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Silent Invaders: Mapping the pest peril in warehouses storing medicinal products

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Abstract

A structured survey-based study was conducted to assess storage conditions, pest infestations and management strategies in medicinal crop produce storage warehouses. Data were collected from ten warehouse locations across Tamil Nadu through structured questionnaires and direct observations. The warehouses, specializing in storing medicinal plant parts such as seeds, roots, leaves and bark, were analyzed based on storage capacity, duration and environmental conditions, including temperature and humidity levels. Pest infestations were documented by identifying species diversity, infestation rates and seasonal trends. Infestation levels were categorized as low, moderate, or high, with data on estimated storage losses. Pest control measures were assessed, including preventive approaches like sanitization, ventilation and humidity control, as well as curative strategies using synthetic insecticides, fumigants and botanical-based pest management solutions. The collected data were pre-processed in MATLAB, utilizing Principal Component Analysis (PCA) and K-means clustering to identify significant infestation patterns. PCA results indicated that the first two principal components captured most of the variance in pest associations, with certain crops such as *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) showing high susceptibility to *Lasioderma serricorne*, whereas *Myristica fragrans* (nutmeg) exhibited infestations from multiple pests, including *Sitophilus oryzae* and *Oryzaephilus* sp. K-means clustering identified distinct groupings of medicinal crops based on pest infestations, highlighting the need for tailored pest management strategies. A heat map analysis further confirmed that *L. serricorne* and *Oryzaephilus* sp. posed the greatest threats to specific medicinal crops, emphasizing the importance of targeted pest mitigation efforts. The hierarchical clustering of medicinal crops suggested shared susceptibility patterns, reinforcing the necessity for customized interventions. These findings provide crucial insights for optimizing storage conditions, improving pest management practices and reducing post-harvest losses in medicinal crop warehouses.

Keywords

cluster analysis; medicinal crop products; pest management; principal component analysis; storage pest; survey

Introduction

Medicinal plants serve as crucial raw materials for traditional healthcare systems such as Siddha, Ayurveda, Unani and Homeopathy, taking a pivotal role in pharmaceutical formulations. However, post-harvest losses due to insect infestations in storage warehouses pose a formidable challenge to maintain the quality, potency and clinical efficacy of these medicinal produce. Deficient storage practices yield moisture buildup, fungal contamination, secondary insect infestations and degradation of bioactive compounds, leading to economic and medicinal losses (1). Among the key storage pests, species such as cigarette beetle (*L. serricorne*), drugstore beetle (*Stegobium paniceum*), rice weevil (*S. oryzae*), red flour beetle (*Tribolium castaneum*) and Indian meal moth (*Plodia interpunctella*) are commonly found in warehouses storing medicinal crops. These insect pests cause both substantial and qualitative deterioration by feeding on stored materials, contaminating them with excreta, webbing and facilitates fungal spores which further accelerate spoilage (2).

Storage pests exhibit host preference based on factors such as moisture content, chemical composition and storage conditions. For instance, *L. serricorne* is known to target aromatic plant materials, while *S. paniceum* predominantly infests starch-rich roots and barks (3). Similarly, *S. oryzae* primarily attacks seeds, causing significant losses in seed-based medicinal produces (4). In addition to direct weight loss, these infestations lead to reduction in the bioactive compound potency such as alkaloids, flavonoids, terpenoids and such compounds which are crucial for the therapeutic properties of medicinal plants (5). Additionally, insect activity paves ways to fungal contamination (*Aspergillus*, *Penicillium*, *Fusarium* spp.), leading to mycotoxin contamination, which causes substantial health risks.

Given the high sensitivity of medicinal crops, pest control strategies must be residue-free and eco-friendly to ensure product safety for drug formulations. Various non-chemical approaches have been explored, including modified atmosphere storage using CO_2 or N_2, which effectively reduces the insect activity without leaving any chemical residues over the products (6). Similarly, botanical insecticides derived from neem, clove and eucalyptus offer natural repellent properties against stored-product pests (7). Other mitigation measures include hermetic storage, vacuum packaging, cold storage (≤10°C) to inhibit pest development and biological control using predators and parasitoids (8). Despite these strategies, detailed and scientific documentation of species diversity, infestation levels and host preferences in medicinal crop storage facilities are lacking.

This study aims to fill this gap by documenting major insect pests infesting medicinal crop produce across multiple warehouse locations around Tamil Nadu, assessing their infestation levels, nature of damage and documenting the existing pest control strategies.

Materials and Methods

Survey design and data collection

A structured survey-based study was conducted to document the storage produces, pest infestation and pest management strategies in medicinal crop produce storage warehouses. Data were collected from multiple warehouses engaged in wholesale, domestic retailing and exporting of medicinal plant materials used in Siddha, Ayurveda, Homeopathy and Unani drug formulations through pre constructed questionnaire.

Study sites and sampling

The study covered ten different warehouse locations around Tamil Nadu, with responses gathered from storage personnels through structured questionnaires and through direct observations. The warehouses solely intended for storing medicinal plant parts including seeds, roots, leaves, bark, and whole plants, utilized for pharmaceutical formulations were selected. Data on storage capacity, quantity of stored produce and storage duration were recorded. Sampling was done for documenting the insect species and pest infestation rate. The collected samples were securely sealed in bags and transported to the Department of Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore, for species identification. Morphological analysis was performed to confirm the identity of the insect species.

Storage conditions and management practices

Storage conditions were assessed based on parameters such as temperature (°C), relative humidity (RH %) and type of storage structures (*e.g.,* specialized storage, ordinary storage, bag storage and silos). Information on sanitization procedures and their frequency was collected to evaluate hygiene practices.

Pest occurrence and infestation assessment

Storage personnels were asked to report the presence of storage pests, their species diversity and the extent of damage caused. Infestation levels were categorized as low, moderate, or high, with additional data on seasonal trends in pest abundance and the estimated loss percentage due to infestations.

Pest control and management strategies

The study documented the preventive and curative measures employed against storage pests, including preventive measures such as regular cleaning, proper ventilation, temperature and humidity control; chemical control - use of synthetic insecticides or fumigants (if any) and botanical control including application of plant-based products.

Data analysis

The survey data was collected through pre constructed questionnaire and recorded in a tabular format. Preprocessing in MATLAB involved handling missing values, standardizing variables, normalizing numerical features and encoding categorical variables. Outliers were identified and addressed using statistical methods. Principal Component Analysis (PCA) was performed using R software and the plots were 3D visualised using MATLAB's PCA function to simplify data structure while retaining maximum variance with the first two principal components. K-means clustering was applied using the K-means function, with the optimal number of clusters and the results were visualized through scatter plots with centroids. Heat map was generated using MATLAB's heat map function, incorporating Pearson correlation coefficients to assess variable relationships. Descriptive statistics, including mean, standard deviation and frequency distribution, were calculated and statistical tests were conducted to validate clustering and PCA results. All analyses were performed in MATLAB (R2024) using the Statistics and Machine Learning Toolbox and Data Visualization Toolbox.

Results

The survey of pest infestation in medicinal crop storage warehouses revealed varying levels of insect presence across different stored plant materials. Among the identified storage pests, *L. serricorne* was predominantly found in *C. longa* (40 insects/100g), *Z. officinale* (52 insects/100g), *Alpinia officinarum* (5 insects/100g), *Curculigo orchioides* (20 insects/100g) and *Papaver somniferum* (25 insects/100g), indicating a high susceptibility of these crops to this pest. *Oryzaephilus* sp. was most abundant in *Caesalpinia bonducella* (22 insects/100g), *Glycyrrhiza glabra* (20 insects/100g), *M. fragrans mace* (36 insects/100g) and *Trachyspermum ammi* (36 insects/100g), suggesting a broader infestation across different medicinal crops. *S. oryzae* was detected only in *M. fragrans* (1 insect/100g), while *T. castaneum* was recorded in *T. ammi* (6 insects/100g). The infestation levels varied significantly, with *Z. officinale* exhibiting the highest incidence of *L. serricorne*, while *Oryzaephilus* sp. was dominant in *M. fragrans* and *T. ammi*.

Based on infestation patterns, the 3D PCA plot best illustrates the association between medicinal crops and their related insect pests (Fig. 1). With 84.07 % of the overall variance comprised, the first principal component (PC1) influences crop differentiation about pest diversity and infestation severity. Higher PC1 values in crops like *C. longa* (Turmeric) and *Z. officinale* (Ginger) attest to distinct pest relationships; the nutmeg maze seems apart and indicates a different infestation pattern. While PC3 (0.38 %) catches minimal variances, PC2 (15.53 %) offers greater variations across crops with mild infestation. This emphasizes that most differentiations exist in PC1 and PC2. The clustering observed in the plot suggests that certain crops encounter alike pest issues, necessitating similar pest management strategies, whereas others display unique infestation patterns requiring targeted management practices.

While *Quercus incana*, *C. bonducella* and *G. glabra* are more entwined with *Oryzaephilus* sp., crops such as *C. longa*, *Z. officinale* and *C. orchioides* exhibit strong ties to *L. serricorne*. Indicating several pest occurrences, *M. fragrans* (nutmeg) is linked with both *S. oryzae* and *Oryzaephilus* sp. Emphasizing the varied and complicated dynamics in preserved medicinal items, *T. ammi* (omam) also exhibits infestation by both *Oryzaephilus* sp. and *T. castaneum*. The color-coded crop points in the plot improve clarity, therefore helping to identify patterns of susceptibility and pest interactions. These observations are crucial for optimizing storage conditions, implementing precise pest mitigation strategies and curbing post-harvest losses in medicinal crop warehouses.

The heat map highlights the infestation levels of various insect pest species across different medicinal crops, with colour intensity implying severity (Fig. 2). Notably, *L. serricorne* exhibits the maximum infestation in *Z. officinale* (52) and *C. longa* (40), with moderate levels in *C. orchioides* (20) and *P. somniferum* (25), while other crops show little to no presence of this pest. Similarly, *Oryzaephilus* sp. shows major infestation in *M. fragrans* (36) and *T. ammi* (36), with moderate occurrences in *C. orchioides* (22) and *G. glabra* (20), although its presence is minor in most other crops. In contrast, *S. oryzae* has a minor impact, with only *M. fragrans* (1) being affected, while *T. castaneum* is similarly limited, spotted only in *T.ammi* (6). These data imply that *L. serricorne* and *Oryzaephilus* sp. offer the biggest dangers to medicinal crops, necessitating targeted pest management techniques. Furthermore, the lack or minimal presence of pests in specific crops may suggest intrinsic resistance or environmental variables that reduce infection.

The K-means clustering analysis of medicinal crops based on pest infestations highlighted three unique groupings, revealing variability in pest susceptibility (Fig. 3). The first cluster, which constitutes many of the crops, includes

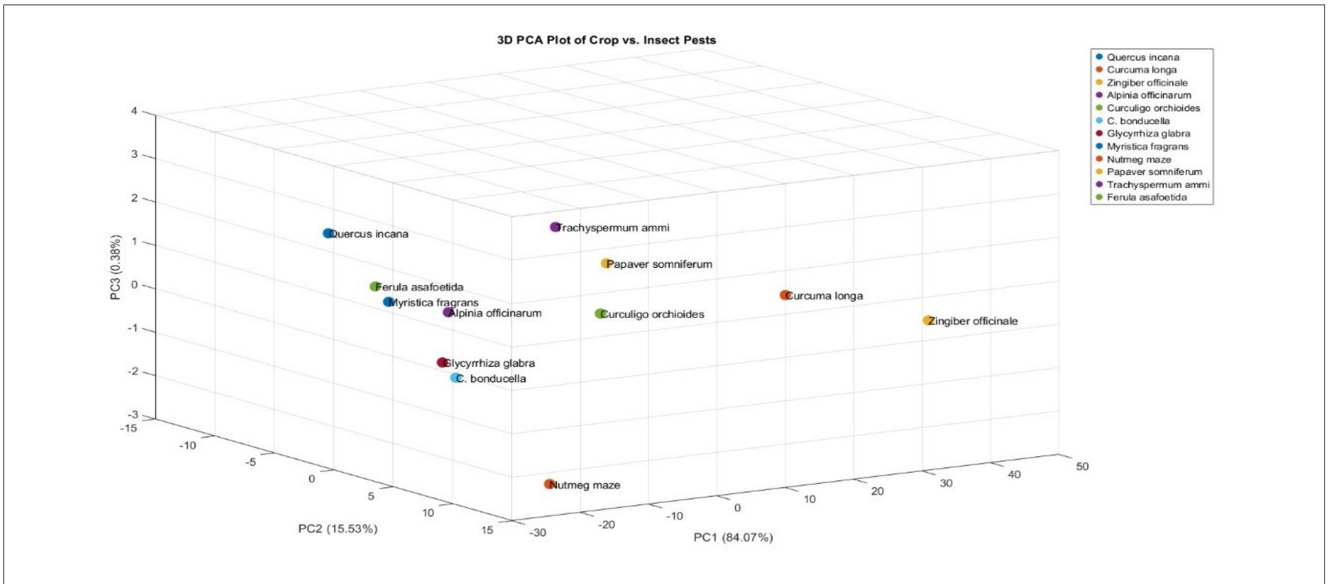

Fig. 1. PCA visualization of crop-pest associations in medicinal product storage warehouses.

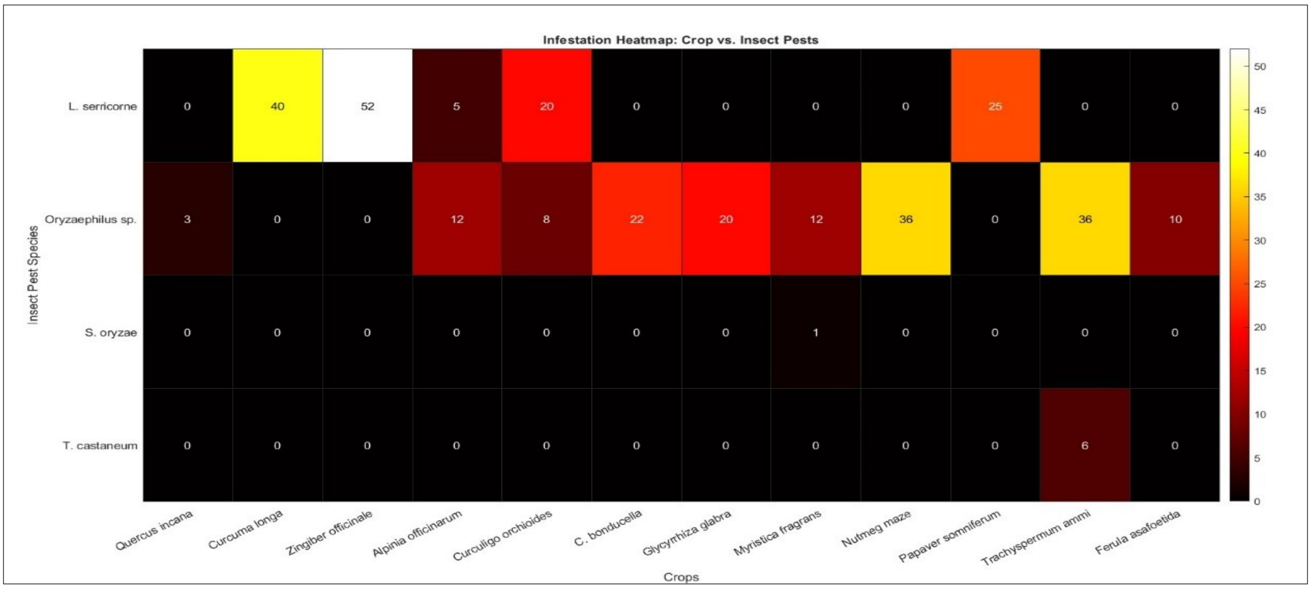

Fig. 2. Visualizing pest infestation patterns in stored medicinal crops: A heat map approach.

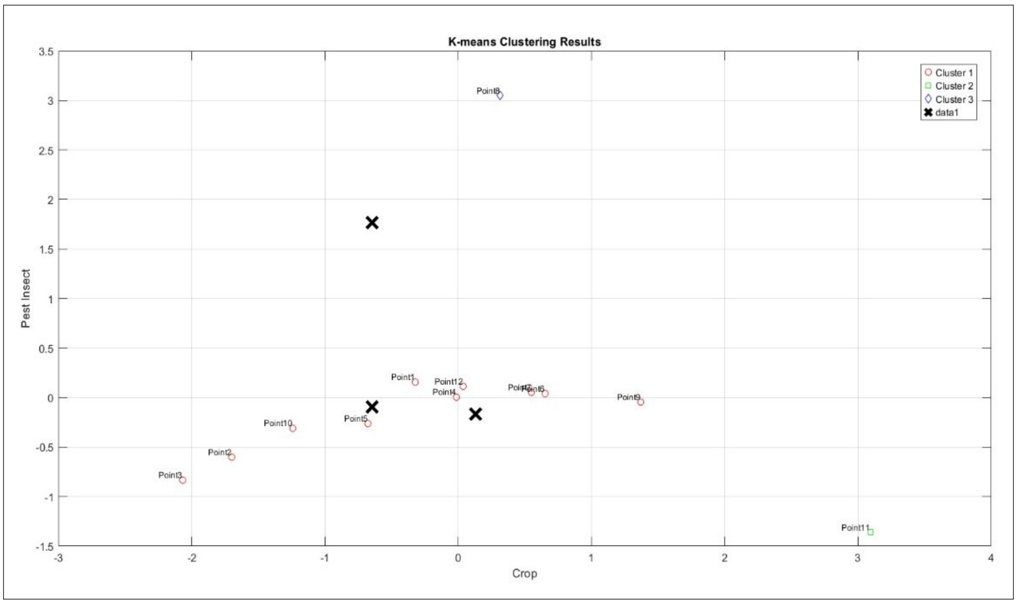

Fig. 3. K-means clustering of crop-pest interactions in medicinal product warehouses.

those having moderate infestations from certain insect species. For instance, *A. officinarum* and *C. orchioides* are clustered together due to their vulnerability to *L. serricorne* and *Oryzaephilus* sp., with moderate infestation levels. Similarly, *C. bonducella* and *G. glabra* constitute another subgroup within this cluster due to their greater infestation levels of *Oryzaephilus* sp. The second cluster, comprising fewer data points, displays crops with distinctive infestation patterns that distinguish them from the majority. A prominent example is *T. ammi*, which undergoes a high infestation by *Oryzaephilus* sp. coupled with *T. castaneum*. Another potential member, *Q. incana*, reveals low overall infestations but shows a specific attack by *Oryzaephilus* sp., distinguishing it from the first cluster. These specific infestation tendencies imply the necessity for catered pest management measures for such crops. The third cluster consists of a single outlier, likely *Z. officinale*, set apart due to its exceptionally high susceptibility to *L. serricorne* (52 occurrences). This substantial infestation level needs more investigation into the variables contributing to its vulnerability, such as chemical composition, storage conditions, or environmental impacts.

Overall, the clustering results disclose that some medicinal crops share comparable pest pressures, others exhibit unusual or high susceptibility to certain pests. These findings underline the need for specific pest management strategies, particularly for highly vulnerable crop like *Z. officinale*.

The scatter plot of crop infestations by insect pests offers significant additional insights on the varying degrees of susceptibility among various medicinal crops (Fig. 4). With 52 and 40 occurrences of *L. serricorne* correspondingly, suggesting a great degree of damage to *Z. officinale* and *C. longa*. Comparably, *T. ammi* highlights an apparent pest preference for this crop with a distinctive infestation of *Oryzaephilus* sp. (36 occurrences). Among the moderately affected crops, *C. bonducella* and *G. glabra* portray similar infestation levels by *Oryzaephilus* sp., with 22 and 20 occurrences, respectively, suggesting proportionate susceptibility. Likewise, *C. orchioides* encounters a moderate infestation by *L. serricorne* (26 occurrences), situating it alongside other crops with significant but less extreme pest interactions. *M. fragrans* also falls into this group, with 12 occurrences of *Oryzaephilus* sp., showing a moderate yet substantial susceptibility. The scatter plot also indicates crops with minor pest infestations, such as

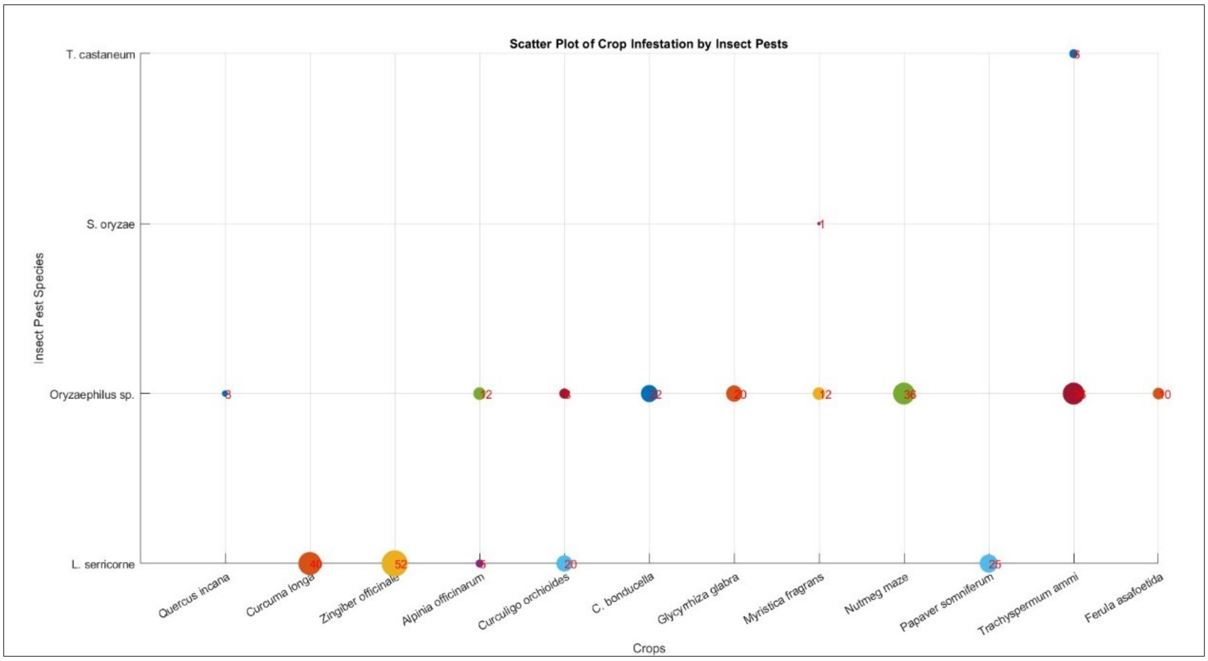

Fig. 4. Mapping crop-pest interactions in medicinal product warehouses using scatter plot.

Q.incana which displays only 3 occurrences of *Oryzaephilus* sp., indicating a decreased vulnerability. *Ferula asafoetida* and *P. somniferum* have comparatively moderate infestations (10 and 25 occurrences, respectively), suggesting a lower level of pest predilection. A unique case is identified in *T. castaneum*, where *T. ammi* has an isolated infestation (6 occurrences), further defining its pest interaction profile. Overall, the scatter plot efficiently categorizes crops based on their infestation intensity, differentiating highly susceptible crops like *Z. officinale* and *C. longa* from those with moderate or minimum infestations. The findings underline the requirement for focused pest management measures, particularly for crops with significant infestations, to limit possible economic losses and preserve crop quality. The dendrogram analysis presents a hierarchical clustering of medicinal crops based on their pest infestation similarities, delivering significant insights into their vulnerability and resistance patterns. Crops such as *Z. officinale* and *C. longa* cluster closely, indicating a similar sensitivity to *L. serricorne*, a key pest of essential oil-rich crops. This clustering aligns with PCA findings, emphasising the severity of infestation and the need for focused pest management techniques. In contrast, crops like *Q. incana* and *F. asafoetida* form separate clusters, suggesting decreased infestation risks maybe due to their chemical composition or storage conditions. The hierarchical structure further underscores the requirement of grouping crops based on identical pest management approaches while separating those that require unique management approaches. These findings underline the significance of targeted insect mitigation techniques to prevent post-harvest losses and ensure the preservation of medicinal crop quality.

Discussion

The 3D PCA analysis provides a full insight of pest infestation dynamics in medicinal crop storage. PC1 (84.07 %) emphasises the significant impact of pest diversity and infestation severity in figuring out crop susceptibility. *Z. officinale* and *C. longa* exhibit high infection levels by *L. serricorne*, a known pest of essential oil-rich crops. Prevalence of the pest leads to severe losses in quality and marketability due to degradation of bioactive chemicals required for pharmaceutical formulations (9). The presence of *L. serricorne* can lead to severe losses in both quality and marketability of these crops. The pest is renowned for its potential to infest dried crops and deteriorate their biochemical composition, rendering the products to be unfit for use in medicinal formulations (10). Factors such as temperature, humidity and duration might influence pest activity and the degree of damage (11).

Crops like *Q. incana, C. bonducella* and *G. glabra* are closely connected within *Oryzaephilus* spp., showing their vulnerability to grain-infesting pests. This shows inappropriate storage or proximity to grain-based goods can worsen cross-infestations (12). *M. fragrans* and *T. ammi* experience infestations from numerous pests such *S. oryzae* and *T. castaneum,* significantly complicating storage pest management (13). The existence of multiple pest species in these crops necessitate integrated pest management strategies to prevent cumulative damage and post-harvest losses. The clustering analysis underlines the association between pest infestation patterns and crop susceptibility. Medicinal crops exhibiting similar pest burdens, such as *Z. officinale* and *C. longa,* cluster together, indicating a need for shared pest control measures. In contrast, crops with lower infestation rates, such *Q. incana*, develop separate clusters, suggesting intrinsic resistance or changes in storage conditions. This clustering trend underlines the need of establishing crop-specific pest management techniques based on susceptibility levels (14).

The scatter plot further affirms these findings by visually distinguishing crops based on pest infestation severity. The substantial separation of *Z. officinale* and *C. longa* at the high end of the infestation scale corresponds with the PCA results, highlighting the susceptibility of these crops to *L. serricorne*. Conversely, crops like *Q. incana* and *F. asafoetida* appear at the lower end of the range, illustrating their relative resistance to infection. This distribution underlines the necessity for precision pest control tactics customised to each crop's infestation profile.

The grouping identified in the PCA analysis shows the significance of specialised pest management tactics. Preventive treatments such as controlled humidity and temperature can be applied for the crops infested by *L. serricorne* while crops vulnerable to *Oryzaephilus* spp. require specific chemical or biological interventions (15). Sustainable pest management options such as Integrated Pest Management (IPM), biological controls and botanical insecticides have shown beneficial in reducing infestation risks while lowering dependency on chemical pesticides (13). The utilisation of PCA and other statistical methods like hierarchical clustering can provide a more diligent knowledge of pest-crop interactions, enabling the development of more accurate pest management strategies (16).

The integration of PCA, hierarchical clustering and scatter plots boosts our capacity to build precision pest management techniques designed to the specific infestation dynamics of each crop. These findings underscore the requirement for persistent pest monitoring and further research into pest ecology, particularly in medicinal crop storage systems. The survey's findings show that different medicinal crops have differing degrees of pest infestation, which may indicate that some herbs are less vulnerable to storage pests. High level of infestation of *L. serricorne* in *Z. officinale* and *C. longa* from our survey were consistent with the previous studies (17, 18). *Q. incana* and *F. asafoetida*, two medicinal crops, for instance, had little to no infection, suggesting that they may have inherent insecticidal or repellent qualities. Secondary metabolites found in medicinal plants, including as alkaloids, flavonoids and essential oils, have been shown in earlier research to have poisonous and insect-repelling properties against storage pests. These results are consistent with our survey's conclusions that certain medicinal crops may naturally have anti-pesticide qualities, as seen by the absence or reduced infestation rates in particular herbs (19). The active ingredients that prevent pests need to be confirmed by additional biochemical investigation.

Preventive and control methods are both necessary for effective pest management in the storage of medicinal crops. Controlling humidity, temperature and cleanliness during storage reduces the likelihood of infestations (20). Physical techniques such as heat treatment, sieving and storage in a modified atmosphere storage are efficient substitutes (21, 22). Eco-friendly pest control can be accomplished through incorporating two or more pest management strategies like biological control, cultural and mechanical control methods. Sustainable management may be achieved by using insect repellents, insect traps and by biological control using entomopathogenic fungi and parasitoids. Although chemical fumigants such as phosphine are employed, their use must adhere to safety regulations. A comprehensive strategy that incorporates these tactics guarantees improved storage protection for medicinal crops.

Future Perspectives

Looking ahead, further research should focus on developing sustainable, efficiently managing infestations. The incorporation of advanced storage technologies, such as automated pest detection systems and controlled storage conditions could facilitate better warehouse management and efficient mitigation of pest. Long-term studies that monitor pest populations over time and investigate the success of pest management measures are vital for enhancing the effectiveness of these approaches. Additionally, stronger regulatory frameworks and standardized guidelines for pest management in medicinal products storage will be crucial for assuring global consistency in protecting these valuable produces. Harmless pest management options that minimize chemical exposure while efficiently managing infestations.

Conclusion

This study emphasises the enormous risks caused by insect pests in warehouses housing medicinal raw materials. Pests can contribute to contamination, loss of product efficacy and significant health concerns, thereby rendering it prerequisite to manage pest infestations within these environments. The findings highlight the significance of implementing effective pest management measures, enhanced storage procedures and more severe regulations for safeguarding the safety and integrity of medicinal products. By documenting the key pests and their impact, this study provides a good foundation for creating better monitoring and management approaches in storage facilities.

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Authors' contributions

All the authors contributed equally in executing the research idea, designing the survey, supervising the study, and interpreting the data.

Compliance with ethical standards

Conflict of Interest: The authors have no conflict of interest.

Ethical issues: None

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