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Systematic Review

# Sustainable Earthen Construction: A Meta-Analytical Review of Environmental, Mechanical, and Thermal Performance

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**Abstract:** This study examines the main earthen constructions—such as adobe, compressed earth blocks (CEBs), and rammed earth walls (REWs)—highlighting their potential to reduce the environmental impact compared to conventional materials. Through a systematic literature review (2013–2024) and a meta-analysis, the mechanical, thermal, and sustainability properties of these constructions are analyzed. Emphasis is placed on the use of additives, such as stabilizers and fibers from various industrial and agro-industrial by-products, as leading actors influencing the mechanical and environmental performance of earthen constructions (EnCs). Remarkable improvements in the compressive and flexural strength are found, especially in stabilized CEBs and REWs, where strengths of up to 24 MPa are reached in certain mixtures, comparable to conventional materials such as concrete. However, the impact of these admixtures on environmental aspects, as measured through metrics such as the global warming potential (GWP), remains poorly documented. This review also shows that numerical methods like finite element modeling (FEM) have been crucial to modeling and predicting the performance of these materials, contributing to the understanding of their dynamic and structural responses. The findings suggest that, although CEB is currently the most studied onshore technique, future challenges include the standardization of admixtures and regulation of sustainable practices globally.

**Keywords:** adobe; compressed earth blocks; fibers; meta-analysis; rammed earth; stabilizers; sustainability; systematic review

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## 1. Introduction

In the last few decades, earthen constructions have re-emerged as environmental alternatives for building [1]. Earth is the most widely used natural resource in residential structures, especially in hot, arid, and temperate climates such as India, Latin America, and North Africa [2]. Table 1 presents the most common earthen construction techniques: cob, wattle and daub, poured earth, adobe, compressed earth blocks (CEBs), and rammed earth walls (REWs). Unlike conventional materials such as concrete and steel, producing earthen buildings requires less thermal and electrical energy consumption, significantly reducing the carbon footprint [3]. These properties make them a desirable option in the current context of the climate crisis, where the industrial and construction sectors are key to reducing greenhouse gas emissions and driving global adaptation to more environmental practices [4].

With a history dating back to the earliest civilizations, earthen constructions have demonstrated a remarkable ability to adapt to diverse cultural and geographic contexts. In ancient cultures, techniques such as adobe and rammed earth walls (REWs) were developed to construct buildings that not only responded to climatic conditions but also to local resource availability [5]. However, the irruption of industrial materials in the 20th century relegated these techniques as they were considered less durable and modern, associating them mainly with communities with low resources and limited construction quality [6]. This paradigm has changed in recent decades: increased environmental awareness and the need for more environmentally friendly materials have driven interest in earthen constructions, motivating research into their mechanical, dynamic, and thermal properties and their potential to meet environmental construction needs.

Despite this renewed interest, previous studies have approached earthen construction from fragmented perspectives. For example, Giuffrida et al., 2019 focused on the hygrothermal properties of raw earth materials, emphasizing their potential for passive indoor climate regulation but lacking a comparative analysis of different construction techniques and additives [7]. Brumaud et al., 2024 explored the viability of poured earth construction, highlighting its rapid fabrication process and reduced carbon footprint but also pointing out the challenges related to its durability and standardization [8]. Similarly, Walter et al., 2024 examined the role of mineralogical compositions and chemical dispersants in optimizing the mechanical behavior of earthen materials in tropical climates, but their study was limited to specific soil types and did not evaluate broader performance trends across different environments [9]. Additionally, Bailly et al., 2024 provided a detailed review of the stabilization and reinforcement techniques for adobe and CEBs, offering valuable insights into the effectiveness of natural fibers, industrial by-products, and alternative binders in improving mechanical and hygrothermal properties. Their comprehensive analysis of the stabilization methods serves as a strong foundation for understanding the materials [10].

However, despite their environmental advantages, earthen constructions face significant structural challenges. Traditional techniques often exhibit low compressive strength and increased susceptibility to water erosion and seismic loads, limiting their applicability in regions where high durability and safety standards are required [11]. In response to these challenges, there has been a growing trend in the research on using additives to improve the mechanical properties of earth materials. These additives seek to reinforce natural materials, allowing earthen constructions to withstand greater loads and exhibit greater durability. Among the most common admixtures is cement [12–14], which increases the compressive strength; however, it affects the environmental aspects of the earthen constructions (EnCs). Lime [15,16], which improves cohesion and durability against moisture; industrial waste materials, such as fly ash [17–19] and glass fibers, [18,20], which reinforce the soil without compromising sustainability; and natural fibers, such as straw and sawdust [21], banana fiber [22], and coconut fiber [23], have been combined with stabilizers such as cement to improve the compression, tenacity, and flexibility of the materials, allowing them to resist deformations without fracturing easily. These advances are beginning to position earthen constructions as competitive alternatives to conventional materials, encouraging research into techniques that optimize their resistance without losing their environmental character.

Recent studies show how the environmental performance of earthen constructions can vary according to the additives used but also depending on the construction technique and the geographical context [5]. In Portugal, a life cycle analysis of CEBs and REWs revealed a reduction of up to 50% in the environmental impact compared to conventional materials [3]. In Iran, the carbon footprint of REWs stabilized with different proportions of cement and expanded polystyrene was investigated, finding that while cement increases the carbon footprint, the use of polystyrene reduces it significantly [11]. In Australia, the use of industrial by-products in REWs, such as crushed brick, concrete, blast furnace slag, fly ash, silica fume, and hydrated lime, has been successful in reducing greenhouse gas emissions by up to 73% compared to traditional materials [24]. These studies emphasize the importance of a local and environmental design strategy adapted to each region's specific resources and conditions.

Despite these advances, previous reviews on earthen constructions present considerable limitations. Turco et al., 2021 [25] reviewed the optimization of compressed earth blocks with natural materials and concluded that fibers and ashes improve their thermal and mechanical properties, favoring sustainability. Valenzuela et al., 2024 [26] highlighted the potential of industrial additives in CEBs in South America but noted the lack of carbon footprint quantification and the need for a comprehensive database for a global review. Avila et al., 2022 [15] and Jiménez et al., 2024 [27] agreed that, although admixtures improve mechanical and thermal properties, there are gaps in the research on the calculation of the optimum amount and type of additive. These previous reviews have also been limited in their approach, focusing their analysis on local contexts or specific properties without offering a broad and comparative view of earthen constructions globally.

This study presents a comprehensive meta-analysis covering most earth construction techniques, enriching the information provided by previous research focused on one or two specific types. For this purpose, the physical, mechanical and thermal properties are analyzed, allowing us to calculate the mean and standard deviation and, from these data, to identify the most efficient admixtures in terms of the mechanical performance and thermal behavior. In addition, the most relevant standards are compared, detecting challenges in calculating the percentages of admixtures used in various construction techniques. On the other hand, the evolution of research in this field is examined from the perspective of the Global North and the Global South over the last decade. Instead of directly comparing construction techniques, this study objectively sets out the results obtained concerning the materials, additives, and proportions, offering a comprehensive and coherent view of the current state of earth construction.

This review provides a comprehensive and global overview of the current state of the research on earthen constructions, focusing on adobe, CEBs and REWs. First, global research trends and opportunities are analyzed, identifying the predominant approaches in different geographical contexts. In addition, a meta-analysis is presented that reveals which additives significantly improve the mechanical and thermal properties of earthen constructions, highlighting that, in most cases, non-conventional additives, such as industrial and agro-industrial wastes, comply with international standards, thus challenging traditional perceptions about their structural feasibility and energy efficiency. In assessing environmental performance, it is evident that incorporating certain industrial additives, such as cement and lime, can compromise the inherent sustainability of these constructions, underscoring the need to balance durability and eco-efficiency. The paucity of data on the environmental impact of unconventional wastes on these techniques highlights a knowledge gap that represents a key opportunity for future research on sustainable construction. Finally, the compilation and analysis of advances in numerical modeling and structural simulation provide fundamental tools to optimize the design and performance of earthen buildings, consolidating them as a viable and sustainable alternative to conventional construction methods.

**Table 1.** Most commonly used earth construction techniques around the world.

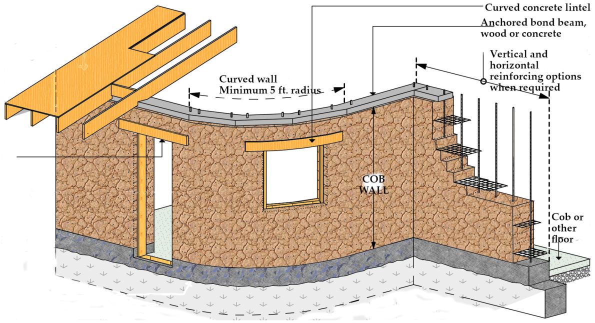
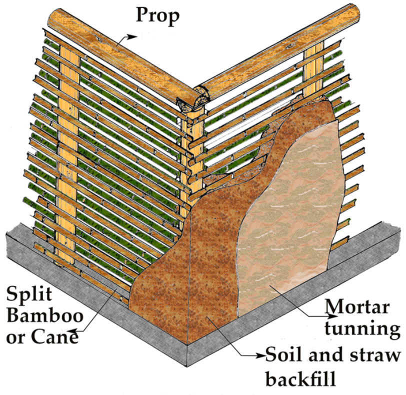
| Earth Construction Techniques | | Description | Attributes | Performance | Refs. |
|---|---|---|---|---|---|
|  Adapted from: [28] | Cob | Technique of wet soil accumulation without formwork. The mixture of clay and straw is compacted in successive layers directly on the site, creating solid walls with high thermal mass. | Advantages: excellent thermal mass and energy efficiency. Disadvantages: time-consuming and labor-intensive. | Good compressive strength and high thermal mass but limited in tension without reinforcement. | [29,30] |
|  Adapted from: [31] | Daub and wattle | Traditional system that combines woven wood as a structure and mud as a filler, offering an economical construction that can be quickly implemented in rural areas. | Advantages: economical and easy to implement. Disadvantages: low durability without proper maintenance. | Good dynamic performance with medium compressive strength, but sufficient for light applications and non-load-bearing walls. | [32] |

**Table 1.** *Cont.*

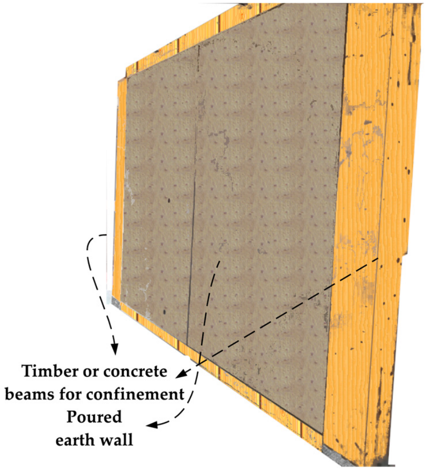
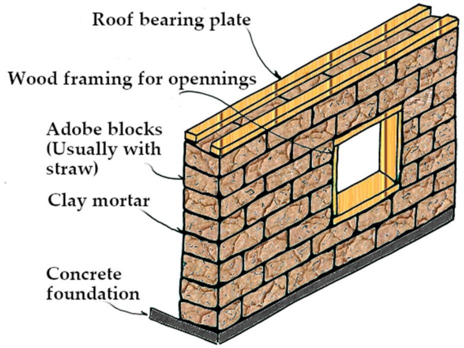
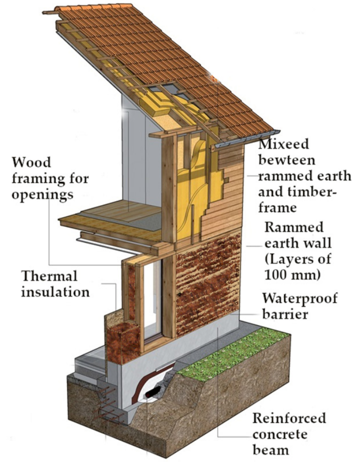
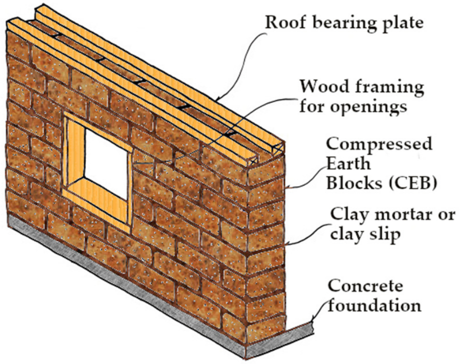
| Earth Construction Techniques | | Description | Attributes | Performance | Refs. |
|---|---|---|---|---|---|
|  | Poured Earth | A recent technique that involves wet earth, with aggregates and gypsum, with a consistency like concrete, poured into molds, forming monolithic walls once dry. The technique is fast and versatile, although less used in modern construction. | Advantages: fast and adaptable to different shapes. Disadvantages: less availability of technical knowledge and specific materials. | Adequate strength for non-load-bearing structures. However, it depends on the soil mix, drying process, and additives. | [9,33] |
|  <br>Adapted from: [34] | Adobe | Sun-dried clay blocks prepared from a mixture of clay, sand, and water. This method is ideal for dry climates and allows for an adaptable and environmental construction system. | Advantages: low cost and accessibility of materials. Disadvantages: limited resistance to moisture without treatment. | Low compressive strength in dry conditions, vulnerable to moisture without treatment. | [35,36] |

**Table 1.** *Cont.*

| Earth Construction Techniques | | Description | Attributes | Performance | Refs. |
|---|---|---|---|---|---|
|  <br>Adapted from: [37] | Rammed Earth Walls (REWs) | A construction method in which the soil is compacted in successive layers within formwork, generating robust, high-density structures that offer great strength and durability. | Advantages: great durability and resistance. Disadvantages: needs machinery for adequate compaction. | High compressive strength and durability, suitable for stable load-bearing structures. | [38,39] |
|  <br>Adapted from: [40] | Compressed Earth Blocks (CEBs) | Compacted earth blocks in molds are used similarly to conventional bricks, combining earth and, sometimes, stabilizers to achieve a modular and energy-efficient structure. | Advantages: modular and easy to replicate. Disadvantages: less insulation than other techniques. | High compressive strength in individual blocks, usually used as a partition material, modularity allows fast construction. | [38,39] |

This manuscript is organized into four sections. Section 2 describes the research methodology, including the tools and methods used for data processing. In Section 3, a systematic review is first conducted to identify the main trends and relevant issues in earth construction research during the last decade and their increasing importance globally. Then, a comprehensive review of the environmental performance of these constructions is offered, highlighting the aspects evaluated in terms of sustainability and the use of additives from industry and agribusiness to improve their properties. A meta-analysis is also presented, providing the global average values of different physical and mechanical properties of earthen constructions and a detailed analysis of the most outstanding findings in terms of mechanical, dynamic, and thermal performance. Finally, Section 4 brings together the main conclusions, current challenges, and future perspectives for earth construction research.

## 2. Materials and Methods

Figure 1 shows the flow diagram implemented in this research. The first phase describes the systematic review process carried out. Subsequently, a meta-analysis was conducted to extract and evaluate the primary mechanical, physical and thermal properties, classify the additives and analyze the environmental aspects. The data were synthesized using raincloud graphs, which allowed visualization of the most relevant additives from the perspective of their impact on mechanical performance, the environmental and thermal benefits, together with the advances in modeling during the last decade.

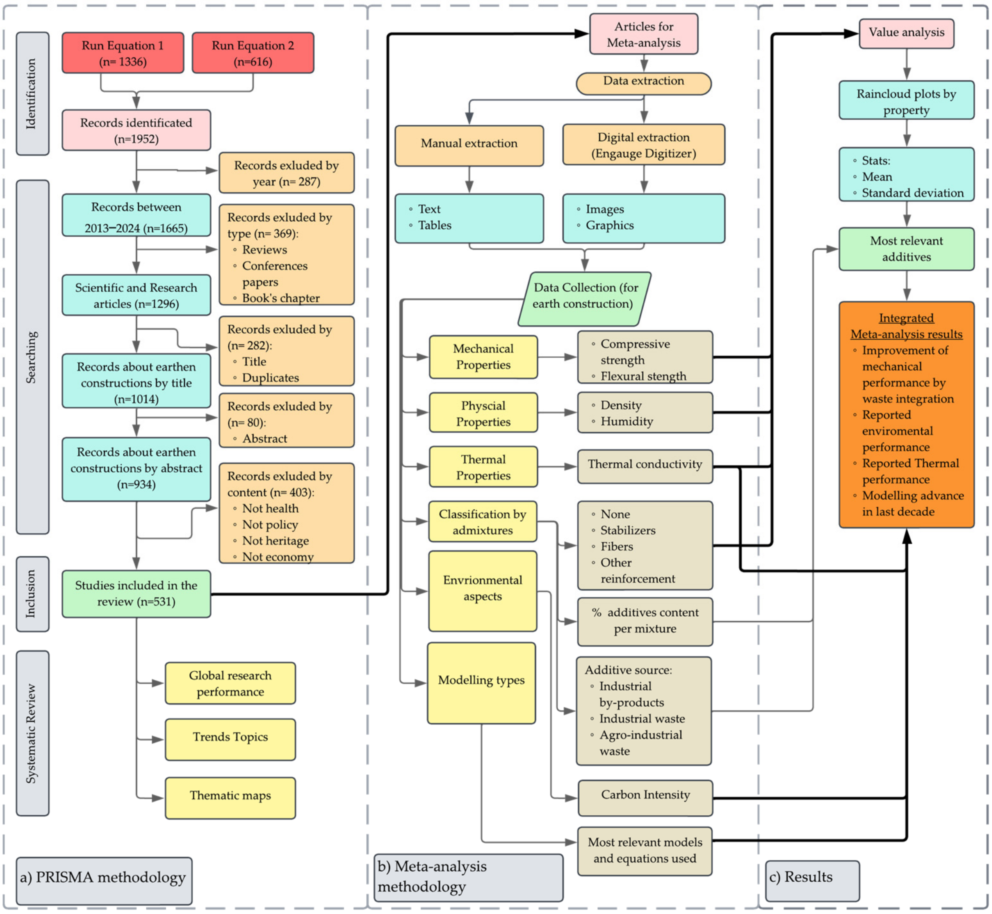


**Figure 1.** Flowchart of the present review. (**a**) The selection process for articles from 2014 to 2024 with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA®) methodology, (**b**) meta-analysis methodology, and (**c**) results.

### 2.1. Search Query

An exhaustive literature analysis was carried out using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA®) methodology, which, due to its versatility, has been applied in different fields of study [41–43]. The PRISMA® was carried out with tools such as Bibliometrix 4.3.0® and VOSViewer 1.6.18® to delineate the current situation and identify trends and research gaps. The search equations detailed in Table 2 were used in widely recognized databases such as SCOPUS®, Web of Science®, and SciELO from 2013 to 2024.

**Table 2.** Search strategies and equations utilized in this research.

| Adobe ID | Search Focus | Search Equation | Rationale and Keyword Justification |
|---|---|---|---|
| 1 | Mechanical and Structural Performance of Earthen Materials | (“rammed earth” OR adobe OR “mudbrick” OR “compressed earth blocks” OR CEB) AND (“compressive strength” OR “flexural strength” OR “shear strength” OR “tensile strength” OR “ductility” OR “elastic modulus” OR “stress-strain behavior” OR “load-bearing capacity” OR “seismic resistance” OR “dynamic response” OR “cyclic loading” OR “pseudostatic testing” OR “thermal performance” OR “hygrothermal properties” OR “push-over analysis” OR “pull-out strength” OR “fatigue behavior”) | This equation captures studies investigating the **mechanical, structural, and dynamic behavior** of earthen construction materials, including **compressive and flexural strength**, **seismic performance**, **thermal and hygrothermal properties**, and **experimental methodologies** such as **push-pull tests and pseudostatic testing**. |
| 2 | Sustainability and Environmental Impact of Earthen Construction | (“rammed earth” OR adobe OR “mudbrick” OR “compressed earth blocks” OR CEB) AND (“ecological industries” OR “life cycle assessment” OR “embodied carbon” OR “carbon footprint” OR “sustainable construction” OR “environmental performance” OR “energy efficiency” OR “resource efficiency” OR “circular economy” OR “low-impact materials” OR “green building materials”) | This equation is designed to retrieve research that evaluates the **sustainability aspects** of earthen construction, including **carbon footprint, life cycle analysis, energy efficiency, and circular economy principles** in the context of eco-friendly construction. |

The selected search queries were formulated using an advanced approach to **Boolean logic** and **domain-specific terminology**, ensuring comprehensive coverage of the literature related to **earthen construction technologies**. 1. **Search Query 1** focused on the **mechanical integrity** of earthen materials, integrating key experimental and structural evaluation parameters relevant to construction engineering. 2. **Search Query 2** addressed the **sustainability dimensions** of earthen architecture, capturing aspects related to **environmental footprint, material efficiency, and green building standards**. The **keywords** were systematically selected and validated using the **ScienceDirect® Thesaurus**, ensuring alignment with established terminologies used in **peer-reviewed literature and technical databases**.

### 2.2. Selection Criteria and Data Cleaning

The data collected from the databases were organized in a command separated value (CSV) format file following specific criteria: (i) include search terms in at least one of the main fields (title, keywords, or abstract), (ii) select only reviews and scientific articles, (iii) limit the search to articles in English, and (iv) consider the publication period between January 2013 and August 2024. The selection process followed the PRISMA methodology, beginning with two search equations identifying 1952 records. The dataset was refined to studies associated with engineering topics through sequential filtering by publication year, document type, and content relevance. These selected articles were analyzed through a systematic review, which explored the global research trends and thematic topics. A thorough review of the relevance of the results was performed by evaluating the titles and abstracts, resulting in the selection of 531 articles for analysis, as detailed in Figure 1.

### 2.3. Organization, Data Structure, and Data Analysis

The information from the articles was cleaned and organized in Excel V. 2502®. Data extraction was performed both manually for text and tables, and digitally through image and graphic analysis using Engauge-digitizer 12.1® [44], which made it possible to construct an exhaustive and systematic database. General data such as the authors, year of publication, abstract, and country were collected. The data were classified by the EnC technique (adobe, CEBs, and REWs), types of study (mechanical, dynamic, thermal, and environmental aspects), and additives used in different percentages (stabilizers and fibers). In addition, the following physical, mechanical, and thermal properties were analyzed: density, humidity, unconfined compression, flexural strength, and thermal conductivity.

### 2.4. Information Processing with Specialized Software

The information in the database was analyzed using open-source software such as Bibliometrix 4.3.0® [45] and VOSViewer 1.6.18® [46], tools widely used in literature reviews and bibliometrics [47]. VOSViewer 1.6.18® was used to create and visualize bibliometric networks based on word associations, identifying the EnC and cementitious material clusters, with a minimum threshold of three occurrences per term. Bibliometrix 4.3.0® facilitated bibliometric analysis through matrices, evaluating the annual scientific production and distribution by country and generating a thematic map that classifies the topics into driving, basic, emerging or declining, and niche, providing a structure for exploring the research trends [48].

### 2.5. Meta-Analysis

Information from the database collected from various scientific articles was verified, and the data were tabularly grouped according to the construction types: without inclusions, with stabilizers, and with fibers. Data on the density, moisture content, unconfined compressive strength, flexural strength, and thermal conductivity were collected for each type of construction. It is important to mention that the mechanical properties were only included in the 28 days of reported strength. Since these parameters were not studied in all the investigations, the amount of data varies by parameter and construction technique. Raincloud plots produced with Python (3.10.4) software [49] were used to visualize the data distributions, combining box plots, violin plots, and kernel density plots, with a red line indicating the median.

## 3. Results and Discussion

### 3.1. Overview of Earth Construction

Earthen construction has been fundamental to housing and monuments, and today, about one-third of the world's population lives in earthen structures, especially in the Middle East, North Africa, Latin America, and Central Asia [50] This material is valued for its sustainability, low environmental impact, and lower resource consumption compared to other materials [51]. However, these constructions present weaknesses in supporting lateral loads, which are common in seismic events, which have led to the study of new alternatives to overcome this problem [52]. Based on the above, cement or lime has been incorporated into earthen constructions to improve resistance. Although this reduces their sustainability, it continues to generate a lower environmental impact compared to other conventional materials [53].

Regulations related to earthen construction have evolved to establish technical criteria to ensure the stability and durability of buildings constructed using CEBs, adobe, and REWs. Table 3 presents an analysis of the most complete standards available, which detail the physical–mechanical requirements covering both the soil composition and the percentage content of conventional additives (cement, lime, fly ash, blast furnace slag, asphalt, chlorides, silicates, and natural fibers). However, although percentage ranges are specified for these admixtures, no precise method is established to determine the optimum amount to be used, being limited in general to requiring that the mixture reaches an unconfined compressive strength higher than 2 MPa [54–59] and, in some cases, a flexural strength higher than 0.5 MPa [58–61].

On the other hand, in terms of seismic resistance, regulations have been developed for the structural reinforcement of existing earthen buildings, as opposed to new ones. Regulations such as AIS 610-EP-17 in Colombia [62], RPS 2000 in Morocco [63], BCOP-2007 in Pakistan [64] and IS 13827 in India [65] provide specific solutions to improve the seismic resistance of these structures.

Despite these advances, future challenges include standardizing the additives by developing methodologies to accurately determine their optimum content based on the soil characteristics and service conditions. Currently, there are no global guidelines for incorporating industrial and agro-industrial by-products into earth construction, despite promising results reported in recent research. While in conventional construction there are widely adopted international procedures, such as the ACI method for the design of concrete mixes, which establishes proportions based on the physical properties of the materials to guarantee a specific strength, in earth construction there are no globally recognized equivalent methodologies.

The growing interest in substituting cement for alternative admixtures in earthen constructions reflects a focus on sustainability to maximize resource utilization and minimize waste. Replacing cement reduces $CO_2$ emissions, as its production is energy-intensive and generates about 2% $CO_2$ annually worldwide [66]. From this perspective, a pattern is shown in the evaluation of alternative cementitious agents and their impact on the mechanical properties [67], the dynamic response [68] and the thermal performance of earthen buildings with alternative additives for energy-efficient construction [69].

On the other hand, the key challenges include the social perception and acceptance, the lack of regulations, the variability of soil properties [70], the use of cement for stabilization, and the need for education and training in construction techniques [71]. Economically, the limited investment and the high cost of implementing new regulations are significant obstacles [72]. In addition, the interests of the conventional construction industry may influence the prioritization of regulations for earthen construction [73]. Despite these challenges, earthen constructions have been shown to be an economically and environmentally sustainable option compared to clay masonry and concrete [74]. Investing in EnC research and development and implementing training programs for EnC professionals are essential to overcome these obstacles. Promoting earthen construction's environmental, economic, and cultural benefits can help change social perceptions. A recommended strategy is to develop gradual regulations adapted to local contexts and take advantage of international knowledge [75].

Among the main challenges are the perception and social acceptance of earthen constructions and the lack of normative methodologies to accurately calculate the optimal percentage of admixtures according to the soil type. In addition, the high variability of soil properties and the limited incorporation of alternative admixtures further complicate the scenario. This highlights the need to update the regulatory framework and promote more thorough training in these construction techniques.

**Table 3.** Regulations for earthen constructions.

| Standard/Country/Year | Earth Technique | Additive Types and Content | Physical–Mechanical Requirements | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Type of Soil | Humidity | Density (kg/m$^3$) | Water Absorption (%) | Compressive Strength (MPa) | Flexural Strength (MPa) | Ref. |
| NBR 8491 /Brazil/1986 | CEBs | 6–12% cement | 100% pass 4.75 mm, 10–50% pass 0.075 mm, IP ≤ 18%. | Optimum moisture proctor test | - | ≤20% | ≥2.0 | - | [54] |
| NBR 10833 /Brazil/1989 | CEBs | 6–10% cement | 100% pass 4.75 mm, 10–50% pass 0.075 mm, LL ≤ 45%; IP 18%. | | - | ≤20% | ≥2.0 | - | [55] |
| NBR 13553 /Brazil/1996 | REWs | 6–12% cement, 2–8% lime, 10–30% fly ash, 15–40% blast furnace slag, 5–20% silicates, 0.5–2% chlorides, 0.2–2% natural fibers | 100% pass 4.75 mm, 15–50% pass 0.075 mm, LL ≤ 45%; IP 18%. | | - | ≤20% | ≥1.0 MPa | - | [76] |
| NTC 5324 /Colombia/2004 | CEBs | No specified cement content | 75–50% pass 4.75 mm, 15–18% pass 0.075 mm, LL ≤ 45%; IP 18%. | | 1800–2100 | 12–15% | 1.0–6.0 | - | [57] |
| NMAC 14.7.4 /EEUU/2004 | Adobe, REWs and CEBs | 6% cement | No specified soil type, % soluble salts. | ≤10% | - | - | ≥2.0 | ≥0.345 | [58] |
| UNE E 41410 /Spain/2008 | CEBs | Max 6% cement, lime, or gypsum. | 0–15% retain 2 mm, 50–75% between 2 mm and 0.075 mm, 10–25% between 0.075 mm and 0.002 mm, and 10–20% pass 0.002 mm. | Optimum moisture proctor test | - | - | 1.0–5.0 | - | [77] |
| IS 2110 /India/1980 | REWs | 2.5–3.5% cement | ≥35% pass 4.75 mm, IP 5.3–10.5%, LL ≤ 27. | | ≥1800 | - | 0.7–1.4 | - | [78] |
| NTE E 0.80 /Peru/1979 | REWs and Adobe | 16% straw | 30–40% pass 4.75 mm, 20–30% pass 0.075 mm. | | - | - | 0.6 | ≥0.14 | [79] |
| NTP 331.202 /Peru/1979 | Adobe | 0.5–4% asphalt | - | | - | ≤20% | ≥1.2 | ≥0.5 | [80] |

### *3.2. Global Intellectual Productivity Scenario: Global North (GN) and Global South (GS) Regions*

In the last decade, scientific productivity in terms of EnCs has grown, as shown in Figure 2, which details the global evolution of this field from January 2013 to August 2024, with 531 reviewed articles. Between 2013 and 2015, the Global North (GN) dominated publication, with 36 of the 52 articles; however, since 2016, the GS has significantly increased its participation in this area. Between 2016 and 2019, the Global South region showed an average growth rate of 19 articles per year, compared with 14 articles from Global North countries. By the end of 2019, cumulative production was 91 items for both regions, indicating equal total production.

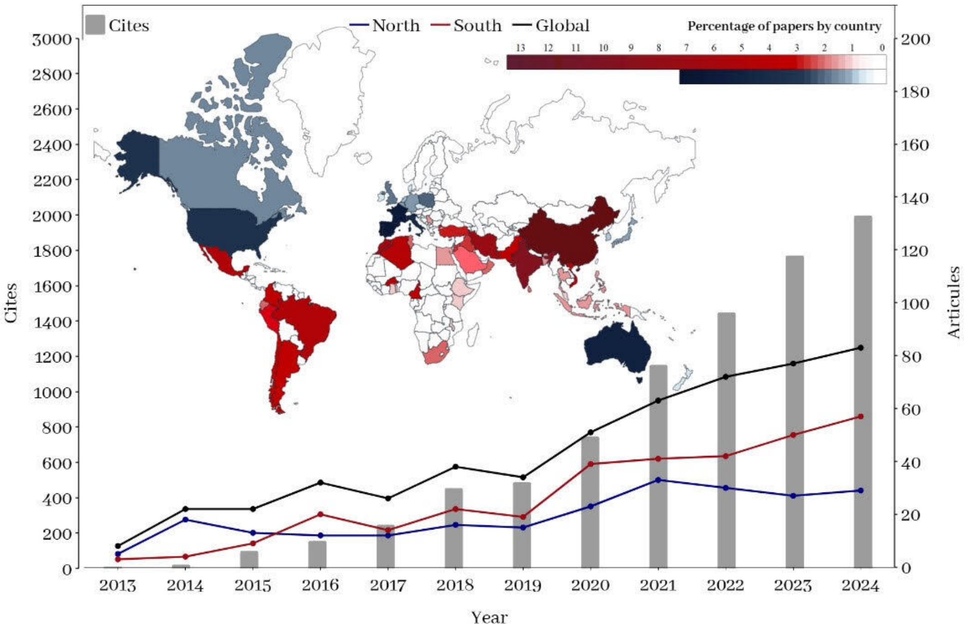


**Figure 2.** Number of articles on earthen construction by year in the world.

Between 2020 and 2024, scientific production continued to grow, with the GS countries publishing an average of 43 articles per year, surpassing the GN, which produced an average of 27 articles per year. This increase in the output of the Global South countries translates into 307 articles compared to 224 articles from the Global North countries from 2013 to August 2024. Currently, the Global South accounts for 58% of the publications in this field, indicating a significant shift toward greater prominence in earthen construction research in these countries. This shift can be attributed to the growing interest in environmental and locally adapted solutions that the Global South countries are developing. The equality achieved in scientific output between the GN and the GS by the end of 2019, together with the recent dominance of the south region, suggests a diversification of the sources of innovation and a growing recognition of the relevance of research conducted in non-traditional contexts. These results evidence more significant equity in global scientific output in this field, with the GS countries playing an increasingly crucial role.

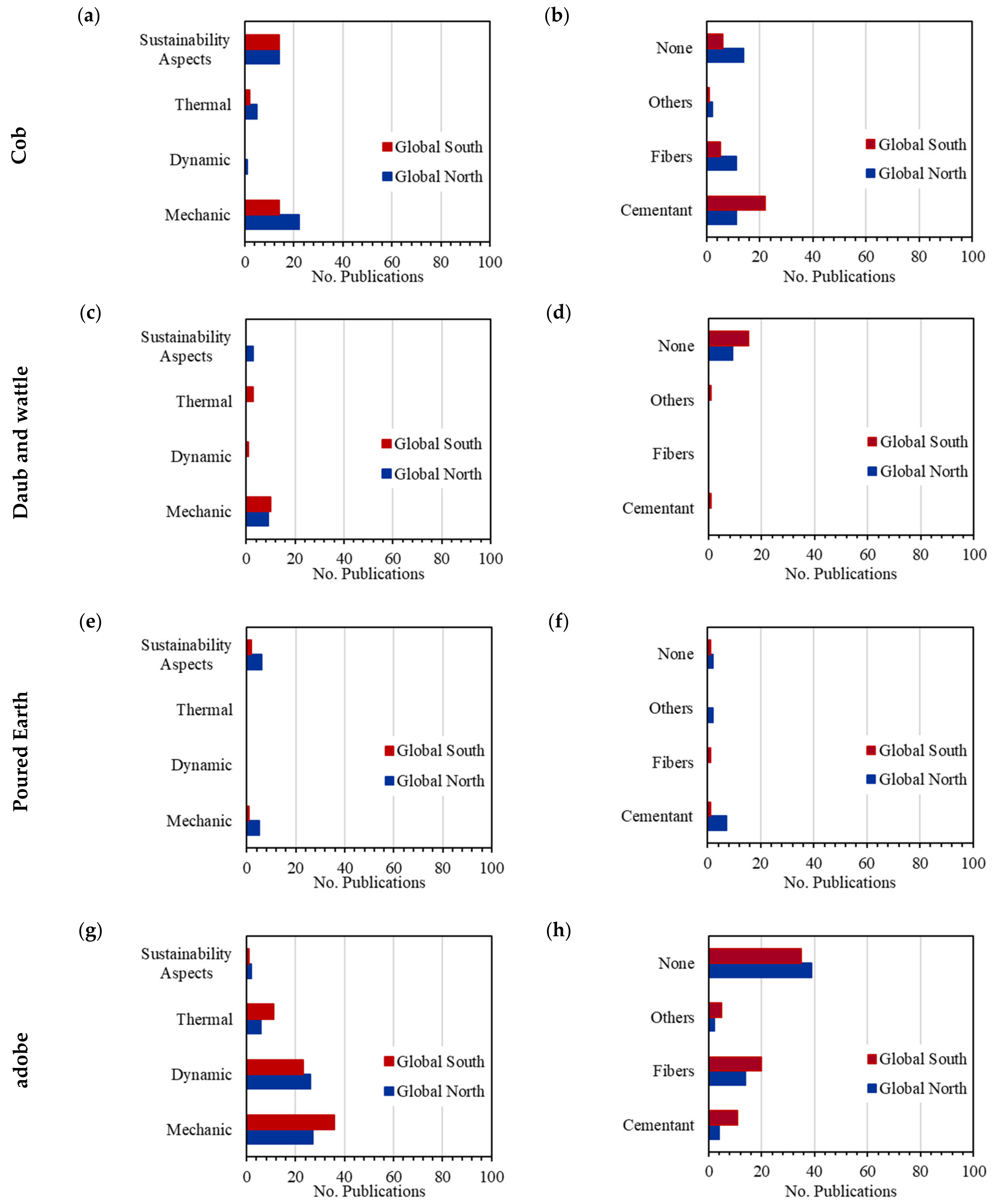
Also, the geographical distribution of the scientific productions on earthen constructions in the period evaluated shows a marked difference between the number of publications in the north and south regions. In the context of northern countries, research is concentrated in Western Europe, with Portugal (36), Spain (32), and France (30) as the main centers of study on earthen constructions, in addition to moderate interest in earthen constructions in other regions of the world, such as the United States and Australia. In the south, China (65) widely leads the research, with a much higher number of publications than any other country, followed by India (36), Iran (29), Morocco (15), and Algeria (12), showing a clear interest in North African and Asian countries. This pattern may be related to the growing need for environmental infrastructure to mitigate the adverse effects of accelerated urbanization and economic resource constraints in these countries.

Regarding Latin America, there is a more limited contribution in terms of publications, with few countries from the region appearing on the map. Mexico (14) and Brazil (14) are the most active countries, although their contribution is relatively low compared to other emerging countries such as China and India. This low level of publications could be related to lower investment in research on EnC techniques or prioritization of different construction materials and methods, even though many of the traditional EnC techniques have a long history in the region [81,82]. On the other hand, the lack of research in this area in Latin America could suggest a missed opportunity to develop environmental solutions adapted to local needs in the region.

In the Global North, in Portugal, Spain, and France, research on earthen constructions predominantly focuses on REWs, while studies on CEBs and adobe present a lower frequency. Regarding the areas of analysis, mechanical behavior is the focus in these countries, particularly in Spain, where it constitutes most of the research. Although dynamic aspects also receive considerable attention, especially in Portugal and France, there is little interest in this area in Spain. Studies related to thermal properties are more frequent in France, although they continue to represent a secondary area of research. Exploration of issues related to sustainability is minimal in these contexts, indicating that research prioritizes the structural stability and functionality of buildings, with less emphasis on environmental and sustainability concerns.

In the GS region, the research trends show regional variations, with a dominant focus on REWs in China and India, while Iran shows a balance between REWs and adobe. In Morocco and Algeria, interest is mainly directed toward CEBs, while in Mexico, the focus is on adobe. Mechanical behavior remains the focus of study in all these contexts. However, studies on dynamic behavior are more relevant in China and Iran than in other regions. On the other hand, the thermal and sustainability aspects are less studied and are even absent in some countries.

Figure 3 shows an analysis of the adobe, CEB, and REW publications classified according to sustainability, thermal, and physical–mechanical aspects. According to the use of additives, they were classified as without additives, with cementitious agents, with fibers, and with others, where the latter include materials that do not fall into the previous categories, such as reinforcements. For the case of adobe (Figure 3g,h), there is a global trend focusing on the material's mechanical properties. On the other hand, it is visualized that most of the research on adobe does not include additives in both contexts because this research usually deals with case studies of existing structures [83,84]. However, other research has used fibers such as straw [85], sawdust [21], pineapple leaves [86], cane [87], rice husk [88,89], agave [90], jute [91], seagrass [92], palm [93], polyethylene [94], textiles [95] and glass fibers [20] to improve flexural strength, control shrinkage, and increase material cohesion. In addition, the use of alternative stabilizer agents, such as lime [96], fly ash [97], bentonite with metakaolin [98], paper ash [99] and construction and demolition waste (CDW) [100], has been investigated. These inclusions aim to improve the mechanical strength and offer more environmental alternatives to conventional cement, although there are studies that still use this as a stabilizer [101]. Finally, other types of inclusions are found, such as steel [102], wood [36] and geotextiles [36], which have been used to reinforce this structure; however, it is a very specialized category in both the GN and GS.



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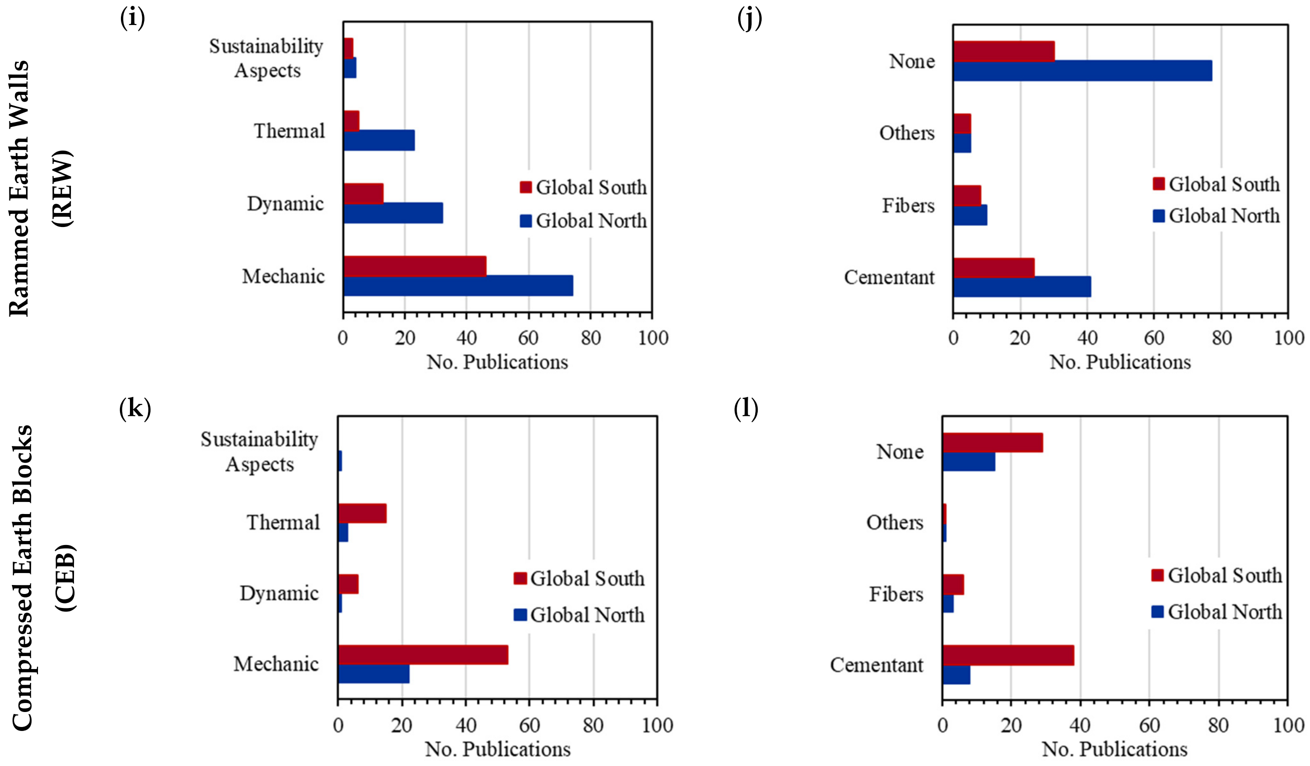

**Figure 3.** Number of articles published according to their technical approach and additives in different earth constructions: (**a**) Cob technical approach; (**b**) Cob additives; (**c**) Daub and wattle technical approach; (**d**) Daub and wattle additives; (**e**) Poured Earth technical approach; (**f**) Poured Earth additives; (**g**) adobe technical approach; (**h**) adobe additives; (**i**) REW technical approach REW; (**j**) REW additives; (**k**) CEB technical approach; (**l**) CEB additives.

On the other hand, Figure 3k,l show that the GS countries are much more interested than northern countries in studying CEBs. This contrasts with the previously mentioned finding because, despite being more studied in these countries, some Global South countries tend to research other EnCs, such as REWs. This may be because this technique is the most current and has attracted more interest in its study in the context of a developing search for environmental construction alternatives. From this perspective, research on this EnC has focused more on evaluating the mechanical and thermal properties of the material [103–106], mainly focusing on evaluating the strength of the material with and without additives. From this perspective, the most studied additives are cement [68], lime [107], calcined clay-based alkalis [108], glass powder [109], red clay [110], bentonite [111], kaolinite [112], rice husk ash [112,113], calcium oxide aluminate [16], metakaolin [112], fly ash [19], phosphogypsum [110], blast furnace ash [114], CDW [115] and calcium carbide [116]. Despite this trend, many investigations focused on analyzing the material properties without additions to the structure, focusing on mechanical and dynamic behavior, were also found. On the other hand, few studies with CEBs have included fibers such as sawdust [69], bamboo [117], pig hair [118], polypropylene fibers [119], banana [22], sisal [120], and hemp [121], which have shown promising results in improving flexural strength. Finally, in the classification of "other" additives, there are those that do not fall into the categories of fibers or cementitious agents, such as oil shale [103], steel bars [122], and geogrids [123].

In the REW research (Figure 3i), it can be observed that there is a greater focus on studies related to mechanical behavior in the GN region. However, a good number of articles are still focused on dynamic and thermal aspects. In this context, the interest is concentrated on the mechanical behavior of the material, with a lower proportion of studies dedicated to other properties. On the other hand, sustainability aspects receive hardly any attention in both groups, being even lower in the GS region, which has been a clear trend in all the types of EnCs. In addition, it is shown that a significant proportion of the studies do not use any additive or reinforcement for the evaluation of REWs (Figure 3j), especially in northern regions, where these correspond to case studies of pre-existing dwellings.

On the other hand, stabilizer agents have an important contribution from both regions, despite being studied more in the GN. Additives such as cement [124], lime [125], limestone [126] and blast furnace slag [127] are the most used for this type of study. Different studies were also found in both country typologies focused on the incorporation of fibers such as textiles [128], waste tire textile fibers (WTTFs) [129], jute [23], coconut [23] and wool [130], which are integrated into an REW to improve its flexural strength and durability. In the category of others, although in a considerably reduced percentage, we find concrete [24], cork [131] and steel plates [132], which are mainly used as structural reinforcement and are more frequent in REWs than in CEBs and adobe. Overall, the northern countries tend to investigate the properties of REWs more variedly, while in the Global South, the focus has been on improving the mechanical properties using cementitious binders.

### *3.3. Research Trends on Earthen Constructions in the World*

The Bibliometrix® thematic map in Figure 4 shows the most commonly used keywords in EnC publications in the GN countries (Figure 4a) and GS countries (Figure 4b), dividing the areas into driving, basic, niche, and emerging/declining topics, according to their relevance and development. In the northern region, the quadrant of driving themes highlights, in particular, the orange cluster, which encompasses terms such as “Sustainability” and “Fly Ash”, reflecting the use of alternative cementitious materials to improve mechanical properties while maintaining an environmental approach [3]. However, as previously shown, little research focuses squarely on material sustainability because the use of alternative additives or waste is considered inherently environmental without a thorough analysis of their life cycle or carbon footprint. On the other hand, the green cluster, which includes “Strengthening” and “Shear Behaviour”, shows that structural behavior and mechanical property evaluation is a well-developed topic in the Global North countries [24]. In the basic themes, the red and lilac clusters include “adobe Masonry,” which highlights this type of construction as a theme that has already been well developed and is gaining clear relevance within the research [36]. On the other hand, the blue cluster with “Rammed Earth” and “Compressive Strength” reflects a crucial interest in the structural analysis of REWs, consistent with previous findings, where it was shown that the most significant number of publications in northern countries are focused on mechanical properties. The niche topics, such as the pink cluster with “Additive Manufacturing” and “Earth Architecture” and the green cluster with “Dynamic Identification” and “Energy”, show emerging research areas with high relevance but low density, indicating that these areas are in an intensive development phase but are not yet central.

In the Global South region, the quadrant of driving themes highlights the green cluster, which includes terms like “Physical and Mechanical Properties” and “Thermal Comfort.” This cluster strongly focuses on optimizing both the structural and thermal performance of earthen materials, essential for enhancing the comfort and durability of constructions in diverse climates [105,133–135]. Similarly, “adobe Masonry” in this quadrant underscores the sustained interest in refining traditional techniques for modern applications [20]. In the basic themes, the red and blue clusters feature “Rammed Earth” and “Compressive Strength”, pointing to a fundamental interest in analyzing the structural aspects of REWs. This aligns with findings that show a substantial body of research dedicated to the mechanical properties of earthen materials in the Global South [82,103].

The consistent appearance of “Mechanical Properties” and “Compressed Earth Blocks” in these themes indicates a well-established research area, especially for CEBs, which are particularly relevant in southern countries due to their accessibility and sustainability [135]. In the niche themes, the orange cluster with “Seismic Performance” and “Strengthening” represents specialized topics crucial for regions prone to seismic activity. While highly relevant, these themes still need further research to become central topics in the field. Additionally, emerging themes such as “Dynamic Increase Factor” and “Tensile Strength” are highlighted, showing that while these areas are gaining traction, they remain in an exploration phase, with high potential for further development.

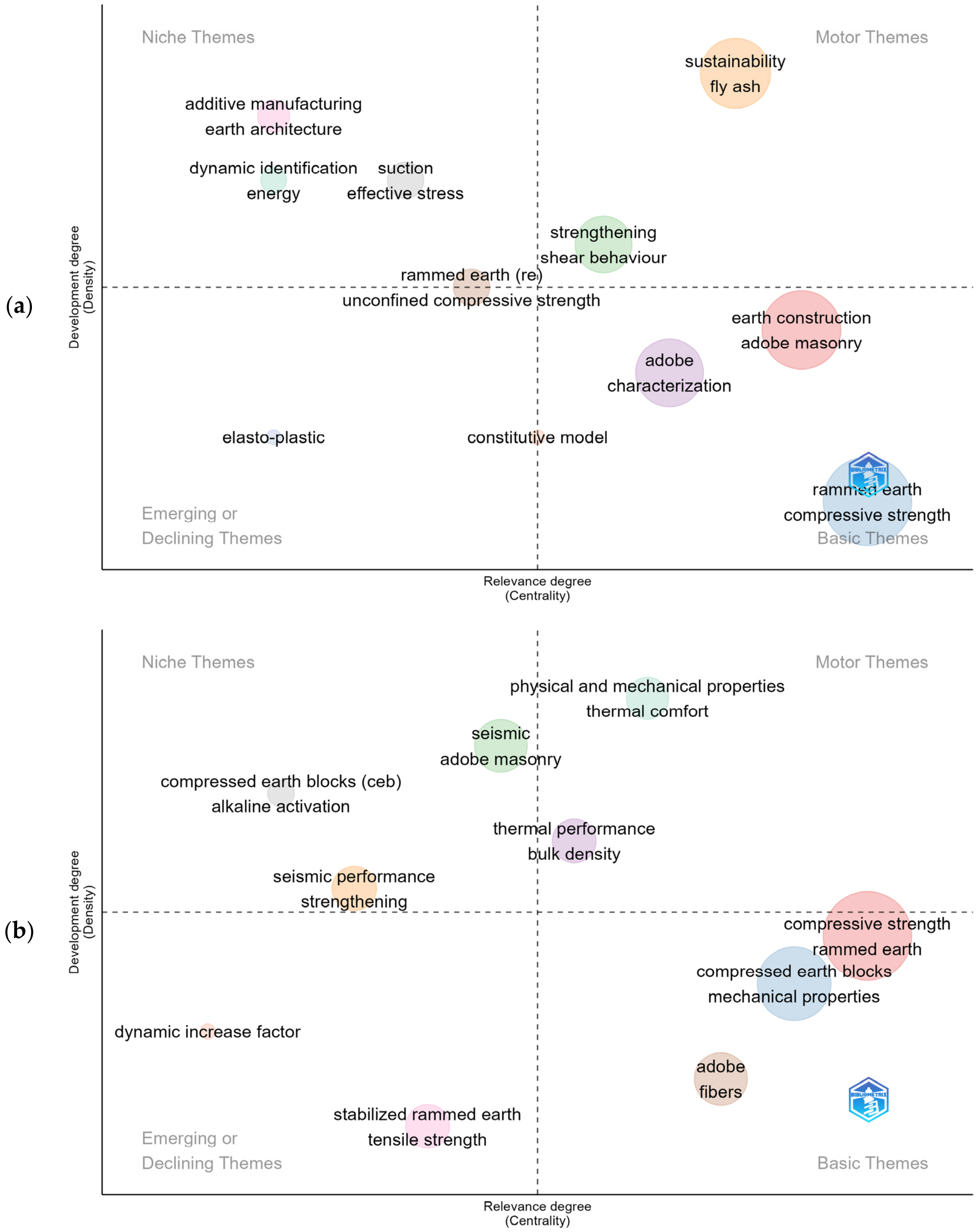

**Figure 4.** Thematic map of earthen constructions (EnCs): (**a**) Global North (GN) region; and (**b**) Global South (GS) region.

Figure 5 presents a detailed overview of trends in the EnC research over the last decade. In the Global North (Figure 5a), between 2013 and 2015, the topics "activation", "seismic", and "aging" show a temporary increase in the frequency of publications, although without establishing a lasting trend. Between 2014 and 2022, "shear strength" remained a relevant topic, with a notable peak in 2016 related to advances in techniques for evaluating the strength of materials in earth structures in response to growing interest in improving safety in seismic construction [52]. Other themes, such as "Strength", "Rammed Earth," and "Compressive strength", also show significant peaks in 2018, 2019, and 2020, respectively, reflecting a trend in the research on the structural behavior of this type of building [136]. Finally, in 2022 and 2023, the topics of "Sustainable construction" and "Numerical simulations" gained relevance, marking a more environmental approach and a transition toward more detailed structural modeling based on the experimental results of previous years [137].

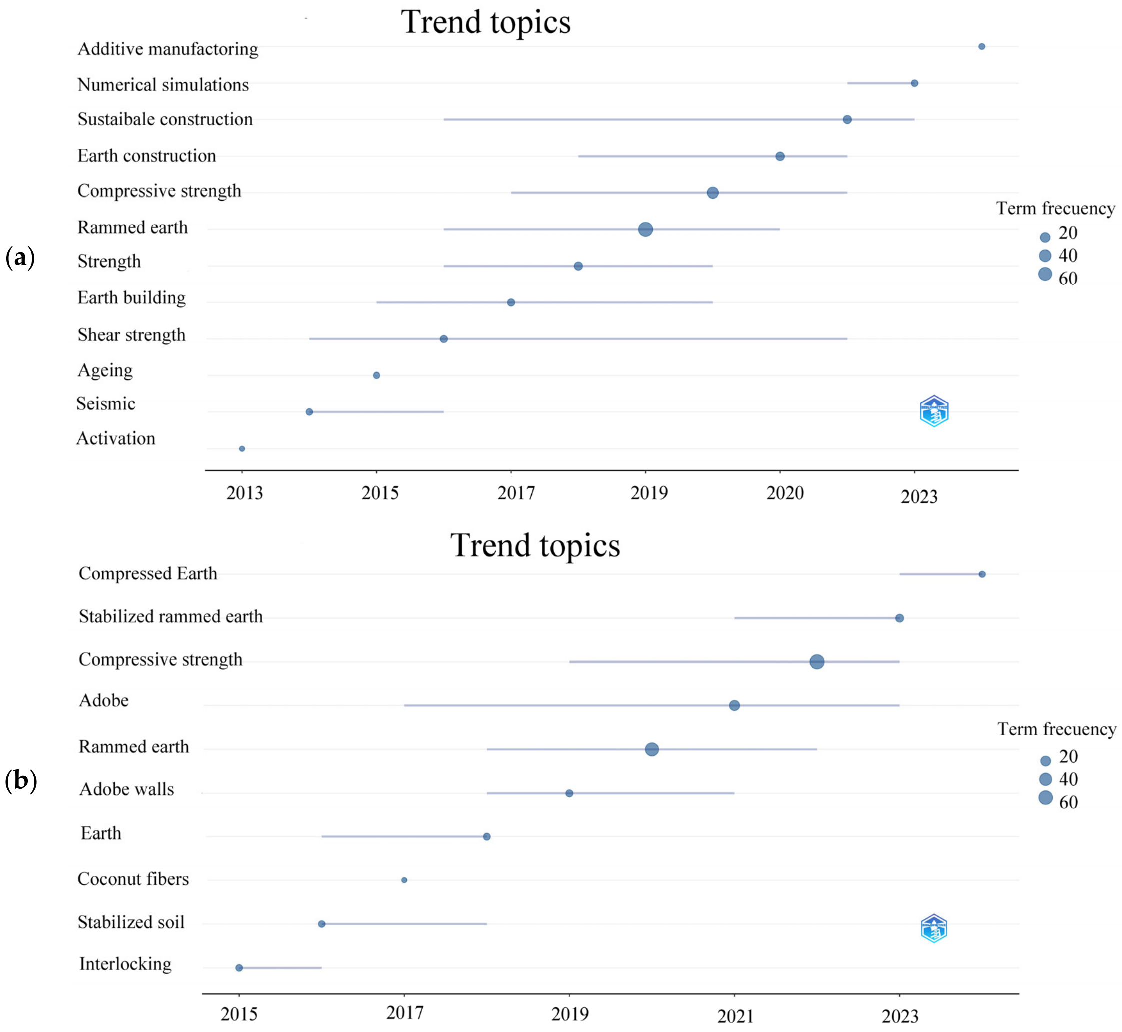

**Figure 5.** Keyword trends: (**a**) Global North region; and (**b**) Global South region.

In the Global South, during the years 2013 to 2016, an increase in the research on topics such as "compressive test", "absorption", and "seismic retrofitting" is seen, showing the mechanical and dynamic behavior of materials [138]. Then, by 2016, "Stabilized soil" had a peak, showing that the research in these countries was directed toward the search for soil stabilization techniques to improve the durability and strength of this type of construction [68]. Between 2018 and 2021, "Adobe walls" and "rammed earth" recorded peaks in 2019 and 2020, respectively, showing that the research focused on the analysis of this specific type of construction [139]. Recently, topics such as “stabilized rammed earth” and “Compressed earth” have gained prominence, with peaks in 2023 and 2024. This is consistent with the fact that, in southern countries, the focus of the research is currently on the use of additives and the study of CEBs and REWs.

## *3.4. Environmental Performance of Earth as a Material*

### 3.4.1. Environmental Performance of Earthen Constructions

Construction on land faces social and sustainability challenges in both the Global North and Global South countries, influenced by negative perceptions, lack of regulations, and scarcity of technical training [140]. In the GN, the main barrier is the perception of inferiority compared to modern materials, especially in urban areas, which limits their adoption despite the environmental benefits [141]. Examples in Algeria, Italy, and Turkey show how cultural and economic factors hinder the preservation and development of these techniques. In some cases, the conservation of the heritage is valued [142–144]. In the GS, earthen construction is associated with rural and low-income communities, which, together with the lack of regulations, complicates its acceptance in urban contexts in search of modernization. However, research in Peru, India, Bangladesh, and Colombia demonstrates efforts to integrate local materials and environmental technologies [145–147].

This systematic review revealed that “sustainability” is prioritized in the Global North, while it has been less emphasized in the Global South. This also evidenced a significant gap in the research on the sustainability of earthen constructions in the Global South. Table 4 presents some research that has addressed environmental aspects such the global warming potential (GWP) expressed in terms of the carbon intensity. From this perspective, the GWP is a crucial metric for measuring and tracking embodied carbon, as measured in $kgCO_{2eq}$. From this perspective, conventional building materials such as concrete and steel report values close to 80 $kgCO_{2eq}/m^2$ [148]. Other materials, such as 15 cm and 26 cm ceramic brick walls, show values of 39.1 $kgCO_{2eq}/m^2$ and 57.4 $kgCO_{2eq}/m^2$, respectively, while lightweight concrete blocks have reported values between 32 and 82.6 $kgCO_{2eq}/m^2$ [149]. In the case of EnCs, although few investigations have quantified these heats, Fernandes et al., 2019 [3] reported that CEBs have a GWP of 16.6 $kgCO_{2eq}/m^2$ and traditional REWs of 28.5 $kgCO_{2eq}/m^2$, significantly lower than conventional building materials. However, other authors, such as Meek et al., 2021 [24], have pointed out that stabilizing earthen constructions with traditional cementitious agents, such as cement and lime, can raise the GWP of REWs to 56.11 $kgCO_{2eq}/m^2$, considerably decreasing their environmental status. This shows that in terms of the GWP, earthen constructions present environmental potential in reducing greenhouse gas generation. On the other hand, it shows the importance of studying alternative cementitious agents in stabilizing these materials due to the negative impact of conventional cementitious agents on the material’s sustainability.

The environmental performance of various earthen construction techniques, including cob, adobe, REWs, and CEBs, was assessed by calculating their embodied carbon across life cycle stages A1 to A3, as defined in the European standard CEN 15804 + A2 (2019) [150]. These stages—covering raw material extraction (A1), transport to the manufacturer (A2), and manufacturing (A3)—provide insights into the initial environmental impact of these materials. The assessment utilized regionally specific Environmental Product Declarations (EPDs) from the French INIES database [151], the Swiss Construction Material Database [152], the British Inventory of Carbon and Energy (ICE), and the ecoinvent database. The ICE database, developed by the University of Bath and documented by Hammond and Jones et al., 2011, is renowned for its extensive data on embodied carbon across a wide range of building materials [153]. Additionally, the ecoinvent database was instrumental in providing detailed life cycle inventory data for key processes in earthen material production. Specific “nodes” within ecoinvent were used to model processes such as soil extraction, stabilization, and transportation, allowing for accurate tracking of emissions associated with each stage of the life cycle [154]. By structuring the assessment through these nodes, we could isolate and quantify the environmental impacts of individual stages, ensuring compliance with the CEN 15804 + A2 requirements. Additionally, research by Ben-Alon et al., 2020 [29] provided a comparative analysis of earthen construction techniques, highlighting the low-carbon advantages of using these materials. Together, these references facilitated a comprehensive comparison of embodied carbon in earthen construction, supporting the identification of sustainable, low-carbon building alternatives.

The embodied energy (EE) reflects the energy demand at all the stages of a material’s life cycle. Conventional materials, such as concrete and steel, have a high EE due to the intensive energy demand in their extraction, processing, transportation, and construction [149]. In this context, Fernandes et al., 2019 [3] compared the EE of CEBs and REWs with traditional masonry, finding that CEBs have an EE of 165 MJ/m$^2$, while REWs present an EE of 358 MJ/m$^2$. In contrast, 15 cm and 26 cm ceramic brick walls present an EE of 349 and 540 MJ/m$^2$, respectively, showing that earthen constructions require considerably less energy. For their part, Christoforou et al., 2016 [85] evaluated the EE for the manufacture of adobe, finding that in situ production with local soil and transported straw has an EE of only 51.06 MJ/m$^3$. These data reveal a clear benefit of earthen constructions over other materials due to the low energy consumption for their production.

**Table 4.** Environmental performance of different earthen construction techniques based on the embodied carbon calculated for modules A1–A3 based on CEN 15804 + A2 (2019).

| **Earth Technique** | **Additive Content** | **Density (kg/m$^3$)** | **Carbon Intensity (kg $CO_2$/kg)** | **Carbon Intensity (kg $CO_2$/m$^3$)** | **Carbon Intensity (kg $CO_2$/m$^2$ of Floor Area, 20 cm Thickness)** | **Ref.** |
|---|---|---|---|---|---|---|
| Cob | 0% | 1600–1800 | 0.022–0.025 | 40–44 | 8–9 | [153] |
| Daub and Wattle | 0% | 1200–1400 | 0.018–0.023 | 25–28 | 5–6 | [153] |
| Poured Earth | 0% | 1800–2000 | 0.095–0.011 | 19–20 | 4–5 | [153] |
| Adobe | 0% | 1600–1800 | 0.023–0.028 | 42–45 | 8–9 | [85,155] |
| Rammed Earth | 0% | 1900–2200 | 0.010–0.015 | 25–35 | 5–7 | [3] |
| Rammed Earth Stabilized (Cement) | 8–10% | 1900–2200 | 0.072–0.090 | 140–200 | 28–40 | [24] |
| Rammed Earth Stabilized (Fly Ash) | 8–10% | 1900–2200 | 0.02–0.045 | 75–95 | 15–19 | [24] |
| CEB | 0% | 1800–2000 | 0.014–0.017 | 28–30 | 5–6 | [3] |
| CEB Stabilized (Cement) | 10% | 1800–2000 | 0.082–0.095 | 165–172 | 33–34 | [3,156] |
| Cinder Block (Cement) | 10% | 1800–2000 | 0.085–0.097 | 170–175 | 34–35 | [153] |

### 3.4.2. Industrial and Agro-Industrial By-Products as the Key to the Future of Earthen Construction

The sustainability of earth as a building material was demonstrated in the previous section; however, one of the main challenges facing these materials is the improvement of their mechanical properties, such as the compressive strength, durability, and erosion resistance [50]. To address these limitations, several studies have focused on incorporating additives to optimize the structural performance of these materials [17,26,127,157–159]. In this context, it has been observed that the use of industrial products has been consistently explored globally. Among the most prominent additives are cement and lime in different proportions, whose application as stabilizers has shown an improvement in the mechanical properties and durability of blocks and walls [160]. This review found that cement has been widely used as a stabilizer in proportions between 2.5% and 20% in different climatic contexts around the world, mainly for the CEB and REW techniques [68,161]. For its part, lime has been employed in proportions commonly ranging between 3 and 10% [109,162];

however, this additive is usually combined with other waste materials, such as fly ash [17] or natural pozzolana [163]. This is because although the incorporation of these additives contributes significantly to improving the properties of earth materials, the impact on sustainability is high.

On the other hand, Table 5 shows several investigations have incorporated waste from different industrial sources, seeking to improve the properties of the materials and to reduce the environmental impact associated with waste management. Table 4 shows different materials and industrial wastes that have been used to improve the properties of earthen constructions. Within the fibers, the main additives found have been polyethylene fibers and glass-reinforced polymer fibers (GRPFs); these fibers have shown considerable improvement in the mechanical properties of earth constructions, especially in terms of the tensile strength. On the other hand, research has been reported on REW walls in which textile tire fibers have been incorporated, which have shown an increase in flexural strength, a property typically low in materials such as REWs [164].

This review also showed an extensive list of stabilizers used in earthen constructions. The industrial waste that appeared most frequently for all the earthen techniques analyzed was fly ash, since in the last decade, different sources of recycling and reuse of this industrial waste have been sought. Likewise, efforts have been made to incorporate CDW in compressed earth blocks, achieving stability through the incorporation of geopolymer mixtures. In these mixtures, alkaline activators such as sodium hydroxide and sodium silicate produce chemical reactions that increase the cohesion of the earth elements, incrementing the mechanical and durability performance of earthen materials.

**Table 5.** Industrial and industrial waste by-products used in the improvement of earthen construction performance.

| Type of Aggregate | Adobe | | | CEB | | | REW | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Additive** | **Industrial Waste** | **Ref.** | **Additive** | **Industrial Waste** | **Ref.** | **Additive** | **Industrial Waste** | **Ref.** |
| Fibers | Polypropylene | ⁂ | [94] | Polypropylene | ⁂ | [119] | Waste Tire Textile Fibers (WTTFs) | ✓ | [165] |
| | Polytene | ⁂ [1] | [166] | - | - | - | Polypropylene | ⁂ | [167] |
| | Textile | ✓ | [95] | - | - | - | Wool | ⁂ | [130] |
| | Rubber | ✓ | [168] | - | - | - | Textile | ✓ | [169] |
| | GRPF | ⁂ | [20] | - | - | - | Glass Fiber | - | [170] |
| Stabilizers | Fly Ash | ⁂ | [17] | Cement | ⁂ | [171] | Cement | ⁂ | [172] |
| | Paper and Paper Plasters | ⁂ | [99] | Lime | ⁂ | [163] | Lime | ⁂ | [172] |
| | Cement | ⁂ | [173] | Fly Ash | ✓ | [174] | CDW | ✓ | [127] |
| | Bentonite | ⁂ | [98] | Granulated Blast Furnace Slag (GBFS) | ✓ | [114] | Magnesium Chloride | ⁂ | [175] |
| | Lime | ⁂ | [86] | CDW | ✓ | [115] | Mud | ✓ | [97] |
| | CDW | ✓ | [176] | Bentonite | ⁂ | [111] | Fly Ash, Sodium Hydroxide | ※ | [177] |
| | Mud | ✓ | [97] | - | - | - | - | - | - |
| Stabilizers + Fibers | Polymer, Gypsum and Lime | ⁂ | [178] | Cement + Polypropylene Fibers | ⁂ | [119] | Cement, Steel Fibers | ⁂ | [132] |
| | - | - | - | Lime + Polypropylene Fibers | ⁂ | [179] | - | - | - |
| Others | Geogrid | ⁂ | [180] | Oil Shales | ✓ | [103] | Geogrid | ⁂ | [181] |
| | Steel Mesh | ⁂ | [81] | - | - | | - | - | - |

[1] The industrial waste materials used in earthen constructions are marked with an ✓, research that incorporated a mixture of industrial and waste materials is represented with an ※, and finally, the investigations that only incorporated only industrial by-products are represented by a ⁂.

On the other hand, Table 6 shows the use of different agro-industrial products, classified as materials or wastes, which have been the subject of study in the last decade, with particular emphasis on the use of vegetable fibers. Fibers obtained from residues such as coconut, kenaf, jute, hemp and straw have been widely investigated due to their capacity to improve the tensile and flexural properties of materials, as well as to increase their resistance to cracking and improve their thermal insulation. In addition, some ashes derived from agro-industrial processes have been reported as potential stabilizing agents for earth constructions. This has been mainly in terms of adobe, where more than five different types of stabilizers of natural origin are reported, versus fewer in constructions such as CEBs and REWs. Among the most prominent alternative cementitious agents are rice husk ash, sugarcane bagasse ash and ground olive stones (GOSs). The reviews showed that these additives, in addition to improving the mechanical properties, provide thermal characteristics that can make these constructions have better energy performance. Although fewer natural stabilizers were found in REWs and CEBs, research was reported where cement was combined with natural fibers, mainly banana, sisal and bamboo. This suggests that, although advances have been made in the use of stabilizers of natural origin, standardized processes have not yet been defined for these materials that are comparable in structural behavior to the benefits provided by cement.

**Table 6.** Agro-industrial waste by-products used in the improvement of earthen construction performance.

| Type of Aggregate | Adobe | | | CEB | | | REW | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Additive** | **Waste** | **Ref.** | **Additive** | **Waste** | **Ref.** | **Additive** | **Waste** | **Ref.** |
| Fibers | Straw | ⁂[1] | [182] | Pig hair | ✓ | [118] | Bambu fibers | ✓ | [23] |
| | Reed | ⁂ | [87] | Green mussel shells (GMS) + pig hair fibers | ✓ | [118] | Jute fibers | ✓ | [137] |
| | Saw dust | ✓ | [21] | Kenaf fibers | ✓ | [158] | Coconut fibers | ✓ | [183] |
| | Jute fibers | ✓ | [91] | Saw dust | ✓ | [69] | Barley fibers | ✓ | [164] |
| | Agave fibers | ✓ | [90] | Hemp | ✓ | [121] | Palm fibers | ✓ | [164] |
| Stabilizers | Gypsum and straw | ※ | [184] | GOS | ✓ | [185] | Tannin | ✓ | [130] |
| | Rice husk | ✓ | [159] | Sugar cane bagasse ash | ✓ | [157] | Lignin sulfonate | ⁂ | [186] |
| | Gypsum and sugarcane molasses | ※ | [187] | Rice husk ash | ✓ | [188] | - | - | - |
| | Natural biopolymer brown algae | ✓ | [189] | - | - | - | - | - | - |
| Stabilizers + fibers | Cement + fiber *Pinus Roxburghii* | ※ | [173] | Date palm, cement and lime | - | [190] | Cement, coconut fibers | ※ | [191] |
| | CaO3 + straw | ※ | [35] | Banana fibers and cement | ※ | [183] | - | - | - |
| | Lime + pineapple fiber | ※ | [86] | Sisal fibers, cement | ※ | [120] | - | - | - |
| | - | - | - | Bambu fibers, cement | ※ | [117] | - | - | - |
| | - | - | - | | | | - | - | - |
| Others | Wood | ⁂ | [36] | - | - | - | Bambu and steel frames | ※ | [192] |
| | Rice starch | ✓ | [193] | - | - | - | Bambu, cement and steel frames | ※ | [194] |

[1] The agro-industrial waste materials used in earthen constructions are marked with an ✓, research that incorporated a mixture between industrial and agro-industrial materials are represented with an ※, and finally, the investigations that only incorporated agro-industrial by-products (non-waste) are represented by a ⁂.

### 3.5. Meta-Analysis: Uses and Characteristics of Earthen Constructions

This section presents a meta-analysis that compiles statistics on various physical, mechanical, and thermal properties of earthen building materials, including adobe, CEBs, and REWs. A raincloud plot incorporating the density, moisture content, compressive strength, flexural strength and thermal conductivity is illustrated in Figure 6. For the mechanical properties, only the 28-day strength values reported in the studies reviewed were considered. The amount of data collected for each construction technique varied according to the availability of information in the meta-analysis.

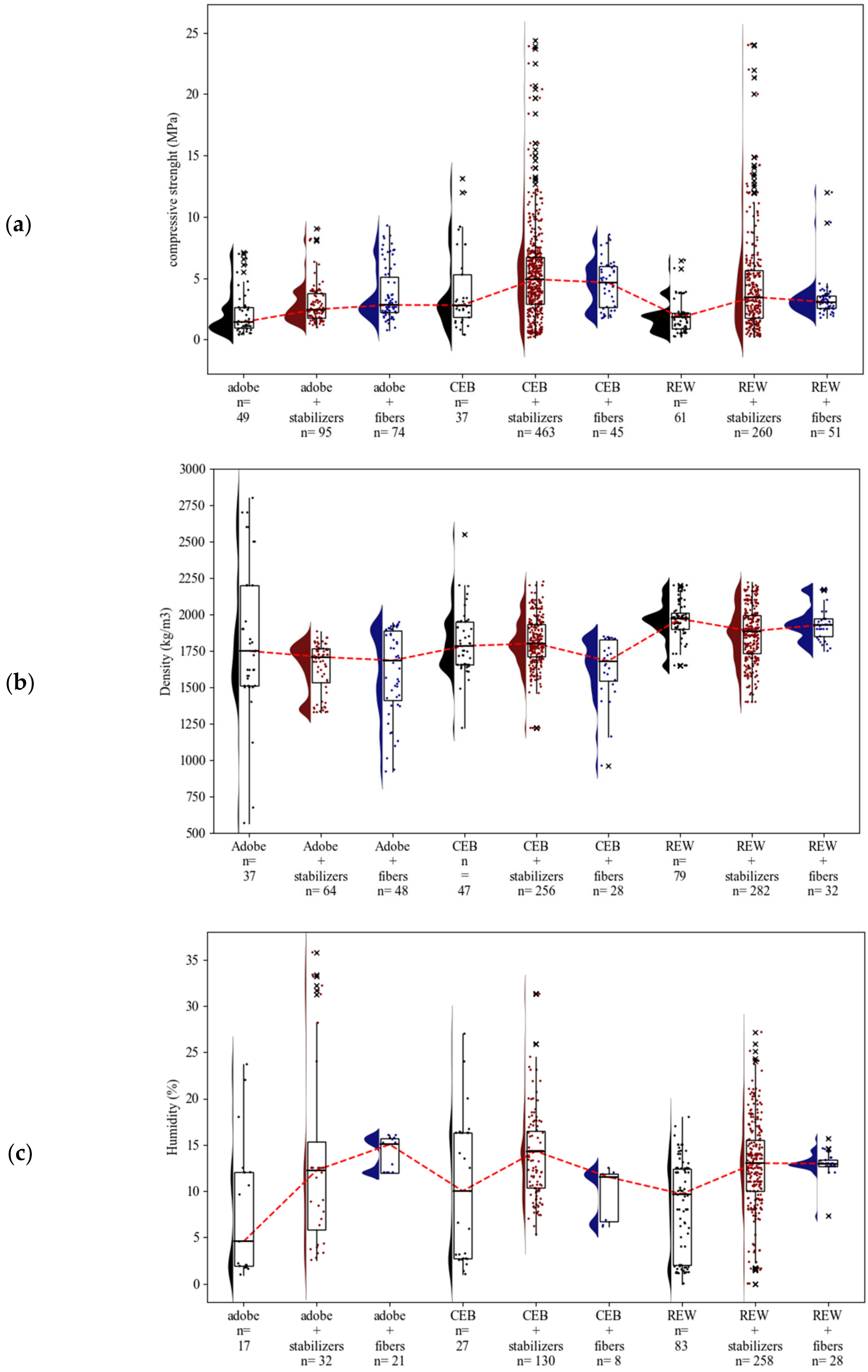

**Figure 6.** *Cont.*

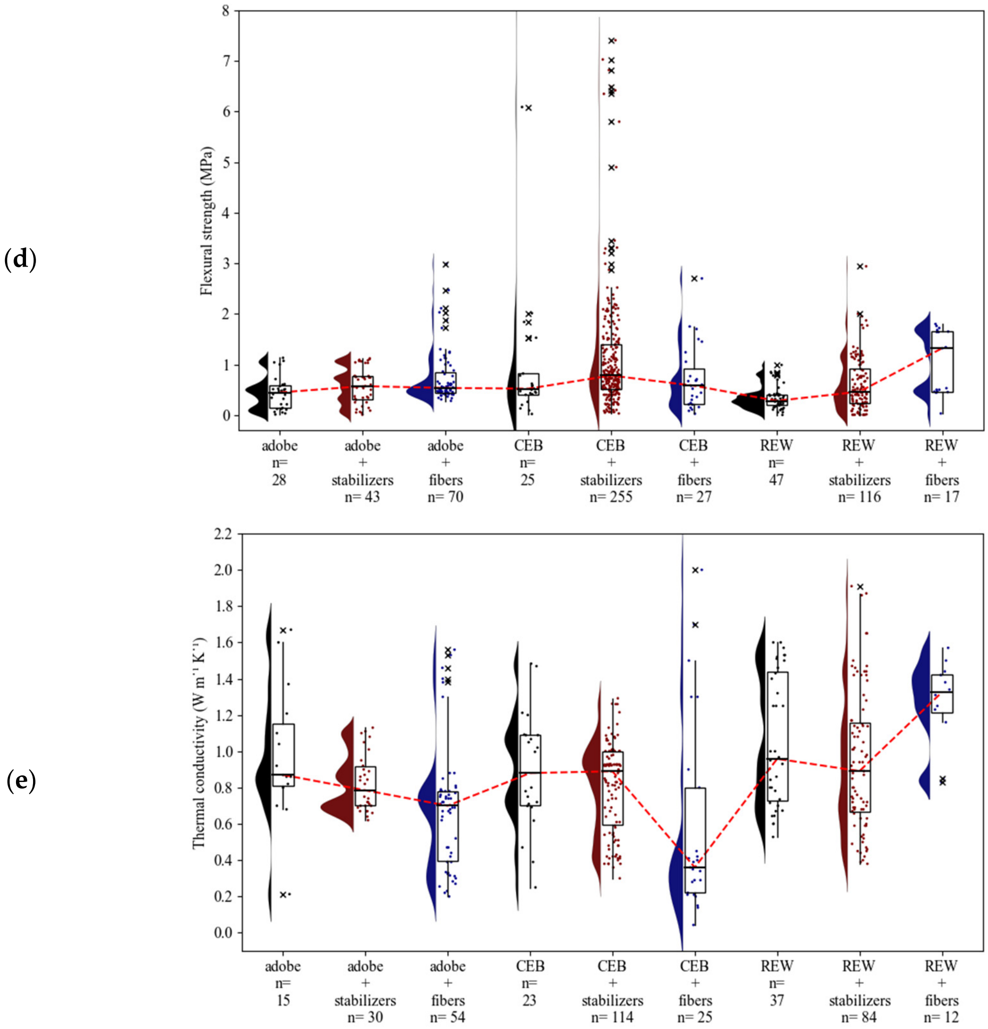

**Figure 6.** Physical, mechanical, and thermal characteristics of earthen constructions: (**a**) unconfined compressive strength, (**b**) density, (**c**) humidity, (**d**) flexural strength, and (**e**) thermal conductivity. Note: earth constructions (black), stabilized earth constructions (dark red), fiber-reinforced earth constructions (dark blue).

In Figure 6, the data collected were classified into three categories: constructions without additives, with stabilizers and with fibers. When the investigations included both types of additives, they were classified in the category corresponding to the predominant additive in the mixture. The results show a clear dispersion in all the properties analyzed, attributable to the high variability of the data within each category and to the volume of data collected. This dispersion is also explained by the fact that several investigations, especially in adobe and REWs, evaluated old structures that, due to their long consolidation periods, present significantly lower strength levels compared to studies that analyzed elements with shorter curing and consolidation periods.

Regarding density, values of less than 1000 kg/m$^3$ were reported in some studies on adobe and CEBs, which is due to the incorporation of fibers in the mix, aimed at reducing the weight of these materials. In the case of mechanical properties, outliers were identified, particularly in CEBs and REWs, where some investigations reported compressive strengths of up to 24 MPa, which is significantly higher compared to the mean of 5.45 MPa for CEBs and 4.59 MPa for REWs obtained in the meta-analysis. These increases in the mechanical performance of earthen constructions are significant, positioning these materials as potential replacements for conventional materials such as clay blocks and concrete. On the other hand, a more significant amount of data were found for materials such as CEBs and REWs with cementitious materials, which allows better identification of the trends in these typologies. Finally, the meta-analysis revealed that, regardless of the type of construction, the median thermal conductivity (Figure 6e) varies between 0.6 and 1.3 $Wm^{-1}K^{-1}$. Although these materials are not considered insulators, their thermal conductivity values are lower than those of conventional materials such as concrete, making them a good option for thermal efficiency in temperate or hot climates.

In terms of the compressive strength, adobe without stabilization presents a mean value of 2.17 MPa, while with stabilization it reaches 2.9 MPa. For CEBs, the unconfined compression without additives showed a mean value of 3.55 MPa, increasing to 5.35 MPa with stabilizers and 4.58 MPa with fiber reinforcements. On the other hand, the values in the REWs showed a mean of 1.85 MPa without additives and reached 4.59 MPa with the addition of stabilizers. As for density, the adobe without stabilization presented a wide range of values as mentioned above, from 600 to 2700 $kg/m^3$, explained by the different degrees of consolidation of the material (old structure, element in laboratory with a short curing period), the type of climate where it was developed, the type of weather, the type of weathering, and the type of weathering.

The type of climate where the research was carried out and even the type of soil reported differ in the different investigations. The investigations of adobe with additives showed a lower dispersion, with a dispersion between 1250 and 1700 $kg/m^3$ approximately. For the CEBs, although the density varied in the three groups, the mean values tended to be similar, except for the fiber-bound blocks, which showed a slight decrease, while in the stabilized blocks there was a greater accumulation of points toward higher density values without generating a significant increase in the mean of this property. On the other hand, the REWs showed a higher density in all cases compared to the other earth constructions, with values between 1500 and 2000 $Kg/m^3$.

Regarding humidity, the greatest dispersions are presented for all the techniques. This is because the data reported in the investigations are less common than the previous properties analyzed, so the uncertainty is greater. Considering the above, it can be seen that adobe without stabilization showed values between 2 and 25%, although most of the points were below 5%, which contrasts with the results of adobe with additives that increased to average values of 12% for stabilizers and 15% for fibers. For CEBs and REWs, the moisture without stabilization was between 9 and 12%, increasing to 12–15% after stabilization. The above shows that in all the earth construction techniques, there is a tendency for moisture to increase with the addition of additives regardless of their typology, which is normal behavior, considering that additives tend to retain water within their own internal structures, generating a greater demand for water [35,195,196].

In terms of thermal conductivity, adobe without stabilization presented an average value of 0.85 $Wm^{-1}K^{-1}$, with a slight decrease with the use of stabilizers and fibers. In the case of CEBs without additives and with stabilization, the average value varied approximately around 0.9 W/m-K, while the incorporation of fibers significantly reduces the average value of thermal conductivity, increasing it by 0.25 $Wm^{-1}K^{-1}$. On the other hand, for the REWs, the opposite case is presented. While the mean value of the walls without additives was between 0.9 and 1.0 $Wm^{-1}K^{-1}$, there was an increase in the treatments with incorporated fibers up to mean values of 1.2 $Wm^{-1}K^{-1}$ with stabilization.

Taking bending as another important mechanical parameter, it is visualized that for all the EnCs, the mean bending has to be similar, with an approximate mean range of 0.5–0.7 MPa; however, some values for the CEBs and REWs with stabilizers and adobe and REWs with fibers showed a significant increase in their resistance, of which more detail will be given in later sections of the document.

From a comparative perspective, the addition of stabilizers improves the mechanical strength and density, which is consistent with the densification of the material due to the cohesion usually provided by stabilizers in soils, but also shows a slight decrease in thermal conductivity, indicating a slight increase in thermal insulation capacity. Data from the stabilized CEBs and REWs showed the highest compressive strength (up to 24 Map), significantly exceeding adobe. On the other hand, although the thermal conductivity of the materials tended to show a significant dispersion, as previously indicated, their values were low in comparison to other traditional materials. This is significantly visible in the CBEs with fibers that showed a significant reduction in this thermal parameter, which may be since there are larger spaces between the structure of the material, storing more air that allows for this better thermal behavior. In addition, a relevant aspect is the role of the fibers, which in adobe and CEBs seem to have not only a positive effect on the reduction of thermal conductivity, without generating a significant impact on the compressive or flexural strength, reporting higher average values than the techniques without reinforcements.

A comparison of these results with the normative values in Table 3 shows that the compressive strengths of all the stabilized materials meet or exceed the minimum requirements by far. UNE 41410 (Spain, 2008) requires a minimum of 2 MPa for CEBs, while CEBs with stabilizers exceed this value up to six times (depending on the additive used) [77]. NTC 5324 (Colombia, 2004) establishes a range of 1.0–6.0 MPa for CEBs, which is met even by the non-stabilized versions of these materials [57]. Regarding density, NBR 13553 (Brazil, 1996) and NTC 5324 (Colombia, 2004) establish values higher than 1800 kg/m$^3$, which are only met by stabilized materials [57,76]. Regarding moisture, the strictest standard (NMAC 1474, EEUU, 2003) establishes a maximum of 10%, a criterion that applied for all the EnCs considered by it. With stabilization, none of the materials meet this limit, since humidity increases to 12–25%, which could compromise the durability of the structures in humid environments [58].

Thermal conductivity does not have a clear regulatory threshold in Table 3, indicating a challenge for future regulatory updates in terms of the energy efficiency of these materials. This is especially important since the reinforcement of fibers (except for REWs) shows good thermal performance, which is a crucial parameter in regions where thermal insulation is a priority. In addition, it is important to note that the standards refer to conventional stabilizers (cement, lime, asphalt) but do not specify other additives, such as those shown in Tables 5 and 6, which also show to improve EnC properties, as shown in Figure 6.

### 3.5.1. Compressive Strength Performance of Earthen Construction

Table 7 presents a list of additives by the type of earth construction technique, with results higher than the mean compressive strength + one standard deviation obtained in the meta-analysis, specifying the best-recorded strength and the percentage of additive used. Chokhani et al., 2018 [17] demonstrated this improvement by manufacturing earth blocks with fly ash (30–60%), cement (5–8%), lime (3–8%), and sand. The results showed a significant increase in compressive strength and reduced water absorption, especially in specimens with 50% fly ash and 8% cement. Although these blocks are not composed chiefly of earthy materials, the authors highlight their potential as an environmental alternative due to their high proportion of recycled materials.

As for fibers, the use of sawdust has shown benefits in terms of the compressive strength of adobe. Costi de Castrillo et al., 2021 [21] evaluated straw and sawdust as reinforcements in adobe blocks. Although straw is a traditional additive, the results revealed that sawdust, at approximately 30% by volume, provides more significant mechanical improvements, while straw helps reduce water absorption. Limami et al., 2023 [69] also experimented with sawdust in compressed earth blocks, achieving compressive strengths of up to 8.55 MPa, well above standards such as ASTM E2392 [60]; IS 1725 [197] and UNE 41410 [77], which require a minimum of 2 MPa for CEBs. However, they observed that the strength depends on the amount and length of the fibers; the optimum mixture contained 1% by volume of 0.5 mm fibers, achieving maximum mechanical performance without compromising the cohesion of the material. The volumetric quantity reported by Limami et al., 2023 [69] is significantly lower than that reported by Costi de Castrillo et al., 2021 [21], which is explained by adobe's larger dimensions and moisture content concerning CEBs.

On the other hand, this review shows that cement is the most widely used industrial stabilizer in the earth construction research. Research has shown two trends: evaluating the technique with cement as the sole stabilizer or in combination with others, such as lime [68,125,160], CDW [115], oil shale [103] and fly ash [198]. These have shown promising results regarding improving the mechanical performance of ground techniques; however, these investigations commonly need to include the impact on parameters, such as the GWP and EE, with this additive. On the other hand, other research that has included cement even sought to work on sustainability by replacing other materials. For example, Al-Jabri, K. et al., 2021 [199] explored cement as a stabilizer in CEBs, using wastewater from oil plants as mixing water. This approach contributes to sustainability and achieves compressive strengths of up to 14 MPa, exceeding the mean of 5.45 MPa observed in the meta-analysis and complying with standards such as the ASTM C90 [200] and the NTC 4205 [201], which require concrete blocks to have strengths of 13.8 MPa and 10 MPa, respectively. These results underscore the potential of earthen constructions with industrial admixtures to match, and even exceed, the strength requirements of conventional materials.

Another industrial waste that is on trend is CDW, incorporated in research with varied climatic and regional contexts, especially in CEBs and REWs. Alexandre et al., 2019 [115] and Joshi, A. et al., 2019 [176] indicated that CDW improves earth blocks' mechanical strength and durability properties. Nshimiyimana, P. et al., 2020 [202] combined calcium carbide and rice husk ash waste, achieving compressive strengths up to 7 MPa in CEBs with 16% and 4% additions, respectively. However, other research has indicated that alkaline solutions such as potassium hydroxide are required to achieve higher strengths with this type of waste. These activators break down the crystalline structures of minerals such as silica and alumina in CDWs, releasing silicate and aluminate ions that recombine and polymerize, creating a cohesive material with improved mechanical strength [174,203]. Thus, the research by Meek, A. et al., 2021 [127] manufactured REW specimens with recycled concrete brick (73.4%), fly ash (7.3%), GBFS (3.7%), kaolin (3.7%), silica fume (2.9%), and sodium hydroxide (1.65%), achieving an average compressive strength of 24.07 MPa, which was the highest compressive strength recorded for this type of earth construction during the meta-analysis.

**Table 7.** Better compressive strength performance of earth constructions produced with and without aggregates reported in the literature.

| Earth Construction Technique | Type of Aggregate | Additive | Source | Reported Optimal Mixture Content | Max. Density (kg/m$^3$) | Reported Humidity (%) | Element Size (mm) | Compressive Strength (MPa) | Meta-Analysis Compressive Strength Average (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Adobe | None | - | - | 0% | - | - | 200 × 200 × 45 | 4.43 | Adobe: 2.17 | [204] |
| | Stabilizer | Fly ash and cement | IIW | 50% (fly ash), 8% (cement), 42% (sand) | 1746 | 3.71 | 230 × 108 × 70 | 9.03 | Stabilized adobe: 2.90 | [17] |
| | Fibers | Saw dust | AIW | 30% (Saw dust), 70% (clay) | 1505 | - | 450 × 300 × 50 | 7.32 | Adobe with fibers: 3.71 | [21] |
| CEB | Stabilizer | Fly ash FA, sodium hydroxide NH, GBFS | IWP | Sand + 36% FA + 10% GBFS + 22.77% NA | - | - | 50 × 50 × 100 | 16 | CEB: 3.55<br>Stabilized CEB: 5.35<br>CEB with fibers: 4.58 | [174] |
| | Stabilizer + fibers | Cement and date palm fibers | IPAW | CEBC8%F0.05% | - | - | 100 × 100 × 200 | 12.7 | | [205] |
| | Stabilizer | Lime and natural pozzolana | IP | CEB10%L30%PN | - | - | 100 × 100 × 200 | 16.00 | | [163] |
| | Stabilizer | Cement, and residual water from oil fields | IP | 15,38%C | 1786 | 23.08 | 300 × 150 × 100 | 14.63 | | [199] |
| | Stabilizer | Cement kiln powder with Adjika clay | IWP | AdjibaCKB25 | - | - | 40 × 200 × 160 | 22.72 | | [206] |
| | Stabilizer | Fly ash, waste glass and activator/precursor wt. ratio | IWP | 50%, 50% and 0.5% | - | - | - | 11.66 | | [18] |
| | Stabilizer | Cement and glass powder | IIW | S17-C + 4%CP + 3%GP | - | - | 100 × 200 × 60 | 12.26 | | [109] |
| | Stabilizer | Ceramic waste | IWP | 50% ceramic | 1765 | 18.15 | 100 × 50 × 40 | 19.7 | | [207] |
| REW | Stabilizer + fiber | Cement, WTTF | IIP | 7% y 1% | 1700 | 18.5 | 70 × 142 | 6.24 | REW: 1.85<br>Stabilized REW: 4.59<br>REW with fibers: 3.35 | [165] |
| | Stabilizer | Cement and lime | IP | 9% C, and 4% L | 2164 | 17 | 550 × 550 × 200 | 6.84 | | [125] |
| | Stabilizer + fiber | Cement, coconut fibers 25 mm | IPAW | C 1% CF 25 mm | 1740 | 11.32 | 100 × 100 × 100 | 7.63 | | [186] |
| | Stabilizer | Concrete masonry recycled, fly ash, GBFS, kaolin, silica fume and sodium hydroxide | IWP | 73.4%, 7.3%, 3.7%, 3.7%, 2.9% and 1.65% | 1950 | 7.35 | 200 × 200 | 24.07 | | [127] |
| | Stabilizer + fiber | Cement, steel | IP | C 8% S 10 mm | 1900 | 10.22 | 150 × 150 | 5.21 | | [132] |
| | Stabilizer | Cement | IP | 8% | 1919 | 9 | 104 × 200 | 14.9 | | [208] |

**Table 7.** *Cont.*

| Earth Construction Technique | Type of Aggregate | Additive | Source | Reported Optimal Mixture Content | Max. Density (kg/m$^3$) | Reported Humidity (%) | Element Size (mm) | Compressive Strength (MPa) | Meta-Analysis Compressive Strength Average (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Cob | None | - | 0% | - | 1789 | 18–21 | 300 × 300 × 70 | 0.6–1.65 | - | [29,209] |
| Daub and wattle | None | - | - | 0% | | 3% | 1500 × 2200 × 120 | 2.08 | - | [32] |
| Poured Earth | None | - | - | 0% | 1850 | 20% | 40 × 40 × 160 | 3.2 | - | [8] |
| | Stabilizer | Ceraplast 300–naphthalene-based superplasticizer | IWP | 3% | 2260 | 16% | 100 × 100 × 100 | 47.7 | - | [8,9,210] |
| | Fiber | Alginate | IPAW | 6%, 9% and 12% | 2200 | | 300 × 500 | 2.1–2.8 | - | [33] |

Note: Includes physical characteristics reported, best mixture content, type of aggregate, additive, and max. compressive strength at 28 days. The source is expressed in the following: industrial and industrial waste products (IIW), agro-industrial waste products (AIW), industrial by-products (IP), industrial waste products (IWP), industrial by-products and agro-industrial waste products (IPA). Although uncommon, some studies incorporated agro-industrial waste as stabilizers. Examples are rice husk ash [114,211], sugarcane bagasse ash [157], GMS [118], lignin sulfate [130], and tannin [130]. Salim et al., 2014 [157] investigated the incorporation of sugarcane bagasse ash in CEBs, obtaining a compressive strength of 3.8 MPa with 10% replacement. Ouedraogo et al., 2022 [159] included rice husk ash in adobe blocks, reaching a strength of 3.67 N/mm$^2$ at 0.4% inclusion. Although lower than industrial wastes, these results comply with regulations such as the AFNOR-XP P13-911 (French standard) [212], improving the material's mechanical performance. However, the above shows that, although agro-industrial waste improves the compressive strength properties of earth materials, industrial products generate superior mechanical performance in earth constructions regardless of the source. On the other hand, few residues of agricultural origin were recorded, so the research is open in this field to find new agro-industrial by-products that achieve adequate competition of mechanical properties.

The meta-analysis also reveals that, compared to other earth construction techniques, stabilized CEBs have an advantage in structural performance over REWs and adobe blocks. This is due to the smaller dimensions of CEBs, which facilitate specimen handling and additive control, contributing to improved mechanical properties. In addition, compressed earth blocks have been a prominent focus in recent research (especially in the Global South), reflecting their increased study and not necessarily improved mechanical performance. These results demonstrate that the type of stabilization is critical to enhancing cohesion bonds and increasing the compressive mechanical performance of the elements.

### 3.5.2. Flexural Strength Performance of Earthen Construction

Table 8 summarizes the best flexural strength results, indicating the additions and mix percentages documented in the literature review. According to the meta-analysis, only studies that exceeded the mean plus one standard deviation were included here. Despite the wide variety of natural and industrial fibers, the results show that the best flexural performances in earth constructions are achieved with a combination of fibers and stabilizers.

Daniel, J. et al., 2021 [86] found that adding lime and pineapple leaf fiber increased the compressive and flexural strength six times compared to the original block, with an optimum mix of 0.9% lime and 0.5% ash fiber. In addition, they observed a sustained residual tensile load, indicating a significant improvement in the ductility of the block. On the other hand, Raavi, S. et al., 2020 [186] evaluated the reinforcement with coconut fibers and cement in CEBs, observing improvements in the mechanical properties. Although adding fibers increased the flexural strength, it affected the compressive strength, suggesting that the type and amount of fiber should be carefully adjusted. The authors also stress that cement is commonly used as a stabilizer. However, the literature highlights industrial waste as a viable option, which offers comparable mechanical performance but with a lower carbon footprint.

**Table 8.** Better flexural strength performance of earth constructions produced with and without aggregates reported in the literature.

| Earth Construction Technique | Type of Aggregate | Additive | Source | Reported Optimal Mixture Content | Max. Density ($kg/m^3$) | Reported Humidity (%) | Element Size (mm) | Flexural Strength (MPa) | Meta-Analysis Flexural Strength Average (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Adobe | Stabilizer + fibers | Lime and leaf pineapple fiber | IPAW | 0.9% and 0.5% | - | - | 400 × 200 × 200 | 0.77 | Adobe: 0.44<br>Stabilized adobe: 0.58<br>Adobe with fibers: 0.74 | [86] |
| CEB | Stabilizer | Geopolymer | IWP | CEB_20%G | 1760 | 22.3 | 140 × 140 × 94 | 1.68 | CEB: 0.51<br>Stabilized CEB: 1.14<br>CEB with fibers: 0.71 | [123] |
|  | Fibers | Kenaf fibers | AIW | 1.2% 20 mm | - | 12.5 | 40 × 40 × 160 | 2.70 |  | [158] |
|  | Stabilizer | Cement kiln powder with Adjika clay | IWP | 25% | - | - | 40 × 20 × 160 | 6.89 |  | [206] |
|  | Stabilizer + fibers | Cement and glass fiber | IP | 4% and 0.25% | - | - | 100 × 200 × 60 | 3.31 |  | [109] |
|  | Stabilizer | Cement | IP | 8% | 2080 | 12.06 | 40 × 40 × 160 | 3.29 |  | [213] |
| REW | Stabilizer | Concrete masonry recycled, fly ash, GBFS, kaolin, silica fume and sodium hydroxide | IWP | 73.4%, 7.3%, 3.7%, 3.7%, 2.9% and 1.65% | 1950 | 7.35 | 200 × 200 | 2.94 | REW: 0.34<br>Stabilized REW: 0.62<br>REW with fibers: 1.05 | [127] |
|  | Stabilizer + fibers | Cement and tire textile fibers | IIW | 8% and 4% | - | 4 | 600 × 600 × 150 | 1.32 |  | [129] |
|  | Stabilizer + fibers | Cement and coconut fibers | IPAW | 5%, 25 mm | 1600 | 17.77 | 100 × 100 × 100 | 1.20 |  | [186] |
| Cob | None | - | - | 0% | 1789 | 18–21 | 300 × 300 × 70 | 0.25 |  | [29,209] |
| Daub and wattle | None | - | - | 0% | - | - | 40 × 160 | 2.47 |  | [214] |
| Poured Earth | None | - | - | 0% | 1850 | 20 | 40 × 40 × 160 | 0.75 |  | [8] |
|  | Stabilizer | NaHMP, citric acid, Na2CO3, oak tan | IWP | 0.5%, 2%, 3.5%, 5% | 1800–1950 | 20–30 | 40 × 40 × 160 | 0.75–1.5 |  | [8] |

On the other hand, investigations with stabilizers and fibers of industrial origin have shown promise in offering above-average mechanical strength. Cherif, B. et al., 2021 [215] evaluated CEBs stabilized with different proportions of cement, glass powder, and glass fiber. They found that a mixture of 4% cement and 3% glass powder generated a compressive strength of 12.26 MPa and a flexural strength of 1.75 MPa. Another mix with 4% cement and 0.25% glass fiber obtained 7.2 MPa and 3.31 MPa in compression and flexure, respectively. Both results meet the minimum requirements of some earth construction codes, demonstrating the potential of combining stabilizers and fibers to improve the quality of the material. However, it has been reported that the inclusion of fibers in isolation often has a negative effect on the compressive strength. This is attributed to the fact that the fibers alter the internal structure and stress distribution in the matrix, which, in compression, reduces its capacity to support uniaxial loads. This effect depends on factors such as the compaction, orientation, and distribution of the fibers, as well as their mechanical properties and moisture absorption capacity.

Notably, most of the studies [103,115,118,171,198,215] on flexural strength have focused on CEBs, with this technique being the most commonly used compared to other earth constructions. However, there still needs to be uniformity in the results among different investigations, which evidences the need to continue studying the behavior of cementitious materials and fibers to establish specific standards and regulations. Further studies on matrix–fiber and matrix–stabilizer interactions would be beneficial in understanding how these inclusions affect the microstructure and mechanical behavior of earth constructions, which could support their incorporation as a standard in this type of construction.

### 3.6. Dynamic and Numerical Approach in Earthen Construction Field

Research has been carried out on the dynamic behavior of adobe, CEBs, and REWs to understand the structural behavior and vulnerability of earth constructions under loading conditions. These investigations cover both simulation models and experimental tests, evaluating each type of construction's strength and failure modes and considering factors such as lateral, vertical and seismic loads.

In adobe walls, Li et al., 2020 [216] and Greco et al., 2021 [217] used finite element modeling (FEM) and discrete element modeling (DEM) to evaluate how structures respond to compressive and flexural loads, identifying low tensile strength and diagonal cracking as the main failure modes in unreinforced walls. On the other hand, Zhang et al., 2023 [218] used advanced techniques such as near-surface mounted (NSM) in mortar and bamboo walls, increasing the energy absorption capacity and lateral resistance, significantly improving the ductility in seismic scenarios. In addition, Bossio et al., 2013 [180] studied the use of geometric reinforcements such as geogrid and natural fibers, observing that these techniques transform the failure mode to a more ductile one, preserving the structural integrity of the adobe. Also, Ahmadi et al., 2022 [219] developed crack propagation and volume loss indicators in historic adobe structures to quantify the accumulated damage, which facilitates the preservation of these structures in seismic zones.

For CEBs, advanced numerical models, such as FEM and plastic damage models, have been used to simulate stress propagation. For example, Bouhiyadi et al., 2022 [220] demonstrated that macro-cracks in a CEB originate at the ends of the block under compressive loading and propagate toward the center. On the other hand, Qu et al., 2015 [161] analyzed the seismic behavior of CEB walls, showing that geometric factors, such as the height-to-width ratio and structural bracing, significantly improve the lateral resistance and energy absorption capacity. In addition, Laursen et al., 2015 [221] studied the out-of-plane behavior in walls connected with dry joints and suggested additional reinforcement in critical areas to avoid flexural failures. Also, Huamani et al., 2022 [68] confirmed that numerical micro-modeling models accurately predict the capacity and ductility curve of these masonry systems in seismic zones.

In the case of REWs, FEM models with Mohr–Coulomb theories and hierarchical elastoplastic models were used to simulate shear and tensile failures. In this case, Miccoli et al., 2017 [222] and Wangmo et al., 2020 [223] captured the nonlinear behavior of the material and its response under extreme loads. On the other hand, Mora-Ruiz et al., 2024 [224] evaluated the reinforcement of REWs with Arundo donax "caña brava" fibers, observing that, although they maintain lateral stiffness, they introduce planes of weakness that reduce the load-bearing capacity and energy dissipation compared to unreinforced walls. In addition, Huamani et al., 2022 [68] demonstrated that the incorporation of textile mesh and polyester strips increases the load-bearing capacity and energy dissipation, limiting diagonal crack propagation in these walls. In structural restraint applications, Ahmadi et al., 2022 [219] applied multicriteria verification methods to historical structures such as the Seville city walls, confirming their stability against earthquakes and humidity changes.

Table 9 presents some of the most relevant equations found in the investigations for the three types of earth constructions (adobe, CEBs, and REWs). In adobe, the Von Mises creep criterion and the Riedel–Hiermaier–Thomas (RHT) model allow for analyzing the onset of plastic deformation and the response to impacts, critical aspects given its fragility under specific stresses. For CEBs, the Coulomb equation and the plastic moment are essential to evaluate the shear and bending resistance, which are crucial in structures that must withstand lateral forces, such as seismic forces. In REWs, the Mohr–Coulomb friction model applied to interfaces evaluates the resistance to interlayer sliding. At the same time, the horizontal force equation allows for predicting the overturning stability, both key aspects for out-of-plane stability under lateral loading conditions.

Research in adobe, CEBs, and REWs shares the goal of improving earthen constructions' strength and durability. However, each approach varies according to the properties and applications of each type of construction. In the case of adobe walls, research focuses on heritage preservation and structural reinforcement, especially in seismic zones, with techniques such as NSM using mortar and bamboo and the use of the crack propagation rate and vertical load resistance indicators to quantify the accumulated damage without compromising historical integrity, as shown by Ahmadi et al., 2022 [219] and Zhang et al., 2023 [218]. In contrast, studies in CEBs are oriented toward optimizing structural resistance in modern constructions, analyzing geometric configurations and reinforcements that improve the ductility and energy absorption capacity, a strategy that makes them viable in seismic environments, see Bouhiyadi et al., 2022 [220] and Qu et al., 2015 [161]. For REWs, the emphasis is on the analysis of behavior under high loads and the integration of internal reinforcements such as textile mesh and natural fibers, research advancing both contemporary architecture and heritage conservation, as shown by Miccoli et al., 2017 [222] and Wangmo et al., 2020 [223].

**Table 9.** Equations for the evaluation of structural behavior in adobe, CEBs and REWs.

| | Equation | Description | Variables | Ref. |
|---|---|---|---|---|
| Adobe | $J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] = k^2$<br>$k = \frac{1}{\sqrt{3}}\sigma_0$ | The yield criterion determines the limit at which a material begins to deform plastically. It is based on Von Mises′ theory in adobe walls, analyzing principal stresses at different load states. | For the tensile test, the values for σ1, σ2 and σ1. σ3 in this equation are as follows: σ1 = σ0, σ2 = σ3 = 0, where σ0 is the yield stress of the tensile test. | [216] |
| | $p(\rho, e) = A_1\eta + A_2\eta^2 + A_3\eta^3 + \Gamma\rho e$<br>$\eta = \frac{\rho}{\rho_0} - 1$ | The Riedel–Hiermaier–Thomas (RHT) model is a concrete model used to simulate the behavior of materials such as adobe under impact or blast loads. The RHT model uses an equation of state (EOS) based on the form p-α, which is represented as follows for porous materials such as adobe. | Hereby, Γ is the Grüneisen parameter, ρ the current density, e the specific internal energy of the material, and ρ0 the initial density. A1, A2, A3: specific coefficients describing the stiffness of the material under compressive conditions. | [225] |
| CEBs | $\tau = \sigma_n \cdot tan\varphi$<br>$T = \frac{N \cdot\ sin(\alpha) \cdot \cos(\alpha)}{S}$<br>$\sigma_n = \frac{N \cdot cos^2(\alpha)}{S}$ | The Coulomb equation is used to determine the moment of failure of the CEB wall that occurs when the tangential stress (τ) on a surface exceeds the resistance value, which is related to the normal stress (σn) and the angle of internal friction (ϕ) of the material. | σn: normal stress on the sliding surface, N: compressive force applied, S: area of the surface on which the force acts, α: sliding angle between the contact surfaces. | [220] |
| | $M_p = C_m\left(c - \frac{a}{2}\right) + \sum_i^n T_{si}(d_i - c) + P\left(\frac{L}{2} - c\right)$ | The plastic moment resistance of a wall refers to the maximum capacity of the wall to resist bending forces before undergoing permanent plastic deformations such as in the case of earthquakes. | Mp: maximum plastic moment, Cm: compressive strength of the block, c: depth of the neutral axis, a: depth of the equivalent tension block under compression, approximately 0.8c, Tsi: tensile strength in the reinforcing bars.di: distance from each reinforcing bar to the compressed edge of the wall, P: axial force applied at the top of the wall, L: total width of the wall. | [226] |
| REWs | $\tau = c + \sigma_n \cdot tan\varphi$<br>$k_s = \frac{k_n}{2(1+v)}$ | The Mohr–Coulomb friction model is applied to the interfaces between compacted soil layers. In this model, the evaluated parameters E, v, fc, Gc, ft and G′f are not a direct part of the equation but affect the elastic and fracture properties of the material and its interfaces in the finite element model (FEM). | τ: maximum shear stress, c: cohesion of material, represents the inherent resistance of the interfaces between layers. ϕ: internal friction angle, defines the resistance to sliding at the interfaces. The fc (compressive strength) and Gc (compressive fracture energy) values regulate how the material resists and fails under compression, while ft (tensile strength) and Gf′ (tensile fracture energy) determine when tensile fracture occurs. | [222] |
| | $F_{ht} = \frac{W \cdot t}{2} \cdot \left(\frac{2}{3}H\theta\right) \cdot (h - t\theta)$ | The equation predicts the horizontal force required to rotate a compacted earth wall as a rigid body. This prediction allows estimating the wall's ability to resist overturning under horizontal loads, which is crucial for evaluating its out-of-plane behavior in the face of lateral forces, such as those produced by an earthquake. | Fht: horizontal force required to induce rotation.W: weight of the compacted soil section rotating as a rigid body.t: wall thickness.H: total height of the wall.θ: angle of rotation of the wall with respect to the pivot point.h: height from the point of rotation to the point of application of the force. | [223] |

Future lines of research in terms of adobe should focus on refining the numerical models that evaluate the plastic behavior and stress distribution under load, using criteria such as the Von Mises theory. For CEBs, it is essential to develop mixed formulations and configurations that optimize both the compressive strength and the ability to withstand plastic moments, based on models derived from the Coulomb equation. For REWs, it is key to integrate numerical and experimental methods that accurately capture nonlinear behavior and stability under lateral loads, using friction models such as the Mohr–Coulomb model. This research, based on the analysis of structural equations, will allow the establishment of standardized protocols to evaluate and improve the mechanical performance of earth constructions.

### *3.7. Thermal Comfort Performance of Earth Construction Field*

Recent research on the thermal performance of adobe focuses on reducing thermal conductivity through environmental additives. Studies without additives show relatively high reference values; e.g., Muñoz et al., 2020 [99] report a conductivity of 0.87 $Wm^{-1}K^{-1}$ in blocks of 30 cm × 15 cm × 10 cm, while the models of Mosquera et al., 2014 [227] predict values between 0.80 and 0.90 $Wm^{-1}K^{-1}$, depending on the humidity of the material. To reduce these values, sustainable additives have been tested, as in the case of Muñoz et al., 2020 [99] showing that using wastepaper decreases the conductivity by 30%, reaching 0.62 $Wm^{-1}K^{-1}$. In addition, Olacia et al., 2020 [92] report that Posidonia algae fibers, in 4 cm × 4 cm × 16 cm blocks, achieve a conductivity of 0.62 $Wm^{-1}K^{-1}$. On the other hand, Gandia et al., 2019 [20] find that the incorporation of GRPF waste at a proportion of 10% reduces the thermal conductivity to 0.68 $Wm^{-1}$ $K^{-1}$ in 60 cm × 35 cm × 10 cm blocks. Additionally, Araya-Letelier et al., 2021 [91] note that using jute fibers improves the thermal insulation of adobe, achieving a conductivity of 0.69 $Wm^{-1}K^{-1}$.

Recent research on CEBs has focused on improving thermal insulation and reducing reliance on cement through sustainable additives such as ash, natural fibers, and industrial by-products. Studies on CEBs with 8% cement show high thermal conductivity values; for example, Oubaha et al., 2022 [110] show that CEBs stabilized with 8% cement reach thermal conductivities of up to 1.26 $Wm^{-1}$ $K^{-1}$ in blocks of 25 cm × 12.5 cm × 7.5 cm, while stabilization with phosphogypsum and mining waste in blocks of the exact same dimensions reduces these values to a range of 0.484–0.506 $Wm^{-1}K^{-1}$. Furthermore, Limami et al., 2023 [69] highlight that adding recycled sawdust reduces thermal conductivity by up to 0.2 $Wm^{-1}K^{-1}$ with 20% additive. Similarly, Bouchefra et al., 2022 [228] find that CEBs reinforced with treated doum fibers in 30 cm × 15 cm × 10 cm blocks achieve a decrease in thermal conductivity to 0.51 $Wm^{-1}K^{-1}$. In addition, Hema et al., 2020 [229] suggest that a layered CEB wall design, combining insulating materials in the outer layer and CEBs on the inside, optimizes thermal comfort in hot and dry climates by reducing the internal thermal fluctuations.

Research on the thermal performance of REWs focuses on compacted in-place walls, taking advantage of their thermal mass and passive insulation capacity. Jain et al., 2019 [230] show that the inclusion of industrial by-products, such as recycled rubber in 30 cm thick walls, reduces thermal conductivity by 10%, which improves thermal resistance, with a slight compromise in mechanical strength. On the other hand, Strazzeri and Karrech 2022 [126] explore the use of natural fibers, such as Spinifex, in cement-stabilized REWs, achieving a conductivity of 0.87 $Wm^{-1}K^{-1}$ in 35 cm thick walls, suitable for semi-arid climates. In addition, Jiang et al., 2020 [231] analyze the impact of a moisture barrier on 50 cm thick walls, showing that this technique improves thermal stability in humid environments. However, it reduces the moisture regulation capacity. Dong et al., 2014 [232] indicate that, in hot and dry climates, 30 cm thick walls in REWs can reduce internal temperature variations by up to 45% when combined with optimal ventilation and shading.

Research on adobe, CEBs, and REWs coincides with improving thermal performance and reducing environmental impact through sustainable additives such as natural fibers and recycled materials. All seek to optimize thermal conductivity to increase insulation. However, adobe and CEBs rely more on molded blocks stabilized with cement or geopolymers, while REWs are built on-site with thick compacted walls, taking advantage of their thermal mass. At the hygrothermal level, REW research explores the use of moisture barriers for extreme climates, while adobe and CEB research prioritizes the reduction of water absorption and erosion resistance.

## 4. Recommendations

Future research should continue expanding the study of alternative stabilizers in earthen construction, especially industrial and agro-industrial by-products, which have shown great potential for improving mechanical and thermal properties while maintaining sustainability. While significant progress has been made in terms of adobe, CEBs, and REWs, other techniques such as cob, wattle and daub, and poured earth still need further exploration to better understand their structural behavior, material optimization, and environmental benefits. Additionally, establishing standardized methodologies to determine the optimal type and proportion of stabilizers based on the soil characteristics and climate conditions would help expand the use of earthen materials in modern construction.

It is also essential to incorporate comprehensive environmental evaluations to strengthen the sustainability case for earthen construction. Life cycle assessments, carbon footprint analyses, and embodied energy studies can provide a more complete picture of the environmental impact of these materials. Furthermore, numerical modeling and advanced simulations should be further explored to optimize material compositions, predict mechanical performance, and evaluate seismic resistance. Advancing these areas will help establish a structured framework for assessing earthen constructions, making them more competitive and adaptable for climate-responsive architecture and sustainable construction worldwide.

## 5. Conclusions

Additives in earthen constructions are essential to improve their mechanical properties and make them competitive with conventional materials. Cement and lime stand out for their capacity to increase the strength and durability among the most used additives. However, other additives, such as fly ash, GBFS, and ceramic waste, have also shown promising results, reaching strengths of up to 24 MPa in mixtures with CEBs and 9 MPa in stabilized adobe. Natural and industrial fibers, such as coconut and polypropylene, have shown considerable improvement in the flexural strength in terms of mechanical performance, where the use of combinations with fibers and cementitious agents has resulted in flexural strengths above average values, up to 3.3 MPa in the case of CEBs stabilized with glass fiber.

Regarding dynamic behavior, numerical methods have been most widely used to model and analyze the response of earth constructions to lateral forces and vibrations. These models have made it possible to simulate the stability and behavior of these materials under seismic conditions, providing a theoretical basis that drives the optimization of construction techniques in different climatic and geographical contexts.

In relation to thermal properties, progress has been made in the characterization of the thermal conductivity of materials on land, with average values of 0.6 to 1.3 $\mathrm{Wm^{-1}K^{-1}}$ in stabilized CEBs and REWs. Although these values are lower than those of materials such as concrete, further improvements are needed to optimize the energy efficiency in extreme climates, where they still present limitations.

The meta-analysis and systematic review have revealed that CEBs represent the most researched ground-based construction technique in recent years, reflecting a trend toward modular and rapid construction methods, particularly in the Global South. This approach poses challenges, such as the variability in mechanical properties, which depend on the control over the mixes and the quality of the base material. However, adobe remains less studied and presents high property variability due to its lack of standardization and susceptibility to moisture. Finally, the REW stands out for its durability and load-bearing capacity but requires specific machinery for adequate compaction, which implies higher costs in certain regions.

These results demonstrate that earthen buildings have significant potential to contribute to the Sustainable Development Goals (SDGs), particularly in the context of SDGs 11 and 13, through the reduction of $CO_2$ emissions and the use of local and sustainable materials. However, there is a need for additional research that integrates sustainability metrics, such as the GWP and EE, into the evaluation of these additives. Developing specific regulations and standardization methods will also be essential to ensure consistent and efficient use of these materials in construction. Future research should focus on establishing performance standards for additives, especially those that combine sustainability and mechanical benefits, such as fly ash, natural fibers, and industrial wastes. Applying numerical methods has great potential to optimize these materials according to local needs and resources, contributing to their practical and economic implementation in different contexts. With these advances, earthen constructions can be positioned as a robust and ecologically viable alternative for the future of construction.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CDW | Construction and Demolition Waste |
| CEBs | Compressed Earth Blocks |
| DEM | Discrete Element Modeling |
| EE | Embodied Energy |
| EnCs | Earthen Constructions |
| EPDs | Environmental Product Declarations |
| EOS | Equation of the State |
| FEM | Finite Element Modeling |
| GBFS | Granulated Blast Furnace Slag |

| | |
|---|---|
| GMSs | Green Mussel Shells |
| GN | Global North |
| GOS | Grounded Olive Stone |
| GS | Global South |
| GRPFs | Glass Reinforcement Polymer Fibers |
| GWP | Global Warming Potential |
| ICE | British Inventory of Carbon and Energy |
| NSM | Near-Surface Mounted |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analysis |
| REW | Rammed Earth Walls |
| RHT | Riedel–Hiermaier–Thomas Model |
| SDGs | Sustainable Development Goals |
| WTTFs | Waste Tire Textile Fibers |

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