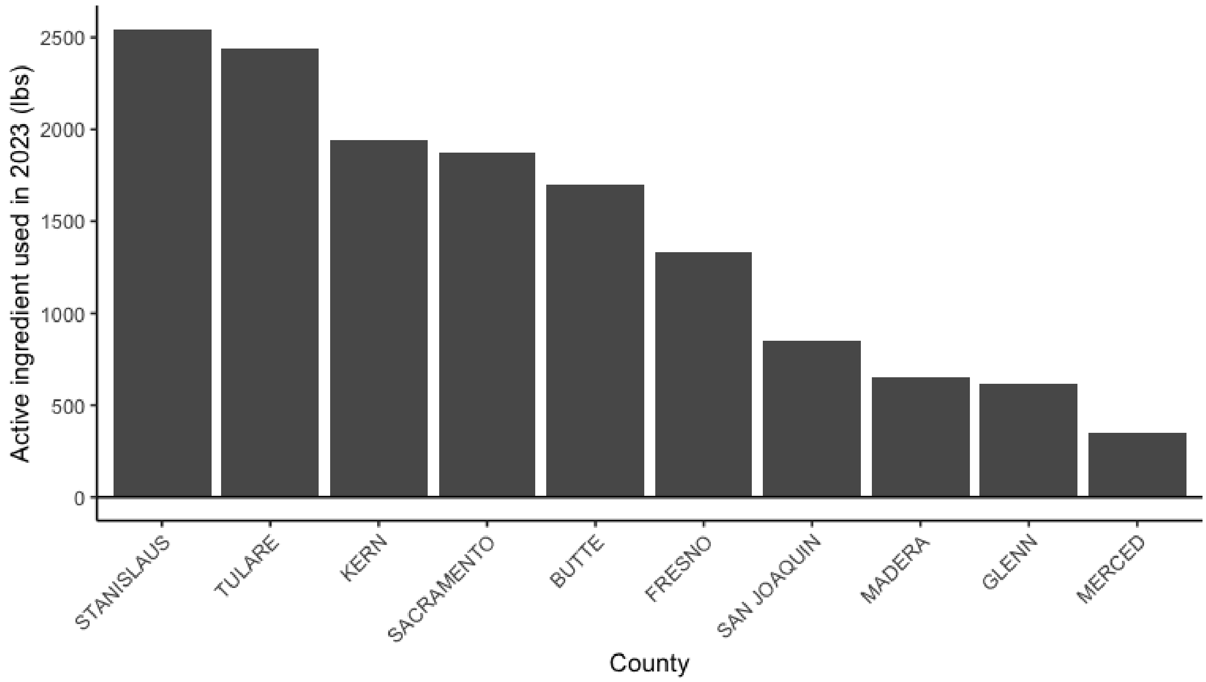
# Phosphine

The use of phosphine in post-harvest applications shows relative consistency year-to-year, with the exception of 2019–2021, during which comparatively high volumes of the active ingredient were applied. Excluding those three years, average annual use during the time frame examined was approximately 18,800 pounds, while use in 2021 peaked at 88,300 pounds, nearly 5 times higher.

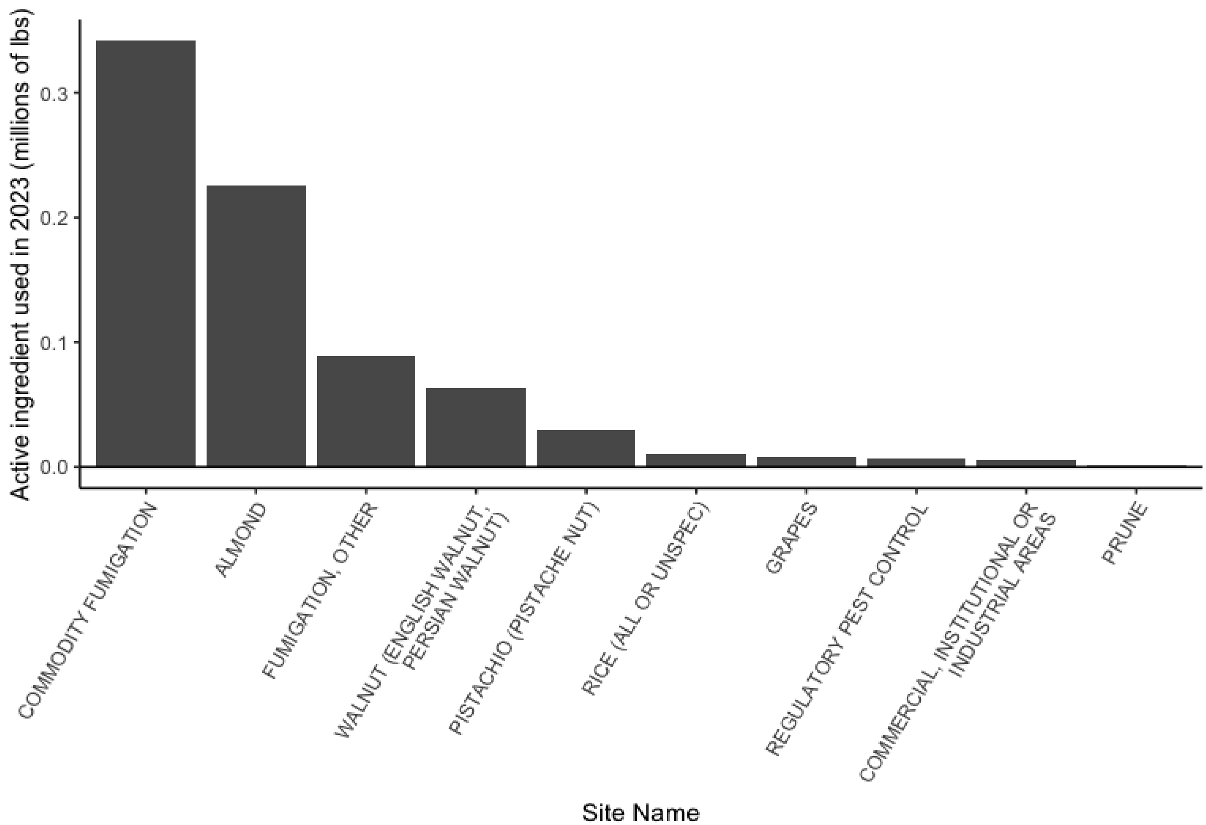



**Appendix Figure 14.** Post-harvest applications of phosphine in terms of pounds of active ingredient.

In 2023, Stanislaus and Tulare Counties reported the greatest total amount of phosphine used for post-harvest applications (***Appendix Figure 15***).

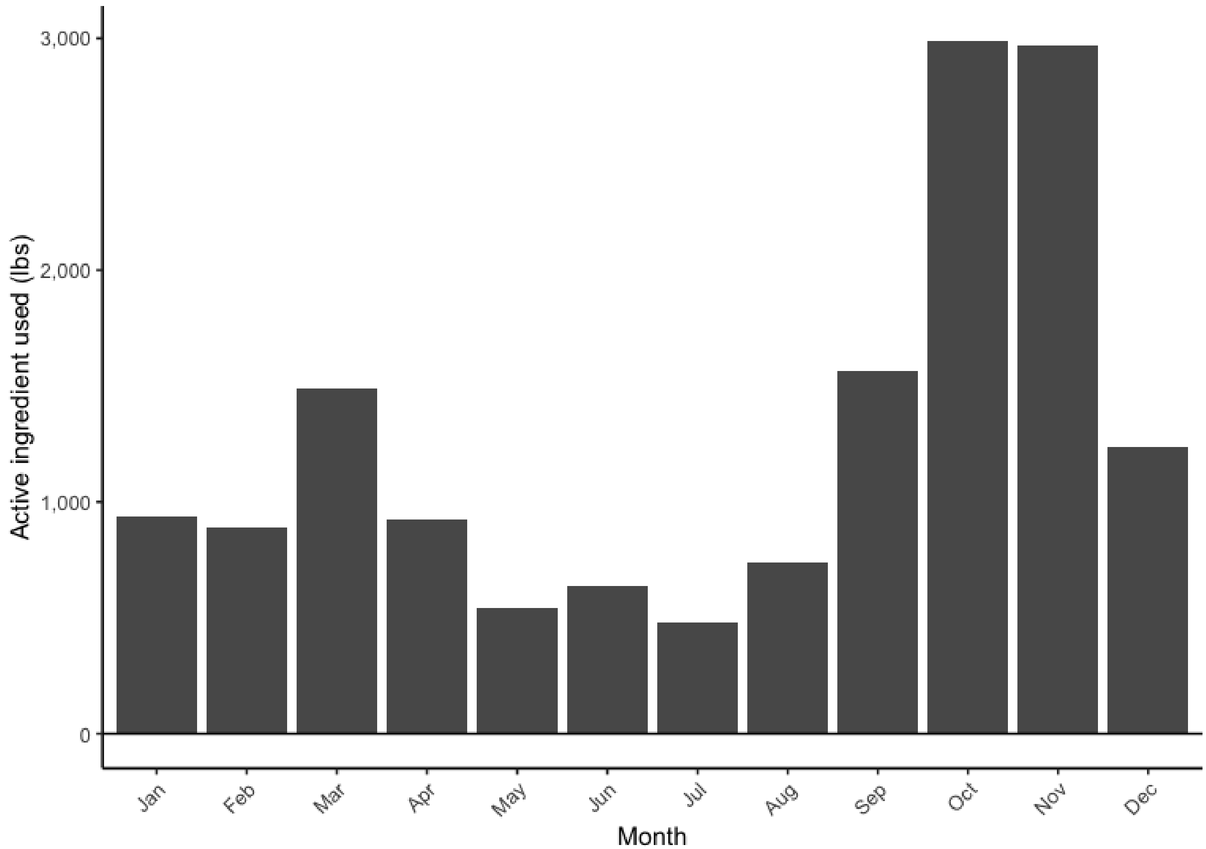



**Appendix Figure 15.** Pounds of phosphine active ingredient applied in 2023 for the 10 counties accounting for the greatest total use of post-harvest applications.




**Appendix Figure 16.** Pounds of phosphine active ingredient applied in 2023 for the 10 "sites" (commodities) accounting for the greatest total use of post-harvest applications.

Monthly use of phosphine shows seasonal variability in 2023 (***Appendix Figure 17***). Use was lowest in the summer months, with moderate levels in winter and spring and peak use in the fall (October and November).




**Appendix Figure 17.** Pounds of phosphine active ingredient applied by month in 2023.

**Appendix Table 11.** Unique SITE_NAME and corresponding SITE_CODE identifiers for post-harvest commodity fumigant applications in the Pesticide Use Report.

| SITE_NAME | SITE_CODE |
|---|---|
| ALMOND | 3001 |
| BAMBOO SHOOTS | 13051 |
| CHERRY | 5002 |
| CITRUS FRUITS (ALL OR UNSPEC) | 2000 |
| COMMERCIAL, INSTITUTIONAL, OR INDUSTRIAL AREAS | 77000 |
| COMMODITY FUMIGATION | 90 |
| CORN, HUMAN CONSUMPTION | 29119 |
| FUMIGATION, OTHER | 91 |
| GRAPES | 29141 |
| PLUM (INCLUDES WILD PLUMS FOR HUMAN CONSUMPTION | 5005 |
| PISTACHIO (PISTACHE NUT) | 3011 |
| POMEGRANATE (MISCELLANEOUS FRUIT) | 6015 |
| PRUNE | 5006 |
| REGULATORY PEST CONTROL | 100 |
| RICE (ALL OR UNSPEC) | 28072 |
| STRAWBERRY (ALL OR UNSPEC) | 1016 |
| WALNUT (ENGLISH WALNUT, PERSIAN WALNUT) | 3009 |

# Post-Harvest Commodity Fumigation in California

## Roundtable Convening Proceedings

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