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Research Article

Systematic Review on the Use of Biodegradable Materials as a Sustainable Building Strategy: Adobe and Tapial

Ana María Lebrún Aspíllaga [1], Estela Karem Samamé Zegarra [2], Leydy Nataly Zamora Terrones [3], Anya Montserrat Pulido Cavada [4], Roberto Alonso González-Lezcano [5]

[1] Ph.D., Professional School of Architecture, Faculty of Architecture of the Sacred Heart Women's University – UNIFÉ, La Molina Campus, Lima, Peru
[2] Ph.D. Candidate, Professional School of Architecture and Urbanism, Faculty of Civil Engineering of the National University Santiago Antúnez de Mayolo (UNASAM), University City of Shancayán, Huaraz, Peru
[3] Msc, Professional School of Architecture and Urbanism, Faculty of Civil Engineering of the National University Santiago Antúnez de Mayolo (UNASAM), University City of Shancayán, Huaraz, Peru
[4] Ph.D. Candidate, Architecture and Design Department, Escuela Politécnica Superior, San Pablo-CEU University, CEU Universities, Montepríncipe Campus, Madrid, Spain
[5] Ph.D., Architecture and Design Department, Escuela Politécnica Superior, San Pablo-CEU University, CEU Universities, Montepríncipe Campus, Madrid, Spain
* **Corresponding Author:** rgonzalezcano@ceu.es

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ABSTRACT

Over the last two decades, earth construction techniques have gained attention as solutions to challenges in the construction sector, driven by the need for more housing due to population growth and rising welfare, alongside the urgent need to address global warming and biodiversity loss. This has led to a deeper understanding and modernization of traditional methods, such as those used in the construction of the Arg-é Bam citadel, the world's largest molded mud building. This article explores the advantages of using biodegradable materials as a sustainable design strategy, focusing on two ancient construction systems—Adobe and Tapia—both deeply connected to the environment and ecology. A systematic review of scientific articles published between 2016 and 2021, mainly from European and South American countries, was conducted. The analysis reveals that despite its many benefits, such as low environmental impact and resilience against extreme weather events, earthen construction remains a niche market. It offers an architecture that balances safety, sustainability, and ecology but is often perceived as exclusive to either the very wealthy or the very poor.

Keywords: Earthen Architecture; Vernacular Architecture; Sustainable Building; Sustainable Design; Sustainable Construction; Sustainable Design.

INTRODUCTION

Construction is one of the sectors with the greatest impact on the environment and natural resources. Environmental and energy challenges, both current and future, require a radical transformation in the philosophies, strategies, technologies, and methods of building design and construction. The growing need for new spaces to cope with population growth and ensure optimal living standards conflicts with the global commitment to curb global warming and biodiversity loss. To address this double challenge, it is essential to move towards a more circular economy, through the widespread use of alternative construction practices and materials with low environmental impact (Morel et al., 2021; Díaz et al., 2018). In this context, vernacular architecture has experienced a resurgence in recent decades, which has aroused the interest of various research groups and architectural studios, attracted by its potential to offer innovative solutions. Between 1998 and 2019, the Scopus database showed an increase of more than 98% in the publication of articles related to land use in the field of engineering. Earth, a material used worldwide throughout history for its accessibility, versatility, low cost and rich tradition, currently constitutes approximately 30% of the world's cultural heritage (Larraz, 2015). However, the question arises: Why hasn't this remarkable increase in research been reflected in a similar way in the construction sector?

The great impact that the construction sector generates on biodiversity is well known; about 50% of the waste produced by the European Union is generated by this sector and represents 25% worldwide. Among other waste, about 75% refers to natural soils and stones; in short, the earth is considered waste in Western countries even though it has been used as a building material since the origins of construction, as it does not support the ideology of progress that emerged with the Industrial Revolution and has prevailed ever since. Technical barriers to the use of land as a building material have aroused great interest from researchers since the 1990s and have been increasing since then. However, two-thirds of the actual barriers identified by the researchers are neglected in the literature. Social, economic, organisational and political aspects have been little addressed by the scientific community apart from the recent publication by Rabia Charef, which exposes a series of socio-economic and environmental barriers with respect to the use of land as a building material and how to achieve a circular economy (Morel et al., 2021; Charef, Ganjian, & Emmitt, 2021).

Vernacular constructions, which have evolved over the centuries, are deeply influenced by cultural traditions and an intuitive understanding of the natural environment. In addition, the use of local and sustainable materials not only respects the environment, but also promotes the adoption of passive construction techniques, which are increasingly valued in contemporary construction (Zhai & Previtali, 2010). This type of construction, present in various cities in Latin America, many of which are part of today's historic centers, is characterized by combining an understanding of the local climate, the use of indigenous materials, and traditional construction techniques (Oliver, 1997; Fernandes, Mateus, & Bragança, 2014; Lawrence, 2006), always linked to the historical and cultural traditions of the communities (Foruzanmehr & Vellinga, 2011; Rashid & Ara, 2015). In the words of Hubka (2012), vernacular architecture arises from the basic needs of housing and the collective ingenuity of people, without the intervention of experts, to meet the demands of the community (Oliver, 1997; Fernandes, Mateus, & Bragança, 2014; Loo, Leila, & Mohammad, 2016). In ancient times, means of transport were limited and builders had to adapt to locally available materials. Earthen construction has the advantage of ease of transport and automation of on-site manufacturing. Its use in construction should be more popular now than ever; However, history has marked this material as of low quality with respect to other modern materials such as concrete or steel, being suitable only for less developed countries with few resources, or for tailor-made architectural projects for the rich.

The scarcity of decent housing in many countries, especially in less developed ones, such as Peru, has driven a renewed interest in ancestral construction technologies, such as Adobe and Tapial. The term Adobe refers to a simple and low-cost structural typology made mainly of mud; such typology is based on prefabricated earthen modular elements whose blocks harden after being dried in the open air; after this process, they are commonly known as 'bricks'. Despite being one of the most widely used construction techniques worldwide, many of these practices have not been recognized geographically and chronologically to date (Quiles, Knoll,& Maestre, 2019). This is because, as these structures are highly vulnerable to natural phenomena such as rains and earthquakes, many of them have disappeared throughout history, either due to lack of maintenance or due to the displacement of civilizations to other more prosperous and advanced cities. Secondly, Duarte, Alcindor, and Correia (2018, p. 247) define Tapial as

> The constructive technique of monolithic earthen walls, compressed in sliding formworks. The basis of the system, generically, consists of a constructive system of structural walls formed by thick overlapping layers (50-70 cm), executed from the compaction of the soil inside modular wooden panels that are properly anchored. This technique tamps the wet soil without the inclusion of fibers.

Both systems are based on the use of land, one of the most abundant and accessible materials, representing 30% of the earth's surface (Moscoso-Cordero, 2016). This feature makes it a viable and environmentally friendly alternative.

This article addresses the existing gaps and dualities in research on the revaluation of sustainable natural materials, with a particular focus on earth construction, a material that is gaining relevance in contemporary architecture. Through a systematic review of the literature, the main academic studies on the subject are examined, identifying current trends, the advantages of using natural materials and the associated construction techniques that promote low environmental impact. The main objective of this research is to expand the field of study on the application of sustainable and biodegradable materials in modern architecture, providing a solid basis to promote their use in sustainable design projects. This approach seeks not only to rediscover earth construction from an innovative perspective, but also to recover the close historical relationship between man, architecture and his environment, a fundamental principle of past eras. In times when building with earth responded to a harmonious integration with the context, today that same principle is projected in the contemporary practices of Bioconstruction and Zero Kilometer Construction, which stand as key aspirations for the sustainable architectural design of the future.

METHODOLOGY

In order to identify the problems associated with the introduction of vernacular architectural materials in highly technological environments that are increasingly disconnected from their cultural identity, the scope of this study is based on the systematic review of various scientific articles published between 2016 and 2021, interpreting the term 'Systematic Review' (SR) as an allusion to a specific research methodology developed to obtain and evaluate the available evidence on a specific subject (Kitchenham, Hughes, & Linkman, 2001). SR will allow, through a process of empirical synthesis, an overall conclusion to be drawn about individual studies on the topic in question.

This section presents the databases used during the study and the search criteria. The technical barriers associated with the use of earth as a building material have aroused growing interest in the scientific community since 1990, with a significant increase in publications on the subject. To compile, organize and synthesize all available information on Adobe and Tapia construction, as well as to identify under-explored areas, a systematic review was carried out to address in a structured manner the main aspects and challenges related to this material. Due to the large number of articles indexed in the SciELO and SCOPUS databases, a selection of articles was carried out under a series of keywords representing the main themes presented in the RS; these terms were: Adobe, Tapial, Rammed Earth, Earthen Architecture, Earthen Architecture, Architecture with Earth, Architecture and Earth. These terms were: Adobe, Tapial, Rammed Earth, Earthen Architecture, Architecture with Earth, Architecture and Earth. Under this criterion, the trend of scientific publications on the use of biodegradable materials was established, where the first exclusion criteria were defined, removing studies that were not written in Spanish or that were not published between 2016 and 2021. A total of 102 articles were obtained, as shown in Table 1.

Table 1. Number of Articles Published between 2016 and 2021 after Filtering by Keywords in the Scopus and Scielo Databases

Database	Search Equation	Year					
		2016	2017	2018	2019	2020	2021
SCIELO	Adobe and year cluster ("2018" or "2020" or "2019" or "2017" or "2021" or "2016")	4	7	13	9	13	5
	tapial and year cluster: ("2018")			1			
	(Arquitectura en tierra) and (adobe) and year cluster: ("2018" or "2021")			4			1
	(Arquitectura en tierra) and (tapial) and year cluster: (2018)			1			
	Arquitectura con tierra and year cluster: ("2018" or "2016" or "2017" or "2019" or "2021")	2	2	13	2		1
SCOPUS	Title-abs-key (adobe and arquitectura) and (limit-to (pub. year, 2020) or limit-to (pub. year, 2018) or limit-to (pub. year, 2017) and (limit-to (doctype, "ar") and (limit-to (language, "Spanish"))		2	1		1	
	Title-abs-key (arquitectura and tierra) and (limit-to (pub. year, 2020) or limit- to (pub. year,2019) or limit-to (pub. year, 2018) or limit- to (pub. year, 2017) or limit-to (pub. year, 2016) and (limit-to (language, "Spanish") and (limit-to (srctype, "j"))	1	3	2	1		
	(Pub. year, 2021) or limit-to (pub. year, 2020) or limit-to (pub. year, 2019) or limit-to (pub. year, 2016) and limit-to (doc. type, "ar") and (limit-to (language,"Spanish"))				3		1
	Key (adobe or tapial) and (limit-to (pub. year, 2021) or limit-to (pub. year, 2020) or limit-to (pub. year, 2019) or limit-to (pub. year, 2018) or limit-to (pub. year, 2017) or limit-to (pub. year, 2016)) and (limit-to	1	1	2	1	3	1

Database	Search Equation	Year					
		2016	2017	2018	2019	2020	2021
	(doc. type,"ar")) and (limit-to (language,"Spanish"))						
Total							102

Similarly, Figure 1 shows the article selection process showing the number of articles discarded from each of the considered criteria. Starting from 102 potentially notable articles, the exclusion criterion was applied based on repeated articles (n=28), resulting in 74 potentially relevant articles. Next, references based on the description of the content reflected by the article title were excluded (n=39), resulting in 35 articles. Subsequently, an exclusion criterion was applied based on the narrative and conclusions offered in the abstract of each article (n=14) resulting in 16 potentially relevant journal articles. Finally, the exclusion criterion based on the review of the full body and implications of the article was used (n=01), resulting in 20 studies being included.

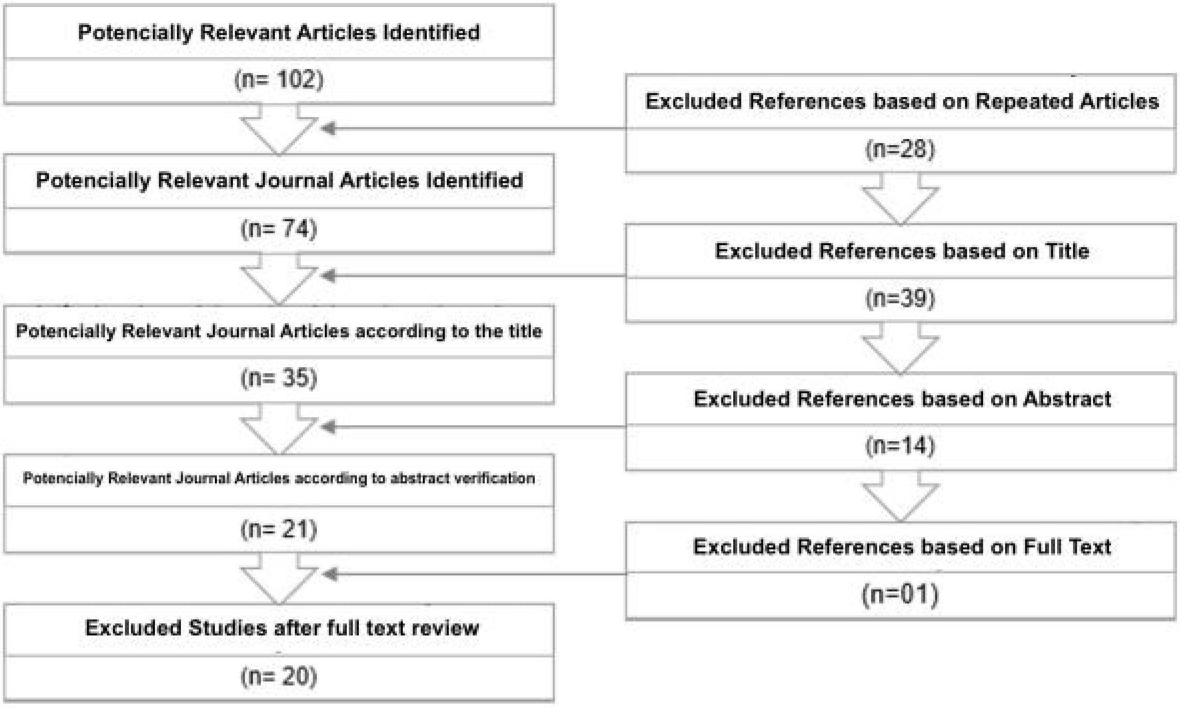

Figure 1. Item Exclusion Flow Chart after the First Exclusion Process

Note: Figure 1 shows the exclusion process that was carried out in this SR to include only studies that are crucial for this review.

The data referring to the 20 articles resulting from the exclusion process are described in Table 2. All of them will be referenced for the development and writing of this SR.

Table 2. Distribution of the Selected Articles for the Review after Applying the Second Exclusion Criterion

Author(s)	Year	Journal	Title	Country	Doi
Ríos Cabrera Silvio	2018	Annals of the Institute of American Art and Aesthetic Research. Mario J. Buschiazzo	Earthen construction in rainy climates: Colonial and independent period developments in the Paraguay, Paraná and Uruguay river basins.	Argentina	http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S2362-20242018000100008&lang=es
Guerrero Luis Fernando	2018	Estoa. Magazine of the Faculty of Architecture and Urbanism of the	Land as a sustainable conservation material	Ecuador	http://scielo.senescyt.gob.ec/scielo.php?script=sci_arttext&pid=S1390

Author(s)	Year	Journal	Title	Country	Doi
		University of Cuenca.			-92742018000100078&lang=es
Basile Silvana	2018	Annals of the Institute of American Art and Aesthetic Research. Mario J. Buschiazzo	Reflections in the context of architectural heritage on land: Protecting, conserving and restoring modest heritage	Argentina	http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S2362-20242018000100003&lang=es
Rivera-Salcedo Hernán, Valderrama-Gutiérrez Ornar Mauricio, Daza-Barrera Ángel Andrés, and Plazas-Jaimes Gerson Santiago	2021	Architecture Magazine	Adobe as ancestral knowledge used in indigenous constructions in Pore and Nunchía, Casanare (Colombia).	Colombia	http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S1657-03082021000100074&lang=es
Duarte Carlos Gilberto, Alcindor Mónica, and Correia Mariana	2018	Annals of the Institute of American Art and Aesthetic Research. Mario J. Buschiazzo	Traditional earthen architecture in Europe: A heritage of half-timbering and basketry, adobe, walling and hand-walling	Argentina	http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S2362-20242018000200009&lang=es
Daneels Annick	2018	Annals of the Institute of American Art and Aesthetic Research. Mario J. Buschiazzo	Mesoamerican earthen architecture: A pre-Columbian heritage in need of revalorisation	Argentina	http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S2362-20242018000200003&lang=es
Joffroy Thierry, Le Tiec Jean Marie, Rakotomamonjy Bakonirina, and Misse Arnaud	2018	Annals of the Institute of American Art and Aesthetic Research. Mario J. Buschiazzo	The rammed-earth architectural heritage of the Auvergne-Rhône-Alpes region: From its (re)discovery to contemporary architecture	Argentina	http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S2362-20242018000200008&lang=es
Carlos Castillo Levicoy and Constanza Pérez Lira	2020	Ge-conservation	Architecture in adobe and quincha: Building an identity around the natural resources of the shores of Lake General Carrera in the Aysén region, Chile.	Chile	https://doi.org/10.37558/gec.v18i1.769
Jacinto Canivell and Gabriela Claudia Pastor	2018	ACE	Evaluation of vernacular architecture built on earth in the province of Mendoza. Approaches and results	Spain	http://dx.doi.org/10.5821/ace.13.37.5180
Abril Revuelta, O. and Lasheras	2017	Construction Reports	Earthenware, stone and mud and stone domes in the auxiliary constructions of popular architecture	Spain	http://dx.doi.org/10.3989/id54749

Author(s)	Year	Journal	Title	Country	Doi
Merino, F.			in the centre of Castilla y León		
Javier Perez Gil	2019	Memory and Civilisation	Manolo's dovecote. A case study of vernacular architecture from the paradigm of culture.	Spain	https://doi.org/10.15581/001.22.002
Teresa Gil Piqueras	2017	Archaeologica-l Drawing	Archaeology of earthen architecture. Graphic study in the valley of the M'Goun river valley, Morocco	Spain	https://riunet.upv.es/handle/10251/107465
Manuel Rubio Valverde	2021	Archaeology of Architecture	The wall in the city of Cordoba during medieval and modern times. A first typological proposal	Spain	https://doi.org/10.3989/arq.arqt.2021.009
Norma Ratto, Néstor Bonomo, and Ana Osella	2019	Latin American Antiquity	Architecture of the village of Palo Blanco (ca. AD 0-1000), Tinogasta Department, Catamarca, Argentina	Spain	https://doi.org/10.1017/laq.2019.71
Santiago Quesada-García and Guadalupe Romero-Vergara	2019	Archaeology of Architecture	The system of Muslim towers in the Sierra de Segura (Jaén). A contribution to the study of the rural world and the landscape of al-Andalus	Spain	10.3989/arq.arqt.2019.001
Juan Chacón, Betzabeth Suquillo, Diego Sosa, and Carlos Celi	2021	Polytechnic Magazine	Evaluation and Strengthening of a Heritage Adobe Structure with Irregularity in Plan	Spain	https://doi.org/10.33333/rp.vol47n1.05
J. D. Rodríguez-Mariscal and M. Solís	2020	Construction Reports	Towards a methodology for the experimental characterisation of the compressive behaviour of adobe masonry	Spain	http://dx.doi.org/10.3989/ic.67456
María Pastor Quiles, Franziska Knoll, and Francisco J. Jover Maestre	2019	Archaeology	Mud, lumps or balls of mud? Balls? Contributions to the archaeological recognition of different building techniques using earthen modules	Spain	10.34096/arqueologia.t25.n2.6868
Natalia Jorquera Silva and C. Torres Gilles	2018	Construction Reports	Seismic reinforcement techniques for the structural recovery of Chile's adobe architectural heritage	Chile	https://doi.org/10.3989/ic.16.128
B. Orta, J. Adell, R. Bustamante, and S. Martínez-Cuevas	2016	Construction Reports	Earthquake-resistant self-construction system: Strength characteristics and construction process	Spain	http://dx.doi.org/10.3989/ic.15.082

Note: Data obtained through combined outcome variables

Of the twenty articles analysed, nine of them were published in 2018, unlike the rest of the publications that were grouped from one to three articles during the years 2016, 2017,2019, 2020 and 2021 written in the Spanish language (Figure 2).

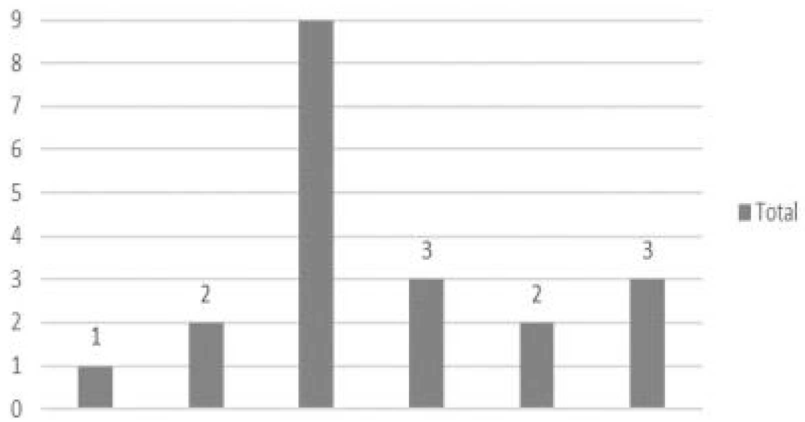

Figure 2. Graph of Publications by Year

Note: Figure 2 reflects publications from 2016 to 2021

Although earth architecture is a widely practiced technique in various regions of the world and is gaining global recognition, its highest concentration is found in Spanish-speaking countries, especially in Latin America and some areas of the Mediterranean. This predominance is due to the historical context dating back to pre-Columbian civilizations, the availability of local materials compared to other resources that are more difficult to obtain, such as cement, and the climatic and environmental conditions typical of dry or semi-arid zones. However, the use of this construction system is not limited exclusively to these regions. Africa, Asia and the Middle East also have a rich tradition of earth construction, although in terms of visibility and academic research, these contexts have not received as much attention. This reality is reflected in Figure 3, where it is shown that the main authors of nine of the twenty articles analyzed are affiliated with Spanish institutions.

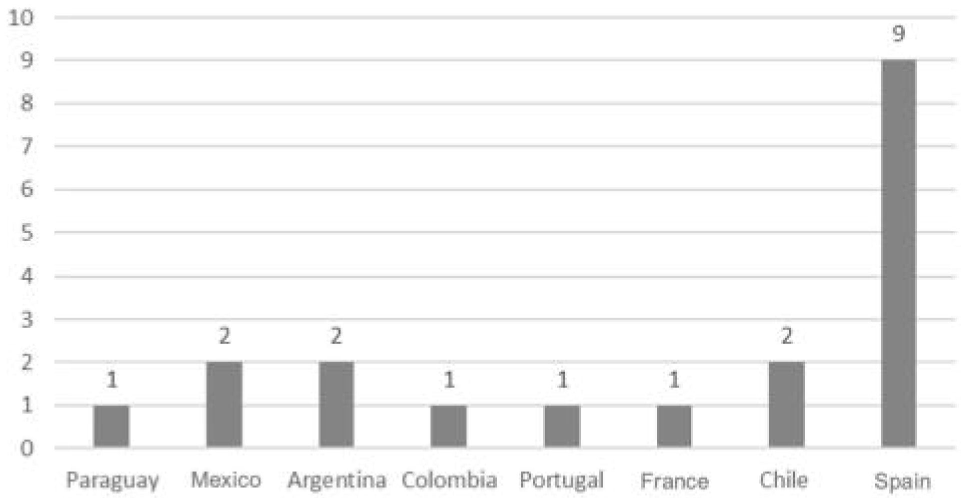

Figure 3. Graph of Publications by Affiliation

Note: The affiliation of Spanish authors represents almost 50%.

Table 3. Selected Articles for the Review Classified by Topic

Topics	Articles
Adobe	Ríos (2018), Rivera-Salcedo et al. (2021), Duarte et al. (2018), Daneels (2018), Castillo and Pérez (2020), Canivell and Pastor (2018), Revuelta and Merino (2017), Pérez (2019)
Tapial	Duarte et al (2018), Joffroy et al (2018), Rubio (2021), Quesada (2019), Ratto, Bónomo, and Osella (2019), Joffroy et al. (2018)
Natural Material for Conservation and Restoration	Guerrero (2018), Basile (2018), Canivell and Pastor (2018), Pérez (2019)
Vernacular Architecture	Ríos (2018), Castillo and Pérez (2020), Revuelta and Merino (2017), Pérez (2019)

Against this background, the general objective of this systematic review is to determine the advantages of using natural materials of a biodegradable nature - adobe and rammed earth - as a design and sustainable development strategy (Table 3).

RESULTS

The desire to reduce the environmental and social impact of the construction industry has led to a renewed interest in earthen construction. Most of the literature on earthen construction covers adobe and/or rammed earth techniques (Hamard, Cazacliu, Razakamanantsoa, & Morel, 2016). However, the adoption of local materials in more developed countries may be hampered by the perennial use of "modern" materials and the lack of standardization of many primitive construction techniques (Morel, Mesbah, Oggero, & Walker, 2001). There is thus the paradoxical situation of the decline of these vernacular building traditions in the face of the rise and acclaim of their modern counterparts, but which are repeatedly cited in the academic literature as exemplary environmental models (Aza-Medina, Palumbo, Lacasta, & González-Lezcano, 2023; Sanchez et al.,2021).

Earth is a building material that has proven to be very durable. Proof of this is the archaeological and architectural heritage that has endured over the years and has reached our days in surprisingly good condition, as Guerrero (2018) states. About 40% of the current population lives in earthen dwellings, a construction tool that represents the oldest material used throughout history. It is abundant, cheap, energy efficient, and affordable for everyone, but earth has historically been associated with poverty and unemployment, migration, and inequality, and is mainly used in resource-poor countries. The application for conservation and restoration of built heritage is appropriate because earth is an "extremely versatile material and employs techniques that are relatively simple to learn and implement" (Guerrero, 2018, p. 58). Despite all this, the simplicity of the material need not be an excuse for poor planning (Becker, 2015).

According to Ríos (2018), vernacular architecture is a response of the inhabitants of a region to climatic conditions, considering the resources of the area and known technologies. Earthen construction covers a specific territory, and, in each region, specific responses are used. This cultural manifestation is found in traditional Latin American architecture, specifically in the region of Aysén, Chile. Between 1925 and 1929, adobe houses were found whose composition, according to settlers knowledgeable about the ancestral technique, reflected the characteristics of the territory since it resembled clay, composed of coirón and horse manure; other additives used were wheat and barley stubble because it was cultivated at the time (Castillo and Pérez, 2020). The application of in-situ soils for building construction is attractive in the framework of sustainable development, as their use integrates low embodied energy and has beneficial hygrothermal behavior. In relation to this behavior, Bui, Morel, Tran, Hans, and Oggero (2016) conducted several investigations to analyze different soil compositions. However, the variability of soil composition and characteristics at each site resulted in an uncertain choice as to the most favorable construction technique (earth concrete, rammed earth, adobe, etc.) that would meet the requirements of modern standards in terms of economics, mechanical, thermal, durability and seismic performance. Therefore, Bui et al., (2016) presented a strategy that would be able to facilitate decision-making regarding the most appropriate construction technique to be carried out according to the type of in situ soil presented for construction, by performing a study of material optimization, architectural design, structural and thermal performance and a life cycle analysis. According to Guerrero (2018), the various methodological procedures, the quality control of raw materials and the use of appropriate tools bring us closer to a more sustainable technological development, aimed at greater attention to the conservation and restoration of the architectural heritage constituted in earth, regardless of the construction system carried out.

Due to the high presence of earthen constructions in many countries, such as Ecuador, Pérez (2019) identified certain sustainable criteria that were verified within this construction typology, based on the analysis of houses located in the south of the country, in the provinces of Azuay and Cañar. Based on these two regions, a critical analysis was carried out based on a selection of houses that complied with traditional construction systems such as adobe, rammed earth and mixed systems; from these, it identified and recorded certain passive measures carried out to cope with local environmental conditions, such as topography, sunlight, ventilation and temperature, which ranged between 6°C and 20°C in both provinces. Adding to this field of research, Bui, Morel, Hans, and Walker (2014) studied the influence of moisture content and its impact on the mechanical properties of the sample. Carrying out different models with variations in the matrix and its dispersed phases -sand, clay and stabilizers- they performed unconfined compression tests with various moisture contents, determining compressive strength, elastic modulus and Poisson's ratio, concluding that a slight increase in the moisture content of dry rammed earth is not followed by a sudden drop in wall strength.

Adobe

Adobe is a material that resonates in the history of construction for thousands of years, being one of the first materials used by man to protect himself from the inclemency of the weather; this is evident both in indigenous peoples of the Americas and in the southwestern United States, as well as in Mesoamerica and the Andean region of South America (Gama Castro et al., 2012). In the study carried out by Rivera-Salcedo et al. (2021) together with the department of Casanare on the use of Adobe in the municipalities of Nunchía and Pore, in Colombia, Adobe is described as an ancestral material applied in different countries around the world. Its use is still visible in numerous constructions thanks to various populations that have chosen to maintain this tradition over the centuries. According to the results of this study, it is revealed that

> The first buildings in the region were made of adobe, but over time this practice has been lost, due to the arrival of industrial materials such as block, iron and cement; even so, there are houses built in this material (adobe) that still maintain their useful life.

The construction techniques to carry out the execution of Adobe have undergone constant modifications throughout history, which is due to the needs and benefits of each territory, considering various factors such as climate, customs, soil and labor, among others. The techniques used by the settlers - Nuncía and Pore - to make adobes, are centered on four stages as described by Rivera-Salcedo et al. (2021): the selection of materials; the mixing process; the molding system, and the conditions of the drying process. Chacón et al. (2021) carried out an analytical study concerning the vulnerability analysis and seismic rehabilitation of a heritage structure made of adobe. The authors found that the seismic deficiency is mainly due to the heavy weight of the structure, the low displacement capacity and the brittle behavior of the material that makes up the walls (Blondet & Aguilar, 2007). Therefore, during severe earthquakes, typical failure modes are severe cracking, disintegration of walls, separation of walls at corners and detachment of roofs from walls (Chacón et al., 2021). In addition, the failure of unreinforced adobe structures is fragile due to the low tensile strength of the material; consequently, failure occurs at the wall ties and at the corners. In this sense, the authors suggest several alternatives to address this vulnerability. Firstly, reinforcement by means of a perimeter wall head beam; secondly, improving the strength of the wall by injecting liquid mud paste with lime or silica into the wall; finally, they propose a drastic intervention with veneers (complete coverings of low-strength concrete with electro-welded mesh) in the most vulnerable areas.

By contrast, in the European territory, the construction technique carried out with Adobe is manifested according to the execution of the walls undertaken; in this way, four generic groups are exposed, as pointed out by Correia, Dipasquale and Mecca (Duarte et al., 2018, p. 247):

> The most common variant is an elaborate system, consisting of wall sections composed exclusively of adobe courses.
>
> Three of its variants are associated with the integration of other elements into the adobe wall, with the aim of increasing its mechanical properties. One of the most common solutions is to introduce alternating structural frames inside the wall, consisting mainly of reed, brick, stone and/or timber frames. In addition to the alternation of materials in the courses, an attempt is made to reinforce those parts of the building that are subject to the greatest stresses by introducing bricks. This is the case of the interlocking of the corner walls, the plinths and the formation of openings. Duarte et al (2018) state that "the combination of adobe with courses of fired bricks, mainly in the most structurally stressed elements, represents one of the most evident evolution, particularly in the most urban and densely populated areas".

One of the most recent trends in both Europe and many middle- and low-income countries is the integration of wooden or bamboo reinforcement rods into adobe constructions. This internal framework, embedded within earthen walls, enhances their resistance to both compression and shear forces, addressing concerns about the stability of these structures, particularly in seismic regions. The need to improve adobe's traction resistance in the face of earthquakes has become a driving factor for reinforcing adobe walls. Several universities in countries such as Israel, Peru, France, and Mexico have already begun experimenting with various adaptations of this earth-based construction technique, especially in urban environments (Dodman et al., 2022).

In countries characterized by hydro magmatic zones, research is beginning to focus on the advantages and disadvantages of using volcanic ash in the production of construction materials, such as adobe. Currently, traditional cement is being replaced by pulverized volcanic rocks, which can reduce the energy required to produce concrete by up to 16% (Baraya, 2022; Serrano Yuste, 2015). The incorporation of volcanic deposits offers several benefits, such as reducing the demand for sand, one of the most extracted materials globally along with gravel, and decreasing the use of cement as a stabilizer, which helps reduce global CO_2 emissions, as cement accounts for about 5% of these emissions. In countries like Germany, Australia, Brazil, Canada, Colombia, Spain, the United States, France, and Portugal, the use of earth for wall construction has experienced a significant resurgence. This material is being reintroduced into modern buildings, adapting its traditional form to meet the demands of contemporary society. However, despite its increasing popularity, the widespread adoption of earth as a building material still faces many challenges. Overcoming these barriers requires addressing a complex array of issues, including cultural and psychological perceptions, aesthetic preferences, technological and technical hurdles, as well as economic and legislative obstacles (Enshassi, Kochendoerfer, & Rizq, 2014).

Tapial

Tapial is characterized on the European continent by the extension of its territory, by the multiple works in proportion to the land covered, by the diversity of techniques carried out and the scale of the building, achieving heights of up to 20 meters. In many localities and municipalities, the rammed earth construction technique represents up to 80% of the pre-existing buildings up to 1945, it is understood that its load-bearing capacity, its high thermal inertia and its peculiar capacity for hygrothermal regulation were conclusive factors in its choice.

A first analysis of the application of the Tapia in Europe confirms the coherence in the execution process, with apparently similar procedures. Approximately 20 categories were identified in the European territory, where Tapia was the most diversified building system in Europe. As Duarte et al. (2018, p. 247) state, "The trend seems to indicate the application of more homogeneous construction systems in the South, in terms of building execution and, particularly, of the heterogeneous architectural element." On the one hand, in Spain, "a greater constructive heterogeneity of the tapia is registered" (Duarte et al, 2018, p. 247), contrary to France, where the technique mainly referred to the execution process, to the compacting action.

As expressed by Duarte et al. (2018), the dominant typology in the south is mainly residential, associated with rural means of agricultural production such as stables and barns. In some regions of Spain and in central areas of the European territory, a greater typological diversity is evident. In the extreme north-east of Europe, with colder and wetter climatic conditions, there are stables and barns of large dimensions and of simple configuration. Traditional rammed-earth architecture in countries such as Belgium, Luxembourg or the Netherlands is extremely scarce.

Continuing with the analysis of the established clichés regarding tapial, Quesada (2019) based his results on the constructive point of view, verifying the quality of execution and development of the technique used in the Muslim towers in the current Sierra de Segura Natural Park, carried out during the 12th century. These structures show that they were built with precise technical knowledge about the functioning of the structures, detecting the presence of embedded logs in their manufacture in the form of a band joined together that act in a similar way to a chain of ties or reinforcement at the points of change of section of the wall; in the same way, regarding the layout and construction of the walls, it was determined that the towers with the greatest height always have three of their four faces inclined with a variation of between one and three degrees. Meanwhile, architecture emerges as village space, with elements that define a specific architectural ensemble that regulates social relations, employing some distinctive features such as:

The use of the construction technique of earth or rammed earth.

The enclosure of closed and open enclosures with a perimeter wall, the surface area of which increases over time, varying from 316m2 to 1,050m2 from the 1st to the 10th century.

The configuration of regular, quadrangular and trapezoidal structures, as well as the absence of structures with a ceremonial function (Ratto et al., 2019).

From the above, it can be considered that the materiality of architecture entails the transformation of matter from its natural state to another to form an object with a specific design. This in turn requires the mobilization of human and natural resources and certain technical and practical skills and knowledge that, in many cases, are passed down from generation to generation (Ratto et al., 2019).

Joffroy et al. (2018) argue that

One of the main advantages of rammed earth in contemporary construction, in addition to its load-bearing capacity, is its high thermal inertia and its interesting capacity for hygrothermal regulation. Particularly noteworthy is its ability to be recycled ad infinitum, without the need for energy input. Finally, due to the great aesthetic interest it arouses, it is easy to transmit heritage values, since it allows cultural continuity to be given to projects (p. 234). The alternative of prefabricated walling, inspired by recent research, can be fully developed when demand is such that a change in the scale of production is warranted. In this way, the current high costs could be reduced to democratize and cover a significant part of the French construction market (p. 236).

One of the greatest risks for the conservation of heritage in Tapial and Adobe is capillarity, one of the most present obstacles in this type of construction as mentioned in the research by Canivel and Pastor (2018); it analyses the state of conservation of buildings such as churches of heritage value in the region of Mendoza, Argentina. Another risk to consider is the difficulty in disseminating traditional knowledge in the present. One of the responses to this problem was undertaken by Dr. Teresa Gil Piqueras (2017), who conducted a detailed study documenting drawings of heritage at risk in Morocco, with the aim of advancing knowledge of Kasbah architecture, square fortified residences with slender towers of mud and adobe. One of the strategies previously mentioned is to integrate earth as a building material in dense urban areas, rather than limiting its use solely to rural housing in so-called "third world" countries. The idea is to introduce this material into a high-tech context and economy that is increasingly detached from its roots and cultural identity. Earth offers numerous benefits as a building material, although these are still little known and scarcely disseminated.

The use of earth in construction and structural elements offers significant advantages, such as its ability to absorb pollutants and moisture much more efficiently than other materials, with an absorption capacity that is 40% to 80% higher. This not only protects organic materials like wood, but also contributes to the reduction, and even elimination, of the need for artificial air conditioning systems. This advantage stems from the excellent thermal properties of the earth, provided that proper architectural design is considered. (Baraya, 2022; Machado, La Roche, Mustieles, & De Oteiza, 2000; Mileto, Vegas, Soriano, & Cristini, 2014; McGregor, Heath, Maskell, Fabbri, & Morel, 2016; Falcone, Origlia, Campi, & Martino, 2021; Serrano Yuste, 2015; Souza, 2021).

The construction industry is one of the sectors with the highest consumption of energy and raw materials, being responsible for a significant proportion of greenhouse gas (GHG) emissions. In fact, cement production accounts for approximately 5% of global GHG emissions, followed by materials such as steel, brick, and plastics (Huovila et al., 2009). This is in addition to the high energy consumption involved in the extraction of minerals and metals required to obtain these materials. In this context, the European Union is conducting research to develop more sustainable materials that require less energy in their production and, as a result, reduce their environmental footprint. Compared to materials like concrete (which consumes between 600-800 KWh/m3) or natural sand (around 45 KWh/m3), earth is considered a low-energy material, requiring only 5-10 KWh/m3 for processing (Baraya, 2022; Botejara-Antúnez, Garrido-Píriz, Sánchez-Barroso, González-Domínguez, & García-Sanz-Calcedo, 2021;Dodman et al. 2022; Goy, 2022; Baca, 2007; Falcone et al., 2021; Masson-Delmotte et al., 2018; Mirzabaev et al., 2022; Katerine Molina Contreras & Eduardo Becerra Becerra, 2020; Bendixen, Best, Hackney, & Iversen, 2019; Jiang & O'Neill, 2017; Serrano Yuste, 2015; Darling et al., 2012; Souza, 2021).

According to Enhassi, Bernd, and Ehset alan (2014), the construction industry generates significant environmental and health impacts, particularly through dust, noise, air pollution, and activities that involve vegetation removal. These factors contribute to serious health risks for workers, including cardiovascular and respiratory issues, sleep disturbances, cancer, and hearing impairment, among others (Baraya, 2022; Botejara-Antúnez et al., 2021; Akom, Sadick, Issa, Rashwan, & Duhoux, 2018; Huovila et al., 2009; Bendixen et al., 2019; Dodman et al., 2022; Enshassi et al., 2014; Goy, 2022; Novoselov et al., 2022; Falcone et al., 2021; Mirzabaev et al., 2022; Niranjan, 2021; Pierre-Louis, 2018a; Seguí, n.d.; Serrano Yuste, 2015; Darling et al., 2012; Souza, 2021)

As resource over exploitation increases, so does the complexity and variety of materials used, along with the production of waste. The construction and demolition industry is the largest producer of waste (Baraya, 2022; Botejara-Antúnez et al., 2021; Akom et al., 2018; Morel & Charef, 2019; Bendixen et al., 2019; Dodman et al., 2022; Enhassi et al., 2014; Goy, 2022; Novoselov et al., 2022;Falcone et al., 2021; Mirzabaev et al., 2022; Niranjan, 2021; Pierre-Louis, 2018b; Seguí, n.d.; Serrano Yuste, 2015; Darling et al., 2012; Souza, 2021). This significantly hampers the reuse and recycling of waste from construction activities, much of which ends up in landfills. We find ourselves trapped in an endless cycle, with a new link added every day, hour, and minute. In contrast, earth as a construction material is known for its low environmental impact when returned to nature, aligning with one of the primary objectives of sustainable architecture. Like other natural materials, such as wood, earth is recyclable. If it has not been mixed with cement, lime, or other chemical additives, it can fully reintegrate into the environment after dissolving in water. This characteristic not only reduces waste but also conserves energy and fosters a circular economy in building, promoting the sustainable use of materials throughout their entire life cycle (De Schiller & Martin Evans, 2020; Javier Castilla Pascual & Núñez Martí, 2005; Yuste, 2015).

Over the last few centuries, new practices and designs based on primitive earth-based architectural models have emerged. Between the 18th and 19th centuries, numerous dwellings were built using a mixture of earth, chalk, and straw, resulting in walls that were bright and whitish. A similar practice was carried out in the design of the Juana Briones houses, built in San Francisco (California) in 1845, where the walls were formed by compacting earth poured into a framework of wooden slats. Over time, other practices evolved into the stacking of flexible sacks filled with earth, offering a quick and affordable solution for emergency housing in response to natural disasters, representing a radical departure from the traditional use of poured earth. There has also been experimentation with the incorporation of plaster into earth mixtures, as seen in the projects of architect Marwan Al-Sayed, which result in bright white walls that reflect sunlight, giving the walls a sense of lightness in contrast to the visual weight that their materiality might otherwise suggest.

One of the main challenges of sustainable construction today is to develop a 100% biodegradable material with virtually no cost for its return to the environment. In this context, various research groups have proposed and experimented with different mixtures and stabilizers to achieve fully biodegradable earth (Olmedo Rodríguez, 2020). Although many countries lack specific regulations for earth construction (although some, like Spain, are currently drafting them), in some regions, it is required that earth mixtures used for wall construction contain at least 15% stabilizers such as cement, lime, or plaster. (De Schiller & Martin Evans, 2020; Javier Castilla Pascual & Núñez Martí, 2005; Yuste, 2015)

In the last three decades, several trends have emerged in the field of architecture. Renowned architectural studios such as Studio Anna Heringer, Hive Earth Studio, and Edra Arquitectura, along with research groups like Centro Tierra, Uni-Terra, and the International Center for Earth Construction, are dedicated to the research, implementation, and dissemination of knowledge related to earth architecture, exploring its use alongside other local materials. A clear example of this approach is architect Francis Kéré, who, throughout his career, has advocated for the use of earth in his architectural designs, challenging the perception of poverty historically associated with this building typology. According to Castillo and Pérez (2020), it is essential to acknowledge the ancestral knowledge embedded in the construction of vernacular architecture, addressing both its techniques and its constructive and technological approach. However, Javier Pérez argues that research in this field should adopt a more cultural perspective. In line with this viewpoint, Pérez's research (2019) on heritage interventions with adobe, such as the case of the Palomar de Manolo in Spain, highlights a strategy based on the use of hybrid techniques, combining adobes (from the past) with industrialized blocks (from the present), showcasing the historical contrast in the building. However, this strategy is, to some extent, subject to critique.

Basile (2018) for his part points out that

> It is necessary to respect and preserve the architectural heritage in order not to lose the identity of the site, and it will be of fundamental importance to have a good knowledge of the buildings, architectural complexes and land sites (e.g. through the inventory/catalogue tool) in order to implement the best and most correct integration strategies in territorial and urban planning. (p.26).

It is currently estimated that half of the world's population lives or works in buildings made of earth. While the vast legacy of traditional and vernacular earth construction has been widely discussed, little attention has been paid to the contemporary tradition of earth architecture. Many people still associate its use exclusively with housing in impoverished rural areas, but there are notable examples of infrastructures such as airports, embassies, hospitals, museums, and factories built with earth. Additionally, the earth is often considered a fragile and ephemeral material; however, some of the oldest buildings that still exist today are made precisely of this material. Another of the fundamental aspects postulated by the author Basile (2018) is that it is necessary to work in the field of training, research, knowledge and dissemination, making it necessary to disseminate knowledge among academics and, above all, within local communities for the defense and promotion of the cultural value of the architectural heritage on land, raising awareness of its proper conservation, restoration, protection, protection and promotion. This type of construction, whose interest has been growing in recent decades, must be recovered and conserved, thus avoiding the loss of knowledge and its transmission to future generations.

DISCUSSION

As mentioned earlier, earth construction began to resurface in the 19th century; however, it was only in the last two decades that there has been a notable increase in the number of projects and research, as well as the establishment of institutions, universities, and events dedicated to this field. During this time, significant progress has been made in modernizing traditional earth construction techniques, successfully adapting them to the demands of contemporary design and construction.

The anthropogenic mass generated since the second half of the 20th century has experienced rapid growth due to technological progress, overpopulation, and consequently, increased production and consumption. The continuous interaction of these three factors has led to uncontrolled extraction and transformation of natural resources, as well as the unchecked expansion of agricultural land, urban areas, and transportation infrastructures. In this context, the use of ancestral techniques, such as adobe or rammed earth, in contemporary architectural design presents an opportunity to revalue a low-energy technology. These techniques make use of local resources, avoiding the transportation of industrialized materials over long distances (Salman, 2019; Halilovic, 2020). Additionally, it is important to note that the most sustainable, healthy, economical, and socially accessible buildings—those most closely tied to the identity of their region—are, for the most part, those that employ locally sourced materials. However, there is still a long way to go in industrializing and mechanizing the use of these materials in construction. Earthen architecture must overcome several changes in the programming, design, construction and use phases. In addition, earthen building systems are different from today's architecture and need to be studied further. Research is also needed in the areas of control and prediction of wall drying kinetics and its impact on mechanical behavior (creep, strength) and durability (freeze-thaw and fire resistance). On the other hand, the lack of regulations for uncommon techniques, the lack of adequate standardization and the lack of incentives are examples of policies that need to be urgently addressed to drastically reduce the environmental impact of the building sector and improve human well-being. Earthen architecture has the potential to achieve these goals and should be encouraged.

Since the late 20th century, there has been a growing push for the adoption of new technologies and alternative construction practices aimed at addressing the increasing need to build with decarbonized materials that help reduce the embodied carbon footprint in buildings. In this context, increasing investment in nature-based solutions and environmental protection fosters, among other things, the implementation of urgent measures to combat climate change (SDG 13), such as reducing extreme weather events, protecting and restoring ecosystem services, and improving the management of solid waste that degrades soils. Additionally, it promotes the sustainable management of forests and the fight against desertification, as well as halting and reversing land degradation and biodiversity loss.

The use of earth as a construction material has posed various technical challenges since its inception, generating significant interest from the scientific community since the 1990s, with a noticeable increase in publications on the subject. However, other types of obstacles, such as economic, organizational, political, and social barriers, have not been addressed with the same level of depth in academic literature. This lack of focus on non-technical factors could be one of the reasons why earthen construction remains a niche market, despite the material's numerous qualities that make it well-suited to address both the current and future climate and resource crises. The assessment of indoor comfort and the impact of earth walls on indoor comfort is also one of the many uncovered technical areas that should be explored in the future. The scientific results obtained on the technical aspect will undoubtedly provide useful information for studies on other non-technical aspects. Additionally, there are inherent challenges associated with the earth as a construction material, such as variability in its composition, the proper content of materials, the availability of suitable soils for construction, and the potential impact that its development could have on the demand for these soils. However, in recent decades, there has been a growing interest in finding an energy balance that aligns with current trends in resource utilization within the built environment, both for the present and the future.

The understanding of the various approaches, construction techniques, and applications of adobe, utilizing the resources of the immediate physical and cultural environment, will enable other researchers interested in sustainable construction with biodegradable materials, such as earth, to better appreciate its possibilities and shift the focus away from its limitations. This process will highlight the potential of earth as a building material, as well as the range of techniques that can be developed with it, demonstrating:

Its flexibility in introducing this material in large cities, adapting it to different contexts and promoting the interest of its users.

It is possible to provide an architectural proposal that satisfies current needs and that does not put future generations at risk.

It contributes to sustainable development, improving and protecting ecosystems and biodiversity, reducing the production of waste and increasing the well-being and health of citizens.

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CONCLUSION

The path toward using earth and its various construction systems, such as adobe and rammed earth, in architecture—both today and in the future—requires research in several key areas. First and foremost, it is essential to advance the industrialization and mechanization of processes to optimize their efficiency. Additionally, it is crucial to explore the use of additives that can stabilize, waterproof, and protect earth structures from the various forces to which they may be subjected. Research is also needed into the use of lightweight agents that reduce the material's weight without compromising its strength, as well as the potential for incorporating industrial waste, such as rubble or ash, into the mix. All these efforts should be accompanied by the development of regulations and standards that facilitate the integration of earth as a viable material within the construction industry.

Promoting the use of biodegradable materials, such as the earth, not only brings social benefits but also offers economic advantages related to the reduction of waste and operational costs, lowering energy demand and operating expenses, and ultimately minimizing environmental impact. In conclusion, all of this translates into more sustainable construction, capable of making a significant contribution to mitigating the global environmental crisis.

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