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Preserving the Scientific Legacy: An Integrated Pest Management Approach from a Heritage Astronomy Library

Erhaltung des Vermächtnisses: ein integriertes Schädlingsbekämpfungskonzept an einer wissenschaftlichen Bibliothek

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Abstract: This study examines the preservation challenges and strategies implemented at the Library of the Kodaikanal Solar Observatory (KSO), part of the Indian Institute of Astrophysics. The library houses rare and sometimes fragile manuscripts, historical documents, and infrastructure of historical importance. Due to KSO's distinct climatic conditions, specialized conservation measures were crucial in safeguarding these scientific heritage resources. A comprehensive approach combining preventive measures with chemical and non-chemical interventions was adopted. Key strategies included CO_2 fumigation to protect paper-based materials from pests and specialized pest control techniques to address threats like wood borers and termites, which endangered both collections and the library's structure. Based on practical experience during the preservation process, this study offers workable solutions for libraries and archives. It emphasizes sustainable, integrated pest management practices that minimize environmental impacts while ensuring long-term preservation. Findings highlight the importance of continuous monitoring, early intervention, and eco-friendly solutions in preservation efforts. By presenting a structured methodology, this case study serves as a model for heritage

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libraries facing similar challenges. It advocates for a holistic approach to balance preservation techniques with the unique needs of heritage materials, ensuring their accessibility for future generations.

Keywords: library conservation; archival preservation; integrated pest management; Kodaikanal solar observatory; heritage library; paper conservation

Zusammenfassung: Diese Studie untersucht die Herausforderungen und Strategien in der Bestandserhaltung an der Bibliothek des Kodaikanal Solar Observatory (KSO), einem Teil des indischen Instituts für Astrophysik. Die Bibliothek lagert seltene und teilweise fragile Manuskripte, historische Dokumente und Infrastruktur von historischer Bedeutung. Aufgrund der besonderen klimatischen Bedingungen an der KSO sind angepasste Konservierungsmaßnamen notwendig, um das wissenschaftliche Kulturerbe zu bewahren. Ein umfassender Ansatz, der präventive Maßnahmen mit chemischen und physikalischen Interventionen kombiniert, kam zum Einsatz. Die Begasung mit CO_2 spielt dabei eine wesentliche Rolle, ebenso wie abgestimmte Techniken der Schädlingskontrolle, um die Bedrohung durch Nagekäfer und Termiten abzuwenden, welche sowohl die Sammlung als auch die Konstruktion der Bibliothek bedrohen. Basierend auf praktischer Erfahrung aus diesem Projekt, bietet diese Studie umsetzbare Lösungen für Bibliotheken und Archive. Sie betont nachhaltige Schädlingsbekämpfungsstrategien, welche Umwelteinflüsse zurückdrängen und eine dauerhafte Erhaltung sichern. Die Ergebnisse betonen die Wichtigkeit von kontinuierlichem Beobachten, frühzeitigem Eingreifen und umweltfreundlichen Lösungen bei den Bemühungen zur Bestandserhaltung. Da wir einen strukturierten Ansatz vorstellen, kann dieses Fallbeispiel als Vorbild für Kulturerbeeinrichtungen mit ähnlichen klimatischen Herausforderungen dienen. Wir befürworten einen ganzheitlichen Ansatz, um Techniken der Bestandserhaltung mit den besonderen Bedürfnissen von Kulturgut abzustimmen, um den zukünftigen Zugang zu gewährleisten.

Schlüsselworte: Bestandserhaltung in Bibliotheken; Bestandserhaltung in Archiven; IPM; Kodaikanal Solar Observatory; Kulturerbe; Papierrestaurierung

1 Introduction

A library is a repository for knowledge that is kept in document form. The process through which library materials are harmed, destroyed, or degraded for various reasons, including biological, chemical, and environmental causes, is known as degradation. As part of preservation, conservation measures are performed on library materials that have previously been degraded or damaged (Mishra 2017; Goswami 2018). Temperature, humidity, and moisture levels significantly impact the

preservation of library materials. These environmental factors accelerate deterioration processes, thereby damaging and causing the loss of valuable collections (Sahoo 2004; Yadav and Kumar 2020). Libraries in tropical countries like India frequently contend with infestations, where insects damage stored paper, books, wooden shelves, and even building structures, resulting in irreversible deterioration on multiple levels (Cabral and Querner 2017; Rasaki, Adewuyi, and Makinde 2023).

Biological agents, comprising microorganisms, insects, and rodents, pose a severe threat to the preservation of library materials. Microorganisms, such as fungi and bacteria, induce significant deterioration through the decomposition of organic matter, resulting in discolouration, structural weakening, and, ultimately, disintegration (Sahoo 2004; Sequeira, Cabrita, and Macedo 2014; Montanari et al. 2021). Insects, including cockroaches and bookworms, consume paper, adhesives, and bindings, creating perforations and tunnels that compromise document integrity. Rodents, such as mice and rats, exacerbate damage by gnawing on paper, leather, and other materials while contaminating collections with excrement and urine (Sahoo 2004; Segaetsho 2015). Various pests can damage library materials, including wood-boring beetles such as *Anobium punctatum* and *Hylotrupes bajulus*, as well as the cigarette beetle (*Lasioderma serricorne*), biscuit beetle (*Stegobium paniceum),* silverfish (*Lepisma saccharina*), and termites (Querner 2015).

The Kodaikanal Solar Observatory (KSO) was established in the late 19th century to conduct scientific observations of the sun. John Evershed, who joined the observatory in 1907, made significant contributions, including the discovery of the radial motion of gases in sunspots, known as the Evershed effect. Through the pioneering work of Evershed, Kodaikanal gained international recognition as one of the world's foremost solar observatories (Mallik 2009). KSO holds one of the world's longest and most homogeneous records of sunspot observations from 1904. These observations, originally recorded on photographic plates, have been digitized to create a comprehensive catalogue of sunspot parameters. This digitized data is crucial for studying long-term solar variability (Jha et al. 2022; Mandal et al. 2017; Ravindra et al. 2013).

The weather in Kodaikanal experiences minimum temperatures ranging from 8.2 °C to 19.7 °C and high humidity levels between 92 % and 95 % (Thulasinathan et al. 2018). While the lower temperatures may help slow down pest activity, as many pests thrive in warmer environments, the high humidity can create favourable conditions for mold, fungi, and certain pests like silverfish and booklice, which are known to damage paper-based materials.

This study addresses a critical research gap in pest management within library and archival settings, explicitly focusing on the impact of pests such as silverfish, wood borers, and termites, among others. These pests, along with the presence of fungi, can significantly damage valuable library materials, often accompanied by

unpleasant smells. The research aims to identify and implement suitable pest control methods to mitigate such damage effectively. Additionally, this article explores best practices developed during the study, offering practical insights into preserving library collections.

2 Review of Literature

Libraries and archives often experience increased air humidity, which fosters the growth of fungi. There is a growing need to study the impact of dust and fungal infections caused by air pollution and to ensure the library environment is conducive to research. This contamination can potentially lead to health issues, particularly respiratory problems, underscoring the need for adequate measures to monitor air quality and implement preventive strategies to safeguard the well-being of users as well as staff (Karbowska-Berent et al. 2011; Pinheiro et al. 2012; Chary 2014; Skóra et al. 2015; Cyprowski et al. 2023). Dust accumulation throughout the library poses a substantial challenge. Visitor activity and external particles entering through windows and doors constitute the primary sources of dust in the library environment (Rasaki, Ogunmodede, and Adedimeji 2024).

Library furniture is often crafted from wood, which has aesthetic and functional significance. In the case of heritage libraries, these wooden furnishings usually hold historical value, linking it to the architectural and cultural traditions of the past. The main agents of wood degradation include fungi and insects. Fungi are the primary cause for deterioration, with enzymatic and non-enzymatic mechanisms degrading wood cell walls. Wood's natural durability and long-term stability is influenced by factors like lignin composition and moisture content (Unger, Schniewind, and Unger 2001; Martín and López 2023). Insects, including termites, pose a significant threat to the longevity of wooden materials in library furniture; chemical agents must be used against that. Chlorpyrifos, a widely used organophosphate pesticide, effectively targets insects' central nervous systems (Jones and Huang 2003; Dong et al. 2022). Despite its broad applications in agriculture and structural pest control, its short-lived efficacy requires frequent, high-concentration applications (Ahmed et al. 2017; Qasim et al. 2024). Studies also highlight chlorpyrifos' protective role against wood-decaying fungi, providing 72–89 % protection to softwood and 66–88 % protection to hardwood (Pant and Tripathi 2010). However, chlorpyrifos poses significant health risks, including cancer, respiratory and reproductive issues, and ecosystem harm through residual toxicity and groundwater contamination (Enserink et al. 2013; Lasagna et al. 2020; Sabbouri et al. 2020).

The degradation of documents caused by termites poses a significant challenge to their preservation, particularly in libraries and archives. Termites feed on

cellulose-based materials, making paper documents highly susceptible to damage. Several preventive measures are implemented to mitigate this issue. Controlling moisture levels in the environment is also critical, as damp conditions are conducive to termite infestations (Su and Scheffrahn 2000). In addition to these preventive steps, one of the most effective methods for addressing termite problems is the application of chemical treatments designed to eradicate termite colonies. When combined with good storage practices, these treatments can significantly reduce the risk of document degradation and help ensure the long-term preservation of valuable records (Naikal and Sahu 2023). Chemical treatments for termite management provide long-term protection by deeply penetrating structural materials, forming a strong defence against both existing and future infestations. Cyfluthrin, a widely used insecticide, plays a crucial role in building preservation by targeting insect activity on structural surfaces to prevent deterioration. Its formulations offer extended residual protection, effectively minimizing insect-related damage. Additionally, its capability to control pests on porous building materials enhances structural integrity, safeguarding against biological agents (Sehgal et al. 2013).

Various insect species threaten books, paper, and archival materials, with larvae developing inside books while adult beetles reproduce outside the substrate. Among the most common pests, silverfish are small, wingless insects, silvery or pearl-gray in colour, measuring about 8–10 mm in length. They thrive in dark places, are active only at night, and are attracted to starch, glue, gelatine in paper, dust, and dirt. They damage paper surfaces, eat starch glue from stamps and envelopes, and create holes in paper, photographs, and cardboard. Common microhabitats for reproduction include dark library racks, catalogue cabinets, and drawers (Brokerhof et al. 2007; Querner 2015; Trematerra and Pinniger 2018).

Insect infestations in heritage collections were addressed using repellents such as cedar oil, paradichlorobenzene crystals, and camphor. However, using these chemicals is not suitable for complete pest eradication. While insecticides like methyl bromide and ethylene oxide have proven effective in eliminating insect populations, their implementation is severely restricted due to their substantial health risks to humans (Faheem 2021). Chemical pest management techniques are inherently hazardous to the environment and humans (Singh et al. 2022). In the past, library preservation efforts have relied heavily on fumigation to prevent infestations and mould growth, ensuring the long-term protection of valuable books, manuscripts, and archives, with its proven track record of efficacy against microorganisms and insects. Recently, CO_2 fumigation emerged as a viable alternative, offering a non-toxic and environmentally responsible approach. By creating oxygen-deprived environments, CO_2 effectively controls pests without introducing hazardous chemicals (Wörle et al. 2019). The non-invasive properties of CO_2 fumigation, which preserves

materials without chemical alteration, have made it a preferred method for sensitive items.

While pesticides are part of Integrated Pest Management (IPM), the goal is to use the safest methods to protect people, collections, and the environment (Radcliffe, Hutchison, and Cancelado 2008). Various studies emphasize the importance of implementing IPM strategies, including monitoring, identifying, treating, and preventing pests (Schott 2003; Querner 2015; Segaetsho 2015; Cabral and Querner 2017). The emergence of new pests and the effects of climate change present major challenges to IPM in museums, archives, and libraries, requiring adaptive strategies to mitigate infestation risks and protect cultural heritage (Querner and Biebl 2024).

Libraries make sure that the information of the past is preserved and protected for future generations by actively working on conservation, restoration, and preservation projects (San Oo 2019). Collaborative efforts are paramount in ensuring the preservation and conservation of library collections. Establishing a national preservation consortium can effectively address preservation challenges across libraries. Such a collaborative platform has the potential to overcome obstacles hindering the preservation of invaluable information resources (Mubofu, Mambo, and Samzugi 2021). To address the challenges of deterioration in libraries, necessary actions must be taken to preserve the collections. Library staff should be trained in proper shelving techniques, and efforts should be made to mitigate environmental conditions that favour biological agents (Amankwah, Bilson, and Atisoe 2022; Mubofu, Mambo, and Samzugi 2022). Consistent cleaning efforts contribute to a healthier and more conducive environment for both library staff, users and collections as a curative measure, the binding and repair of damaged books and documents are essential for preserving library collections. These interventions help to restore the physical integrity of materials and prolong their lifespan (Segaetsho 2015; Rasaki, Ogunmodede, and Adedimeji 2024).

3 Materials and Methods

3.1 Study Area

This study examines the preservation and preventive conservation techniques implemented for library resources at the Kodaikanal Solar Observatory (KSO), a field station of the Indian Institute of Astrophysics, situated in Kodaikanal, Tamil Nadu, India. It evaluates environmental factors affecting pest infestations, examines various pest control methods, and proposes a methodology for the effective preservation of rare and historically significant scientific documents, books, and archives.

3.2 Initial Assessment

A comprehensive survey of the KSO Library collection was conducted to assess pest infestations. A specialized vendor performed an on-site inspection, identifying pest species and evaluating their impact. The assessment included a visual examination for damage signs such as boreholes, chewed edges, and mold growth, with pest samples collected for analysis. Based on entomological references and expert consultations, the specimens were classified to ensure accurate identification (Querner 2015). The evaluation revealed key pests, including silverfish, booklice, and termites, which posed significant risks to the library's materials. Silverfish and booklice primarily targeted paper-based documents, while termites threatened wooden shelves and structural components. These findings provided critical insights into the extent of the infestation, forming the basis for targeted preservation and pest management strategies.

3.3 Development of a Methodology for Implementing Integrated Pest Management (IPM) in Libraries

A structured approach was employed to develop a comprehensive Integrated Pest Management (IPM) implementation methodology, engaging key stakeholders, including the IPM team, vendors, maintenance personnel, and library authorities. The process began with a collaborative brainstorming session utilizing the Crawford Slip Method, a structured technique designed to facilitate spontaneous idea generation and expert input (Ballard and Trent 1989). This method was chosen for its efficiency in collecting diverse perspectives and practical recommendations (Arumugam, Thomas, and Rega 2024). During the session, participants contributed ideas, which were systematically categorized into key themes, including preventive measures, chemical interventions, environmental controls, and monitoring strategies. Each theme was critically analysed through group discussions, evaluating feasibility, cost-effectiveness, and potential impact. The most viable strategies were integrated into a detailed IPM methodology specifically tailored to the challenges of preserving the KSO Library collections. The methodology incorporated a balanced combination of chemical and non-chemical approaches to ensure long-term preservation while minimizing environmental impact. Implementation included the application of chlorpyrifos-based insecticides, environmental control measures, and continuous pest monitoring. Additionally, library staff received comprehensive training on pest identification, material handling, and preventive techniques. This capacity-building

initiative ensured continuous vigilance, contributing to the sustainable preservation of the library's collections.

3.4 Chemical and Non-Chemical Treatments

A combination of chemical and non-chemical methods was employed to implement effective pest control treatments at the KSO Library. Two specialized vendors were engaged: one for chemical and non-chemical treatments and another for varnishing. For dust removal and routine cleaning, local housekeeping staff were assigned to ensure the proper handling of materials and infrastructure. The entire process spanned approximately three months, reflecting the thoroughness and scale of the preservation efforts. To mitigate rodent infestations, 10 rat glue traps and 12 wooden rat traps with bait were placed throughout the library for one week. These measures, including pheromone traps, sticky traps, and rodent control techniques, were systematically implemented alongside routine deep cleaning to maintain optimal hygienic conditions (Sahoo 2004).

For chemical treatments, chlorpyrifos was applied to eliminate infestations in wooden materials, effectively targeting wood borers and termites. To protect wooden library furniture from pests, Durmet® RTU insecticide (chlorpyrifos 2 % RTU) was used in its ready-to-use form without dilution. It was sprayed directly on wooden surfaces, including bookshelves, tables, cabinets, and storage units, with special attention to crevices and joints where pests typically hide. A low-pressure sprayer was used for application, and the chemical was also injected into broken wooden sections wherever possible.

For termite control, Premise® insecticide (Imidacloprid) was injected at floor level, maintaining a 1-foot distance between injection points and a depth of 4–5 inches. Holes were drilled into the flooring to ensure the solution reached termite galleries, creating a continuous protective barrier. The insecticide was diluted at a ratio of 2.1 ml per litre of water. Solfac® EW50 (Cyfluthrin 5 % EW) was sprayed for control of cockroaches and other insects. The insecticide was mixed with water at a ratio of 8 ml per litre of water. These treatments were selected for their proven efficacy and were carefully applied under controlled conditions to minimize any adverse impact on the library's fragile historical materials and structural integrity (Sheets 2010; Sehgal et al. 2013; Dong et al. 2022; Reid et al. 2002).

To minimize chemical exposure and ensure the safe preservation of library and archival materials, CO_2 fumigation was employed as an alternative pest control method. This technique provides an archival-safe, non-invasive approach while avoiding the residual effects of chemical treatments. The treatment was conducted in five sealed bags, with CO_2 levels maintained at 60–90 % and oxygen levels reduced

below 4 % during the final 12 days (out of total 15 days) of the fumigation process to ensure optimal pest eradication. The room temperature in Kodaikanal ranged from 17 °C to 25 °C throughout the process, and real-time gas concentration monitoring was performed to maintain effectiveness. To evaluate efficacy, bioassay vial tubes containing live cigarette beetle (*L. serricorne*) specimens were placed inside the fumigation bag. Mortality rates were recorded at the end of the treatment cycle, confirming the method's effectiveness in eliminating infestations while preserving the integrity of archival materials.

By integrating this non-chemical approach alongside traditional pest control strategies, the KSO Library adopted a comprehensive Integrated Pest Management (IPM) plan, ensuring the longevity and accessibility of its historical collections. Additionally, staff underwent comprehensive training sessions to enhance their ability to identify pest infestations, handle materials correctly, and implement preventive measures effectively (Schott 2003; Segaetsho 2015; Cabral and Querner 2017; Faheem 2021).

4 Results and Discussion

4.1 Dust Removal and Varnishing

We started by carefully taking all the documents from the shelf, ensuring that books and other items were correctly handled to prevent damage or loss. Each item was taken out systematically, keeping everything in its original arrangement to make replacement simple. Each document was meticulously cleaned using microfiber cloths (Figure 1) while vacuum cleaners were employed for thorough floor cleaning. Regular dusting effectively minimized particulate accumulation, mitigating the risks of fungal growth and material degradation (Cyprowski et al. 2023; Rasaki, Ogunmodede, and Adedimeji 2024).

Varnishing is crucial in treating wood surfaces, enhancing their durability and aesthetic appeal. Wood is typically treated with organic and inorganic materials to create a nonporous, morphologically uniform surface. The final step in this process is the application of varnishes or coatings, which serve both functional and aesthetic purposes. These finishes protect the wood from degradation and enhance its visual appeal (Feist and Abdullahi 2016). Coatings fulfil these essential roles as they protect the wood from physical, chemical, and biological deterioration – including exposure to water, chemicals, UV radiation, dirt, fungi, and algae; also, they enhance the wood's aesthetic qualities, providing colour, gloss, and desired surface textures. This dual functionality is crucial for reducing maintenance costs while improving wood

Figure 1: Photograph taken during the dust and mold removal process for the library collection.

surfaces' long-term stability and visual appeal (Viitanen and Ritschkoff 2011; Invernizzi et al. 2021).

Wooden materials were varnished in the KSO Library to ensure their preservation and protection. This protective coating highlights the wood's natural grain, providing a polished, glossy finish that enhances its aesthetic appeal. In addition to improving the appearance, the varnish helps maintain the wood's integrity and extends its longevity (Feist and Abdullahi 2016). We used 'Asian Paints WoodTech Melamyne' (Wood Varnish) for the varnishing of wooden items.

4.2 Rodent Control

Rodent control measures were implemented in the library by strategically placing traps and bait stations in areas with high rodent activity (Figure 2(A–C)). Within a week, two rats were captured, and after a week of observation, no further damage was identified. Regular monitoring and bait replenishment ensured effective control, significantly reducing the rodent population and mitigating the risk of damage to library materials (Buckle and Smith 2015; Kangko and Thren 2017).

4.3 Chemical Treatment for Wood Materials

The pest control measures for wood in the KSO library involved a comprehensive strategy, combining targeted application of insecticides. Figure 3(A and B) shows expert staff meticulously applying chlorpyrifos, an organophosphate insecticide, in adherence to the prescribed standards, ensuring comprehensive pest control (Dong et al. 2022). They sprayed the chemical uniformly across the wooden bookshelves,

Figure 2: (A): Identified areas of rodent infestation (B): glue trap used for rodent control (C): carcass of a rat in a wooden rat trap.

Figure 3: (A): Spraying chlorpyrifos on library shelves for effective surface-level pest control.
(B): Injecting chlorpyrifos into library shelves to treat hidden crevices and deep-seated infestations.

paying particular attention to vulnerable areas. Additionally, they injected the chemical into specific zones, especially targeting corners, cracks, and holes, where pests are likely to hide or breed. This thorough approach aimed to maximize the effectiveness of the treatment (Pant and Tripathi 2010).

4.4 Chemical Treatment Methods for Termite Control

The termite control process began with a thorough inspection of the premises, covering approximately 2,500 square feet, to evaluate termite activity both inside and outside the library building. Based on the findings, holes were drilled at one-foot intervals along walls and floors in affected areas, following standard treatment

Figure 4: (A): Drilling holes at one-foot intervals to prepare for pesticide injection. (B): injecting imidacloprid into drilled holes for termites' control. (C): sealing drilled holes with cement to restore structural integrity.

protocols. Imidacloprid is a widely recognized and extensively utilized neonicotinoid insecticide, particularly effective in managing termite infestations. Due to its potent neurotoxic effects on insects, it has become a preferred choice for termite control in structural pest management. Its systemic action and long-lasting residual properties make it highly effective in preventing and eliminating termite colonies (Reid et al. 2002; Sheets 2010). Imidacloprid was injected at floor level, with holes drilled into the flooring at 1-foot intervals and a depth of 4–5 inches to ensure effective distribution of the solution. The insecticide was prepared by diluting 2.1 ml in 1 L of water before application. Special attention was given to the wall edges, corners, and high-risk zones to ensure comprehensive treatment. Additionally, wooden bookshelves, storage spaces, and the surrounding soil were treated to further safeguard the library's infrastructure. After the chemical application, all drilled holes were sealed with cement to maintain structural integrity (Figure 4(A–C)). In areas where drilling was not feasible, a termite baiting system was deployed, consisting of 20 strategically placed bait stations. This colony elimination approach proved effective, significantly reducing termite activity within three to six weeks, depending on infestation severity. Continuous monitoring confirmed that the combined use of chemical injection and baiting led to a substantial decline in termite presence, ensuring a pest-free environment for the library. Cyfluthrin was sprayed to control cockroaches and other insects, with the insecticide diluted at a ratio of 8 ml per litre of water before application. These treatments were selected for their proven efficacy and were carefully applied under controlled conditions to minimize any adverse impact on the library's fragile historical materials and structural integrity (Sehgal et al. 2013; Dong et al. 2022).

4.5 Non-Chemical Treatment Using CO_2 Fumigation for Pest Control

The KSO Library prepared documents for CO_2 fumigation by sorting, securing, and placing them in airtight bags to optimize space and minimize overexposure (Figure 5(A and B)). Five specialized fumigation bags were established for different document categories, employing the Modified Atmosphere (MA) technique with high CO_2 concentrations as a non-toxic alternative to chemical pesticides (Mbata et al. 2000; Subramanyam and Hagstrum 2000; Riudavets et al. 2009). The process was monitored from 27 August to 12 September 2024, with CO_2 and oxygen levels recorded throughout. Larger bags (20 metric tons) received 19–22 kg of CO_2 per cycle, while smaller bags (5–10 metric tons) received 5–10 kg daily. Oxygen levels declined progressively, with bag no. 1 dropping from 16.8 % to 3.7 % in three days and remaining below 4 % for 12 days, ensuring effective fumigation.

Books and manuscripts were sealed in airtight bags, where CO_2 levels were raised to 60–90 %, creating an anaerobic environment lethal to pests by inducing dehydration and neurotoxicity (Navarro 1978). Table 1 summarizes recorded CO_2 and oxygen levels, demonstrating that sustained oxygen reduction effectively eliminated pests at all life stages. This method also inhibited microbial growth while preserving organic materials like paper without altering their chemical composition (Nicolas and Sillans 1989; Mukhopadhayay and Chatterjee 2023).

Figure 5: (A): Library documents being placed in airtight bags prior to CO_2 fumigation for pest control. (B): CO_2 fumigation process in progress for pest control.

Table 1: CO_2 and oxygen levels recorded during the fumigation process for different airtight bags.

Bag no.	Weight (metric ton)	Dimensions (LxWxH) (meters)	Oxygen supply date	CO_2 quantity (Kg)	Oxygen readings (%)	Fumigation time frame
1	20	3.98 × 3.8 × 2.0	27–29 Aug	22, 19, 19	16.8, 9.6, 3.7	27/08/2024 to 12/09/2024
2	20	3.98 × 3.8 × 2.0	27–29 Aug	20, 19, 21	16.5, 9.45, 3.4	27/08/2024 to 12/09/2024
3	10	3.3 × 2.98 × 1.5	28–30 Aug	10 each day	16.3, 10.11, 3.89	27/08/2024 to 12/09/2024
4	10	3.3 × 2.98 × 1.5	28–30 Aug	5 each day	16.5, 9.4, 3.68	27/08/2024 to 12/09/2024
5	5	2.98 × 1.65 × 1.5	28–30 Aug	10 each day	16.8, 9.72, 3.55	27/08/2024 to 12/09/2024

The eggs and larvae or nymphs were generally more resistant to hypercarbia, while the larvae and adults were more susceptible. Species-specific tolerance varied: cigarette beetle (*L. serricorne*) eggs and larvae required 7–10 days for complete mortality, whereas adults took 24–48 h to achieve full eradication at 50 % CO_2. Silverfish (*L. saccharina*) and booklice (Liposcelis spp.) nymphs exhibited resistance, but their eggs were more sensitive. Adult silverfish and booklice were highly susceptible, succumbing within 24–48 h. A prolonged treatment period of 7–10 days was necessary to effectively control all life stages across CO_2 concentrations, underscoring the importance of species-specific considerations in CO_2-based pest management (Rust and Kennedy 1993; Hashem et al. 2024). In this context, the KSO Library conducted a 15-day treatment to validate its methods. The CO_2 procedure successfully eradicated pests while preserving the physical and chemical integrity of the treated items. Through careful monitoring and controlled oxygen reduction within each bag, all developmental stages of the pests were effectively targeted, ensuring thorough disinfection without leaving any chemical residue.

After fumigation, the chamber was ventilated to disperse CO_2 and restore normal oxygen (O_2) levels. Figure 6(A and B) illustrates bioassay vials used to assess fumigation effectiveness, with live insects serving as biological indicators. The results confirmed that oxygen levels remained below the critical threshold (<4 %) and that CO_2 concentrations were sufficient for complete pest eradication. The vials facilitated gas exchange, ensuring all pest life stages were affected, thereby validating the process without harming the treated materials.

Figure 6: (A): Bioassay vial tubes containing live cigarette beetles inside bag no. 4 prior to fumigation. (B): bioassay vial after a 15-day fumigation period, showing deceased cigarette beetles from bag no. 4 (Vial 1) and bag no. 5 (Vial 2).

4.6 Final Review and Reorganisation of Library Documents

After completing pest control activities, a meticulous reorganisation ensures the library's collections are safeguarded and accessible. The process begins with thorough cleaning and sanitising library spaces and removing any residues from the treatment. Each item is inspected for residual pest activity or damage, with fragile or affected materials set aside for conservation. Items are then rearranged systematically on pest-proofed shelves, utilising archival-quality enclosures and optimised spacing to promote airflow and prevent moisture accumulation (Figure 7(A and B)). Updated documentation records the location and condition of materials while handling guidelines for staff and users to minimise physical stress on items. Library access is restored with enhanced cataloguing for discoverability, and awareness programs educate stakeholders on preventive measures. This reorganisation ensures long-term preservation, improved accessibility, and sustainable management of the heritage astronomy library's valuable collections.

4.7 IPM Project Implementation Methodology: Integrated Pest Management in Heritage Astronomy Libraries

As a key outcome of the study, Figure 8 exhibits a comprehensive Integrated Pest Management (IPM) methodology developed through a collaborative brainstorming session involving key stakeholders, including the IPM team, vendors, maintenance personnel, and library authorities. This session provided a critical platform for

(A) (B)

Figure 7: (A): Removal of library document bundles from the airtight bag after fumigation. (B): Rearranging library documents back onto the shelves.

gathering and consolidating expert insights, ensuring that the methodology addressed the unique pest-related challenges faced by the KSO Library collections. The brainstorming session resulted in the categorization of the process into eight key steps:

1. Assessment and Planning
2. Preventive Measures
3. Monitoring and Detection
4. Control Measures
5. Staff Training and Awareness
6. Continuous Monitoring and Evaluation
7. Documentation
8. Knowledge Sharing

These steps were carefully identified, refined, and validated through detailed discussions that focused on their feasibility, cost-effectiveness, and potential impact. By breaking down the IPM process into well-defined stages, the methodology was tailored specifically to meet the unique pest management needs of the KSO Library. The selected actions, which include both chemical and non-chemical control methods, were integrated into a detailed IPM framework designed to provide a comprehensive and sustainable approach to pest control. This IPM methodology strikes a careful balance between chemical and non-chemical strategies, ensuring the long-term preservation of archival materials while minimizing environmental

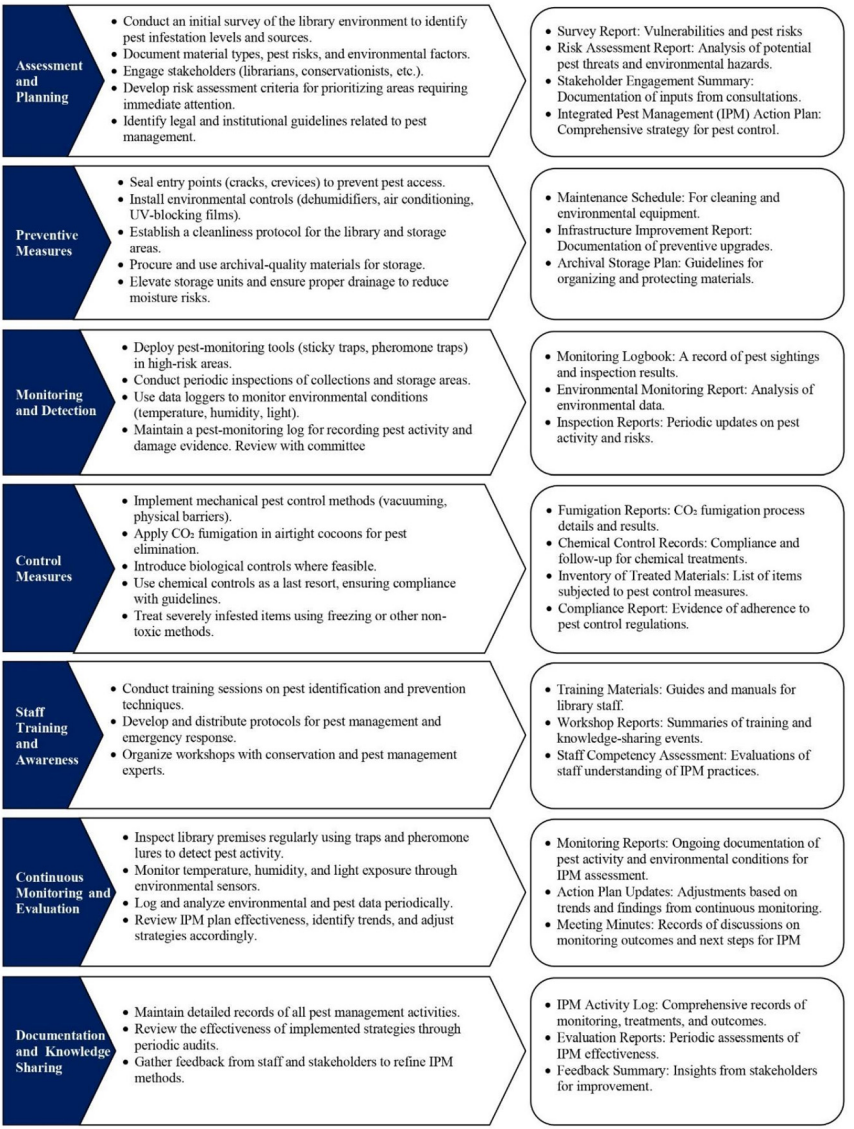

Figure 8: Integrated pest management (IPM) methodology developed through stakeholder brainstorming.

impacts. The development of this methodology reflects the KSO Library's strong commitment to sustainable heritage conservation and highlights the critical role of continuous stakeholder engagement, feedback, and collaborative efforts in

managing pest risks effectively. This methodology can serve as a robust and adaptable model for similar institutions striving to preserve their cultural and scientific heritage. By offering a structured and flexible approach to pest management, it effectively addresses unique institutional challenges while promoting long-term preservation goals. Institutions facing similar pest management challenges can benefit from adopting this IPM framework, ensuring the safeguarding of their valuable collections for future generations.

5 Conclusions

This study addressed the critical challenges of pest infestation and environmental degradation in the Kodaikanal Solar Observatory (KSO) Library, a heritage repository of scientific documents and rare manuscripts. Through a comprehensive Integrated Pest Management (IPM) approach, the research identified and implemented both chemical and non-chemical preservation strategies, including CO_2 fumigation, termite control, and routine dust removal (Querner 2015; Cabral and Querner 2017). Findings underscored the significance of preventive conservation techniques, such as continuous monitoring, staff training, and strategic pest control, in ensuring the longevity of historical collections (Sahoo 2004; Segaetsho 2015). This study contributes to the existing literature on library preservation by demonstrating the effectiveness of a structured IPM methodology tailored for heritage institutions. It highlights the role of eco-friendly and sustainable pest management techniques, advocating for a shift from chemical dependency towards integrated approaches that minimize environmental risks (Faheem 2021; Querner and Biebl 2024).

Practically, the research provides a replicable model for other heritage libraries facing similar conservation challenges, ensuring their collections remain accessible for future generations (San Oo 2019). While the study successfully implemented and evaluated an IPM approach within KSO Library, its applicability to other heritage libraries with different climatic conditions and structural designs remains untested. Additionally, the temporary closure of the library for three months, while necessary, may not be a feasible option for all institutions, highlighting the need for adaptive strategies that minimize service disruptions (Mubofu, Mambo, and Samzugi 2021).

Future research should focus on testing the proposed IPM methodology in diverse library settings to evaluate its adaptability and effectiveness across different environmental conditions. Further studies could explore the impact of digitization as a complementary preservation strategy, reducing the dependency on physical storage while enhancing access to valuable historical documents. Additionally, investigating alternative non-toxic pest management solutions, such as advanced atmospheric control techniques, could provide more sustainable conservation

options (Landsberger et al. 2019; Penz 2024). The preservation of heritage libraries requires a proactive, integrated approach that balances conservation needs with environmental sustainability. By implementing an IPM framework, the KSO Library has set a precedent for heritage institutions, demonstrating that effective pest management can be achieved without compromising the integrity of historical materials. This study reinforces the importance of continuous innovation, collaboration, and commitment to preserving scientific legacies for future scholarly exploration.

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