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Article

Development and application of a natural waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica] in sustainable restoration materials for the conservation of built heritage [vernacular architecture]: case study of the Mezquital Valley, Hidalgo

Desarrollo y aplicación de un impermeabilizante natural a base de mucílago de nopal [Opuntia ficus-indica] en materiales restauradores sostenibles para la conservación del patrimonio edificado [arquitectura vernácula]: caso de estudio Valle del Mezquital, Hidalgo

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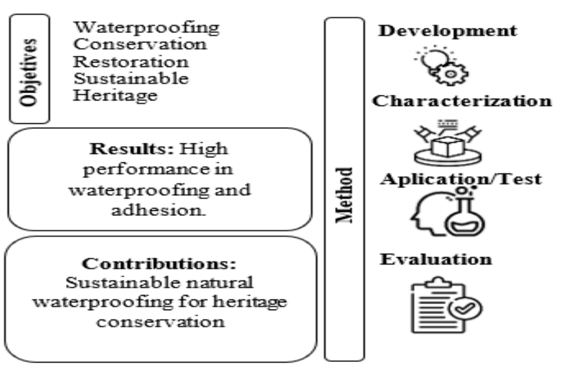
Abstract

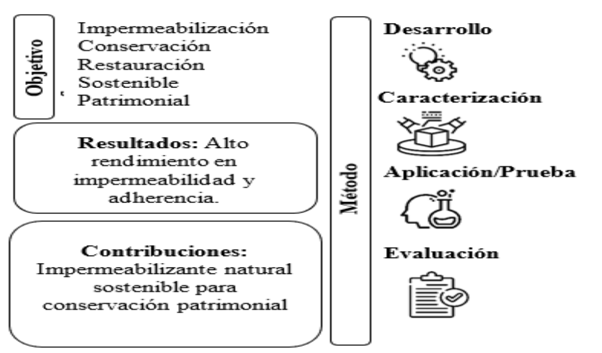
The conservation of built heritage requires the use of compatible, efficient, and sustainable materials. This study develops and applies a natural waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica], intended for sustainable restoration materials. Its adhesion capacity, moisture retention, and compatibility with traditional materials were evaluated through experimental tests and controlled applications. The results show that nopal mucilage performs well in terms of water absorption, constituting an ecological, economical, and effective alternative to conventional synthetic products, contributing to heritage conservation and promoting environmentally friendly restoration practices.



Sustainability, Transdisciplinarity, Resilience

Resumen

La conservación del patrimonio edificado requiere el uso de materiales compatibles, eficientes y sostenibles. Este estudio desarrolla y aplica un impermeabilizante natural a base de mucílago de nopal [Opuntia ficus-indica], destinado a materiales restauradores sostenibles. Se evaluó su capacidad de adherencia, retención de humedad y compatibilidad con materiales tradicionales mediante ensayos experimentales y aplicaciones controladas. Los resultados muestran que el mucílago de nopal ofrece un buen desempeño frente a la absorción de agua, constituyendo una alternativa ecológica, económica y eficaz frente a productos sintéticos convencionales, contribuyendo a la conservación del patrimonio y fomentando prácticas de restauración respetuosas con el medio ambiente.



Sustentabilidad, Transdisciplinaridad, Resiliencia

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

The preservation of architectural heritage requires restoration materials that ensure physical-chemical compatibility, functional performance, and environmental sustainability [D'Agostino *et al.,* 2023]. Historically, the waterproofing agents and additives used in restoration have been synthetic, effective but capable of altering the breathability and hygroscopic balance of ancient materials, causing internal stresses, moisture retention and premature degradation [D'Agostino *et al*., 2023].

Therefore, the exploration of ecological options that are in harmony with traditional construction systems is emerging as a key focus of research for experts in conservation and materials science. Mucilage obtained from Opuntia ficus-indica, an abundant and renewable natural polysaccharide, stands out as a promising biopolymer for enhancing the functional characteristics of cements and mortars, acting as a bioadditive and water retainer without damaging the original porosity or microstructure [Cerchas *et al*., 2024]. Recent research confirms that this mucilage increases the consistency and strength of cement mixtures, preserving or optimising critical aspects such as water absorption and porosity, without adverse long-term impacts [Cerchas *et al*., 2024]. Thus, nopal mucilage emerges as a viable alternative to traditional synthetic additives, with environmental and economic advantages due to its biological origin and local accessibility.

Beyond structural uses, O. ficus-indica mucilage has been tested in cultural heritage conservation, where its adhesive qualities, water retention and biopolymer film formation make it a protective coating that respects the vapour permeability and hygroscopic behaviour of historical materials, without altering their intrinsic properties [D'Agostino *et al*., 2023]. This work is based on the hypothesis that a natural waterproofing agent based on Opuntia ficus-indica mucilage represents an effective, cost-effective and environmentally friendly solution for reinforcing the moisture resistance of sustainable restoration materials, without compromising their compatibility with traditional constructions. It is proposed that this strategy not only mitigates capillary absorption and water infiltration, but also promotes more environmentally friendly restoration practices in line with preventive conservation.

The article is structured as follows: initially, the state of the art on vernacular architecture in the Mezquital Valley is reviewed. Next, the experimental methodology for its extraction and application in restoration materials is detailed, along with tests to measure its response to moisture.

The results and their analysis evaluate adhesion, water retention, and resistance to moisture absorption. Finally, the conclusions address the implications for heritage conservation and suggest future avenues of research in sustainable restoration.

State of the Art: Vernacular Architecture in the Mezquital Valley, Hidalgo

Vernacular architecture in Mexico has been addressed in recent literature as a cultural and constructive manifestation closely linked to the territory, local knowledge and the availability of materials, consolidating itself as a fundamental component of the built heritage and cultural landscape. In the case of the Mezquital Valley, Hidalgo, research highlights that indigenous communities, particularly the Otomí, have developed construction systems adapted to semi-arid climatic conditions, using local materials such as earth, stone and plant resources, including maguey, which demonstrates a direct relationship between the environment, cultural identity and traditional architectural practices [Argüello & Enríquez de los Ríos, 2022].

These studies indicate that vernacular architecture not only fulfils housing functions, but also incorporates social and symbolic values, while facing processes of transformation derived from modernisation, migration and the introduction of industrialised materials.

At the state level, recent research has identified a progressive transition from vernacular architecture to contemporary self-construction processes in various regions of Hidalgo, which has given rise to hybrid built landscapes that combine traditional techniques with modern solutions, generating tensions between heritage conservation and the satisfaction of new social needs [García *et al.,* 2023].

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From a broader theoretical perspective, contemporary literature agrees that vernacular architecture should be understood as a dynamic and living phenomenon, whose conservation requires comprehensive approaches that recognise both its cultural value and its environmental potential and contribution to strategies for sustainability and conservation of the built heritage and cultural landscape [Martínez & Ávila, 2024; Urquijo, 2025].

Traditional materials and construction strategies for protection against rain in the vernacular architecture of the Mezquital Valley, Hidalgo

In the Mezquital Valley region of Hidalgo, traditional vernacular architecture is characterised by the use of local and natural materials that respond both to semi-arid climatic conditions and to the ancestral knowledge of the Hñähñu communities, being a fundamental component of the region's built heritage.

Among the predominant materials are earthen constructions, such as adobe walls and earthen structures with plant reinforcements, which take advantage of thermal mass and the availability of local resources to achieve interior comfort without complex industrial processes [Argüello & Enríquez de los Ríos, 2022].

Likewise, natural stone continues to play an important role in vernacular buildings in the valley, especially in the walls and foundations of Hñähñu constructions, where masonry techniques reflect a long tradition of adaptation to the local biocultural environment and have a high heritage value, although they are at risk of disappearing due to the loss of associated practices and knowledge [Velázquez & Guerrero, 2023]. Wood has also been traditionally used for structural elements such as beams and roofs, integrated with mixed techniques that harmonise stability and construction flexibility [García *et al*., 2023].

These materials not only represent functional and sustainable solutions, but also embody the technical and cultural knowledge of the Otomí-Hñähñu communities, highlighting the need for their documentation and conservation in the face of increasing replacement by industrialised materials that lose the original characteristics of vernacular architecture [Velázquez & Guerrero, 2023].

In the vernacular architecture of the Mezquital Valley, Hidalgo, protection from rain is achieved mainly through a combination of materials and construction techniques, as traditional adobe or rammed earth walls are not completely waterproof. For roofs, fired clay tiles are used, which, because they are fired, offer resistance to moisture and, when installed on sloping roofs with extended eaves, prevent leaks and protect the walls from erosion by rain [Velázquez & Guerrero, 2023].

In addition, coatings of clay mixed with lime or other natural stabilisers are used, which reduce water absorption and increase the durability of the walls, while maintaining their breathability [Argüello & Enríquez de los Ríos, 2022]. At the base of the walls, stone plinths act as a barrier against rising damp and rain splashes, while overlapping plant coverings, such as reed or palm, partially protect the roofs from light rain, especially in older buildings. In recent times, some homes have incorporated metal sheets or fibre cement as waterproof coverings, increasing resistance to rain, although these solutions are not part of the original vernacular tradition [García *et al*., 2023]. Taken together, these strategies show that waterproofing in the valley's architecture does not depend on a single material, but rather on the harmony between techniques, construction methods, and the intelligent use of local resources, adapted to the region's semi-arid climate.

Methodology

Stage 1: Procedure for extracting mucilage from prickly pear [*Opuntia ficus-indica*]

The extraction of mucilage from Opuntia ficus-indica began with the selection of an authorised cultivation area in the municipality of Ixmiquilpan, Hidalgo, avoiding protected areas where the extraction of cacti is restricted. Semi-mature pads, approximately two to three years old, which were not suitable for commercial consumption, were collected, ensuring the use of waste material.

The selected pads were carefully cut with a knife, avoiding injury from thorns, and transferred to suitable containers. In the laboratory, the samples were cleaned and peeled, removing surface and deep thorns, as well as part of the epidermis, in order to obtain clean and homogeneous nopal tissue for mucilage extraction.

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The pads were then cut into julienne strips and then into small cubes, increasing the surface area in contact with water to promote the release of mucilage. The nopal fragments were placed in clean containers, to which 2 litres of purified water were added for every four medium-sized pads, allowing the system to rest for three days at room temperature, facilitating the diffusion of the mucilage from the tissue into the water.

Finally, the liquid mucilage was separated from the solid material by filtration through a fine sieve and stored in sterilised, sealed and labelled glass jars for preservation, ensuring the integrity and stability of the product for subsequent experimental applications.

Box 1

Figure 1
Extraction of mucilage from prickly pear [Opuntia ficus-indica]
Source: Own elaboration

Stage 2: Preparation of waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica]

The following is a list of the materials used to manufacture the waterproofing agent based on nopal cactus mucilage [Opuntia ficus-indica].

Materials
Neutral soap
Alum stone
Lime stone
Water
Nopal mucilage [Opuntia ficus-indica]

Laboratory tools and materials
1 1000 ml test tube
1 25 ml test tube
1 mortar
1 scalpel
1 1 litre beaker
1 thermometer
1 spatula

Box 2
Table 1
Material proportions

Material	Ratio
Neutral soap	15 g
Alum stone	40 g
Water	400 ml
Nopal mucilage	70 ml

Source: Own elaboration

The procedure for preparing the natural waterproofing agent based on nopal [Opuntia ficus-indica] mucilage began with the preparation of the solid materials, including the dosing and grinding of the soap, alum stone and lime stone. Next, two volumes of water were heated in beakers, 460 ml in one and 400 ml in the other, almost to boiling point. The alum stone was dissolved in the first beaker, while the lime and soap were gradually added to the second, avoiding the formation of lumps.

Once the substances had dissolved, the solutions were left to cool and stored separately to prevent unwanted reactions. Finally, the nopal mucilage was added to the jar containing the lime and soap and mixed until a homogeneous solution was obtained, ready for use as a waterproofing agent.

Box 3

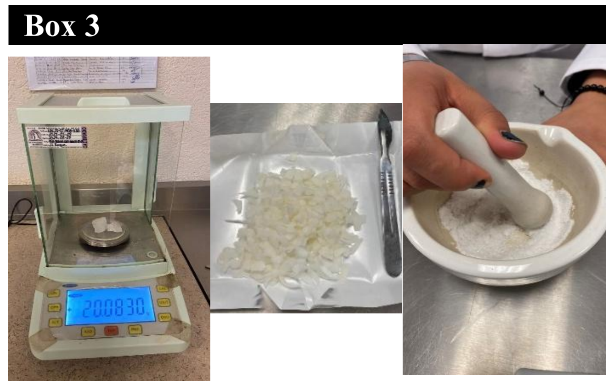

Figure 2
Dosing and grinding of materials
Source: Own elaboration

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Box 4

Figure 3
Preparation of natural waterproofing agent based on nopal [Opuntia ficus-indica] mucilage
Source: Own elaboration

Stage 3: Adobe manufacturing

The adobe bricks were made using a controlled process, starting with the selection of the constituent materials, using clay soil as the main matrix and dry plant fibres as reinforcement. The soil was first crushed and tamped to remove lumps and coarse particles, ensuring a uniform grain size and free of rigid inclusions. Water was then gradually added until a homogeneous and cohesive paste was obtained, to which the plant fibres were added, ensuring uniform distribution and a malleable but structurally stable consistency.

This mixture was shaped into blocks using wooden formwork, ensuring adequate compaction to minimise internal voids and levelling the surface with wooden instruments to obtain flat finishes. Once the formwork was removed, the adobe bricks were subjected to controlled drying in the shade for one or two weeks, which allowed the moisture to evaporate gradually and prevented the appearance of cracks, thus ensuring its mechanical strength and durability, suitable for use in construction or in the restoration of built heritage.

Box 5

Figure 4
Adobe block manufacturing process
Source: Own elaboration

Stage 4: Determination of water absorption capacity in adobe

To determine the water absorption capacity of adobe, controlled laboratory tests were carried out. Initially, a sample of adobe was placed on a suitable surface that allowed the progress of water filtration to be clearly observed. Subsequently, a 20 ml syringe was used to gradually deposit water on the upper surface of the sample, controlling the flow evenly.

During the process, the time it took for the water to be absorbed and filtered through the material was recorded, allowing for a quantitative assessment of the adobe's permeability and its behaviour in response to moisture.

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Box 6

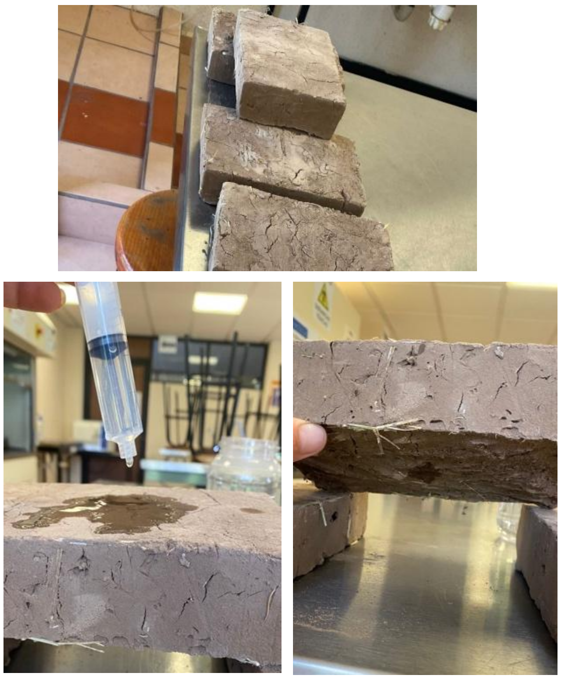

Figure 5
Determination of water absorption capacity in adobe
Source: Own elaboration

Stage 5: Application of waterproofing to adobe blocks.

The natural waterproofing agent made from nopal cactus mucilage was applied to the surface of the adobe samples in an even layer, ensuring that the material was completely covered to guarantee its effectiveness. Once applied, it was left to rest for 3 to 4 hours to allow the active components of the mucilage to adhere to the substrate and form a film that promotes waterproofing.

Box 7

Figure 6
Application of waterproofing agent on adobe blocks
Source: Own elaboration

Stage 6: Determination of water permeability in adobe samples waterproofed with nopal mucilage [Opuntia ficus – indica]

Subsequently, the samples underwent permeability testing, evaluating water absorption on the treated surface and thus verifying the mucilage's capacity as a natural agent for protection against moisture.

Box 8

Figure 7
Evaluation of permeability in adobe blocks waterproofed with nopal cactus mucilage [Opuntia ficus-indica]
Source: Own elaboration

Results

The study confirmed that Opuntia ficus-indica mucilage acts as an effective natural waterproofing agent for adobe, a material widely used in the vernacular architecture of the Mezquital Valley in Hidalgo.

The results showed that its application reduces water absorption and infiltration rates without completely sealing the pores or affecting the breathability and hygroscopic balance of the material. The process of extracting the mucilage and preparing the waterproofing agent was carried out using simple, low-cost techniques with low environmental impact, obtaining a homogeneous and stable solution.

Application to the adobe blocks produced a uniform film with good adhesion, improving moisture resistance compared to untreated samples. Taken together, the findings show that the use of nopal mucilage represents a sustainable, compatible and suitable alternative for the protection and conservation of traditional materials in the field of architectural heritage.

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Conclusions

The study concluded that Opuntia ficus-indica mucilage is a viable natural waterproofing agent for application to adobe, as it effectively improves the material's resistance to moisture without compromising its porosity or breathability, which are essential characteristics in vernacular architecture. The methodology for extracting and preparing the waterproofing agent was simple, accessible and had a low environmental impact, which favours its possible application in rural contexts and heritage conservation projects.

The tests showed that the treated adobe blocks had lower water absorption and permeability compared to those without treatment, confirming the effectiveness of the mucilage as a protective agent. Overall, the results support the use of this biopolymer as a sustainable and compatible alternative to synthetic waterproofing agents, contributing to the conservation of traditional architectural heritage and promoting restoration practices in line with the cultural and environmental context.

Declarations

Conflict of interest

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

Author contributions

ABR and JCRU conceptualisation and methodology; JCRU and ZBTT validation and writing; MBA review.

Availability of data and materials

All material and data will be available for consultation upon direct request to the corresponding author, subject to applicable ethical restrictions.

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Basics

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Supports

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