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Evaluation of radiation-induced decontamination of permethrin on model materials for cultural heritage

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ABSTRACT

The presence of pesticides in cultural heritage items poses significant health risks to museum professionals and others who handle contaminated objects. Therefore, alternative effective decontamination methods are essential. Ionizing radiation, particularly gamma radiation, has emerged as a promising technique for this purpose, as previous studies have demonstrated its effectiveness in degrading organic pesticides in various substrates. This study investigates the application of gamma radiation for decontaminating model materials artificially contaminated with permethrin made of cotton fabric, wood, vegetable fiber, and feather. Samples were irradiated with gamma rays with 30 kGy, under two distinct conditions: dry and moistened samples. Quantification of permethrin was performed using gas chromatography–mass spectrometry (GC-MS). Gamma radiation effect was analyzed using colorimetry, and scanning electron microscopy (SEM). Under dry conditions, permethrin removal was 93 % for the cotton sample, 66 % for the vegetal fiber, 83 % for the wood, and 16 % for the feather. In contrast, under moistened conditions, removal rates were 88 % for cotton, 57 % for vegetal fiber, 71 % for wood, and 94 % for the feather mock-ups. Results showed no significant colorimetric changes, except for the feather in a moistened condition, nor any changes in the morphological properties of the samples. These findings suggest that gamma radiation is a feasible method for decontaminating cultural heritage materials, offering a potential solution for mitigating pesticide contamination in museum collections.

1. Introduction

Chemical treatments are traditional methods used for the preservation of many collections around the world. Since the 18th century, collectors and museum professionals have employed a variety of toxic substances through the direct application of pesticides to improve the conservation of objects. The constant threat of pests has driven diverse measures to protect these items, as infestations can lead to scientific, cultural, aesthetic, financial, and other significant losses.

The use of pesticides, including herbicides, fungicides, and insecticides, have been widely used in collections (Angelova et al., 2023; Odegaard and Sadongei, 2005). Synthetic pyrethroids, such as permethrin (PMT), are persistent insecticides and it has been suggested for use in sprays due to its rapid effects and long-term efficacy (Linnie, 2001). Introduced in 1984 for insect and fungus control, permethrin provided advantages over traditional substances such as camphor, naphthalene, and paradichlorobenzene (Kühn, 1986). Among the pesticides used in cultural heritage, permethrin belongs to the pyrethroid class and has been widely used in museums due to its low cost and easy accessibility. Additionally, it is still marketed and employed by some museum professionals, despite the recommendation of non-toxic techniques in the field of cultural heritage conservation (Delgado Vieira and Vasquez, 2024).

Since the 2000s, various studies have investigated methods to reduce

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pesticide contamination in cultural heritage objects. Techniques tested include controlled aspiration and wet cleaning (Glastrup, 2001; Tello, 2006; Anderson et al., 2014; Odegaard et al., 2014), supercritical fluid extraction (SFE) using carbon dioxide under varying process parameters (Tello, 2006; Tello and Unger, 2010; Unger, 2012; Wörle et al., 2020), laser cleaning (Asmus, 2011; Schmidt et al., 2017), biological removal using specialized microorganisms (Roane and Snelling, 2010), and thermal degradation through exposure to high temperatures (Paz and Wilke, 2022). Each of these methods presents specific advantages and limitations, and their applicability must be carefully evaluated to ensure effective pesticide reduction without compromising the integrity of the object. To date, these approaches remain in the research phase and have not yet been systematically implemented by cultural institutions.

Ionizing radiation has been successfully used for the degradation of organic pesticides in soils, food, aqueous waste, and other substrates (Abdel Aal et al., 2001; Basfar et al., 2012; Brabo, 2015; Chowdhury et al., 2014; Ciarrocchi et al., 2021; Duarte et al., 2007; Javaroni et al., 1991; Khedr et al., 2019; Lépine, 1991; Lippold et al., 1969; Luchini, 1995; Mori et al., 2005). However, there are no documented experiments in the literature demonstrating that ionizing radiation can degrade pesticides applied to tangible cultural objects, nor previous studies showing the degradation of permethrin using ionizing radiation.

The objective of this study is to evaluate the effectiveness of ionizing radiation, specifically gamma radiation, in degrading permethrin applied on model materials, with the goal of identifying the most suitable conditions for pesticide mitigation. The study investigates the potential of gamma radiation as a decontamination method for objects composed of materials commonly found in museum collections, such as cotton, wood, vegetable fibers, and feathers. The experimental results obtained from model materials are presented and discussed with a view toward informing future applications in the treatment of real cultural heritage objects.

2. Materials and methods

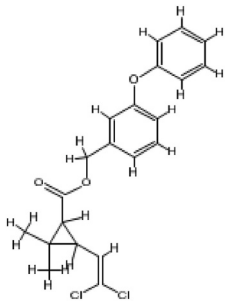
2.1. Chemicals and reagents

The reference material of permethrin of isomers cis (30,3 %) and trans (61,5 %) was provided by Sigma-Aldrich (St. Louis, USA). The chemical structure, molecular formula and chemical name (IUPAC), as well as the family and mode of action for permethrin are outlined as follows:

Permethrin: Insecticide (Synthetic pyrethroid group).

(3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate.

$C_{21}H_{20}Cl_2O_3$



Organic solvents (residue analysis grade) were used for dissolving, extracting, and clean-up including acetone (Labsynth, São Paulo, Brazil) and hexane (Sigma-Aldrich, USA).

2.2. Pesticide standard solutions

Permethrin is soluble in acetone, methanol, ether, and xylene, but has low solubility in water. Acetone was chosen as the solvent to dissolve permethrin and prepare solutions at different concentrations, as it has low toxicity compared to other solvents. A stock solution of permethrin 1000 ppm was prepared in acetone. This stock solution was then diluted with acetone to produce working solutions at concentrations of 0.1, 0.2, 0.5, 1, 2.5, 5, and 10 ppm. The solutions were stored in sealed containers, in a refrigerator and in the dark to protect them from light.

2.3. Mock-ups preparation

Replicating the physical characteristics of real museum objects in experimental studies is a complex task, given the wide variety of typologies, manufacturing techniques, and materials used in cultural artifacts. For this reason, the use of standardized model materials is a common and practical approach in the literature. Previous studies have shown that, regardless of the total thickness of a mock-up, pesticide residues tend to concentrate near the surface. Unger (2012) reported that up to 90 % of a biocide can be retained within the first 5 mm beneath the surface of a wooden object. Similarly, Shugar and Sirois (2012) investigated pesticide distribution in mock-ups of different thicknesses (2.5 mm, 5 mm, and 10 mm) and found that the thinnest samples (2.5 mm) exhibited the highest concentration of arsenic, while the 5 mm and 10 mm samples had similar levels—approximately half of those in the 2.5 mm samples. These findings suggest that thinner samples may actually overrepresent surface contamination, which is particularly relevant for assessing exposure risk and evaluating the effectiveness of decontamination treatments.

With this framework in mind, samples of raw cotton fabric (3.0 x 1.0 × 0.1 cm), buriti fiber intertwined (3.0 x 1.0 × 0.1 cm), balsa wood (3.0 x 1.0 × 0.2 cm), and chicken feather (2.0 x 2.0 × 0.5 cm) were contaminated with a 10 ppm permethrin solution (Fig. 1).

The choice of 10 ppm permethrin concentration for sample contamination was based on data available in the literature regarding the use and detection of pesticides on cultural heritage objects. According to Unger et al. (2001), conservation manuals suggest the application of permethrin solutions with concentrations ranging from 100 to 25,000 ppm for the treatment of insect-infested cultural objects. However, quantitative studies on pesticide residues in museum objects remain limited. Available data indicate a wide range of detected concentrations, from as low as 0.01 ppm (Uden et al., 2014) to as high as 21,000 ppm (Salmo et al., 2017).

Given this wide variation, the choice of 10 ppm aims to represent a feasible concentration, consistent with values found in quantitative studies. This concentration is suitable for simulating realistic contamination conditions in the laboratory, enabling an effective assessment of pesticide decontamination and its potential impacts on materials representative of cultural heritage, while avoiding excessive exposures that could complicate result analysis.

Fig. 1. From the left to the right: cotton, vegetal fiber, wood and feather mock-ups contaminated with permethrin 10 ppm. The image is for illustrative purposes only and does not represent the actual scale of the samples. The sample dimensions are described above.

The contamination process of the model materials involved several sequential steps. Initially, each mock-up was weighed to record its initial mass. It was placed into an Erlenmeyer flask containing 10 mL of a standard pesticide solution at a concentration of 10 ppm. This setup was kept on a magnetic stirrer (Cienlab, Campinas, Brazil) for 8 h to ensure uniform contact and absorption of the pesticide. After this period, the material was transferred to a clean beaker. The Erlenmeyer flask was rinsed with 20 mL of hexane, and the resulting wash solution was also transferred to the same beaker. Subsequently, the beaker with the mock-up was left to dry at room temperature. Finally, the model material was weighed again to record any changes in its mass after the contamination process.

2.4. Radiation processing

Two separate experiments were conducted to evaluate the effects of ionizing radiation on permethrin. The first experiment involved the irradiation of standard permethrin solutions at varying concentrations to assess the interaction between ionizing radiation and the synthetic pyrethroid. The second experiment aimed to examine the effects of radiation processing on model materials artificially contaminated with permethrin.

Samples were irradiated with gamma-rays at the Multipurpose Gamma Irradiation Facility at the Radiation Technology Center (CETER) of the Nuclear and Energy Research Institute (IPEN–CNEN/SP).

In the first experiment, standard pesticide solutions were prepared at concentrations of 1, 5, and 10 ppm. These solutions were irradiated with absorbed doses of 0 (control), 1, 3, 6, 10, 25, 50, and 100 kGy. To facilitate batch processing, the solutions were organized into labeled plastic containers according to their assigned doses. During the irradiation process, the containers were placed in insulated styrofoam boxes containing artificial ice packs to maintain a refrigerated temperature. The irradiation was performed at a dose rate of 5 kGy h^{-1}. The pH of the pesticide standard solutions was not monitored during the irradiation experiments, as the primary focus of this study was on the decontamination of pesticides applied to material samples rather than in liquid form.

The primary purpose of using high absorbed doses in this initial phase was to evaluate the interaction between the pesticide and ionizing radiation, identifying the potential for degradation under varying conditions. It is important to note that these high doses were not intended for direct application to cultural heritage materials, as such levels may induce adverse effects on the integrity of these items.

The second experiment examined the effects of ionizing radiation on model materials made of cotton fabric, wood, vegetable fiber, and feathers contaminated with a standardized concentration of 10 ppm of permethrin. These mock-ups were divided into three distinct groups: control samples (non-irradiated), irradiated samples under dry condition, and irradiated samples under moistened condition. For the moistened condition, distilled water was lightly sprayed onto the samples before irradiation, while the dry samples received no pre-treatment. All samples were individually sealed in zip-lock plastic bags (Fig. 2).

In the second experiment, the irradiation dose range applied to the model materials was selected based on the results of the first experiment, balancing effective pesticide decontamination with the need to minimize any detrimental effects on the materials being treated.

An additional aim of the second experiment was to evaluate whether the presence of water could influence the degradation of the pesticide during radiation treatment. While wetting cultural heritage materials is generally avoided due to the risk of damage, certain conservation treatments incorporate water under controlled conditions to minimize associated risks. With this context in mind, the inclusion of moistened samples was designed to assess whether this approach could yield different or satisfactory outcomes in pesticide degradation.

It is important to note that permethrin is not soluble in water (ILO-WHO International, 2021), and thus the moistening process would not extract this contaminant from the samples. The mock-up samples were irradiated with absorbed doses of 30 kGy conducted at a dose rate of 5 kGy h^{-1}

Fig. 2. Batch of cotton mock-ups contaminated with 10 ppm permethrin, separated into the three experimental conditions (control, dry and moistened).

2.5. Extraction procedure

The extraction process of the model materials samples began with weighing the contaminated mock-ups to record its initial mass. The material was then eluted in 10 mL of hexane and placed on a magnetic stirrer (Cienlab, Campinas, Brazil) for 24 h to ensure thorough extraction. After this period, the material was allowed to air dry in a clean beaker at room temperature. Once dried, it was weighed again to document any changes in mass. Subsequently, the analyte was re-suspended in 0.5 mL of hexane prior to chromatographic analysis.

2.6. Chromatographic conditions

A Shimadzu GC-MS 2020 (Shimadzu Corporation, Kyoto, Japan) gas chromatograph (GC, 2010) with quadrupole mass analyzer and the analytical capillary column DB-5 (5 %phenylsilicone, 95 % methylsilicone; 30 m, 0.25 mm I.D., 0.25 mm film thickness) (Agilent Technologies, Santa Clara, California, USA, J&W Serial Number USN108762H) were used.

The program of GC was set as follows: the initial temperature of the oven was 60 °C and held for 1 min, and then the temperature increased at a rate of 10 °C/min up to 250 °C and held for 15 min. Injection was performed in split ratio mode (5.0) with an injection volume of 3 μL. Helium (99.999 % chemical purity) was used as the carrier gas with a column flow rate of 1.63 ml/min.

2.7. Pesticides analysis

To validate the analytical method, parameters including selectivity/specificity, linearity/working range, limit of detection (LOD), limit of quantification (LOQ), precision, and accuracy were evaluated. Since there is no specific published standard for laboratories involved in pesticide residue control in cultural heritage objects, various documents were consulted to develop a methodology appropriate for the objectives of this study (INMETRO, 2020; Peters et al., 2007; Ribani, 2004).

To determine the analyte quantities, equations from the calibration curves were used using GCMS Postrun Analysis software from Shimadzu® and Origin® 2022b. Model materials samples were analyzed in triplicate, and the mean value was calculated to describe the degradation of the tested pesticides. The recovery rates for model material experiments ranged between 62 % and 103 %. These parameters are in accordance with the criteria established by the European Commission, which considers recovery rates between 70 % and 120 % acceptable for pesticide residue analysis in complex matrices such as food (EC

European Commission, 2021), and are therefore deemed acceptable within the context of this study.

2.8. Pesticide radiation chemical yield (G-value)

The radiation chemical yield (G-value) was calculated for each absorbed dose in the first experiment. G represents the number of radicals, excited states, or other products formed or lost in a system absorbing 100 eV of energy (Getoff, 1996). These results provide valuable insights into the nature of radiolytic reactions. The definition of the G-value is determined using equation (1), as defined by Kurucz et al. (1991):

$$G = \frac{[R]N_A}{D(6.24 \times 10^{16})} \quad (1)$$

where, [R] is the difference in pesticide concentration in moles per dose of 10^{16}, D is the absorbed dose in Gy, 6.24×10^{16} is the conversion factor from Gy to 100 eV L^{-1}, and NA is Avogadro's number (6.02×10^{23}). To calculate the G-value in the International System of Units (SI) (in μmol J^{-1}), the value was multiplied by 0.1036 (Mohamed et al., 2009; Ciarrocchi et al., 2021). The calculation of the G-value considers the difference in concentration relative to the initial concentration of the solutions (0 kGy).

2.9. Colorimetric analysis

To evaluate the results, the parameters ΔE*, ΔL*, Δa*, and Δb* were determined for each sample. ΔE* represents the total color difference and is calculated by comparing the three-dimensional reference values L*, a*, and b* to determine the distance between two colors within the CIELAB color space. ΔL* indicates the variation in lightness, where positive values signify increased brightness and negative values denote reduced brightness.

The CIE 1976 Lab* color space, published by the Commission Internationale d'Eclairage (CIE) in 1976, has become the universally accepted reference system for quantifying color perception (International Commission on Illumination, 2004). A more advanced measure of color difference is the CIEDE2000 equation, derived from the CIELAB color space. Compared to earlier color difference equations within the CIELAB space, the CIEDE2000 equation demonstrates a higher level of sophistication and computational complexity (SHARMA et al., 2005). These parameters are calculated by the following equation (2):

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_c s_c}\right)^2 + \left(\frac{\Delta H'}{k_H s_H}\right)^2 + R_T \frac{\Delta C'}{k_c s_c}\frac{\Delta H'}{k_H s_H}} \quad (2)$$

Hardeberg (2001) proposes a range of values for the acceptability of color differences. In this study, the colorimetric analysis results will be interpreted based on this criterion: $\Delta E^*_{a,b}$ value of less than 3 indicates a hardly perceptible effect, values between 3 and 6 are noticeable but still acceptable, while values greater than 6 are considered unacceptable.

Colorimetric measurements were conducted using a Spectrophotometer PCE-CSM 8 (PCE Deutschland GmbH, Meschede) equipped with the CIEDE2000 color coordinate system and SQC8 Color Management Control System (0°/45° geometry; 58 mm diameter aperture) connected to a computer. Each measurement positioned the analyzed point at the center of a white tile for reference, with spectra of white and black recorded using calibrated standards before each measurement session.

Due to the small size of the samples, only one reading point was taken on each of them. The selected monitoring point was the central area of each sample. Considering the anatomy of the feathers, the reading was performed in the flattest area, which is usually near the rachis (in the central shaft) or at its tip.

2.10. Scanning electron microscopy (SEM)

Scanning Electron Microscopy (SEM) was performed to detect structural changes in the samples, both non-irradiated (0 kGy) and irradiated (30 kGy), under dry and wet conditions. SEM images were acquired using a Hitachi TM3000 microscope operating at an accelerating voltage of 15 kV. The sample fragments were mounted on a holder with conductive double-sided carbon tape, and the ends of the samples were coated with a thin layer of carbon tape to improve conductivity and minimize electron charging effects. The images were captured at magnifications ranging from 50x to 300x.

3. Results and discussion

3.1. Effect of ionizing radiation on removal of pesticide residues

3.1.1. Standard solutions

In this first experiment, the results indicate that, in general, an increase in absorbed dose correlates with a higher percentage reduction in concentration. Permethrin degradation in solution exceeded 80 % at initial concentrations of 1 ppm and 10 ppm when subjected to absorbed doses of 100 kGy and 50 kGy, respectively. The 5 ppm solution showed a reduction of only 77 % within the same dose range. The 5 ppm solution shows no detectable peaks at an absorbed dose of 100 kGy, remaining below the method's detection limit (LD = 0.18). It was observed that the degradation of permethrin is more effective in more concentrated solutions. Comparing the 1 ppm and 10 ppm concentrations, both subjected to the same radiation dose of 100 kGy, the 10 ppm concentration exhibited a higher degradation rate than the 1 ppm concentration. This suggests that at higher concentrations, the radiation's effectiveness in degrading permethrin is greater (Table 1).

Under γ-irradiation, acetone does not simply function as a solvent; rather, it serves as the primary target of the radiation beam, transforming into a source of reactive species. The radiolysis of acetone primarily produces acetyl radicals ($CH_3C\bullet O$), methyl radicals ($\bullet CH_3$), and solvated electrons (Barker, 1962; Spinks and Woods, 1990). These reactive species can interact with permethrin, potentially initiating the breakdown of its molecular structure, including the C–Cl bonds, ester C–O bonds, and the unsaturations in the aromatic ring. This leads to processes such as dechlorination, ester cleavage, and ring fragmentation, converting permethrin into less chlorinated fragments or small acids and carbonyls. As the absorbed dose increases, the pool of radicals formed *per* unit volume also rises, thereby enhancing the likelihood of radical–permethrin collisions and, consequently, improving the removal efficiency, as observed in the data. At very low concentrations of permethrin (1 ppm), some radicals may recombine or react with acetone, thereby limiting the degradation process. However, at higher concentrations (5–10 ppm), the greater number of target molecules allows for more effective competition for the available radicals, resulting in higher removal rates at intermediate doses.

Permethrin is degraded into byproducts that were not fully identified by the NIST reference library of the GC-MS. However, we identified the presence of aliphatic hydrocarbons, phenols, and carbon dioxide (CO_2) as the main degradation products. Exposure of the permethrin solution to 100 kGy of radiation resulted in a significant breakdown of molecular chains, indicating a potential process of oxidation and mineralization. Confirming this would require additional analyses, which fall outside the scope of this study, as its primary focus is on investigating the decontamination of model material samples.

However, these degradation products are consistent with the expected mechanisms of photodegradation and oxidation mentioned in the literature (Creeger), where cleavage of permethrin's ester bond leads to the formation of smaller compounds. The generation of CO_2 suggests partial or complete mineralization of the organic structure of permethrin, while the phenols may be related to aromatic fragments remaining from its original structure. Thus, radiation induces

Table 1
Comparison of permethrin standard solutions irradiated at their respective absorbed doses.

Absorbed dose (kGy)	Standard Solutions					
	1 ppm[a]		5 ppm[a]		10 ppm[a]	
	Concentration (ppm)	Removal (%)	Concentration (ppm)	Removal (%)	Concentration (ppm)	Removal (%)
1	1.099	2.09	2.995	2.14	10.268	2.15
3	1.083	3.58	1.914	37.46	10.230	2.52
6	1.058	5.76	1.875	38.73	5.045	51.93
10	0.966	13.95	1.780	41.83	5.009	52.27
25	0.769	31.51	0.874	71.42	3.126	70.21
50	0.388	65.42	0.692	77.39	1.137	89.17
100	0.206	81.61	<LD	<LD	1.117	89.35

[a] Targeted concentration (ppm).

degradation similar to photodegradation, but more intense, resulting in the formation of byproducts ranging from hydrocarbons to inorganic compounds. To date, no studies on permethrin radiolysis have been identified, making result comparisons unavailable.

G-values are important indicators of radiolytic reactions. The efficiency of pesticide removal can be quantitatively described in relation to the chemical yield of radiation. The results suggest that these values decrease as the absorbed dose increases, due to the degradation of the analytes and the competition between degraded pesticide molecules and reactive radicals. As the absorbed dose increases, the concentration of intermediates increases while the pesticide concentration decreases. This increases the likelihood of reactive radicals reacting with intermediate molecules instead of the original compound, resulting in lower G-values (Ghaffar et al., 2023).

This suggests that pesticide degradation is directly influenced by the applied radiation dose, with higher doses resulting in greater reductions in analyte concentrations but with a tendency for G-values to decrease from doses of 25 kGy onwards (Table 2).

Based on the obtained results, the decision to irradiate the model material samples at 30 kGy was made to balance effective pesticide degradation with the preservation of the materials. At doses exceeding 25 kGy, a decrease in G-values was observed, suggesting a shift in radical reactivity, with a greater likelihood of interaction with intermediate molecules rather than the original pesticide compound. Additionally, higher radiation doses could potentially cause secondary negative effects on the physical and chemical integrity of the materials, such as color and structural changes, or other forms of degradation.

The choice of 30 kGy also considered the heterogeneous nature of the model materials, which may respond differently to radiation compared to liquid standard solutions. While the initial experiments with standard solutions identified 25 kGy as a threshold for effective degradation, the slightly higher dose of 30 kGy was selected to evaluate whether it would yield comparable or improved results in these complex materials. This approach also allowed for the investigation of how material heterogeneity might influence radiolytic reactions, generating data that is more relevant and potentially applicable to the decontamination of real cultural heritage items.

Table 2
G-value according to the absorbed doses for standard permethrin solutions.

Absorbed dose (kGy)	Standard solution		
	1 ppm[a]	5 ppm[a]	10 ppm[a]
	G-values (μmol J-1)	G-values (μmol J-1)	G-values (μmol J-1)
1	5.18E-05	2.61E-04	5.38E-04
3	2.96E-05	1.54E-03	1.96E-04
6	2.38E-05	7.96E-04	2.13E-03
10	3.43E-05	5.16E-04	1.29E-03
25	3.11E-05	3.52E-04	6.93E-04
50	3.23E-05	1.91E-04	4.40E-04
100	2.01E-05	<LD	2.20E-04

[a] Targeted concentration (ppm).

3.1.2. Model materials samples

In this second experiment, the interactions of ionizing radiation on permethrin decontamination applied to model material samples were investigated. The data in Table 3 show the concentrations of irradiated samples under both dry and moistened conditions.

At a dose of 30 kGy, the cotton sample showed a greater reduction in pesticide concentration under dry conditions. Likewise, the vegetal fiber sample and the wood mock-up experienced a more pronounced decrease in the dry state compared to the moistened condition. In contrast, the feather sample exhibited minimal pesticide removal when dry but showed a significant reduction when moistened (Fig. 3).

The comparison between the estimated pesticide removal from the standard permethrin 10 ppm solution at 30 kGy (approximate linear interpolation estimate 74 %) and the decontamination efficiencies observed in model material samples reveals significant insights into the influence of material composition on the effectiveness of radiation in pesticide degradation.

The standard permethrin solution exhibits a higher decontamination efficiency than some of the model materials, such as vegetal fiber (dry and moistened samples), wood (moistened sample) and feather (dry sample). This suggests that the standards solutions allows for a more efficient interaction between the reactive species generated by radiation and the pesticide residues, as there are fewer organic substances in the solution to compete for these reactive species.

On the other hand, the model materials samples contain a variety of organic compounds, which may limit the availability of reactive species to interact with the pesticides. This interference could reduces the overall effectiveness of the radiation in breaking down the pesticide residues.

However, some materials demonstrated removal efficiencies even greater than that of the standard solution. Cotton samples (both dry and moistened), wood (dry), and feather (moistened) all exhibited higher permethrin degradation, suggesting that these substrates may possess characteristics that favor the diffusion or exposure of the pesticide to reactive species, even in the presence of organic matter. This indicates that under certain conditions, specific material properties can enhance

Table 3
Comparison of model material samples after and before irradiation at 30 kGy in different conditions. The values represent the average of three repetitions.

Model Materials Concentration (ppm)			
	Control[a] (0 kGy)	Dry Irradiated Sample	Moistened Irradiated Sample
Cotton	10	0.67	1.16
Feather	10	8.42	0.61
Vegetal Fiber	10	3.39	4.27
Wood	10	1.69	2.88

[a] Targeted concentration (ppm).

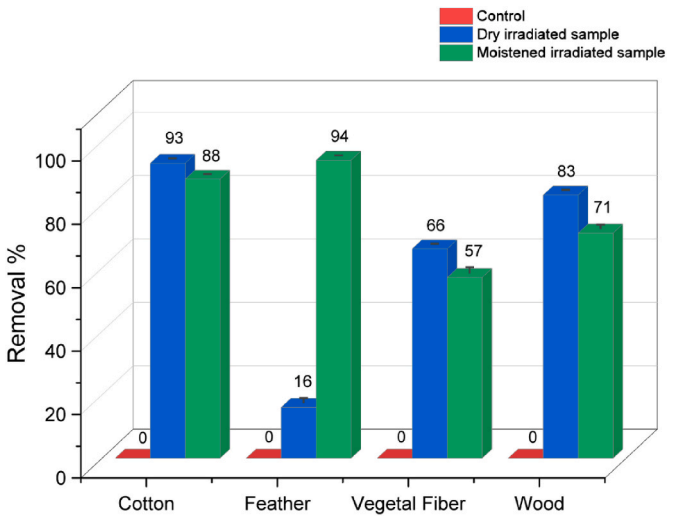


Fig. 3. Removal (%) of permethrin under different processing conditions of the model material samples at 30 kGy. The values represent the average of three repetitions and their DP.

the reactivity and accessibility of permethrin to degradation.

The results clearly show that the material matrix plays a decisive role in determining the efficiency of radiolytic pesticide removal. Materials such as cotton and wood exhibited greater degradation under dry conditions, likely because excess moisture competes with permethrin for reactive species, which may quench the reaction or redirect radical activity. In contrast, feather samples, composed of keratin and characterized by low hydrophilicity, showed limited removal when irradiated in a dry condition, but a marked increase in degradation when moistened (from 16 % to 94 %), possibly due to improved permethrin diffusion and enhanced generation of reactive species in the presence of water.

Vegetal fiber consistently exhibited the lowest removal rates under both dry and moistened conditions. Despite being the least porous among the tested materials, buriti fiber is chemically complex, with high contents of cellulose and extractives (Demosthenes et al., 2020). These compounds may promote strong binding to permethrin or scavenge reactive species, decreasing the efficiency of radiolytic degradation. Materials with such complex organic compositions appear to inhibit the full potential of reactive species, especially when compared to simpler systems like the standard solution (Basfar et al., 2012).

Taken together, the observed differences can be attributed to a combination of factors, including physical structure, chemical composition, and the presence or absence of moisture, which collectively influence the accessibility of permethrin to degradation pathways.

The decontamination behavior of the model materials can be grouped into two main trends: cotton, vegetal fiber, and wood performed better under dry irradiation, while the feather sample showed significantly greater removal when irradiated in the moistened condition. Overall, the decontamination values for the pesticide in dry conditions were more satisfactory, with the exception of the feather sample, which demonstrated better performance when irradiated in the moistened condition. This suggests that moisture may enhance pesticide removal for certain materials, while it appears to slightly inhibit the effectiveness of radiation on others, such as cotton, vegetal fiber, and wood model material samples.

3.2. Color changes in model materials samples

The model materials samples irradiated showed mostly minimal changes in ΔE* values, except for the feather irradiated under moistened conditions, which indicated a significant change in color perception (Fig. 4). All other samples remained within the limit proposed by

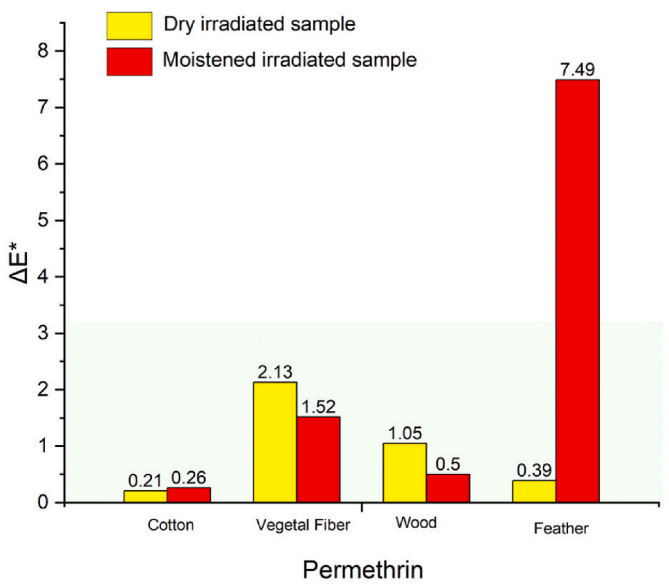


Fig. 4. Total color difference (ΔE*) comparison of model material samples after and before irradiation at 30 kGy in different conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Hardeberg (2001), ΔE* < 3, where the color change is hardly perceptible.

ΔE* values quantify the magnitude of a color difference but do not necessarily indicate the direction of that difference (Hardeberg, 2001). For a more comprehensive understanding of the color changes caused by irradiation, it is essential to examine the individual color parameters (Marušić et al., 2016). Table 4 shows the values of ΔL*, Δa*, and Δb* for each mock-up sample.

The colorimetric parameters evaluated under different irradiation conditions are presented in Fig. 5.

The cotton mock-up irradiated in the dry condition showed minimal perceptible changes in the color coordinates, indicating that the irradiation had a minimal impact on its hue. In contrast, the sample irradiated in the moistened condition exhibited more pronounced color changes, with no significant variation in luminosity, but alterations suggesting a shift toward a cooler colors.

The vegetal fiber sample irradiated in the dry condition showed a decrease in luminosity and changes in hue, with a slight shift toward reddish tones, resulting in a change that was not overly intense. The sample irradiated in the moistened condition also showed reduced luminosity, although less pronounced. The variations in red and yellow hues were more moderate compared to the dry condition.

The wood sample irradiated in the dry condition showed a slight decrease in luminosity, with noticeable changes in hue, particularly toward yellow, while the changes in the other color coordinates were

Table 4
Perception of color changes in the model material samples before and after irradiation at 30 kGy under different conditions.

Material	Irradiation Condition Sample	ΔL*	Δa*	Δb*
Cotton	Dry	0,25	0,05	0,18
	Moistened	0	−0,16	−0,28
Vegetal Fiber	Dry	−2,18	1,46	0,43
	Moistened	−1,57	1,00	0,51
Wood	Dry	−1,05	0,33	1,26
	Moistened	−0,23	−0,05	0,74
Feather	Dry	−0,34	0,21	0,23
	Moistened	−7,96	−0,67	−2,15

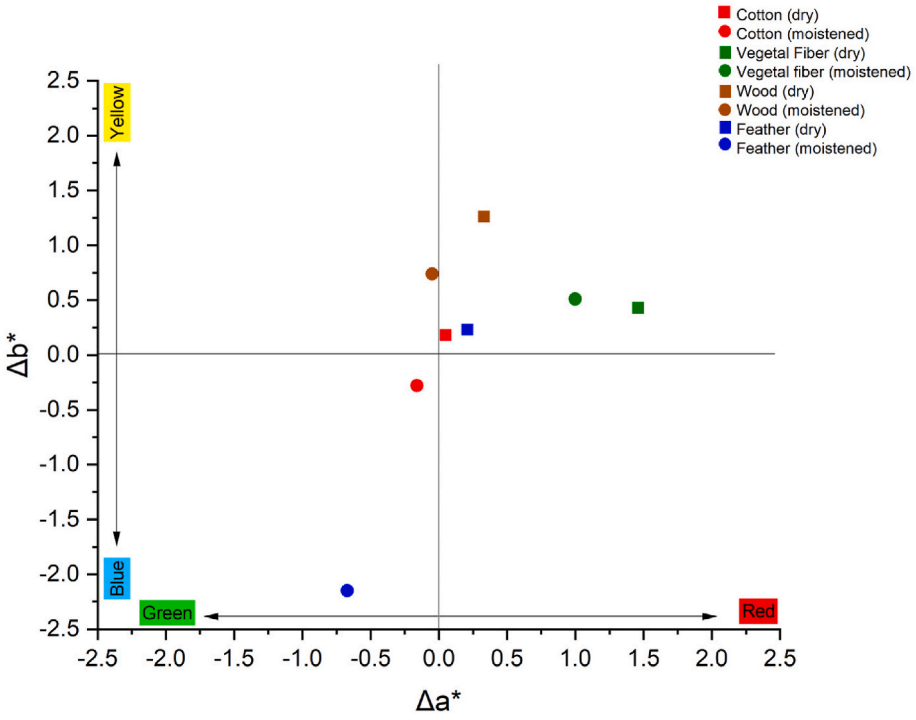


Fig. 5. Comparative values of the Δa* and Δb* parameters of model material samples irradiated under different conditions.

subtler. In the moistened condition, the changes were more discrete. The reduction in luminosity was less pronounced, and the color variations, including the shift toward yellow, were also more subtle.

Finally, the feather mock-up irradiated in the dry condition showed a slight change in color, with a modest decrease in luminosity and small alterations in the red and yellow hues. In contrast, the feather irradiated in the moistened condition showed much more significant changes, with a substantial loss in luminosity and intense variations in hue. The values of Δa* slightly decreased and shifted toward the greenish range, while Δb* also reduced, tending toward blue. These values indicated a much more significant change, with a large loss in luminosity and more intense variations in hue, especially in the a* and b* coordinates, resulting in a noticeable alteration in the color of the feather. The irradiation of this sample in the moistened condition seems to have amplified the effects of color change, leading to visible and pronounced alterations in the feather's color.

Materials such as cotton, vegetal fiber, and wood demonstrated greater stability, with subtle changes in both dry and moistened conditions. In these samples, the changes remained within the limits of imperceptible changes, suggesting that decontamination of these materials through ionizing radiation processing could be safely applied to cultural heritage items made from these materials.

In the case of the feather sample, it is important to consider that the very process of humidifying the material may have caused topographical rearrangements, which could have led to changes in the geometry of the analyzed point. Previous studies indicate that featherwork can be exposed to radiation up to 200 kGy without changing their chromatic properties (Delgado Vieira et al., 2021). Therefore, further experiments on feather materials are needed to evaluate whether it is indeed the irradiation in the moistened condition that is responsible for these changes or whether the humidification process itself, along with the potential removal of natural surface impurities from the material, is the main factor causing these alterations.

3.3. Scanning electron microscopy (SEM) analysis

Fig. 6 presents SEM images of model material samples before and after processing with irradiation under both dry and wet conditions. In the textile sample, the intact ligaments that form the weft and warp of the fabric structure are clearly visible, as well as in the plant fiber sample. The wood sample displays, in the fractured cross-section, the vessels and fibers that comprise its anatomical structure. Similarly, in the feather sample, the rachis, barbules, and pennaceous barbs remain well-preserved. A comparison revealed that these structures were perfectly preserved following irradiation. The topographic features of the irradiated samples showed no signs of damage, even when exposed to different irradiation conditions.

4. Conclusions

The results demonstrate that gamma radiation is an efficient method for significantly reducing the concentration of permethrin, both in standard solutions and in model material samples, and holds potential for decontaminating cultural heritage items. The removal of permethrin from samples irradiated in dry conditions showed satisfactory values, except for the feather mock-up, which performed better when moistened. However, in this moist condition, the sample exhibited a color change beyond the ideal limits. Although this condition showed a high decontamination rate, the color change is undesirable. However, further tests on this material are necessary to determine whether the observed change was caused by the moistening process, which may have altered its topography and removed inherent surface dirt, or if it resulted from the radiation treatment in a moistened condition.

In general, irradiation under dry conditions is recommended, as it achieved effective decontamination while minimizing physical or visual changes. For heritage objects, moistening the material before irradiation to reduce contaminants may result in negative side effects that should be carefully considered. In such instances, the involvement of a conservator is essential to assess potential damage and define the most appropriate protocol.

Based on the findings of this study, gamma irradiation at a dose of 30 kGy under dry conditions is recommended as a reference protocol for the treatment of heritage objects containing moderate to high concentrations of permethrin. This condition provided satisfactory

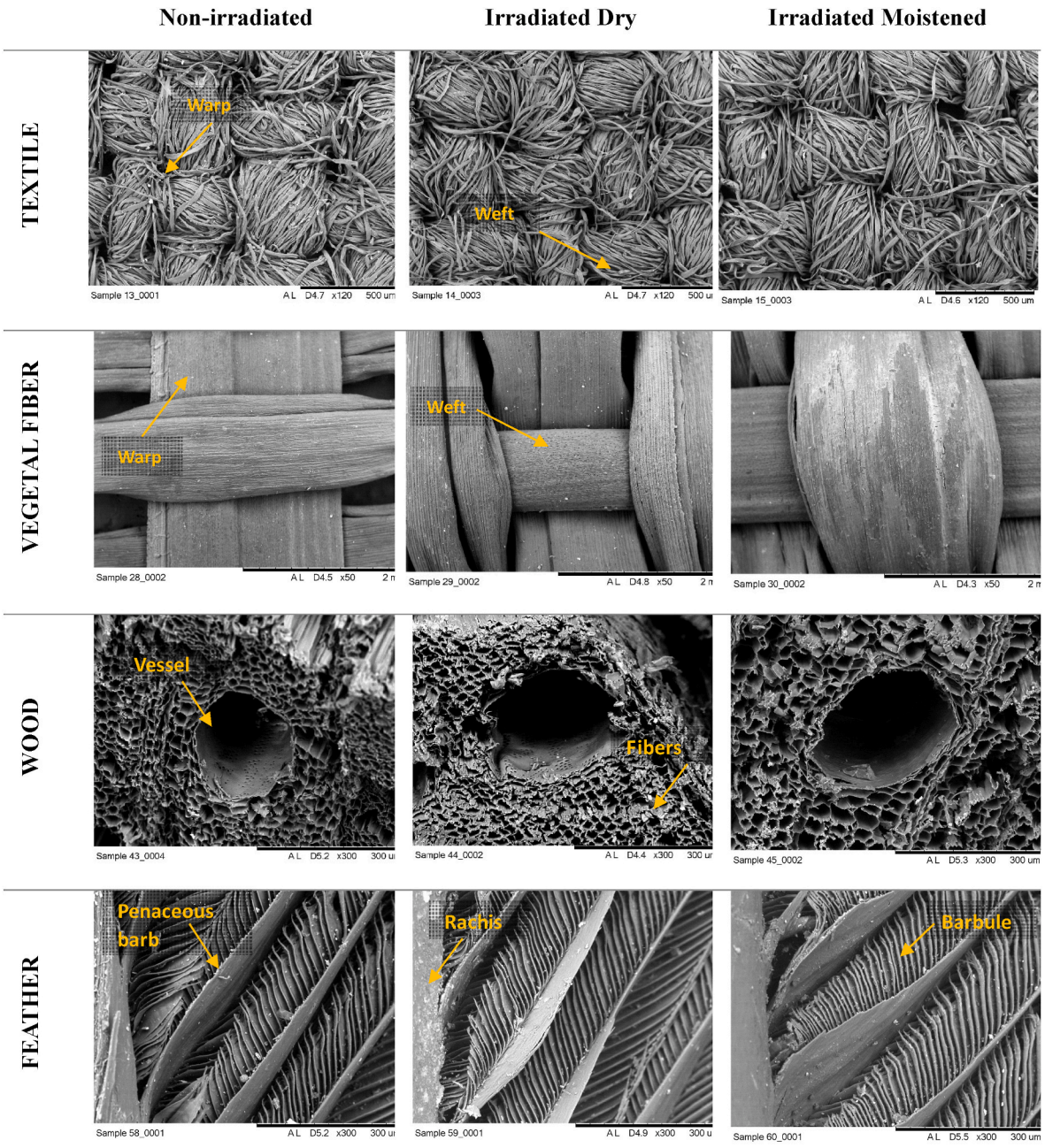


Fig. 6. SEM micrographs of non–irradiated and irradiated of model material samples irradiated under different conditions.

decontamination efficiency across most tested materials while minimizing the risk of visual or structural damage. For heritage items with lower pesticide concentrations, lower irradiation doses may be considered, especially when the primary goal is to mitigate occupational exposure risk rather than achieve complete degradation.

Although the feather sample showed significantly higher removal of permethrin when irradiated in the moistened condition, it also exhibited pronounced chromatic alterations that are considered unacceptable according to conservation guidelines for cultural heritage interventions. Therefore, practical applications should prioritize treatments that balance decontamination efficacy with material integrity. In all cases, preliminary testing and close collaboration with conservation professionals are essential to ensure that the treatment meets both decontamination goals and preservation standards.

Overall, the pesticide removal rates presented here suggest that ionizing radiation could be a viable technique for removal pesticides from cultural heritage collections. However, the application of ionizing radiation on heritage items must be carried out within specific limits to avoid undesirable side effects. Future research should consider whether other pesticides applied in museums are also susceptible to degradation by this technique.

CRediT authorship contribution statement

Ana Carolina Delgado Vieira: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pablo Antônio Vasquez Salvador:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Maria José Alves de Oliveira:** Visualization, Supervision, Resources, Methodology. **Marcio Nardelli Wandermuren:** Writing – review & editing, Validation, Resources, Methodology, Data curation. **Joyce**

Cristale: Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Abdel Aal, S., Dessouki, A., Sokker, H., 2001. Degradation of some pesticides in aqueous solutions by electron beam and gamma-radiation. J. Radioanal. Nucl. Chem. 250, 329–334. https://doi.org/10.1023/A:1017912132599.

Anderson, J.R., Odegaard, N., Dawley, M., Farley, D.J., Zimmt, W., 2014. Coping with arsenic-based pesticides on textile collections. Am. Instit. Conserv. Historic Artistic Artworks (AIC) – Objects Spec. Group Postprints 21, 181–204. https://resources.culturalheritage.org/wp-content/uploads/sites/8/2015/03/osg021-08.pdf.

Angelova, L.V., Nawaz, S., Kafadaroğlu, B., Paz, B., Moreta, F., Woollaston, H., Vermeulen, M., Vervoorst, J., 2023. The use of 'poisonous insecticidal solutions' in bookbinding: coping with historic pesticide treatments in the archive. Herit. Sci. 11, 51. https://doi.org/10.1186/s40494-023-00866-y.

Asmus, J.F., 2011. Decontaminating pesticide-exposed museum collections. In: RADVAN, R., et al. (Eds.), Lasers in the Conservation of Artworks VIII. Proceedings of the International Conference on Lasers in the Conservation of Artworks VIII (LACONA VIII), 21–25 September 2009. CRC Press, Sibiu, Romania. Boca Raton, pp. 33–37.

Barker, R., 1962. Gamma-radiolysis of liquid acetone. Trans. Faraday Soc. 59, 375–385. https://doi.org/10.1039/TF9635900375.

Basfar, A.A., Mohamed, K.A., Al-Saqer, O.A., 2012. De-contamination of pesticide residues in food by ionizing radiation. Radiat. Phys. Chem. 81 (4), 473–478. https://doi.org/10.1016/j.radphyschem.2011.12.040.

Brabo, P.C., 2015. Degradação De Pesticidas Em Solos Cultivados Com Café: O Uso Da Radiação Gama, CG/EM/EM E a Metodologia Quechers Modificada. Instituto Militar de Engenharia, Rio de Janeiro, p. 77. Master degree thesis (Departamento de Ciência e Tecnologia - Instituto Militar de Engenharia - Curso de Mestrado em Química).

Chowdhury, M.A.Z., Jahan, I., Karim, N., Alam, M.K., Rahman, M.A., Moniruzzaman, M., Gan, S.H., Fakhruddin, N.M., 2014. Determination of carbamate and organophosphorus pesticides in vegetable samples and the efficiency of gamma-radiation in their removal. BioMed Res. Int. 45159. https://doi.org/10.1155/2014/145159/, 2014.

Ciarrocchi, I.R., Mendes, K.F., Pimpinato, R.F., Spoto, M.H.F., Tornisielo, V.L., 2021. The effect of radiation in the degradation of carbendazim and azoxystrobin in strawberry. Radiat. Phys. Chem. 179, 109269. https://doi.org/10.1016/j.radphyschem.2020.109269.

Delgado Vieira, A.C., Vasquez, P.A., 2024. The past and present of Pest mitigation: results of an international survey of practices. Revista do Museu de Arqueologia e Etnologia 43, 114–128. https://doi.org/10.11606/issn.2448-1750.revmae.2024.227497.

Creeger, S.. Review: Exposure Assessment Branch. File: 279-3014. Index of cleared science reviews for permethrin (pc code 109701). EPA's Web Archive. https://archive.epa.gov/pesticides/chemicalsearch/chemical/foia/web/pdf/109701/109701-086.pdf.

Delgado Vieira, A.C., Kodama, Y., Otubo, L., Santos, P. de S., Vasquez, P.A., 2021. Effect of ionizing radiation on the color of featherwork. Brazilian Journal of Radiation Sciences 9 (1-A), 1–18. https://doi.org/10.15392/bjrs.v9i1A.1367.

Demosthenes, L.C. da C., Nascimento, L.F.C., Monteiro, S.N., Costa, U.O., Garcia Filho, F. da C., Luz, F. S. da, Oliveira, M.S., Ramos, F.J.H.T.V., Pereira, A.C., Braga, F.O., 2020. Thermal and structural characterization of buriti fibers and their relevance in fabric reinforced composites. J. Mater. Res. Technol. 9 (1), 115–123. https://doi.org/10.1016/j.jmrt.2019.10.036.

Duarte, C.L., Mori, M.N., Kodama, Y., Oikawa, H., Sampa, M.H.O., 2007. Decontamination of pesticide packing using ionizing radiation. Radiat. Phys. Chem. 76 (11–12), 1885–1889. https://doi.org/10.1016/j.radphyschem.2007.02.108.

EC European Commission, 2021. Guidance document on analytical quality control and method validation procedures for pesticide residues and analysis in food and feed (SANTE/11312/2021). https://www.eurl-pesticides.eu/userfiles/file/EurlALL/SANTE_11312_2021.pdf.

Getoff, N., 1996. Radiation induced degradation of water pollutants-state of the art. Radiat. Phys. Chem. 47, 581–593. https://doi.org/10.1016/0969-806X(95)00059-7.

Ghaffar, A., Masaaki, T., Aziz, R., Sarfraz, S., 2023. Catalytic degradation of lindane using gamma radiations: degradation products. Radiat. Phys. Chem. 205, 110741. https://doi.org/10.1016/j.radphyschem.2022.110741, 2023.

Glastrup, J., 2001. The effectiveness of compressed air in the removal of pesticides from ethnographic objects. Collect. Forum 16 (1–2), 19–22.

Hardeberg, J.Y., 2001. Acquisition and Reproduction of Color Images, Colorimetric and Multispectral Approaches. Dissertation.com, USA. https://bookpump.com/bwp/pdf-b/11213350b.pdf.

ILO-WHO International, 2021. Chemical safety cards (ICSCs): permethrin. https://chemicalsafety.ilo.org/dyn/icsc/showcard.display?p_version=2&p_card_id=0312.

Instituto Nacional de Metrologia Qualidade e Tecnologia (INMETRO), 2020. Orientação Sobre Validação De Métodos Analíticos - DOQ-CGCRE-008. Coordenação Geral de Acreditação, Brasília. https://www.gov.br/cdtn/pt-br/assuntos/documentos-cgcre-abnt-nbr-iso-iec-17025/doq-cgcre-008/view.

International Commission on Illumination, 2004. International commission on illumination technical committee 3-22, museum lighting. Control of damage to museum objects by optical radiation. Comm. Int. de l'Éclairage 157. Vienna, Austria, 2004. https://cie.co.at/publications/control-damage-museum-objects-optical-radiation.

Javaroni, R. de C., Talamoni, J., Landgraf, M.D., Rezende, M.O. de O., 1991. Estudo da degradação de lindano em solução aquosa através da radiação gama. Quim. Nova 14 (4), 237–239. https://quimicanova.sbq.org.br/pdf/Vol14No4_237_v14_n4_%281%29.

Khedr, T., Hammad, A.A., Elmarsafy, A.M., Halawa, E., Soliman, M., 2019. Degradation of some organophosphorus pesticides in aqueous solution by gamma irradiation. J. Hazard Mater. 373, 23–28. https://doi.org/10.1016/j.jhazmat.2019.03.011.

Kühn, H., 1986. Conservation and Restoration of Works of Art and Antiquities. Butterworth & Co, London.

Kurucz, C.N., Waite, T.D., Cooper, W.J., Nickelsen, M.G., 1991. High energy electron beam irradiation of water, wastewater and sludge. In: Lewins, J., Becker, M. (Eds.), Advances in Nuclear Science and Technology. Plenum Press, New York, pp. 1–43. https://link.springer.com/chapter/10.1007/978-1-4615-3392-4_1.

Lépine, F.L., 1991. Effects of ionizing radiation on pesticides in a food irradiation perspective: a bibliographic review. J. Agric. Food Chem. 39, 2112–2118. https://doi.org/10.1021/jf00012a002.

Linnie, M.J., 2001. Conservação: Conceitos E Práticas. Cap. Controle De Pragas Em Museus: a Utilização De Produtos Químicos E Problemas De Saúde Correlatos. UFRJ, Rio de Janeiro.

Lippold, P.C., Cleere, J.S., Massey Jr., L.M., Bourke, J.B., Avens, A.W., 1969. Degradation of insecticides by cobalt-60 gamma radiation. J. Econ. Entomol. 62 (6), 1509–1510. https://doi.org/10.1093/jee/62.6.1509.

Luchini, L.C., 1995. Degradação Do Inseticida Paration Etílico Em Diversas Matrizes Ambientais Por Meio Da Radiação Ionizante Gama Do Cobalto-60. In: Doctoral Thesis (Doutorado Instituto De Química De São Carlos). São Carlos. Universidade de São Paulo, 1995. https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/011/31011549.pdf.

Marušić, K., Pucić, I., Desnica, V., 2016. Ornaments in radiation treatment of cultural heritage: color and UV–vis spectral changes in irradiated nacres. Radiat. Phys. Chem. 124, 62–67. https://doi.org/10.1016/j.radphyschem.2015.11.028.

Mohamed, K.A., Basfar, A.A., Al-Kahtani, H.A., Al-Hamad, K.S., 2009. Radiolytic degradation of malathion and lindane in aqueous solutions. Radiat. Phys. Chem. 78, 994–1000. https://doi.org/10.1016/j.radphyschem.2009.06.003.

Mori, M.N., Oikawa, H., Sampa, M.H. de O., Duarte, C.L., 2005. Descontaminacão de embalagens de clorpirifós utilizando radiacão ionizante. In: Proceedings International Nuclear Atlantic Conference - INAC 2005. Santos, SP, Brazil, August 28 to September 2. ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN. Santos, 2005. https://www.ipen.br/biblioteca/cd/inac/2005/full/2018.pdf.

Odegaard, N., Sadongei, A., 2005. Old Poisons, New Problems: a Museum Resource for Managing Contaminated Cultural Materials. Altamira Press, Walnut Creek.

Odegaard, N., Watkinson, G., Pool, M., 2014. Woven wonders: revitalizing collections and community relationships. ICOM Comm. Conserv. 17th Trienn. Meet., Melb. Aust. 19–23 September, 1–8. https://www.icom-cc-publications-online.org/1522/Woven-Wonders–Revitalizing-Collections-and-Community-Relationships.

Paz, B., Wilke, N., 2022. An investigation into the decontamination of biocide polluted museum collections using the temperature and humidity controlled ICM method. In: Furferi, R., Giorgi, R., Seymour, K., Pelagotti, A. (Eds.), The Future of Heritage Science and Technologies: Materials Science. Florence Heri-Tech 2022. Advanced Structured Materials, 179. Springer, Cham. https://doi.org/10.1007/978-3-031-15676-2_12.

Peters, F.T., Olaf, H.D., Musshoff, F., 2007. Validation of new methods. Forensic Sci. Int. 165, 216–224. https://doi.org/10.1016/j.forsciint.2006.05.021.

Ribani, M., 2004. Validação em métodos cromatográficos e eletroforéticos. Quim. Nova 27 (5), 771–780. https://doi.org/10.1590/S0100-40422004000500017.

Roane, T.M., Snelling, L.J., 2010. Bacterial removal of Mercury from museum materials: a new remediation technology? In: Charola, A.E., Koestler, R.J. (Eds.), Pesticide

Mitigation in Museum Collections: Science in Conservation. Proceedings from the MCI Workshop Series. Smithsonian Institution Scholarly Press, Washington DC, pp. 29–34. https://doi.org/10.5479/si.19492359.1.1.

Salmo, R., Palmer, P.T., Tribe, K., 2017. Fast, nondestructive, and cost-effective methods to detect pesticide residues: a case study of several repatriated karuk tribe artifacts. Collect. Forum 31 (1–2), 23–33. https://doi.org/10.14351/0831-4985-31.1.23.

Sharma, G., Wu, W., Dalal, E.N., 2005. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. Color Res. Appl. 30 (1). https://doi.org/10.1002/col.20070.

Schmidt, B.A., Pentzien, S., Conradi, A., Krüger, J., 2017. Femtosecond and nanosecond laser decontaminations of biocidal loaded wooden artworks. Appl. Phys. Mater. Sci. Process 123, 696. https://doi.org/10.1007/s00339-017-1316-4.

Shugar, A.N., Sirois, P.J., 2012. Handheld XRF use in the identification of heavy metal pesticides in ethnographic collections. In: Shugar, A.N., Mass, J.L. (Eds.), Handheld XRF for Art and Archaeology, vol. 3. Leuven University Press, pp. 313–348. https://doi.org/10.2307/j.ctt9qdzfs.13.

Spinks, J.W.T., Woods, R.J., 1990. An Introduction to Radiation Chemistry, third ed. John-Wiley and Sons, Inc., New York.

Tello, H., 2006. Investigations on super fluid extraction (SFE) with carbon dioxide on ethnological materials and objects contaminated with pesticides. Berlim: Hochschule Für Technik Und Wirtschaft Berlin. Thesis (Studiengang Restaurierung/Grabungstechnik der Fachhochschule für Technik und Wirtschaft Berlin). https://www.hornemann-institut.de/de/epubl_hochschularbeiten1526.php.

Tello, H.E., Unger, A., 2010. Liquid and supercritical carbon dioxide as a cleaning and decontamination agent for ethnographic materials and objects. In: Charola, A.E., Koestler, R.J. (Eds.), Pesticide Mitigation in Museum Collections: Science in Conservation. Proceedings from the MCI Workshop Series. Smithsonian Institution Scholarly Press, Washington DC, pp. 35–50. https://doi.org/10.5479/si.19492359.1.1.

Uden, J., Charlton, A., Domoney, K., 2014. The analysis of pesticide residues on the cook-voyage collections in the pitt Rivers museum. ICOM Committee for Conservation 17th Triennial Meeting Melbourne Australia 19-23 September 2014. University of Oxford. https://www.icom-cc-publications-online.org/1380/The-Analysis-of-Pesticide-Residues-on-the-Cook-Voyage-Collections-in-the-Pitt-Rivers-Museum-University-of-Oxford.

Unger, A., 2012. Decontamination and “deconsolidation” of historical wood preservatives and wood consolidants in cultural heritage. J. Cult. Herit. 13S, 196–S202. https://doi.org/10.1016/j.culher.2012.01.015.

Unger, A., Schniewind, A.P., Unger, W., 2001. Conservation of Wood Artifacts: a Handbook. Springer, Berlin.

Wörle, M., Lombardo, T., Hubert, V., Hildbrand, E., Mürau, E., Mayer, I., Hinterleitner, C., Von Arx, U., Moser, H., Lehmann, R., 2020. Decontamination of biocide treated museum objects of the Swiss national museum’s collection by liquid CO2 technology. Stud. Conserv. 65 (2), 77–85. https://doi.org/10.1080/00393630.2019.1662644.