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Can Sustainability Be Measured? LCA Analysis for Environmental Impact Evaluation of New Cultural Heritage Conservation Methodologies

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Abstract

This study investigates the application of Life Cycle Assessment (LCA) as a tool to evaluate the environmental performance of innovative methodologies in cultural heritage conservation. Three categories of restoration treatments were analyzed: disinfection of stone surfaces, consolidation of degraded organic materials, and dry cleaning of metal surfaces. For each category, experimental or alternative conservation solutions were compared with conventional commercial or artificial products, focusing exclusively on environmental impacts rather than technical performance. The results highlight significant variability across treatments. In stone disinfection, the biological approach based on Serratia ficaria SH7 shows a substantially lower environmental impact compared to the synthetic biocide Preventol RI50. In contrast, the consolidation scenario reveals a more complex pattern: crystalline nanocellulose demonstrates low impacts when water-based, but its environmental performance worsens considerably when organic solvents are used, in some cases exceeding that of the synthetic resin Plexisol P550. For dry cleaning, all tested eraser formulations exhibit relatively low impacts, although silicone-based systems outperform latex-based alternatives due to reduced material consumption. Beyond comparative results, the study critically examines methodological limitations of LCA in conservation contexts, including data asymmetry between laboratory-scale and industrial processes, sensitivity to modelling assumptions, and restricted system boundaries. The findings demonstrate that environmental performance depends not only on material origin but also on formulation, energy use, and operational conditions. Overall, LCA proves to be a valuable but context-dependent decision-support tool, requiring transparent assumptions and careful interpretation to effectively guide sustainable practices in cultural heritage conservation.

Keywords: sustainable conservation; life cycle assessment; disinfection treatment; consolidation; dry cleaning

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1. Introduction

Research in the field of cultural heritage conservation has played a fundamental role in the development of innovative materials, products, and methodologies aimed at ensuring

the long-term preservation of artistic and historical artefacts [1–4]. Over the past decades, scientific investigation and technological advancement have led to the formulation of new conservation solutions which, following phases of stabilization, experimental testing, and validation, have progressively entered the professional restoration market [5,6]. Today, many of these are widely adopted by conservators and restorers, becoming essential tools in routine and specialized conservation practice [7,8].

Traditionally, the evaluation of conservation materials has focused primarily on their effectiveness, compatibility with heritage substrates, durability, and reversibility [9–11]. While these criteria remain central to conservation ethics and practice, growing awareness of environmental challenges has expanded the scope of material assessment. In recent years, the conservation science community has increasingly recognized the need to integrate environmental considerations into the development and selection of conservation products [12]. This shift reflects broader global concerns related to climate change, resource depletion, and the environmental impacts associated with industrial production processes [13–15].

Within this context, research institutions and conservation laboratories are increasingly directing their efforts toward the development of materials designed to reduce environmental burdens without compromising conservation performance [16–20]. Large-scale national and international research projects have further accelerated this trend, promoting interdisciplinary approaches that combine materials science, chemistry, conservation theory, and environmental assessment. As a result, waste-derived materials, bio-based compounds, natural products, and self-produced or locally sourced materials have emerged as key areas of investigation in contemporary conservation research [21,22]. These alternatives are often proposed as more sustainable options compared to traditional commercial and artificial products, particularly due to their potential to reduce reliance on non-renewable resources and energy-intensive manufacturing processes. Several studies have reported promising results regarding the technical performance of these innovative materials, highlighting improvements in terms of compatibility with original substrates, treatment efficacy, and reduced toxicity for both operators and the environment. However, claims of sustainability are frequently based on qualitative considerations or partial evaluations of material composition and origin. A comprehensive understanding of their actual environmental impact requires a systematic assessment that considers all stages of a product's life cycle, from raw material extraction and production to use and end-of-life scenarios.

Life Cycle Assessment (LCA) represents a well-established and standardized methodology for quantifying the environmental impacts associated with products and processes throughout their entire life cycle. Widely applied in industrial, engineering, and environmental sciences, LCA enables the identification of critical impact categories and hotspots, offering a robust framework for comparing alternative solutions on a quantitative basis. In recent years, the application of LCA has progressively expanded into the cultural heritage sector, where it is increasingly recognized as a valuable decision-support tool during the material selection [23,24]. These studies focused on evaluating specific types of conservation treatments [25,26], their implementation processes [27,28], or comparative assessments of materials used in restoration practice [29–31]. Other studies, instead, examined the environmental impact associated with the entire restoration intervention of monuments [32]. But none of these have assessed the environmental impact of research products currently being tested as alternatives to commercial products and explore epistemic uncertainty in conservation science of the LCA method.

2. Research Aim

In the present study, LCA analysis is used as an integrated tool in the development and evaluation of experimental and alternative solutions for selected conservation treatments.

An evaluation of the environmental impact of new-generation conservation products developed by research institutions to address different types of conservation challenges was conducted. Through a comparative Life Cycle Assessment, these innovative materials are analyzed alongside traditional commercially and artificial available products currently used in conservation practice, without taking their efficacy into account. Indeed, by assessing their environmental performance and identifying critical impact categories, this research aims to provide a more comprehensive understanding of the sustainability implications of emerging conservation solutions. At the same time, the LCA tool is critically evaluated to verify its reliability and suitability for assessing conservation products during the assessment process. Ultimately, the study intends to contribute to the integration of environmental impact assessment into conservation science, supporting more informed, transparent, and sustainable decision-making processes in cultural heritage conservation.

3. Context of Application of the Study

The study presented in this paper is carried out within the framework of the European project CHANGES and represents one of its final outcomes in terms of methodological and applied research. The CHANGES project has fostered the development of innovative solutions for cultural heritage conservation by supporting both the formulation of new materials and the definition of intervention strategies tailored to recurrent conservation challenges. Through an interdisciplinary approach combining conservation science, materials engineering, and heritage practice, the project worked on designing and validating alternative products and treatment protocols intended to respond to different deterioration mechanisms while improving compatibility with heritage substrates and operational feasibility for practitioners [33]. In this context, the present work translates the technological advancements generated within CHANGES into an environmental evaluation perspective, applying LCA to compare selected CHANGES-derived materials and approaches with traditional commercial solutions. By doing so, the study contributes to framing the environmental dimension as an additional decision-making criterion alongside technical performance and conservation requirements, and provides evidence on the opportunities and limitations of LCA when used to support the selection and development of innovative conservation products.

4. Materials and Methods

4.1. Materials

LCA evaluation has been conducted for three categories of restoration practices (Table 1):

- Disinfection treatment of stone surfaces;
- Consolidation treatment of degraded organic material;
- Dry cleaning of metal surfaces.

Table 1. Treatments and products under analysis.

Treatments	Experimental Product	Commercial or Artificial Product
Disinfection treatment of colonized stone surfaces	Serratia ficaria SH7	Preventol RI50
Consolidation treatment of degraded organic material	Crystalline nanocellulose	Plexisol P550
Dry cleaning	latex with 30% sodium bicarbonate latex with 30% calcium carbonate	silicone with 30% sodium bicarbonate

For each of the treatments listed, specific methods will be analyzed: these methods may involve the use of both products and equipment.

The types of products selected for the study reflect three different approaches of new alternatives to chemical materials; the analysis included microbiological products, products made from cotton waste, and self-produced materials.

4.1.1. Disinfection of Stone Surfaces

Stone monuments exposed outdoors are highly vulnerable to deterioration, with biological colonization representing a major degradation factor. Biodeterioration results from the interaction between stone materials and microorganisms, whose chemical and physical actions vary according to organism type, growth mode, stone properties, conservation state, and environmental conditions [34]. Conservation treatments aim to remove or inhibit biodeteriogenic organisms and may involve mechanical techniques, physical methods, or, more commonly, chemical approaches [35]. Among these, biocides are widely used to devitalize microorganisms, facilitate their removal, and slow recolonization processes; however, their repeated or indiscriminate application raises environmental and toxicological concerns. As a result, current conservation strategies are increasingly focused on sustainable and eco-compatible alternatives [36].

In this context, Serratia ficaria SH7 is a Gram-negative, non-spore-forming, and facultatively aerobic/anaerobic bacterium belonging to the family Enterobacteriaceae. This species is generally widespread in soil, surface waters, and plant-associated environments, and is rarely isolated from human clinical samples. The SH7 strain was isolated from mining waste in an abandoned sphalerite and galena mine in Sardinia, and is therefore adapted to a heavy metal-rich and nutrient-poor habitat. The metabolism of this strain has been directed toward the production of enzymes useful for biocleaning applications, such as lipases and proteases, through the use of a specific culture medium [37]. After 48 h of growth in liquid medium, at which point it reaches a cell concentration of approximately 10^9 cells per milliliter, the strain is immobilized in a thickening agent (Xanthan gum, 8%), which is compatible with cell viability and suitable for maintaining optimal moisture and pH conditions throughout the treatment duration.

4.1.2. Consolidation of Organic Materials

Canvas consolidation aims to restore sufficient cohesion in degraded fibrous supports and recover the mechanical resistance needed to safely sustain the paint layers. The mechanical behaviour of cellulose textiles depends largely on the integrity of the polymeric chains forming the fibres; when depolymerization occurs, yarns progressively lose strength and extensibility, becoming brittle and unable to support the pictorial stratigraphy. As a consequence, paint layers are subjected to increasing mechanical stresses that can accelerate cracking, detachment and long-term deterioration.

Consolidation is commonly performed using polymeric materials applied in a fluid state (by brush or spraying), either as solutions or dispersions. Among the most widely adopted products is Plexisol P550, an acrylic resin (butyl methacrylate) appreciated for its mechanical performance, wettability and diffusion capacity. However, increasing attention to compatibility and sustainability has led to the consideration of crystalline nanocellulose (CNC) as an innovative alternative for cellulosic supports [38,39]. The CNC analyzed for the study was prepared by the University of Parma and used as an aqueous or hydroalcoholic suspension. The use of CNC in a hydroalcoholic mixture is justified by the aim of reducing the amount of water required for its application, especially for hygroscopic artworks such as canvases. CNC is generally considered non-toxic and could be handled even without personal protection equipment, although gloves and a mask are advisable

when hydroalcoholic media are used, which is preferable when working on hygroscopic canvases. A concentration of 1% or less was deemed to be a good compromise between material addition and structural reinforcement [40,41]. CNC application, both by brush or nebulization, requires strict precautions to avoid the potential negative effects of water on paintings. Minimal quantities of material have to be applied; also, provisional stretching of the canvas is strongly recommended, as well as low-temperature ironing (≤40 °C) after the application to prevent unforeseen movements or deformations of the canvas [42].

4.1.3. Self-Made Erasers for Dry Cleaning

Dry cleaning refers to a method of cleaning artwork surfaces without the use of solvents or aqueous solutions. Examples include the use of a scalpel, micro-abrasive materials, and also laser cleaning or cold plasma cleaning. Among the methods already in use by restorers are erasers, composed of a polymer medium and micro-abrasive powders of varying nature, hardness, and grain size, capable of removing the materials to which they are applied with different degrees of incisiveness [43–48].

This work addresses the topic of dry cleaning with micro-abrasive erasers of brass surfaces, a copper alloy widely used in the artistic and technical fields, which is subject to alteration processes, with the formation of different patinas [49].

During the trial [50], 44 erasers were compared, 25 commercially available, identified in both the artistic and medical-dental fields, and 19 self-produced, based both on synthetic polymers and natural latex, and with three different types of abrasive powder (allumina, calcium carbonate, and sodium bicarbonate) in different concentrations. The erasers were tested on altered brass specimens to evaluate their interaction with the metal, their cleaning power, their esthetic and conservation effectiveness, and the potential damage they could cause to the surface. At the end of the trial, three erasers were selected (calcium carbonate at 30% in latex, sodium bicarbonate at 30% in latex, and sodium bicarbonate at 30% in neutral silicon polymer), achieving the goal of providing restorers with a simple, effective, low-cost tool that can be adapted in terms of shape and hardness, and that anyone can produce themselves [51].

4.2. System Boundaries

In accordance with ISO 14040 and ISO 14044, the system boundaries were defined consistently with the stated goal and scope of the study, ensuring that the breadth, level of detail, and modelling assumptions are appropriate to support the comparative evaluation of alternative restoration techniques (Table 2).

The foreground system comprises the upstream production processes of all chemical products and auxiliary materials involved in the treatments, as well as solvents, distilled or demineralized water, agar, cellulose, and other formulation components. It also includes the production of technical equipment required for application and the treatments, such as brushes, spatulas, scalpels, and tin containers. For reusable equipment, manufacturing impacts were allocated over the expected total number of uses, thereby distributing the environmental burden proportionally to the treated surface area, in accordance with ISO recommendations on allocation procedures. Similarly, the environmental impact of the personal protective equipment required for the implementation of each treatment was also assessed, as specified in the product safety data sheets.

Table 2. Lifetime, Ecoinvent unit process, and mass for each material broken down by category. Lifetime indicates how long a material is in use.

Input (Product)	QTY	Unit	Dataset LCA
Growth medium for Bacteria SH7 (FU = 20 gr)			
Yeast extract	0.03	g	Fodder yeast {GLO}|market for fodder yeast|Cut-off *(Ecoinvent)*
Sodium peptone	0.06	g	Protein feed, 100% crude {GLO}|soybean meal to generic market for protein feed|Cut-off *(Ecoinvent)*
Calcium chloride	0.0272	g	Calcium chloride {RER}|soda production, solvay process|Cut-off *(Ecoinvent)*
Olive oil	0.2	g	Olive {IT}|olive production|Cut-off *(Ecoinvent)*
Tween 80	0.4	g	Chemical, organic {GLO}|chemical production, organic|Cut-off *(Ecoinvent)*
Bacteria SH7 (FU = 100 cm^2)			
Growth medium for bacteria SH7	0.00002	m^3	corresponding volume to 200 mL
Electricity for incubation	0.048	kWh	Electricity, low voltage {IT}|electricity voltage transformation from medium to low voltage|Cut-off *(Ecoinvent)*
Preventol RI50 (FU = 1 kg)			
Benzalkonium Chloride	0.03	kg	Benzal chloride {RER}|benzal chloride production|Cut-off + Chemical, organic {GLO}|chemical production, organic|Cut-off *(Ecoinvent)*
Demineralized water	0.97	kg	Water, decarbonised {RER}|water production, decarbonized|Cut-off *(Ecoinvent)*
Crystalline Nanocellulose (FU = 150 mL)			
Cotton waste	0.1	g	Fibre, cotton {IN}|fibre production, cotton, ginning|Cut-off *(Ecoinvent)*
Sulfuric acid	0.04375	g	Sulfuric acid {RoW}|zinc sulfide production|Cut-off *(Ecoinvent)*
Ice water	0.15	g	Tap water {Europe without Switzerland}|tap water production, conventional treatment|Cut-off *(Ecoinvent)*
Distilled water	3.5	g	Water, decarbonised {CH}|water production, decarbonised|Cut-off *(Ecoinvent)*
Electricity for hydrolysis	0.63	kWh	Electricity, low voltage {IT}|electricity voltage transformation from medium to low voltage|Cut-off *(Ecoinvent)*
Electricity for centrifuge	0.36	kWh	Electricity, low voltage {IT}|electricity voltage transformation from medium to low voltage|Cut-off *(Ecoinvent)*
Plexisol P550 (FU = 1 dm^2)			
Acrylic resin	0.15	kg	Butyl acrylate {RER}|butyl acrylate production, butanol esterification with acrylic acid|Cut-off, U (40%) + Benzene {RoW}|coke|Cut-off, U (60%) *(Ecoinvent)*
Solvent mixture for Plexisol P550	0.85	kg	C3 hydrocarbon mixture {Europe without Switzerland}|C3 hydrocarbon production, mixture, petroleum refinery operation|Cut-off (20%) + Acetone, liquid {RER}|acetic acid production, from n-butane oxidation |Cut-off (80%) *(Ecoinvent)*
$CaCO_3$ at 30% in latex (FU = 1 kg)			
Calcium carbonate	0.3	kg	Calcium carbonate, precipitated {RER}|calcium carbonate production, precipitated|Cut-off
Latex	0.7	kg	Latex {RER}|latex production|Cut-off

Table 2. *Cont.*

Input (Product)	QTY	Unit	Dataset LCA
$NaHCO_3$ at 30% in latex (FU = 1 kg)			
Sodium bicarbonate	0.3	kg	Sodium bicarbonate {RER}|soda production, solvay process|Cut-off
Latex	0.7	kg	Latex {RER}|latex production|Cut-off
$NaHCO_3$ at 30% in neutral silicone (FU = 1 kg)			
Sodium bicarbonate	0.3	kg	Sodium bicarbonate {RER}|soda production, solvay process|Cut-off
Neutral silicone	0.7	kg	Silicone product {RER}| silicone product production|Cut-off

Energy and water consumption during the use stage are included within the system boundaries. This encompasses electricity required for machinery operation, such as electricity consumed during preparation processes, including hydrolysis, centrifugation, and freeze-drying in the case of nanocellulose and bacterial treatments. Water used for dilution, preparation, or direct application is also accounted for. Where relevant, process-related waste and residues were considered, including unused product fractions in spoilage scenarios.

Background processes were modelled using Ecoinvent v3.11, the Swiss Input–Output database, and the World Food LCA database, ensuring technological and geographical representativeness consistent with ISO data quality requirements. The cut-off system model embedded in the background databases was applied consistently across all processes to maintain methodological coherence.

In compliance with ISO 14044, exclusions were clearly stated and justified. The end-of-life stage of the applied restoration products was not included, as consolidants and treatment agents become integrated into the cultural heritage substrate after application and are not intended to be removed within the timeframe of the study. Future re-application scenarios were not considered, since the assessment refers to a single intervention per functional unit. Long-term degradation processes and ageing-related emissions beyond those directly associated with the application were also excluded. These choices reflect the functional characteristics of conservation treatments, which are designed to become structurally integrated into the restored material. Similarly, auxiliary materials were not taken into account for the end-of-life stage either, as the quantity used is irrelevant for the purposes of the calculation.

The functional unit is defined as 1 dm^2 of treated surface area, ensuring that all inputs and outputs are normalized to a consistent reference flow. Material quantities, energy consumption, and allocated equipment shares were expressed per unit surface area, enabling transparent and robust comparison among alternative restoration strategies, as required for comparative assessments under ISO 14044.

4.3. Inventory Modelling

Inventory modelling is based on specific data collected for each process used for the three restoration treatments.

For the selected experimental products, each production step, as well as every material and piece of equipment used, was analyzed in detail, as they were considered well known being primary data sources.

For the commercial reference products when primary data were incomplete or unavailable, representative processes from life cycle databases were adopted, selected according to their technical specifications and geographical relevance. When products were applied in diluted form rather than at full concentration; in these cases, dilution was considered, using the specific dilution ratios reported in the corresponding table.

In addition to production data, material usage data were also taken into account (Table 3), based on the information provided in the technical data sheets and standard operational practices.

Table 3. Auxiliary materials included in the life cycle inventory: materials, masses, and assumed numbers of uses.

Input (Product)	Material	QTY (g)	Uses
Can	Tin	57.876	500
Brush	wood	18.282	100
Gloves	plastic	7.636	5
Scalpel	metal	22.783	200
Tongue depressor	wood	2.531	5
Spatula	metal	28.459	500

4.4. Impact Assessment Method

The primary environmental impact indicator considered in this study is carbon footprint, expressed as $kgCO_2$ eq, in addition to climate change impacts, several complementary environmental indicators were assessed: acidification (mol H^+ eq), freshwater eutrophication (kg Peq), photochemical ozone formation (kg NMVOCeq), depletion of abiotic fossil resources (MJ), and water deprivation potential (WDP, m^3 eq). Carbon footprint calculations were performed using characterization factors from the IPCC 2021 assessment report, while the remaining impact categories were evaluated using characterization factors from the Environmental Footprint (EF) method, version 3.01.

Life cycle impact assessment and data processing were carried out using SimaPro software, version 10.2.0.0 (2025).

4.5. Uncertainty Analyses

Uncertainty analysis was performed using Monte Carlo simulation in SimaPro version 10.2.0.0, with 1000 iterations, to quantify the propagation of inventory input uncertainty through the LCA model. The analysis covered all three treatment categories investigated: disinfection of stone surfaces, consolidation of degraded organic materials, and dry cleaning of metal surfaces. Uncertainty was considered for the elementary flows and technosphere exchanges associated with the modelled production processes. Positive physical quantities were represented using lognormal distributions, parameterised using uncertainty factors derived from the pedigree matrix, which assesses data reliability, completeness, and temporal, geographical, and technological representativeness. At each iteration, input values were randomly sampled from their assigned distributions and the environmental impact indicators were recalculated. The resulting distributions were characterized using the mean, median, standard deviation (SD), coefficient of variation (CV, expressed as a percentage), and the 2.5th and 97.5th percentiles, defining the central 95% uncertainty interval. The standard error of the mean (SEM) was also reported to indicate the precision of the mean estimated from the Monte Carlo simulations. These statistics describe the magnitude and relative variability of the modelled impacts under the specified input uncertainty assumptions.

5. Results

5.1. Disinfection of Stone Surfaces

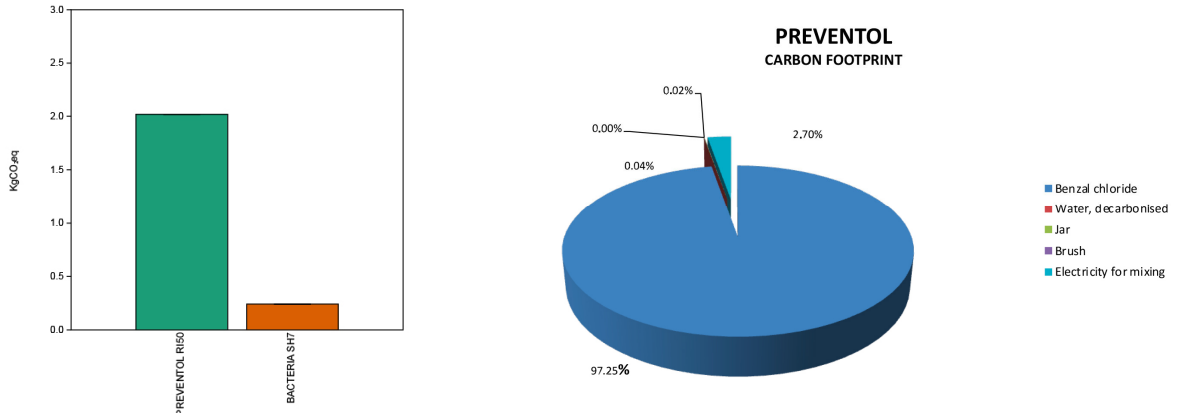
The comparative LCA of disinfection treatments performed per functional unit reveals substantial differences between the synthetic biocide Preventol RI50 (3%) and the biological treatment based on Bacteria SH7.

In terms of climate change, Preventol RI50 exhibits a markedly higher carbon footprint, reaching 2.02 kg CO_2 eq per dm^2, whereas the SH7-based treatment results in 2.42×10^{-1} kg CO_2 eq. This corresponds to an approximately 88% reduction when switching from the synthetic biocide to the bacterial approach under the defined system boundaries.

The same trend is observed across all other midpoint impact categories (Table 4). For each restoration treatment typology, the specific system considered (material or equipment) was individually analyzed. The corresponding tables report the environmental impact values for each system, while the figure (Figure 1a) illustrate a comparative analysis of the restoration techniques based on their carbon footprint.

Table 4. Impact analysis of each treatment for disinfection of stone surfaces [FU = 1 dm^2].

Impact Category	Unit	Preventol RI50	Bacteria SH7
Acidification	mol H^+ eq	8.56×10^{-3}	1.42×10^{-3}
Climate change	kg CO_2 eq	2.02	2.42×10^{-1}
Eutrophication, marine	kg N eq	1.49×10^{-3}	6.31×10^{-4}
Eutrophication, freshwater	kg P eq	7.37×10^{-4}	6.12×10^{-5}
Eutrophication, terrestrial	mol N eq	1.47×10^{-2}	3.87×10^{-3}
Photochemical ozone formation	kg NMVOC eq	9.58×10^{-3}	9.76×10^{-4}
Resource use, fossils	MJ	5.12×10^{1}	4.81×10^{0}
Water use	m^3 depriv.	5.33×10^{-1}	2.14×10^{-1}



(**a**) (**b**)

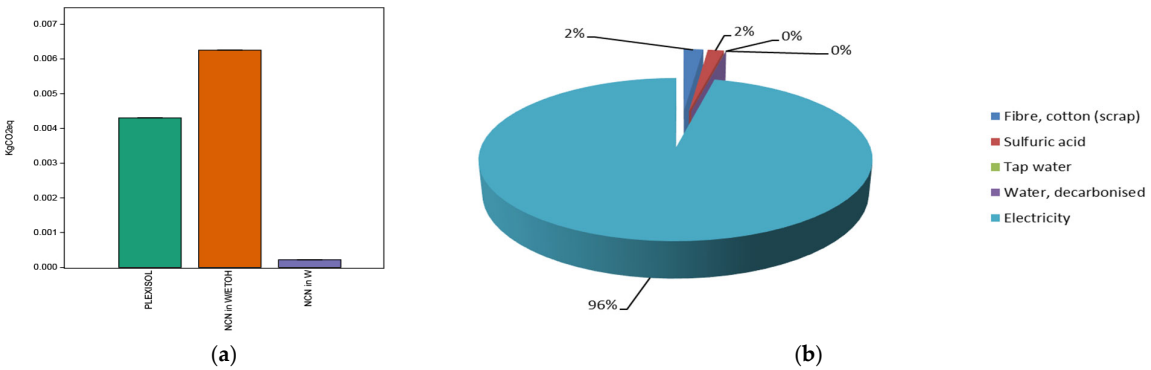
Figure 1. (**a**) Carbon footprint values of disinfection stone surfaces treatments. (**b**) Impact analysis of materials and equipment for Preventol RI50 [FU = 1 dm^2].

Contribution analysis indicates that the production of benzalkonium chloride dominates the environmental profile of Preventol RI50, accounting for the majority of its carbon footprint (Figure 1b). In contrast, the impacts associated with SH7 are primarily driven by electricity consumption during incubation and freeze-drying phases. This distinction highlights a structural difference between the two systems: Preventol RI50's impact is largely material-driven, while SH7's footprint is energy-driven.

From a transparency perspective, it is important to note that Preventol RI50 modelling relies predominantly on secondary database datasets, whereas SH7 includes detailed foreground modelling of culture medium composition and electricity use. Consequently, the comparative outcome is sensitive to assumptions regarding datasets for benzalkonium chloride production.

5.2. Consolidation of Organic Materials

The LCA comparison between crystalline nanocellulose (CNC) and Plexisol P550 for the consolidation of degraded cellulosic materials highlights a more articulated pattern than that observed for the disinfection of stone surfaces (Figure 2). Furthermore, the results obtained from this dataset clearly highlight both material-related differences and methodological challenges inherent to the application of LCA in the conservation field. Among the systems considered, CNC dispersed in water consistently shows the lowest impacts across all the evaluated categories. In contrast, the same material dispersed in a hydroalcoholic mixture exhibits significantly higher values, with the climate change indicator increasing from 2.19×10^{-4} to 6.26×10^{-3} kg CO_2 eq (approximately 28 times higher). The higher carbon footprint of the hydroalcoholic CNC formulation is primarily attributable to the ethanol component and its associated upstream production burdens. Under the modelled application conditions, these additional burdens substantially exceed those associated with water in the aqueous formulation. This divergence between the two CNC formulations is consistent across multiple impact categories (Table 5) and suggests that the dispersing medium may substantially influence the overall environmental profile, in some cases, outweighing the contribution of the polymeric component itself. Plexisol P550 (4.30×10^{-3} kg CO_2 eq), on the other hand, lies between the two CNC formulations. This indicates that, within the system boundaries of the present study, a bio-based material such as CNC does not necessarily result in a lower impact than a synthetic acrylic resin, particularly when organic solvents are involved for its dispersion and application. These findings underline the importance of considering the entire formulation, rather than the active material alone, when evaluating conservation products through LCA.



(**a**) (**b**)

Figure 2. (**a**) Carbon footprint values of consolidation treatments. (**b**) Impact analysis of materials and equipment for CNC [FU = 1 dm^2].

Table 5. Impact analysis of each treatment for consolidation of organic materials [FU = 1 dm^2].

Impact Category	Unit	Plexisol P550	CNC with Ethanol/Water	CNC with Water
Acidification	mol H^+ eq	3.84×10^{-5}	1.90×10^{-5}	8.14×10^{-7}
Climate change	kg CO_2 eq	4.30×10^{-3}	6.26×10^{-3}	2.19×10^{-4}
Eutrophication, marine	kg N eq	1.34×10^{-5}	3.85×10^{-6}	1.74×10^{-7}
Eutrophication, freshwater	kg P eq	7.32×10^{-7}	2.45×10^{-6}	5.46×10^{-8}
Eutrophication, terrestrial	mol N eq	1.33×10^{-4}	4.03×10^{-5}	1.51×10^{-6}
Photochemical ozone formation	Kg NMVOC eq	3.19×10^{-5}	4.04×10^{-5}	6.61×10^{-7}
Resource use, fossils	MJ	1.06×10^{-1}	1.95×10^{-1}	3.95×10^{-3}
Water use	m^3 depriv.	1.06×10^{-3}	3.29×10^{-3}	4.95×10^{-4}

5.3. Self-Made Erasers for Dry Cleaning

For dry cleaning treatments, impacts were assessed for three self-produced eraser formulations: one based on artificial matrix materials and two based on natural ones. Results, normalized to 1 dm^2 treated surface, show relatively low absolute values but clear relative differences among formulations.

The highest climate change impact is associated with the formulation containing 30% sodium bicarbonate in latex (2.12×10^{-5} kg CO_2 eq), followed closely by 30% calcium carbonate in latex (1.91×10^{-5} kg CO_2 eq). The lowest carbon footprint is observed for 30% sodium bicarbonate in neutral silicone (4.91×10^{-6} kg CO_2 eq). Fossil resource use mirrors this ranking, with the silicone-based system showing substantially lower energy demand compared to latex-based formulations (Figure 3).

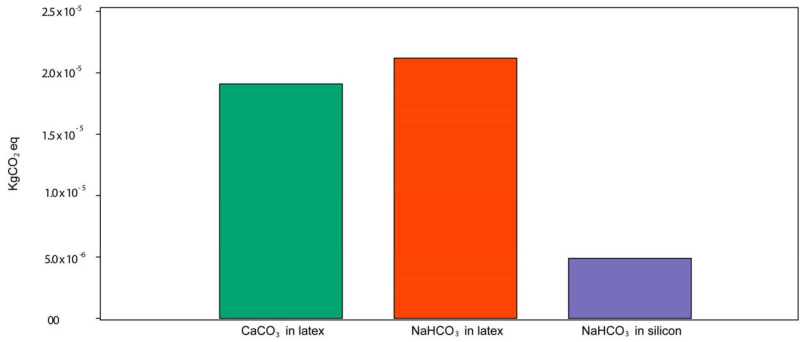


Figure 3. Carbon footprint values of dry cleaning treatments [FU = 1 dm^2].

Experimental measurements of material consumption reveal that silicone-based erasers exhibit significantly lower mass loss during application (0.012 g per 5.75 cm^2) compared to latex-based rubbers (approximately 0.056 g). This reduced consumption directly influences impact allocation per functional unit and partially explains the improved environmental performance of the silicone formulation (Table 6).

Table 6. Impact analysis of each treatment for dry cleaning [FU = 1 dm^2].

Impact Category	Unit	$CaCO_3$ at 30% in Latex	$NaHCO_3$ at 30% in Latex	$NaHCO_3$ at 30% in Silicone
Acidification	mol H^+ eq	1.29×10^{-7}	1.67×10^{-7}	2.49×10^{-8}
Climate change	kg CO_2 eq	1.91×10^{-5}	2.12×10^{-5}	4.91×10^{-6}
Eutrophication, marine	kg N eq	2.87×10^{-8}	3.19×10^{-8}	3.85×10^{-9}
Eutrophication, freshwater	kg P eq	4.58×10^{-10}	1.91×10^{-9}	1.59×10^{-9}
Eutrophication, terrestrial	mol N eq	3.01×10^{-7}	4.12×10^{-7}	5.56×10^{-8}
Photochemical ozone formation	kg NMVOC eq	9.81×10^{-8}	1.06×10^{-7}	1.54×10^{-8}
Resource use, fossils	MJ	5.81×10^{-4}	6.08×10^{-4}	8.24×10^{-5}
Water use	m^3 depriv.	1.85×10^{-5}	2.42×10^{-5}	7.63×10^{-6}

From a modelling standpoint, the impacts are largely determined by background datasets for latex and silicone production. Additionally, scaling experimental consumption data to the standardized functional unit introduces proportional extrapolation uncertainty, particularly given the small surface areas involved in laboratory testing.

5.4. Uncertainty Analyses

The Monte Carlo simulations revealed differences in the relative uncertainty of the fossil climate change indicator across the three treatment categories (Table 7). Coefficients of variation (CVs) ranged from 3.07% to 18.80%, with the highest relative variability ob-

served for the nanocellulose solution and Preventol RI50, and the lowest for the latex-based cleaning formulations.

Table 7. Summary statistics of the Monte Carlo uncertainty analysis for the fossil carbon footprint of the investigated formulations.

		Carbon Footprint						
	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Preventol RI50	kg CO_2 eq	3.493	3.405	0.6372	18.24%	2.472	4.971	0.02015
Bacteria SH7	kg CO_2 eq	0.01345	0.01342	0.0007342	5.457%	0.01215	0.01514	0.00002322
Plexisol P550	kg CO_2 eq	0.001194	0.00117	0.0001858	15.57%	0.0008806	0.001609	5.876×10^{-6}
CNC	kg CO_2 eq	0.0007547	0.0007376	0.0001419	18.8%	0.000523	0.001074	4.486×10^{-6}
$CaCO_3$ in latex	kg CO_2 eq	2.30×10^{-3}	2.29×10^{-3}	7.03×10^{-5}	3.065%	2.182	2.459	2.22×10^{-6}
$NaHCO_3$ in latex	kg CO_2 eq	2.14×10^{-3}	2.12×10^{-3}	8.73×10^{-5}	4.082%	2.01	2.345	2.76×10^{-6}
$NaHCO_3$ in silicon	kg CO_2 eq	0.002324	0.002306	0.0002317	9.966%	0.001924	0.002843	7.326×10^{-6}

For the disinfection products, Preventol RI50 exhibited a mean impact of 3.493 kg CO_2 eq per kg of product, with a median of 3.405 kg CO_2 eq and a standard deviation of 0.6372 kg CO_2 eq. The central 95% uncertainty interval ranged from 2.472 to 4.971 kg CO_2 eq, corresponding to a CV of 18.24%. The bacterial preparation showed lower relative variability, with a mean of 0.01345 kg CO_2 eq per kg, a median of 0.01342 kg CO_2 eq, and a CV of 5.46%. Its central 95% uncertainty interval extended from 0.01215 to 0.01514 kg CO_2 eq. The distributions for the two preparations did not overlap within these intervals at the modelled product reference quantities.

For consolidation, the Plexisol solution had a mean impact of 1.194×10^{-3} kg CO_2 eq per gram, compared with 7.547×10^{-4} kg CO_2 eq per gram for the nanocellulose solution. Relative variability was higher for nanocellulose, with a CV of 18.80%, compared with 15.57% for Plexisol. The corresponding central 95% uncertainty intervals were 5.230×10^{-4}–1.074×10^{-3} and 8.806×10^{-4}–1.609×10^{-3} kg CO_2 eq per gram, respectively. Although nanocellulose showed a lower mean impact, the intervals partially overlapped.

For the dry cleaning formulations, the calcium carbonate–latex and sodium bicarbonate–latex mixtures exhibited the lowest relative variability, with CVs of 3.07% and 4.08%, respectively. The sodium bicarbonate–silicone formulation showed a higher CV of 9.97%. These results indicate narrower relative uncertainty distributions for the latex-based formulations; however, this does not imply lower environmental impacts per treated surface area, which also depend on material consumption during application.

Across all formulations, mean values exceeded the corresponding medians, consistent with positively skewed output distributions. The analysis therefore characterized differences in the magnitude of propagated input uncertainty, while comparisons at the treatment level require results expressed on the common functional unit.

6. Discussion

The results presented in this study highlight both the potential and the methodological fragility of applying Life Cycle Assessment to cultural heritage conservation, particularly when the objective is not only to compare environmental performances but also a thorough understanding of experimental products as alternative strategies. Across the three intervention categories examined, stone surface disinfection, consolidation of degraded organic materials, and dry cleaning treatments, the environmental outcomes are shown to depend not only on material choice but also, and sometimes predominantly, on modelling assumptions, data provenance, system boundaries, and scale representativeness.

In the case of stone surface disinfection, the marked difference between the bacterial treatment based on Serratia ficaria SH7 and the synthetic biocide Preventol RI50 suggests a substantial environmental advantage of the biological approach, particularly in terms of cli-

mate change and fossil resource depletion. Preventol RI50's environmental profile is largely driven by benzalkonium chloride production, modelled using secondary industrial datasets, while the bacterial treatment incorporates foreground primary data describing laboratory-scale cultivation, incubation, and freeze-drying processes. This asymmetry in data origin introduces a layer of epistemic uncertainty: laboratory-scale processes are typically well-defined and well-noted than industrial-scale production, potentially underestimating the impacts attributed to industrial production, whereas database-derived datasets may not fully capture the production process. Furthermore, the relative ranking of treatments is highly sensitive to assumptions regarding the electricity mix, which directly influences energy-intensive processes such as incubation and centrifugation.

A similar tension between innovation and representativeness emerges in the consolidation scenario, where crystalline nanocellulose and Plexisol P550 were compared. Although nanocellulose is often framed within conservation discourse as a bio-based and therefore environmentally preferable alternative, the LCA results indicate that its environmental profile is strongly influenced by energy consumption during hydrolysis and centrifugation stages. The magnitude of this contribution underscores how process intensity, rather than raw material origin alone, governs overall environmental performance. At the same time, the comparison is affected by differences in data resolution: nanocellulose modelling relies on detailed primary laboratory data, while Plexisol P550 impacts derive from generic background datasets representing industrial production. This introduces a structural imbalance in the comparison, as one system is modelled with high specificity but potentially limited scalability, while the other benefits from mature industrial data that may not reflect conservation-scale usage patterns. The resulting interpretation therefore depends on transparency in reporting technological maturity and scale assumptions. Without explicit clarification, readers may mistakenly interpret the results as evidence of inherent environmental superiority of one material over another, rather than as an artefact of system boundary and data availability constraints. On the contrary, the results must be interpreted in light of methodological limitations: the CNC system is modelled using primary laboratory-scale data, where processes such as hydrolysis and centrifugation are relatively energy-intensive and not as efficient as they could be at an industrial scale, while Plexisol P550 relies on datasets that may reflect optimized large-scale production. This asymmetry in data sources introduces structural uncertainty and may affect the comparability of the results. More broadly, it highlights a key issue in the application of LCA to conservation materials, where emerging or experimental systems are often represented by primary data, whereas commercial products are described through generic secondary datasets. This highlights a structural limitation of LCA in conservation contexts, where innovative or laboratory-developed materials are penalized by energy-intensive small-scale processes, which may overestimate impacts compared to potential industrial-scale production, while established commercial products benefit from averaged industrial datasets. These results ultimately suggest that environmentally informed decision-making in conservation cannot rely solely on material identity (e.g., bio-based vs. synthetic) but must account for formulation and data representativeness.

The dry cleaning results highlight the role of material consumption during application in determining environmental impacts per functional unit. The silicone-based eraser generally exhibited lower impacts than the latex-based alternatives, largely because its greater resistance to wear resulted in lower experimentally measured mass loss and, consequently, a smaller quantity of material consumed per treated surface area. This finding illustrates why material origin alone cannot be used as a proxy for environmental performance: the potential advantages of natural latex do not necessarily outweigh the reduced consumption associated with a more wear-resistant synthetic formulation. Environmental assessment

should therefore consider composition and production processes together with the quantities actually consumed during treatment. This example illustrates that uncertainty in conservation LCAs does not derive solely from production datasets, but also from use-phase variability, operator technique, and extrapolation from experimental surfaces to standardized functional units. We must also underline the importance of the characteristics and composition of the treated surface. Moreover, if the adoption of 1 dm^2 as functional unit ensures comparability across treatments, inevitably simplifies the heterogeneity of real conservation contexts, where substrate porosity, deterioration level, and treatment repetition frequency may significantly affect material consumption.

The definition of system boundaries further shapes interpretative precision. By focusing on upstream production, preparation, and application stages while excluding long-term durability, retreatment cycles, and end-of-life considerations, the study provides a focused but temporally limited perspective.

In conservation practice, treatments are selected not only for immediate performance but also for longevity and compatibility with future interventions. A product with slightly higher initial impact but greater durability could yield lower cumulative environmental burdens over time. The absence of dynamic or scenario-based modelling therefore represents a structural limitation inherent to static LCA approaches applied to heritage contexts.

7. Conclusions

This study contributes to the ongoing discussion on uncertainties and transparency in environmental footprint estimation by examining the application of Life Cycle Assessment to cultural heritage conservation. Through the comparative analysis of experimental and commercial treatments, the results demonstrate that environmental performance is highly sensitive to data origin, modelling assumptions, and scale representation. A central outcome of this work is the recognition that LCA, when applied to conservation materials, operates under conditions of structural uncertainty. Differences between laboratory-scale foreground data and industrial background datasets, the simplified representation of use-phase conditions, and the exclusion of temporal dynamics all contribute to shaping results in ways that extend beyond purely technical considerations. As a consequence, environmental impact values should not be interpreted as absolute measures, but as context-dependent indicators that reflect specific modelling choices. In this framework, transparency becomes a key requirement for ensuring the credibility and usability of LCA results. Explicit documentation of data sources, assumptions, system boundaries, and methodological limitations is essential to enable critical interpretation and informed decision-making. Moreover, the integration of uncertainty and sensitivity analyses represents a necessary step toward improving the robustness of comparative assessments, particularly in emerging and data-scarce domains. The findings also highlight the need to move beyond static and product-centred evaluations. Future developments should incorporate scenario-based approaches that account for durability, maintenance cycles, and long-term performance, allowing environmental impacts to be assessed over relevant time horizons. Similarly, efforts to bridge the gap between laboratory-scale experimentation and real-world application will be crucial for enhancing the representativeness of LCA studies in conservation.

Ultimately, this study demonstrates that sustainability in heritage conservation cannot be reduced to the substitution of synthetic with bio-based materials or commercial with self-produced tools; rather, it emerges from the interaction between material composition, process efficiency, energy context, and operational practice. By foregrounding the methodological conditions under which environmental comparisons are constructed, this research contributes to advancing transparency and critical awareness in environmental footprint estimation, aligning with broader efforts to enhance precision and credibility in

LCA applications across complex, small-scale, and context-specific domains such as cultural heritage conservation.

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