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# Investigating the material properties of hemp fiber and puffed rice for use in heritage conservation

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**Abstract**

A nation's customs and traditions are unique, including the appearance of its buildings. Restoring older buildings retains cultural connections and enhances sensitivity to the past. Conservation process materials must be distinguishable from originals for easy removal or change while matching features, a challenging task. The goal is to adopt materials similar in texture, scale, color, and form to the original. The increasing need for a sustainable environment attracts the scientific community towards alternative natural materials instead of traditional ones, adopting ecological principles. Eco-friendly materials from agricultural waste are less polluting. Bio-based materials, like hemp and rice, offer good thermal properties and replace traditional materials. Some are commercialized, while others are in the early production stages. Application conditions and potential adoption in heritage building conservation still need to be studied. Gaps in existing knowledge are addressed by assessing biomaterials' physical properties in various conservation scenarios. Comparative analysis between new and conventional materials identifies vital advantages. The analysis also determines characteristics like thermal resistance, fire resistance, color, texture, environmental and health impact, and the production process. Findings indicate outstanding performance and can be developed in various colors and textures, essential for preserving the original structural appearance.

**Keywords** Heritage building, Conservation, Material, Physical characteristics, UAE

## Introduction

Every nation has developed its unique traditions and customs, including the appearance of buildings [1]. Conserving older buildings is essential to retain a meaningful cultural connection and enhance sensitivity toward the past. There is a long history of research aimed at conserving architectural buildings, preserving monuments, urban renewal policies, streets, landscape, and their identity [2]. In general, conservation involves a range of technical activities intended to restore historic buildings and artwork that have been damaged or degraded over time using fabrics and materials similar to the original ones to prolong the life of buildings while retaining as many of their original features as possible [3].

The United Nations Educational, Scientific and Cultural Organization (UNESCO) has divided cultural heritage into two main categories, as shown in Fig. 1 [4]. As the term implies, intangible heritage includes the language, dance, and music of a nation, as well as its culture and religion. Monuments, areas, and buildings represent tangible heritage. Tangible cultural heritage is further classified into two subcategories: movable and immovable heritage. This includes historical buildings, monuments, and archaeological sites, which are the focus of this research.

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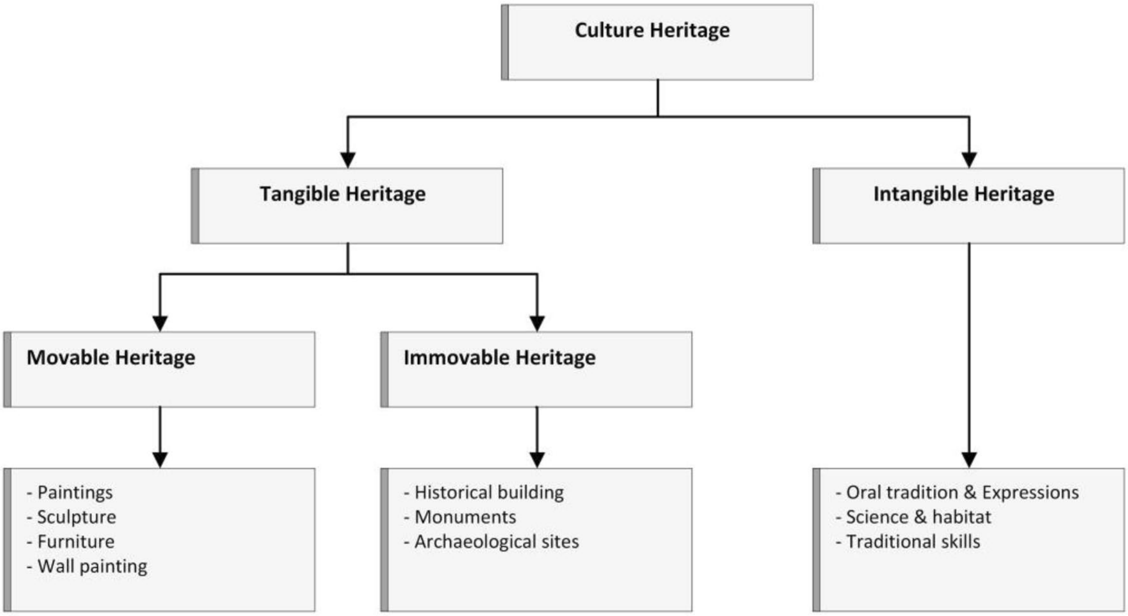


**Fig. 1** UNESCO classification of cultural heritage [4]

The United Kingdom Institute of Conservation UKIC [5] provides several principles and standards based on ethical codes as an international charter to achieve the primary aims of heritage conservation, as shown in Fig. 2. These and other cultural heritage policy documents stipulate that as the removal of authentic materials is not authorized, new materials should be used instead [6]. Moreover, material added in the conservation process must be distinguishable from the original building material so it can be removed or changed easily if required while closely matching the features of the original [7]. These principles suggest that the contractor or

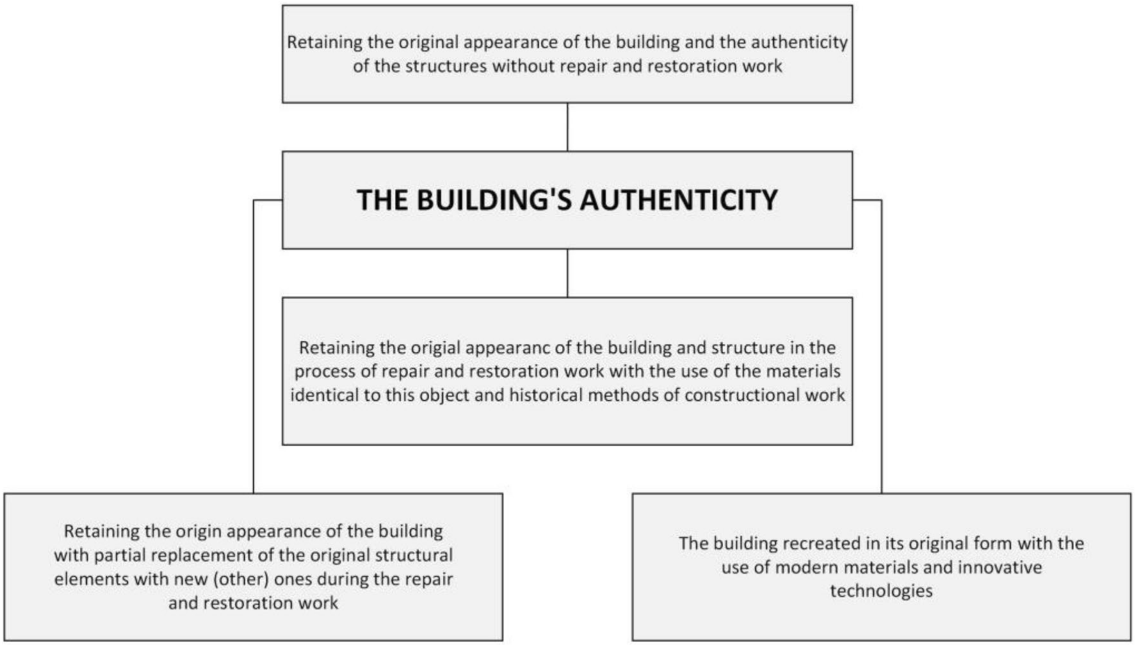


**Fig. 2** Authenticity of a building [8]

the architect in charge of the restoration project must employ materials that match the original structure, which is often challenging. Thus, the objective is to adopt materials compatible with the original regarding strength, texture, scale, color, and form.

As it is imperative to preserve the authenticity of the artistic image of an object for architectural and town planning heritage during conservation, selecting the right material is crucial. Nevertheless, the choice of material should not solely reflect the technical and aesthetic aspects in the absence of the original architectural design of the object to be restored. There are several factors to consider when determining the authenticity of a building, as shown in Fig. 2 [8].

When determining authenticity, consideration is often given to the history and story of the building, the community, or both. Achieving such authenticity can be challenging as sites reflect their times authentically in all aspects of their development [9]. The design, materials, workmanship, and setting must all meet the authenticity requirements for heritage property conservation. Thus, design and materials are the most critical factors. A combination of past and present can be seen in the materials used in the design, which includes architectural styles and construction techniques. These buildings' original designs and materials reflect an era lost in time, ideas, and concepts [3]. To facilitate this process, the technical properties of several biomaterials are evaluated in typical scenarios encountered during heritage building conservation. Furthermore, a comparative analysis between the reviewed materials and conventional materials for heritage building conservation is performed to determine their advantages and test their key characteristics.

The present study introduces a novel approach to selecting conservation materials for heritage buildings by considering sustainability. The study aims to achieve the following research objectives: (1) provide an overview of biomaterials that are suitable for the restoration conservation process; (2) conduct a comparative analysis between the currently used materials and the proposed biomaterials; (3) analyze the proposed material's primary characteristics, including thermal performance, fire resistance, color and texture, health, and production process, based on factors identified in the literature; and (4) identify the most advantageous among the proposed biomaterials and analyze it further in terms of chemical structure, color, and texture.

It is difficult to find original materials for building conservation. Original materials such as roof tiles, stone, and timber trusses were once plentiful sources. Making sure that replacement materials match the original is crucial. Still, the challenges are complicated by both the lack of original materials and interpreting the contract requirements for new materials, which must be tested for texture, scale, and form to ensure they are compatible with the original [10]. Likewise, missing or damaged elements should be reconstructed based on the original technique, and designs should be based on historical data.

## Heritage building materials

Recent studies in conserving heritage buildings have shown increased attention to their properties and morphology [8]. Their findings indicate that besides considering material suitability for the structure, size, and shape of the heritage buildings, their benefits and drawbacks relative to other materials must be considered.

### Traditional materials

Despite the availability of new materials, traditional materials such as stone, brick, ceramic, gypsum, and wood are the most widely used in the conservation of heritage buildings worldwide [11]. Lime and gypsum were generally used along with additives to make mortar. As a result of deforestation and industrialization, the environment is becoming increasingly polluted. Through the absorption of these pollutants, grout and bedding mortar have become wet and deteriorated and have little or no cohesive, compressive, or adhesive properties, making them the weakest link [12]. Nevertheless, stone has a long tradition and is among the most desired conservation materials; thus, it is treated separately [8]. Figure 3 shows the most important characteristics of natural stone, including its texture, color, heat and frost resistance. However, stone materials are subject to deterioration and decay, and natural variations in their color and texture make it challenging to adopt them in conservation projects. This material is also not sufficiently flexible and malleable to produce fine details often needed in building conservation.

Developing new materials from a bio-based background can mitigate traditional materials' drawbacks while addressing sustainability and thermal requirements. Limestone has historically played an essential role in construction. Many mortars and aggregates contain crushed stone and processed limestone [13, 14]. These minerals are found globally, which explains their widespread use [15]. Recent findings suggest that ancient Roman seawater concrete, made from volcanic ash and lime, has aged remarkably well and may offer insights into developing more durable building materials. One study by Ashraf et al. [16] explored the use of calcined clays to mimic the cementation mechanism of Roman seawater concrete and highlighted the importance of understanding and utilizing traditional building materials and methods that have demonstrated exceptional durability

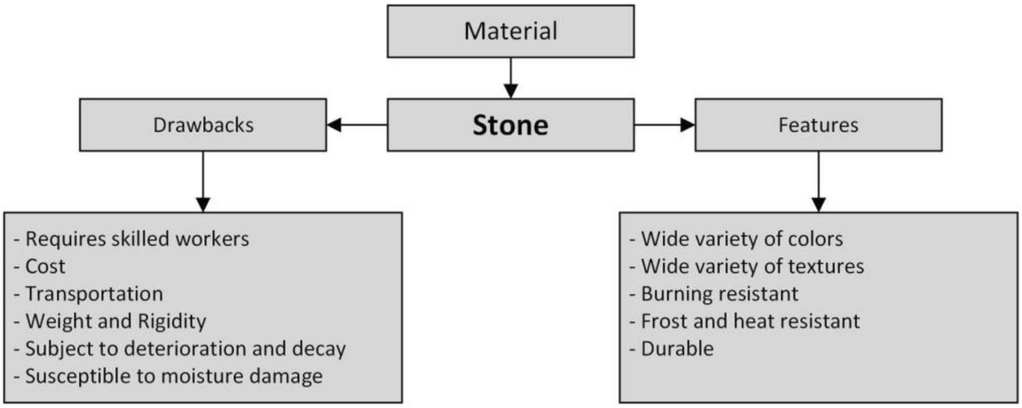


**Fig. 3** Key characteristics of stone: Features and drawbacks

over time, along with providing valuable insights into how modern materials can be engineered to achieve similar properties. Despite some limestone structures being in good condition, many structures have since disappeared, and earlier stone has been replaced [17]. The primary chemical constituent of limestone is $CaCO_3$, but its physical properties can differ widely. Significant factors influencing moisture movement and durability are limestone hardness, fossil content, and porosity [18]. Due to their chemical similarity, it is believed that limestone structures decay primarily through gradual dissolution, much like natural limestone outcrops and other weathering regimes.

### Heritage conservation in the Arabian Gulf region

Several heritage structures in the Gulf region have been preserved over time. Several types of masonry walls were used to construct such structures, including single- and multi-leaved walls. In 2013, a study conducted by Saudi Arabia's Department of Civil and Environmental KFUPM assessed the behaviors of various historical structures in Riyadh made of sandstone and lime mortar, the most widely used materials [19]. Some of the oldest historical sites in the eastern province of Riyadh are from 4300 B.C. Some castles have been damaged from unknown causes and are undergoing conservation and retrofitting.

The United Arab Emirates UAE has developed a traditional architecture influenced by varying nationalities and cultural motivations. Therefore, its architectural features are distinguished by simplicity, durability, and the ability to incorporate elements from different cultures. Construction materials used by Emiratis were traditionally derived from the local environment. Various materials were used, including stone, mud, palm fronds, and animal hair. Al-Zubaidi [20] demonstrated how "climate played a major role in the formation of traditional architecture" through stone houses with pitched roofs as the traditional homes of the Bedouins in the mountain areas of the United Arab Emirates. In addition to earthen brick and plaster, Abu Dhabi's historic buildings are usually constructed using stone, lime mortar, and renders. The Abu Dhabi Authority for Culture and Heritage (ADACH) conserves and manages historical buildings and archaeological sites in Abu Dhabi [21, 22]. In 1993 and 1994, Delma Island's Old Town restored four historical stone buildings. Unfortunately, the original construction and later conservation severely damaged their foundations as the coral stone and gypsum-based mortar contained salts [23].

## Materials and methods

### Proposed materials: technical properties and performance

The recent rapid global growth in the demand for sustainability in buildings and other construction sites has increased the need to develop natural materials commonly known as "bio-based materials" or "biomaterials" [24, 25]. Although the production of biomaterials began in 1974, this sector experienced a marked surge in 1998 and particularly after 2003 due to changes in public perceptions related to sustainability and environmental protection [26]. Some materials are already used commercially, while others are still developing [27]. Bio-based materials are reviewed in terms of their physical and thermal performances. The reviewed materials are assigned to the two categories of commercialized and non-commercialized thermal materials. This paper assesses the commercialized category as it has more information from published research and market data, as shown in Fig. 4. Table 1 shows the available information for the reviewed biomaterial properties [28–31].

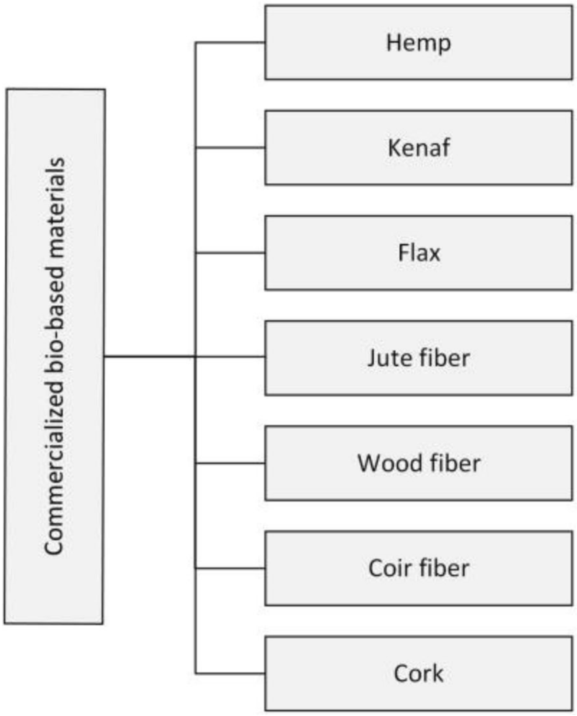


**Fig. 4** Key characteristics of stone: Features and drawbacks

### Heritage conservation material selection factors

Building materials must consider several factors, including their thermal, mechanical, acoustic, hydraulic, and economic properties. Liu et al. [27] recently demonstrated that thermal performance (thermal conductivity, thermal diffusivity, and heat capacity) has been the primary property investigated, as shown in Fig. 5. Materials in the heritage conservation process need to exhibit flexibility and must be available in a variety of colors and textures while having minimal impact on the environment and human health, as discussed in the literature.

Although the proposed materials can be manufactured in various shapes, including standard blocks, boards, or layers, the most appropriate manufacturing process depends on the design of the building and its skeleton. Several studies have found that compaction processes with biomaterials display promising properties, such as, rigidity, and dimensional stability upon loading [32].

### Color and texture

When restoring a monument of architectural or urban heritage, the color of the material should be considered. The color of the chosen building material is often affected by the spectral composition of the light source. In conservation work, color is often misunderstood for its ability to hide flaws [8]. In practice, color does not hide the defects of builders but rather exposes them. For centuries, color has been used to arrange spaces and complement or accentuate tectonic elements in architecture. It is also essential to dictate the motivations for material selection, including its technical, operational, decorative, and architectural characteristics, along with its compatibility with the conservation project.

A building's texture can also reveal how each part functions during construction, contrasting its color. To meet this requirement, bricks with a surface under crushed stone or bricks with rough textures generally cover massive sections of buildings. Bases, pylons, retaining walls, and floors, are all finished with a rough or matte texture. Glossy surfaces are often used to insert small objects, frame textures, or as a color spot [8].

When restoring a monument of architectural or urban heritage, it is essential to consider not only the color and texture of the building materials but also their albedo or the amount of light reflected by the material. Albedo can affect the material's appearance, durability, and ability to withstand solar radiation and thermal stress. Materials with high albedo can reflect more light and heat, helping to reduce thermal expansion and contraction. In contrast, materials with low albedo may absorb more heat, leading to greater stress on the structure [33]. To ensure that building materials are compatible with the original structure and provide the necessary support and protection over time, it is crucial to have a comprehensive understanding of their physical and mechanical properties. In some cases, surface treatments or coatings may be

**Table 1** Thermal and physical performances of commercialized biomaterials [28–31]

| Material | Thermal conductivity (w/m k) | Density (Kg/m$^3$) | Specific heat (KJ/kg k) | Fire classification | Water resistance |
|---|---|---|---|---|---|
| Hemp | 0.038–0.060 | 20–90 | 1.6–1.7 | E | 1.0–2.0 |
| Kenaf | 0.034–0.043 | 30–180 | 1.6–1.7 | D-E | 1.2–2.3 |
| Flax | 0.038–0.075 | 20–100 | 1.4–1.6 | E | 1.0–2.0 |
| Jute fiber | 0.038–0.055 | 35–100 | 2.3 | E | 1–2 |
| Wood fiber | 0.038–0.050 | 50–270 | 1.9–2.1 | E | 1–5 |
| Coir fiber | 0.040–0.045 | 75–125 | 1.3–1.6 | D-Eb | 5.0–30 |

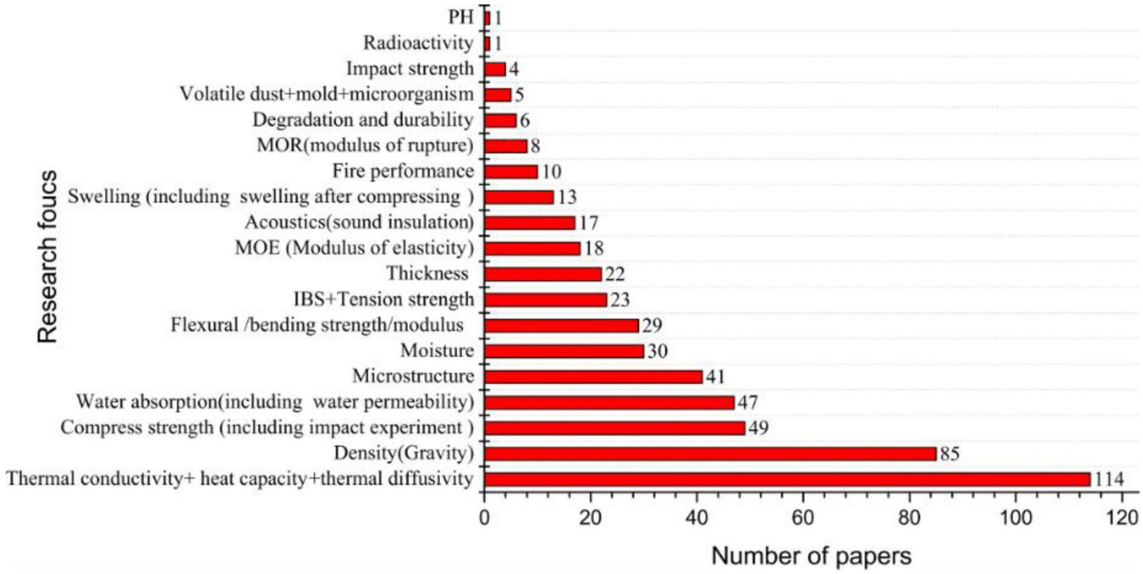


**Fig. 5** Biomaterial properties considered most in the literature [27]

necessary to alter the albedo of the material and achieve the desired aesthetic or functional result.

## Research methodology and framework

This research uses a mixed-method approach, which involves a theoretical overview of the biomaterials together with an integrated approach. Information regarding the reviewed materials was evaluated based on the availability of published research and studies in this field. We restrict the bio-based definition to materials or combinations of materials in which renewable, organic, biological, or agricultural raw materials represent at least 90% of the total mass of the material. These are considered as environmentally friendly organic material alternatives with primary advantages and disadvantages assessed through their physical properties in order to determine their suitability for heritage conservation. Their primary properties were evaluated following a comparative analysis of the selected materials and their suitability for heritage conservation was determined as shown in Fig. 6. At the end the best alternative material among the reviewed one was tested in the lab for more information related to its chemical structure. Analyses such as Fourier transform infrared spectroscopy (FTIR), x-ray powder diffraction analysis (XRD), thermogravimetric analysis (TGA) and scanning electron microscope (SEM) were carried out.

### *Fourier transform infrared (FTIR) spectroscopy analysis*

FTIR of the samples was performed using a Spectrum Two™ spectrometer (PerkinElmer, Massachusetts, USA) in transmission mode, using KBr pastilles prepared with 0.8 mg sample and 80 mg KBr [34]. The spectra were obtained in the spectral range of 400–4000 $cm^{-1}$ using the Spectrum software.

### *TGA analysis*

TGA was performed on a Netzsch STA409 EP instrument. Approximately 8 mg of samples were heated in a TGA pan from 20 to 800 °C in nitrogen atmosphere at a heating rate of 10 °C $min^{-1}$. Differential thermogravimetry (DTG) curves were obtained from the first derivative of the weight loss rate.

### *XRD analysis*

For XRD (XPert3 powder XRD, Malvern Analytical, UK), the sample powder was uniformly placed on the slit, and the XRD commenced scanning with a scattering diffraction angle, $2\theta$, in the range of 10–60° at a scan speed of 0.02° per second, 40 kV voltage, 20 A intensity, and 1.5406 ˚A Cu K$\alpha$ radiation.

### *Morphological analysis*

Morphological analysis was carried out on hemp fibers with an SEM operated at 10 kV and a working distance of 20 mm. All samples were placed on adhesive carbon tape, fixed in the SEM stub, and coated with gold in a sputter coater under a vacuum in the presence of inert gas. The gold-coated samples were then observed under vacuum conditions.

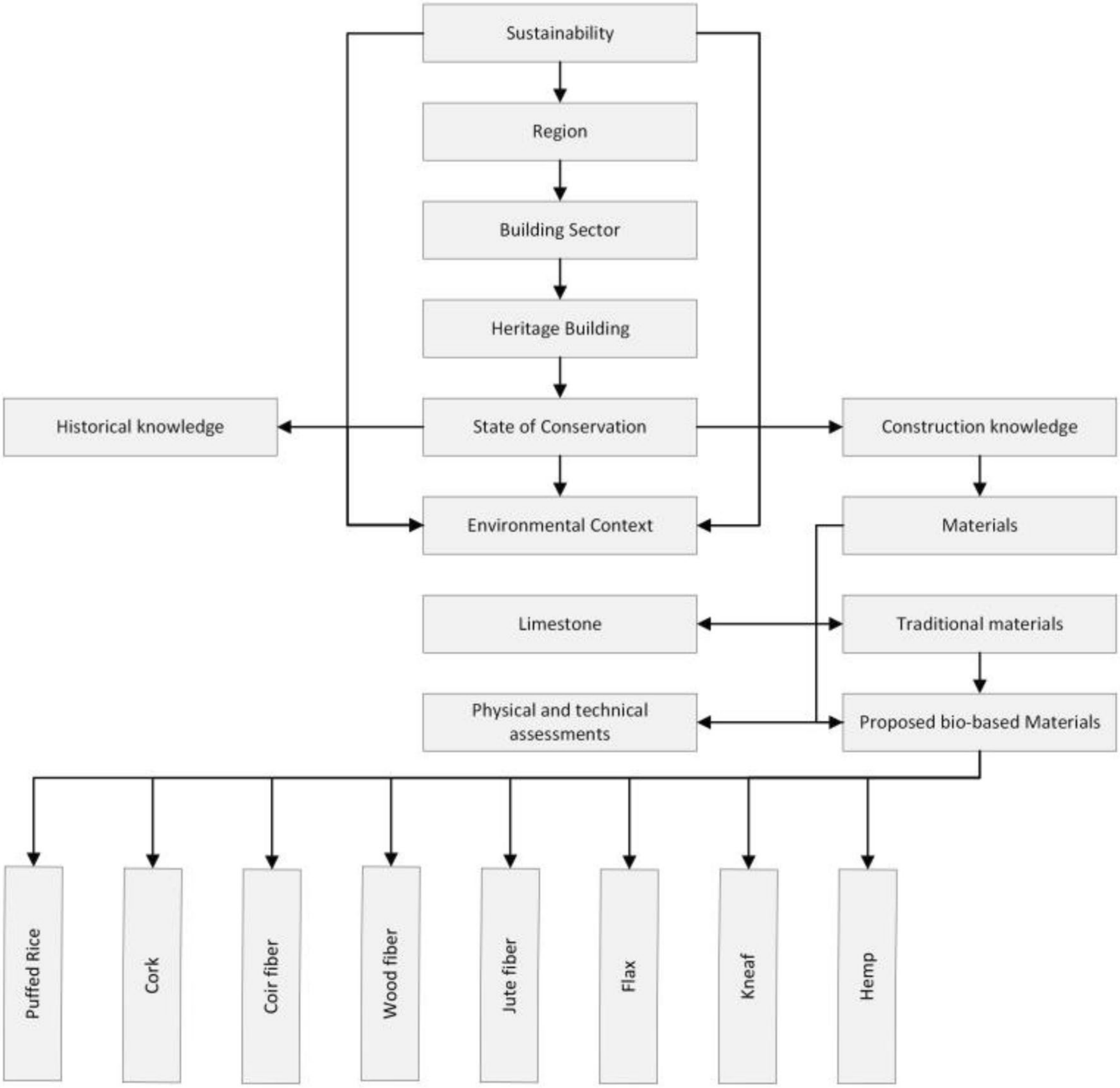


**Fig. 6** Key characteristics of stone: Features and drawbacks

## Results and discussion

### Comparative analysis between conventional materials, alternative materials, and proposed biomaterials

Table 2 compares conventional materials used in heritage conservation processes and the proposed biomaterials in terms of their thermal properties, fire resistance, variety of colors and textures, impact to the environment, and the production process. Despite stone being ubiquitous in heritage buildings, it does have a few drawbacks. First, it has a high thermal conductivity, which affects the overall heat gain to a building. Second, it has high chemical reactions with the surrounding environment. Therefore, the proposed biomaterials are competitive materials with stone due to their low thermal conductivity and ability to overcome chemical reactions through the use of additives. Stone has a variety of colors and textures; however, the considered biomaterials are superior in terms of flexibility and handling fine detail as they use different production technologies such as molding, in situ casting, and injection due to their semi-liquid formula at the initial production stage. Stone has the same features as most biomaterials. Still, it may affect workers' health as it releases dust and impurities during manufacturing, which have harmful long-term impacts on the lungs.

According to the literature, the proposed biomaterials are cost-efficient and straightforward to produce, while stone can be difficult to shape and require additional force and equipment. It can also be costly due to transportation and storage fees. To determine the best alternative based on the evaluation factors in Table 2, each

**Table 2** Comparative analysis between the commonly used building materials, materials, and the proposed bio-based materials

| Category | Type | Thermal conductivity | Fire resistance | Color and texture | Impact on labor health | Production process |
|---|---|---|---|---|---|---|
| Conventional materials | Stone | 2.000–2.160<br>* | Very good<br>*** | Variety of textures and colors<br>*** | Moderate<br>** | Complex<br>* |
| Bio-based materials | Hemp | 0.038–0.060<br>*** | A<br>*** | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>*** |
| Bio-based materials | Kneaf | 0.034–0.043<br>*** | C<br>* | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>** |
| Bio-based materials | Flax | 0.038–0.075<br>*** | B<br>** | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>*** |
| Bio-based materials | Jute fiber | 0.038–0.055<br>*** | E<br>* | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>*** |
| Bio-based materials | Wood fiber | 0.038–0.050<br>*** | B<br>** | Variety of textures and colors<br>*** | Moderate<br>** | Simple<br>*** |
| Bio-based materials | Coir fiber | 0.040–0.045<br>** | B2<br>* | Variety of textures and colors<br>*** | Moderate<br>** | Simple<br>*** |
| Bio-based materials | Cork | 0.037–0.050<br>*** | B<br>** | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>*** |
| Bio-based materials | Puffed rice | 0.049<br>* | A<br>** | Variety of textures and colors<br>*** | Low<br>*** | Simple<br>*** |

***Excellent, **good, *poor

proposed biomaterial was individually compared and ranked using a three-star rating system (*** excellent, ** good, * poor), with each star representing 1% as a value.

Figure 7 indicates that most biomaterials fell within the same range, and hemp received the highest overall rating, followed by flax and cork, jute fiber and wood fiber, and then kneaf and puffed rice. As a result, the study will focus on further analyzing the physical and chemical characteristics of hemp fiber, which was determined to be the best alternative. Additionally, the study will evaluate

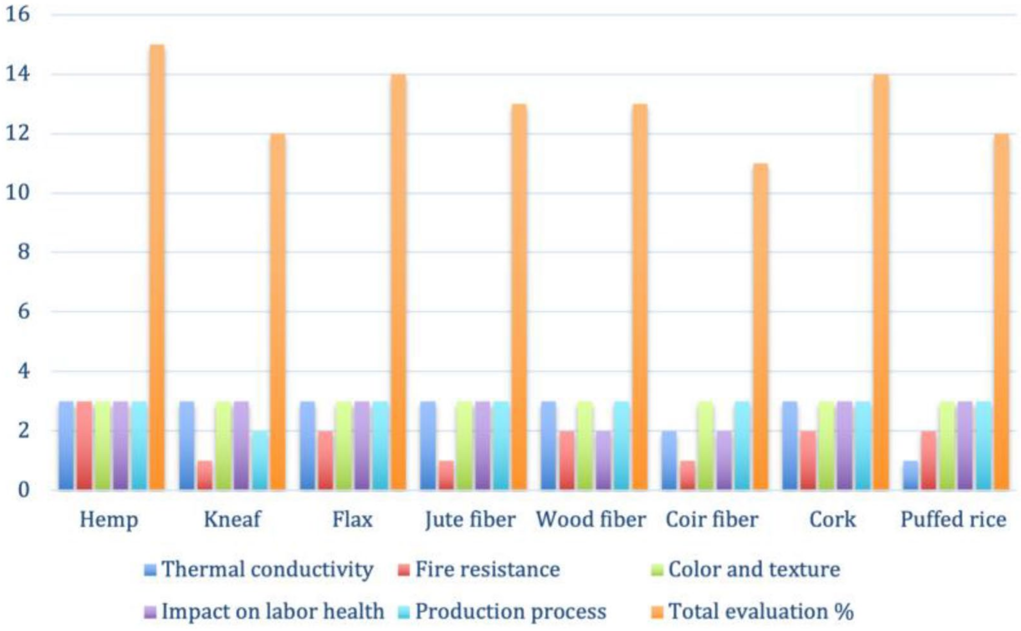


**Fig. 7** Comparison between the proposed biomaterials

the newly developed puffed rice material, which lacks an information database.

### Color and texture

Figure 8 illustrates the proposed biomaterials with stone color shades and textures, indicating the proposed biomaterials share similar textures and colors with stone. Although the biomaterials have a variety of colors and textures, the production process requires them to be dried first, which gives them similar brown shades to natural stone. In addition, the proposed biomaterials can be colored with additives from artificial colors, which will give the exact color needed for preservation.

In the lab, hemp fiber and puffed rice underwent tests for coloring and surface texture modifications. The selected materials demonstrated an ability to easily absorb a variety of colors and undergo changes in texture smoothness. Organic color was used in the tests, and Fig. 9 shows the results of four different colors with varying shades. Additionally, the test evaluated the modification of surface texture for both hemp and puffed rice, with approximately three levels of smoothness being observed.

The textural characteristics of puffed rice are dependent on various parameters, including the type of rice used, temperature and moisture percentage applied during modification, and the amount of rice utilized. Puffed rice demonstrates greater control over texture and requires fewer steps in comparison to hemp fiber, which requires additional modification following primary production

**Fig. 8** Proposed biomaterial and stone color shades and textures

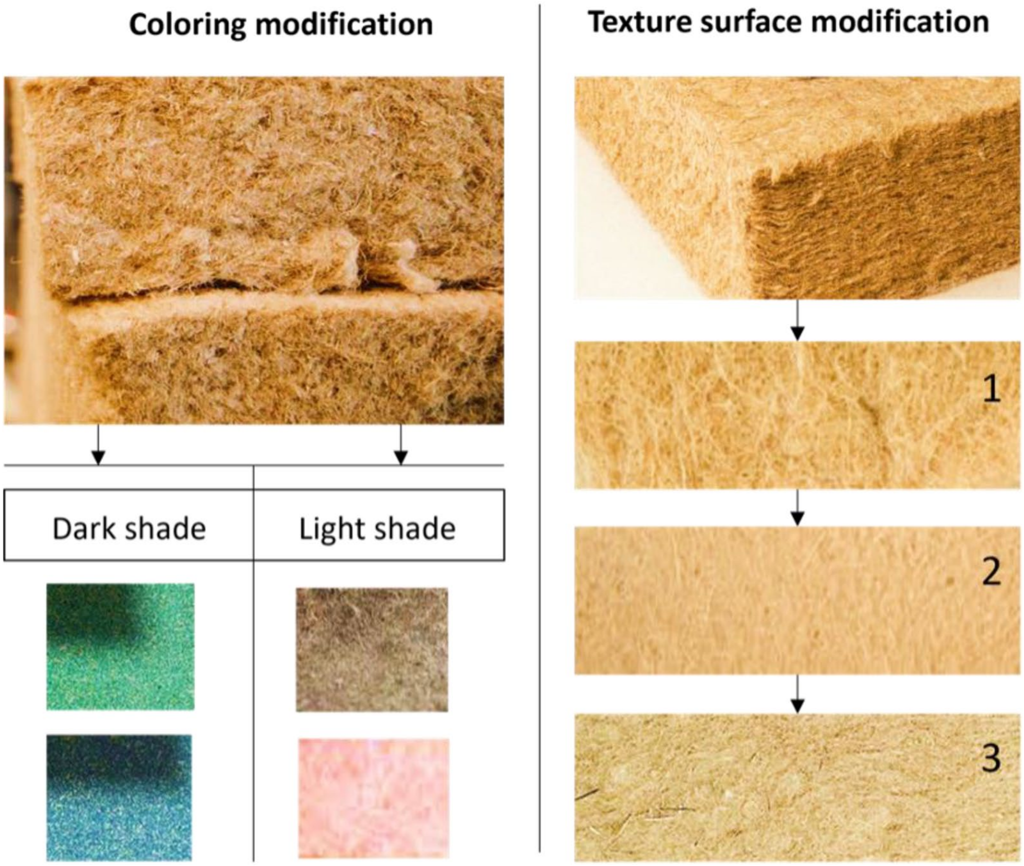


**Fig. 9** Hemp fiber coloring and texture modification

steps. Furthermore, puffed rice can be directly colored during the production process by utilizing different types of rice with varying colors, as illustrated in Fig. 10. Additives such as artificial coloring can be applied to raw rice prior to puffing, specifically during moisture control steps, to achieve the desired color and structure stability tests for hemp fiber and puffed rice.

The functional groups of hemp fiber and puffed rice were identified by FTIR analysis. Figure 11 shows the FTIR spectra for both materials, where each peak corresponds to a particular functional group. For example the peak in Fig. 11a at the wavenumber 673 $\text{cm}^{-1}$ corresponds to the out-of-plane bending of the C–OH group of cellulose and 896 $\text{cm}^{-1}$ corresponds to the symmetric ring-stretching mode of glycosidic bonds of polysaccharides particularly the C–O–C, C–C–O and C–CH deformation and stretching of cellulose. Figure 11b shows at $\lambda = 1250–1500\ \text{cm}^{-1}$ and $1500–1700\ \text{cm}^{-1}$, peaks that represent aromatic asymmetric stretching (C=C) in the puffed rice sample.

Thermogravimetric analysis was used to examine the weight loss associated with the temperature at which the components of hemp fiber degraded to comprehend the thermal behaviour of the samples. The stages of thermal deterioration of the primary components were represented by the DTG curves of the samples, which had four peaks at 55, 268, 365, and 447 °C (Fig. 12). The DTG profile is in line with the typical characteristics of lignocellulosic materials. The peak around 55 °C corresponds to the mass loss of the adsorbed moisture in the fibre, the one at 268 °C corresponds to the degradation and depolymerization of hemicellulose and pectin fraction and those at 365, and 447 °C corresponds to cellulose decomposition, and lignin degradation respectively. Cellulose is more resistant compared to hemicellulose and at temperatures above 300 °C, the dominant reaction taking place is the depolymerization of cellulose. The thermogravimetric curves demonstrate that the $T_{\max}$ (temperature of maximum weight loss) of the hemp fiber was at 365 °C, demonstrating their thermal stability. This characteristic points to the potential use of DFP fiber as potential reinforcing materials.

The X-ray diffraction patterns of hemp fiber are shown in Fig. 13a. The major peaks observed were at $2\theta$ diffraction angles of 16.5 and 22.8°, indicating the presence of crystalline cellulose. The maximum intensity ($I_{cry}$) at 22.8°

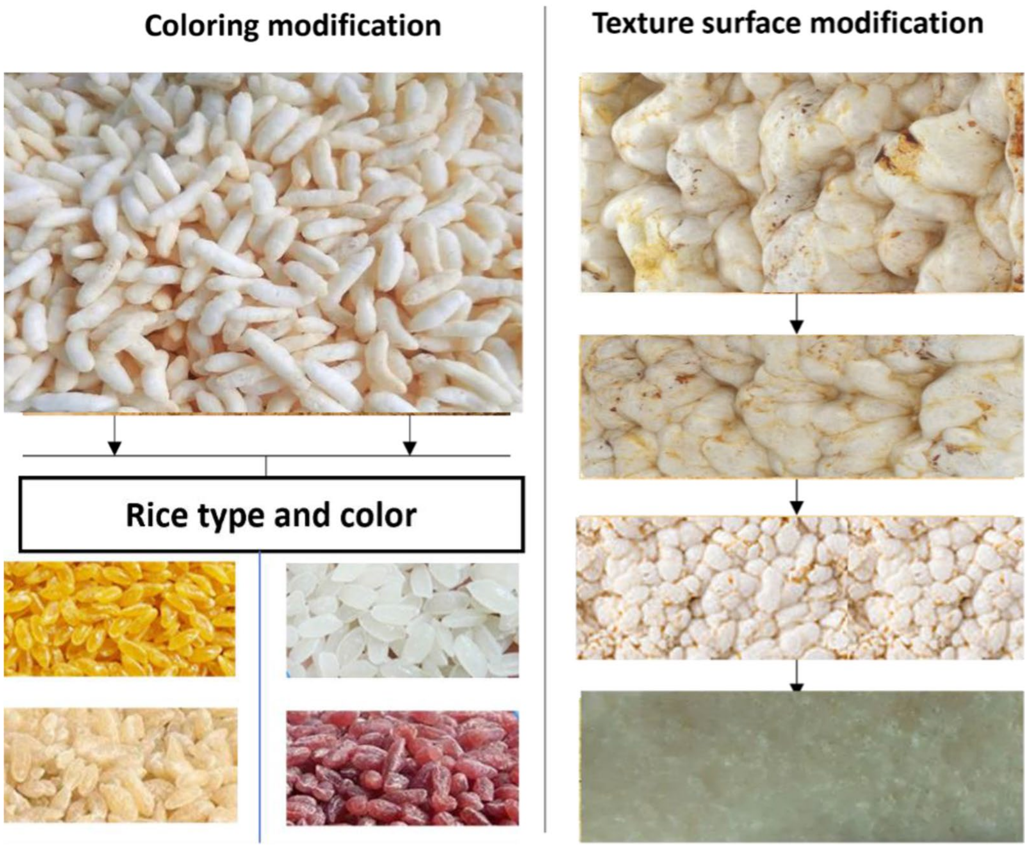
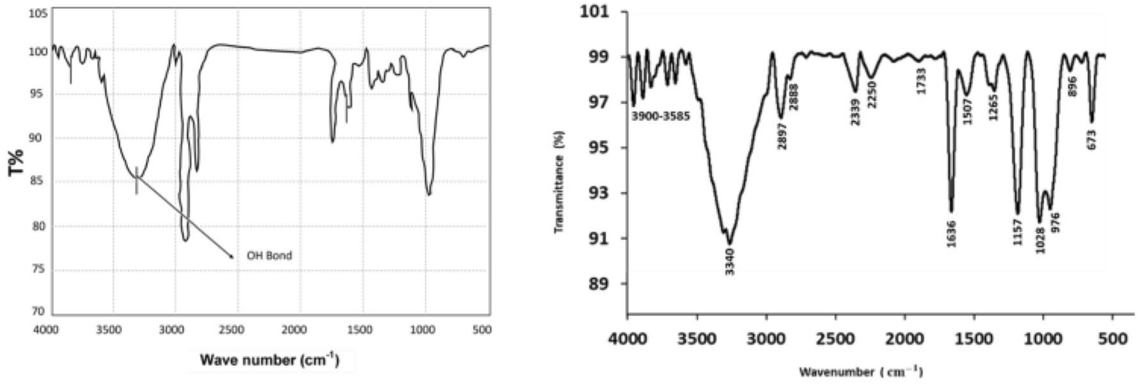


**Fig. 10** Puffed rice coloring and texturing modification



(a) (b)

**Fig. 11** FTIR spectra of **a** hemp fibre and **b** puffed rice

represents the cellulose crystallographic plane. The crystallinity index (CI) was calculated using the Segal empirical method using the equation below:

$$CI = \frac{I_{cry} - I_{am}}{I_{cry}} \times 100\% \tag{1}$$

where $I_{am}$ is the minimum intensity at $2\theta$ value of 18.9°. The CI of hemp fiber wasfound to be 77%.

The structural properties of a puffed rice sample were analyzed using an X-ray diffractometer with a Cu K$\alpha$ radiation wavelength of 1.54 ˚A (as seen in Fig. 13b). The initial examination revealed an A-type diffraction

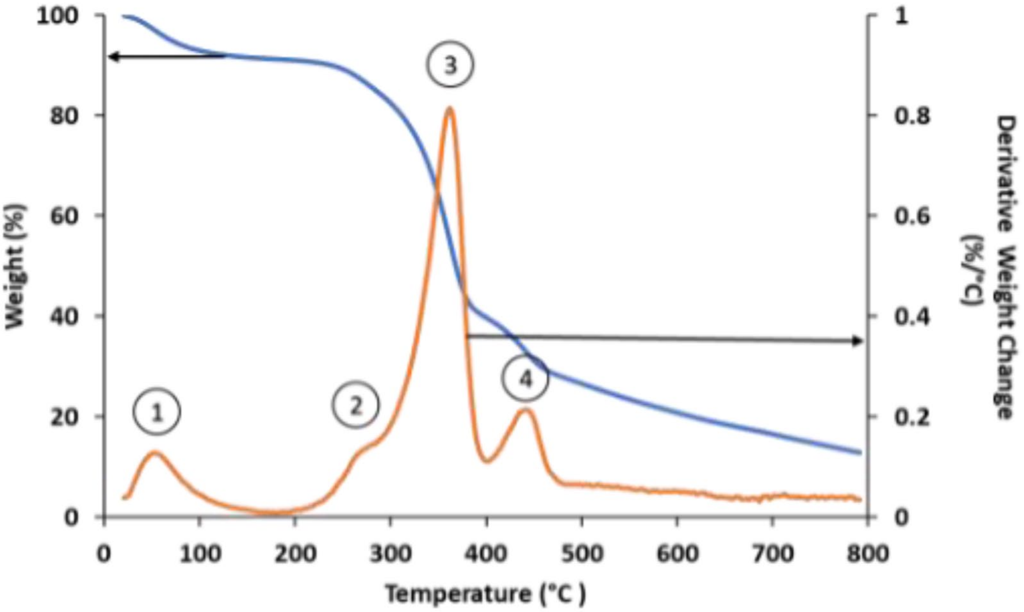
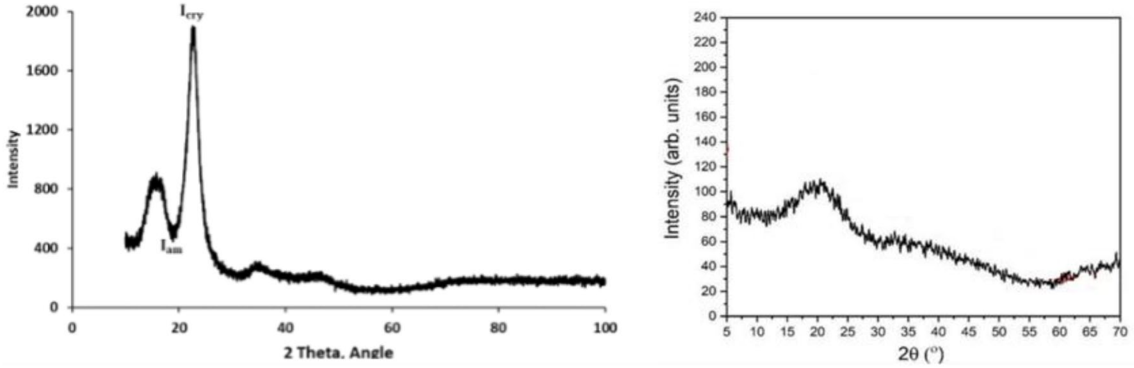


**Fig. 12** Puffed rice coloring and texturing modification



(a) (b)

**Fig. 13** XRD patterns of hemp fibres and puffed rice

pattern, characterized by a prominent peak at $2\theta = 20.3°$ [35].

The morphology of hemp fibers, as observed through SEM, can be seen in Fig. 14. It is mainly composed of fibrous bundles. In Fig. 14a, a highly crystalline (CI 77%) cellulose microfibrils bounded together by lignin and hemicellulose (Dai & Fan, 2010) can be observed. A smooth and glossy fiber surface can be seen in Fig. 14b which is due to the presence of non-cellulosic materials including the gummy polysaccharides of lignin, pectin and hemicelluloses. At some areas, like in Fig. 14c and d, the fiber looks cracked and peeled, exposing the interfibular structure of the fiber.

Upon analysis, the puffed rice sample exhibited a significantly porous internal structure that contained various cavities of varying sizes. Microscopic examination also detected voids and walls within the rice structure, distinguished by black and white colors in the resulting micrographs.

## Conclusion

Conservation is a critical process for the restoration and preservation of historic buildings and artwork that have suffered damage or deterioration over time. This process involves a range of technical activities that aim to restore these structures using materials and fabrics similar to

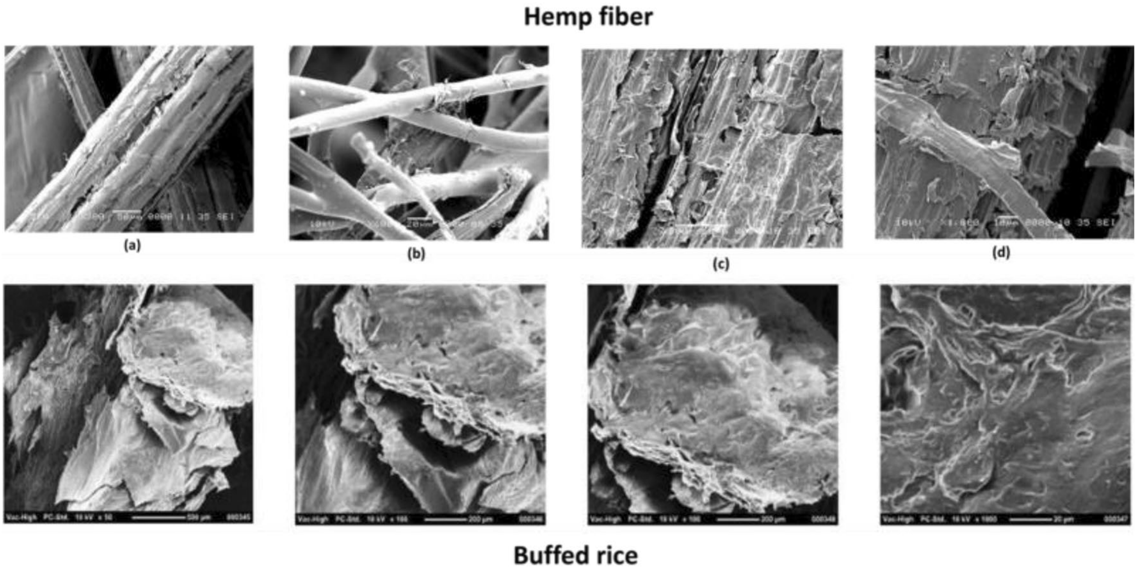


**Fig. 14** Puffed rice coloring and texturing modification

the original ones. The goal is to extend the lifespan of the building while retaining as many of its original features as possible. However, no studies have yet examined the use of biomaterials in heritage building conservation.

To address this knowledge gap, this work reviews the physical properties of select biomaterials in various scenarios commonly encountered in heritage building conservation. The study compares these biomaterials with other materials commonly used in heritage building conservation to identify their key advantages, characteristics (such as thermal and fire resistance, color, and texture), impact on the environment, production process, and cost.

The results show that the proposed biomaterials offer superior performance and can be designed with a variety of colors and textures, which is crucial for preserving the original appearance of structures. Using different production technologies, such as molding, in-situ casting, and injection, further demonstrates the superior physical properties of biomaterials. These materials are easily produced, cost-efficient, and reduce the amount of chemical waste in the system and the environmental impact using unique chemical formulations based on natural and available bio-agriculture waste.

The proposed biomaterials can be formulated to have standard textures and colors with unique characteristics that can be applied to any heritage building condition. These materials can also be used in newly constructed buildings or retrofit constructions. In addition to their use in exterior building structures, biomaterials can also be used in interior decor, furniture, and wall coverings.

The evaluation factors show that hemp is rated the highest, followed by Flax, kneaf, and puffed rice. The physicochemical and structural properties of the best alternative material, “Hemp” indicate that it has a high probability of being used for heritage building structures. Along with the Hemp fiber, the author also investigated the recently developed bio-based material puffed rice, which has great texture and color flexibility and thermal performance, similar to hemp fiber.

The proposed biomaterials offer greater flexibility than traditional stone materials due to their ability to color, shape, mix with other ingredients, and be applied to the building in different ways. This opens the door for more investigation using the proposed bio-based material for a more sustainable and aesthetically pleasing technique.

## Future work

It may be possible to extend the results of this study by obtaining a composition of the proposed biomaterials, along with additional thermophysical and mechanical data, and conducting cost estimation analyses:

- On the basis of the conserved building, an alternative composition of biomaterials can be developed.
- The tensile, strength, compressive strength, fatigue testing, accelerated aging testing, and shear strength of the proposed composite could be evaluated.
- It is essential to assess the cost of large-scale production of the proposed materials.
- Assess the impact of the proposed composite on the heritage building’s environment.

- Investigate the long-term carbon dioxide retention and durability of the proposed materials to ensure their performance over time.

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**Author contributions**
AS worked on research methodology, investigation, data collecting and analysis, as well as writing the original draft. AA is the project administrator and supervisor and contributed to the investigation and data analysis as well as writing the manuscript. MK has contributed to supervision, investigation and data analysis. SH contributed to lab tests, data analysis and writing. All authors read and approved the final manuscript.

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**Availability of data and materials**
All generated or analyzed data are included in this published article; for further details, supplementary information files are available from the corresponding author at a reasonable request.

**Code availability**
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## Declarations

**Ethics approval and consent to participate**
There is no ethics approval to declare. Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interest.

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