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Managing phosphine resistance in Indian grain storage:

Challenges and strategies

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India's agricultural sector faces significant challenges in preserving harvested grains due to biotic stresses during storage, with stored insects posing a substantial threat to stored produce. Among the various pest control methods, phosphine fumigation has been pivotal due to its efficacy and cost-effectiveness. However, the emergence of phosphine resistance in stored insects presents a serious concern. This article explores phosphine resistance within the Indian context, encompassing its mechanisms, prevalence, impacts, and management strategies. It discusses the genetic, physiological, and behavioural factors contributing to resistance, as well as its prevalence among major stored insect pests in India. A case study on phosphine susceptibility in Tribolium castaneum highlights the complexity of resistance mechanisms. The article underscores the economic and food security implications of phosphine resistance and proposes integrated pest management strategies for its management and mitigation. By adopting proactive measures, India can address phosphine resistance and safeguard its agricultural sector's sustainability.

Keywords: Food security, Grain storage, Indian agriculture, Integrated pest management, Phosphine resistance

India, with its vast agricultural landscape and diverse climatic conditions, faces significant challenges in preserving harvested grains from biotic stress during storage. The storage of grains and other agricultural commodities is crucial to meet the food demands of a growing population. However, the presence of stored insects poses a significant threat to the quality and quantity of stored produce. Damage inflicted by these pests is significant, accounting for approximately 5–10% of losses in countries like India. Among the various methods employed for pest control in storage facilities, phosphine fumigation has been a cornerstone due to its efficacy, cost-effectiveness, and ease of application. However, the emergence of phosphine resistance in stored insects poses a serious threat to grain storage management practices, food security, and economic sustainability in India. This comprehensive article aims to explore the phenomenon of phosphine resistance in stored insects within the Indian context, encompassing the underlying mechanisms, prevalence, impacts, and strategies for management and mitigation.

Phosphine fumigation: Toxicity and application

Phosphine (PH_3), a highly toxic gas, is widely used for fumigation to control insect pests in stored grains, pulses, and other agricultural commodities. The primary mode of action of phosphine involves its interaction with respiratory enzymes, particularly cytochrome oxidase, in the mitochondria of insects. Phosphine irreversibly inhibits cytochrome oxidase, disrupting cellular respiration and ultimately leading to the death of susceptible insects due to respiratory failure. The application of phosphine typically involves the introduction of aluminum phosphide (AlP) tablets or pellets into sealed storage structures, where the gas diffuses and permeates through the commodity, reaching all insect-infested areas.

Emergence of phosphine resistance: Mechanisms and factors

The development of phosphine resistance in stored insects is a multifaceted phenomenon influenced by genetic, physiological, and behavioural factors. Genetic mutations in the genes encoding respiratory enzymes, such as cytochrome c oxidase subunits, can confer resistance by altering the target site's affinity for phosphine or reducing the sensitivity of insects to its lethal effects. Mutations in the mitochondrial cytochrome b gene have also been implicated in phosphine resistance in various stored insect species. Additionally,

Table 1. Important stored grain pests of India

Species	Pests
	Beetle
Tribolium castaneum	Ubiquitous
Rhyzopertha dominica	Common in indoor and outdoor stacks, paddy in particular
Sitophilus oryzae	Occur in wheat especially soft varieties and maize
Trogoderma grananum	Confined to extreme climatic zones
Oryzaephilus surinamensis	Common in grains having more dockage
Cryptolestes spp.	Common in milled rice having more dockage
	Moth
Ephestia cautella	Major moth pest in many godowns
Corcyra cephalonica	Occur sporadically on milled rice
Sitotroga cerealella	Noticed in new arrivals especially in paddy
	Other
Liptoscelis spp.	Ubiqitous; serious problem in coastal areas; in other places outbreaks are frequent during monsoon

Source: Rajendran S (1998)

the upregulation of detoxification enzymes, notably cytochrome P450 monooxygenases, combined with antioxidant mechanisms enables insects to metabolize and detoxify phosphine, thereby reducing its efficacy.

Physiological adaptations play a significant role in facilitating phosphine resistance in stored insects. Changes in respiratory physiology, including alterations in gas exchange mechanisms and reduced respiratory rates, enable insects to tolerate higher concentrations of phosphine and prolong their survival. Furthermore, behavioural adaptations such as increased dispersal, avoidance of treated areas, and altered feeding and reproductive behaviours contribute to reduced susceptibility to phosphine fumigation. The combination of genetic, physiological, and behavioural mechanisms underscores the complex nature of phosphine resistance and its adaptive significance in stored insect populations.

Prevalence and distribution of phosphine resistance in Indian stored insects

The prevalence of phosphine resistance in stored insects has been documented across various regions of India, encompassing both rural and urban grain storage facilities. Common stored insect pests exhibiting resistance to phosphine include the red flour beetle (*Tribolium castaneum*), rice weevil (*Sitophilus oryzae*), lesser grain borer (*Rhyzopertha dominica*), and khapra beetle (*Trogoderma granarium*), among others. Resistance levels vary among different insect species, geographical locations, and storage environments, reflecting the dynamic interplay between selection pressure and evolutionary responses.

Several studies conducted in India have reported varying degrees of phosphine resistance in stored insect populations. Resistance ratios, determined through bioassays and dose-response experiments, indicate the magnitude of resistance relative to susceptible reference strains. The widespread occurrence of phosphine resistance underscores its significance as a pervasive and escalating problem in grain storage management across India.

A case study: Phosphine susceptibility in *Tribolium castaneum*

Red flour beetle, *T. castaneum* (Coleoptera: Tenebrionidae), stands out as a notable secondary pest targeting stored agricultural commodities such as flour, cereals, beans, and nuts. Apart from direct consumption losses, *T. castaneum* exacerbates the situation by secreting benzoquinones, a carcinogenic substance with a persistent and unpleasant odour. These compounds not only alter the characteristic colour of the affected flour but also pose severe health risks to human consumers.

Tribolium adult insect

Red flour beetle (*Tribolium castaneum*) is a major pest of stored grains causing qualitative and quantitative losses. Phosphine susceptibility levels were estimated from seven states across India. The median lethal concentration (LC_{50}) values ranging from 0.038–1.277 mg/L, indicating 2.11–70.94 fold resistance compared to susceptible populations. Various respiratory enzymes were responsible for phosphine resistance build up in *Tribolium* species. Our study encompassed antioxidant activities were upregulated except catalase.

Statistical interventions found phosphine resistance closely linked with peroxiadase and superoxide dismutase activities, providing insights into the complex response of antioxidant enzymes to phosphine fumigation in field populations of *T. castaneum*

Impacts of phosphine resistance on grain storage management and food security

Phosphine resistance poses formidable challenges to grain storage management practices, agricultural productivity, and food security in India. The ineffectiveness of phosphine against resistant insect populations necessitates higher concentrations or prolonged exposure times to achieve adequate control, leading to increased operational costs and resource utilization. Farmers and grain handlers are compelled to adopt alternative pest control methods or resort to multiple fumigants with

different modes of action, further complicating storage management strategies.

Bulk grain storage (Stacked jute bags in a warehouse depicting traditional bulk grain storage prior to phosphine fumigation for pest control)

Phosphine fumigant (Celphos tablets-commonly used phosphine fumigant for effective control of storage pests in bulk grain facilities)

The economic implications of phosphine resistance extend beyond increased fumigation costs to encompass post-harvest losses, diminished grain quality, and marketability issues. Infestations by phosphine-resistant insects result in reduced grain yields, weight losses, and contamination by insect fragments and excreta, thereby compromising the nutritional value and market value of stored commodities. Furthermore, the persistence of resistant insect populations in storage facilities perpetuates the risk of secondary infestations and exacerbates grain storage losses over successive seasons.

At the macroeconomic level, phosphine resistance poses a threat to national food security efforts and agricultural sustainability in India. Grain storage facilities serve as critical nodes in the food supply chain, bridging the gap between harvest and consumption. The inability to effectively manage insect pests in storage jeopardizes the integrity and availability of stored grains, particularly in regions prone to post-harvest losses and food shortages. Furthermore, the reliance on phosphine fumigation as a primary pest control measure exacerbates the selection pressure for resistance and undermines long-term pest management strategies.

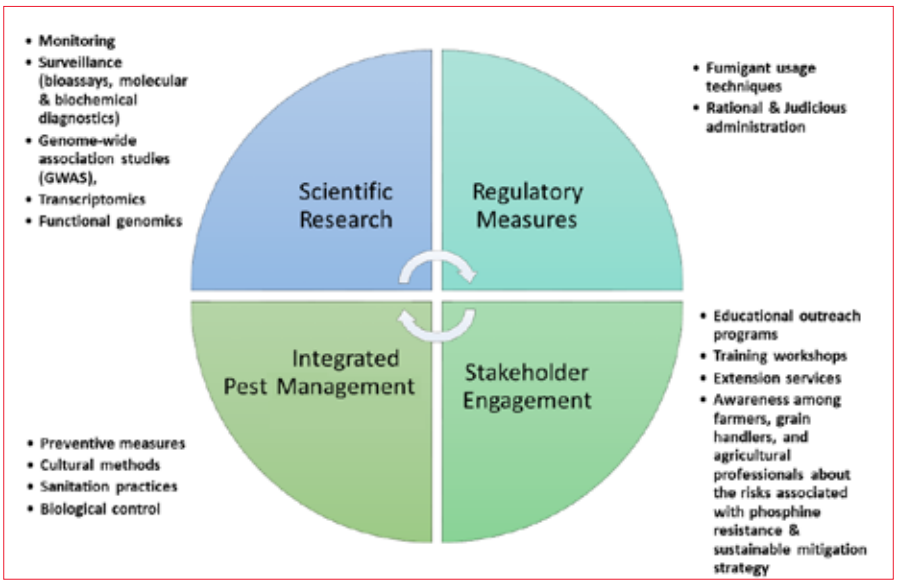
Strategies for management and mitigation of phosphine resistance

Addressing phosphine resistance in stored insects requires a multifaceted approach encompassing scientific research, regulatory measures, stakeholder engagement, and integrated pest management (IPM) strategies. Continuous monitoring of stored insect populations is essential to detect the emergence and spread of resistance, facilitating early intervention and adaptive management strategies. Surveillance efforts should incorporate bioassays, molecular diagnostics, and resistance monitoring programs to assess the prevalence, distribution, and mechanisms of phosphine resistance in Indian stored insects.

Research endeavours should focus on elucidating the genetic basis of phosphine resistance in key stored insect species prevalent in India. Genome-wide association studies (GWAS), transcriptomics, and functional genomics approaches can identify candidate genes and molecular markers associated with resistance traits, enabling the development of diagnostic tools for resistance monitoring and management. Furthermore, research initiatives should explore alternative fumigants, novel insecticides/botanicals, and synergistic combinations to mitigate the selection pressure for phosphine resistance and diversify pest control options.

A holistic framework for combating phosphine resistance in stored grain pests, integrating four interdependent pillars—scientific research, regulatory measures, stakeholder engagement, and integrated pest management (IPM) is depicted in the figure. This strategy emphasizes advanced diagnostics (e.g., genome-wide association study (GWAS), transcriptomics), judicious fumigant application, proactive stakeholder education, and sustainable pest control practices to ensure long-term resistance mitigation and food security.)

Regulatory measures play a crucial role in promoting responsible fumigant usage and resistance management practices in grain storage facilities. Regulatory agencies should enforce compliance with fumigant usage guidelines, recommend rotation strategies, and restrict the availability of phosphine to licensed applicators. Additionally, educational outreach programs, training workshops, and extension services can raise awareness among farmers, grain handlers, and agricultural professionals about the



Phosphine resistance management strategies

risks associated with phosphine resistance and the importance of integrated pest management approaches.

Integrated pest management (IPM) strategies offer a sustainable and holistic approach to managing phosphine resistance while ensuring effective pest control in grain storage systems. IPM practices emphasize preventive measures, cultural methods, sanitation practices, and biological control agents to minimize reliance on chemical fumigants and mitigate the risk of resistance development. Implementing IPM principles requires collaboration among stakeholders, including farmers, extension agents, researchers, policymakers, and industry stakeholders, to promote knowledge sharing, capacity building, and technology transfer.

SUMMARY

In summary, phosphine resistance poses a formidable challenge to grain storage management and food security in India. Addressing this issue requires concerted efforts from the scientific community, policymakers, and agricultural stakeholders to implement sustainable pest management practices and safeguard the integrity of stored commodities. By adopting an integrated and proactive approach, India can mitigate the impact of phosphine resistance and ensure the long-term viability of its agricultural sector.

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