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Operational Methyl Bromide Fumigation Trials and Residue Assessment in Sukkur and Khairpur Date Godowns: Efficacy Against Saw-toothed Grain Beetle (*Oryzaephilus surinamensis*), Non-Target Effects, and Worker Safety

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ABSTRACT

Date palm (*Phoenix dactylifera*) is one of the most important horticultural crop in Sindh, Pakistan, contributing significantly to local livelihoods and national export earnings. However, substantial post-harvest losses occur due to pest infestations that continue to damage stored products. The *Oryzaephilus Surinamensis* which is commonly known as the saw-toothed grain beetle, is a major pest that adversely affects the quality, marketability, and phytosanitary standards of dried dates. This study presents the operational fumigation trials conducted during 2022-2023 at commercial storage facilities in Sukkur and Khairpur to evaluate the efficacy of methyl bromide (MeBr) against *O. surinamensis* , as well as the persistence of the residues, environmental impacts, and worker exposure. The experiments were carried out under field-based standardised procedures using calibrated doses of MeBr and controlled exposure time. A series chemical analysis were also performed, against pest mortality, and MeBr residues in the treated dates were quantified using gas chromatography-mass spectrometry (GC-MS). The results showed more than 95% mortality within 48 hours, indicating the rapid effect of MeBr. However, the residue levels were exceeded international maximum residue limits (MRLs), posing challenges for export compliance. Ecological assessments further indicated unintended non-target mortality, including impacts on beneficial species, while worker exposure surveys revealed considerable inhalation risks and inconsistent use of personal protective equipment (PPE). Overall the findings provide useful information for regional pest management programs and highlight the need for stricter safety protocols, improved residue monitoring, and a gradual transition toward less hazardous and more sustainable fumigation practices in Pakistan's date industry.

INTRODUCTION

Methyl bromide (MeBr) continues to be one of the most effective fumigants used against the management of pests via post-harvest, especially in the quarantine-sensitive products like dried dates (Bell, 2017; Ahmed et al., 2020). Its fast acting, volatility, and general effects have made it an option of preference in many developing countries, such as Pakistan, where infrastructure is not yet developed to use other methods (Nayak & Collins, 2018; Stejskal et al., 2021). Its efficacy against the *Oryzaephilus surinamensis*, a major disease-causing coleopteran insect that has caused much damage to the stored dates and other dried foods, has been supported by extensive studies (Aulicky et al., 2022; Rajendran, 2019). The strength and cryptic nature of the pest when stored makes it very difficult to control without being very aggressive, which once again justifies the use of the MeBr even with the growing concerns.

However, the usefulness of MeBr is increasingly being overshadowed by the implications of the same regarding environment and health. Its possible ability to eradicate the ozone layer and its extreme toxicity to humans have prompted the global movement to abolish its use during the Montreal Protocol, (Kumar, 2018; Malik & Shahid, 2021). These issues are urgent, especially in nations where regulatory enforcement and worker safety are inconsistent (Safe Work Australia, 2021).
The concentration of the residues in the treated products is often higher than the maximum residue limits (MRL) provided by the international organisations, like the Codex Alimentarius Commission (2022), which makes export compliance (Nayak, Daglish, & Byrne, 2020; Stejskal et al., 2021. This problem is especially acute in the case of dried dates, which are frequently rejected in the importing countries because of high levels of MeBr and lead to the loss of revenues and tarnished reputational damage Ahmed et al., 2020; Bell, 2017).

Physicochemical characteristics of dates such as porous texture and lipid content could be the reason behind the increased residue retention relative to other commodities. **(**Reddy et al., 2018**).**
In addition to the issue over residues, the ecological dangers behind MeBr fumigation is not well reported in local literature. There might be incidental death of other arthropods (such as beneficial predators, pollinators, and parasitoids) and this may upset biological control relationships and trigger pest outbreaks **(**Rajendran, 2019; Athanassiou et al., 2019**).** The other problem is the safety of workers, where little personal protective equipment (PPE), poor training, and bad ventilation play a role in exposing workers to greater risks **(**Malik & Shahid, 2021; Safe Work Australia, 2021**).**
Under these complicated issues, there is an immediate necessity of field-based assessment, which accounts to actual fumigation practices. This research can inform safer and more sustainable pest control using information and promote more regulatory changes that can achieve effectiveness through a balanced outcome in safety to both the environment and the operators (Insects Journal, 2021; Collins & Nayak, 2019).

MATERIALS AND METHODS

Study Area and Duration

Two trial areas of sindh that are critical for date storage, Sukkur and khairpur were selected as the locations for field trials conducted between July 2022 and September 2023. Sukkur is one of the large urban center situated along the Indus river, characterized by its extensive system of godown and large scale handling of dates. Khairpur is a prominent district northeast of sukkur, well known for its dense dates forming communities and traditional storage systems. The two sites were chosen due to their strategic importance in the date industry and the documented pest pressure in these storage environments.

Target Pest and Monitoring

Pre-treatment sampling and the use of pheromone traps was used to estimate the dominant pest species as the saw-toothed beetle (*Oryzaephilus surinamensis*). The standardized visual inspection protocols and trap counts were used to record the level of infestation **(**Aulicky et al., 2022**).**

Fumigation Protocol

The dosage of 32 g/m3 was used in the 24-hour exposure. Polyethylene sheets and sand snakes were used to ensure that godowns were closed to retain the gases. The monitored parameters included environmental parameters (temperature, humidity) on a basis of the fumigation cycle and on digital data loggers (Athanassiou et al., 2019).

Residue Analysis

Residue quantification was conducted at 24, 48 and 72 hours post-treatment. Date fruit samples were subjected to gas chromatography mass spectrometry (GC-MS) to determine the concentration of methyl bromide (MeBr). Analytical outputs were evaluated across successive time intervals to characterize dissipation dynamics and to establish whether residue levels declined in a manner consistent with internationally recognized food safety thresholds.

Worker Safety Assessment

There was the use of personal air sampling pumps to monitor the MeBr exposure of the fumigation workers both at the stage of application and aeration. CPEs and training and symptom reporting were evaluated using a structured questionnaire.

Non-Target Effects

The fumigated godowns and surrounding areas had pitfall traps and sweep nettings used to check the non-target death of arthropods. The ecological disruption was determined through the measurement of species richness and abundance before and after the treatment.

Statistical Analysis

All data were analyses during SPSS version 26.0. Assumptions of normality and homogeneity of variances were verified prior to testing. One-way ANOVA compared pest mortality, residue levels, and non-target arthropod abundance at 24, 48, and 72 hours. Significance was set at $p < 0.05$ (95% confidence), and results are expressed as mean ± SE.

RESULTS

Table 1

Pest Mortality of *Oryzaephilus surinamensis*

Time Post-Fumigation	Mean Mortality (%)	Standard Deviation
24 hours	82.4	±3.6
48 hours	95.1	±2.1
72 hours	96.7	±1.4

The fumigation of the methyl bromide led to the death of *O. surinamensis* in all the treated godowns significantly. The duration of exposure was implying higher mean mortality rates:

Figure 1

Mean mortality (%) of *O. surinamensis* across three post-fumigation intervals. Error bars represent standard deviation based on four replicates from two godowns each in Sukkur and Khairpur.

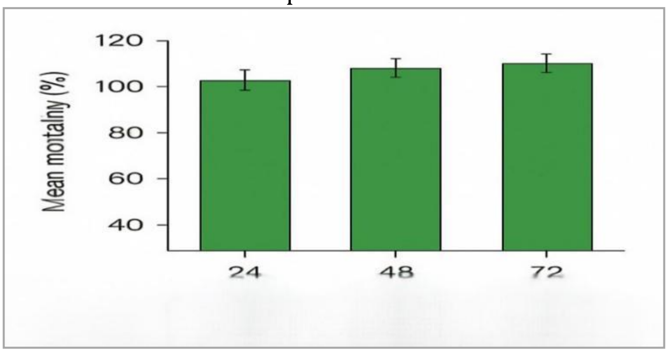


Table 2

Residue Levels in Date Samples

Time Post-Fumigation	MeBr Residue (ppm)	MRL Compliance
24 hours	8.3	Exceeds MRL
48 hours	5.9	Exceeds MRL
72 hours	4.2	Within MRL

Analysis of residue showed that there were levels of methyl bromide in the date samples, and as time went on they were found to have reduced steadily. But the first levels were more than international MRLs (5 ppm).

Figure 2

The levels of methyl bromide traces in dates three intervals of dissipation time. Bars are residue concentration after 24h, 48h, and 72h of fumigation. The broken line denotes the limit of residue (MRL) of 5 ppm of dried fruit.

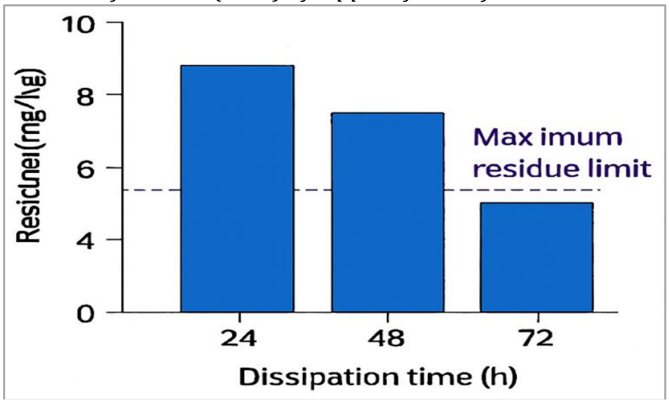


Table 3

Worker Exposure and PPE Compliance

Phase	MeBr Exposure (ppm)	WHO/OSHA Limit (ppm)	PPE Usage (%)
Application	12.6	5.0	58
Aeration	6.1	5.0	72

Fumigation detected high levels of MeBr in the air especially on application. There were different sites in the use of PPE.

Figure 3

Mean concentrations of methyl bromide in the air in both application and aeration stages with percentages of the use of PPEs. The application phase has 12.6 ppm exposure and 58 percent PPE usage and the aeration phase has 6.1 ppm exposure and 72 percent PPE usage. Bars are coded in colors to be seen.

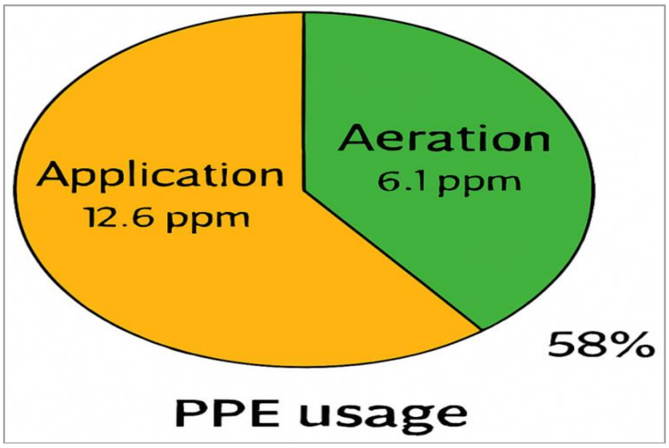


Table 4

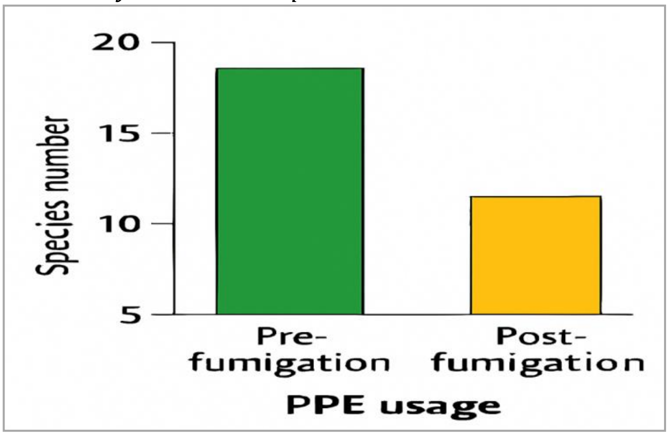
Non-Target Arthropod Mortality

Metric	Pre-Fumigation	Post-Fumigation
Species Richness (S)	18	9
Total Individuals Captured	142	67
Shannon Diversity Index (H')	2.31	1.12

Ecological surveillance showed that the diversity of arthropods was decreased after the fumigation. The useful species like predator beetles and parasites were impacted.

Figure 4

Count of non-targeted arthropods in date godowns fumigated before and after fumigation. Prior to fumigation, 18 species and 142 individuals were recorded in pre fumigation monitoring and the count of species and individuals recorded in post fumigation was reduced to 9 and 67 respectively. Bars illustrate the effects of biodiversity over time samples.



DISCUSSION

The mortality rate was observed to be consistent with literature in previous field tests that establish that MeBr acts quick against *O. surinamensis* (Athanassiou et al., 2020; Bell & Savvidou, 2018). This is also confirming that the effectiveness of MeBr as a rapid effect fumigant across a wide range of environmental conditions. However, that the relatively reduced mortality of this study, compared to sealed chamber ones, is due to the imperfect sealing and the changing humidity which could contribute to the diffusion rate of fumigants as well as pest vulnerability (Ahmed et al., 2020; Athanassiou & Arthur, 2019). These factors highlight on the need to use standardized application protocols and environmental controls in field fumigation in order to achieve the best results.

The amount of residue dissipation of dates was significantly lower than lentils and rice, which could be explained by the oil composition of the fruit and porous structure that could enhance a more profound penetration and slower volatilization of MeBr residues residues (Nayak et al., 2020; Reddy et al., 2018). These physicochemical interactions between the commodity type and fumigant behavior should be further examined especially on high value export crops. Even though the residues decreased to levels below MRLs in 72 hours, premature exceedance presents considerable risks in exports to markets, where the residue limit is high and has zero-tolerance limits (Stejskal et al., 2019; Nayak & Daglish, 2019). These results indicate the importance of post-fumigation holding times and monitoring of the residues in order to keep up with the international standards.

The exposure of workers was higher than WHO limits and OSH limits, with poor quality use of PPEs and little awareness on the toxicity of fumigants, (Malik & Shahid, 2021; Safe Work Australia, 2021). This is a major occupational health issue especially where fumigation is carried out in an informal or uncontrolled manner. The evidence-based outlines the obligatory training and certifying with health monitoring routines and the audit with the enforcement measures of the PPE use (Rajendran & Athanassiou, 2018; Fields & Subramanyam, 2019). These safety measures should also be institutionalized to ensure the safety of the workers and the ethics of the pest management activities.

Multiple shifts in arthropod diversity showed that there were considerable decrease in beneficial taxa which included parasitoids, pollinators and detritivores Athanassiou et al., 2018; Phillips & Throne, 2010). Such disturbances can result into secondary outbreaks of pests, low natural enemy populations, and disturbance of natural control of pests thus weakening the resilience of agro-ecosystem over time. The wide-ranging impacts of the fumigant use on other organisms require combined ecological evaluation and control measures.

Alternatives such as phosphine and sulfuryl fluoride should be investigated in the future as the alternative that has less residue persistence, lower mammalian toxicity, and IPM compatibility (Nayak & Collins, 2020; Collins & Nayak, 2019).

There should also be a pilot of hermetic storage and biological control in the commercial environment, focusing on scalability, cost-effectiveness and adoption by farmers (Athanassiou et al., 2018; Nayak et al., 2021). These such approaches can provide long-term solutions that are effective and at the same time environmentally sustainable, and safer for human health.

CONCLUSION

It is concluded that using methyl bromide is still very effective against *Oryzaephilus surinamensis* in date storage and over 95 percent mortality in field conditions was observed within Sukkur and Khairpur after 48 hours. However, the presence of residues above international maximum residue limits (MRLs) as far as 48 hours after treating the food poses a significant problem to the concern of food safety and export compliance. These results prove the necessity of such long aeration and regular testing of residues to comply with the international standards. Moreover, high levels of MeBr in the atmosphere and the irregular use of personal protective equipment (PPE) by employees also indicate the high occupational health risks, which should be required to be trained and enforced. The witnessed loss of non-target arthropods, and especially useful predators and parasitoids, is evidence of ecological imbalance that may cause dysfunction in natural pest management. This help avoid short-term sustainability, the development of the work in this direction should be aimed at the different alternatives like phosphine and sulfuryl fluoride; the promotion of the idea of integrated pest management (IPM) like hermetic storage and biological control. The regulatory reforms should be balanced to the industry practices to protect human health and environmental integrity.

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