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Mechanical and microstructural performance of compressed earth blocks stabilized with palm oil fuel ash: experimental study, systematic review and meta-analysis

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A R T I C L E I N F O

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A B S T R A C T

This study integrates a systematic review, a meta-analysis, and an experimental program to evaluate palm oil ash (POFA) as a low-impact stabilizer in compressed earth blocks (CEBs). The PRISMA review (2015–2025), supported by Bibliometrix®, compiled 49 articles on CEBs with agro-industrial waste and showed that blocks without additives achieve compressive strengths in the range of 1–3.38 MPa, while systems with industrial cementants can exceed 20 MPa, and mixtures with agro-industrial ashes range between 1 and 12 MPa, with better environmental performance. Against this background, an experimental campaign was developed with loamy soil (ML) stabilized with 0–10% POFA. The ash had $\Sigma(SiO_2+Al_2O_3+Fe_2O_3)$ 34.4%, LOI 40%, quartz 45%, and cristobalite 5%, as well as an alkaline leachate (pH 9.9; CE 433 μS/cm), indicating limited but effective pozzolanicity and a marked filling and stabilizing effect on the clay fraction. At 28 days, the reference CEBs reached 2.2 MPa in compression and 0.4–0.45 MPa in flexure, while the mixtures with 4–6% POFA developed 3.8–4.0 MPa and 0.6–0.7 MPa, respectively. Between 28 and 90 days, both properties continued to increase, suggesting a combination of physical densification and secondary cementation. Overall, under the investigated materials and processing conditions, POFA is a technically feasible additive for non-structural CEBs; however, broader transferability requires validation across different soils, ash sources, and durability-related indicators.

Abbreviations

Abbreviation	Term/Original name

(*continued on next page*)

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Abbreviation	Term/Original name
ASTM	ASTM International
BC	Bottom Ash
CCR	Calcium Carbide Residue
CEBs	Compressed Earth Blocks
CSV	Comma-Separated Values
EDS	Energy-Dispersive X-ray Spectroscopy
FA	Fly Ash
LL	Liquid Limit
LOI	Loss on Ignition
OPMF	Oil Palm Mesocarp Fibre
PI/IP	Plasticity Index
PL	Plastic Limit
POFA	Palm Oil Fuel Ash
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RHA	Rice Husk Ash
SCOPUS	Scopus
SEM	Scanning Electron Microscopy
UfPOFA	Ultrafine Palm Oil Fuel Ash
w_{op}	Optimum Moisture Content
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
γ_{dmax}	Maximum Dry Density

1. Introduction

Rapid population growth and urban expansion have increased demand for more sustainable and economical building materials, such as CEBs. Likewise, the intensification of agricultural activity needed to feed the population has generated more than 3 billion tons of waste per year, which can be incorporated into the manufacture of CEBs [1]. This waste includes straw, husks, and stalks from crops such as rice, wheat, corn, and sugarcane, which can be subjected to controlled combustion to produce ash rich in silica, alumina, and other pozzolanic oxides [2]. However, the proportion of ash in dry weight varies depending on the type of waste: for example, rice husks contain around 16%, rice straw 10.2%, wheat straw 2.2% and corn stalks approximately 7.7% [3].

Since the early 2010s, the use of alternative stabilizer materials with low environmental impact has been explored, using ash from agricultural and industrial waste to improve the properties of CEBs. In 2017, Lie et al., [4] evaluated the incorporation of hemp waste into CEBs and found that with 25% additive, compressive strength increased to 3.11 MPa at 28 days and 3.83 MPa at 150 days, maintaining adequate structural values over time. Later, in 2019, Elahi et al. [5] stabilized CEBs with 30% fly ash (FA) and 5–10% Portland cement, achieving a wet-dry cycle resistance ranging from 51% to 88% of the initial resistance. That same year, Poullain et al. [6] also experimented with CEBs from silty-sandy soil in northern Benin, incorporating up to 1.5% kenaf fibers and observing improvements in strength and thermal conductivity. In 2020, Poullain et al. [6] confirmed these results by comparing kenaf fibers of different lengths and reported that 30 mm fibers reduce thermal conductivity by 30% while reinforcing compression and flexural strength. Also, in 2021, Li et al. [7] demonstrated that coal bottom ash can completely replace fine aggregate in roller-compacted concrete, supporting their finding with an accurate constitutive model.

Since 2020, studies have explored multiscale additives and reinforcements to optimize the strength, insulation, and durability of CEBs. In 2021, Tonduba et al. [8] replaced 10% of cement with ultrafine palm oil fuel ash (UfPOFA), achieving 6.53 MPa at 28 days and limiting water absorption to 15.44%. Later, in 2023, Koungang et al. [9] incorporated 5–15% of fibrous aggregates from coconut shells and Canarium on an 8% cement base; with only 5% fiber, they achieved dry and wet compressive strengths of 9.29 MPa and 6.57 MPa. The following year, in 2024, Abdelkader et al. [10] added 0.1–0.4% palm and glass fibers to CEBs with 14% cement, which increased strength by up to 29%, reduced density by 11%, and reduced thermal conductivity by 22%. Recently, in 2025, Mouih et al. [11] combined 10% date palm fibers with 0.8% cellulose nanocrystals, achieving a density of 1811 kg/m^3, water absorption of 18.14%, and compressive strength of 16.27 MPa, which recovers the mechanical rigidity compromised by the fiber without sacrificing durability or insulation.

On the other hand, palm fibers have proven to be a promising reinforcement in CEBs, although their effects depend on treatment and dosage. For example, Taallah and Guettala (2016) [12] found that alkaline treatment reduced the density and thermal conductivity of the blocks without improving their adhesion or mechanical strength, while Ebanda et al. (2024) [13] observed that the incorporation of only 0.75% palm mesocarp (OPMF) in CEBs with 8% cement increased flexural strength by more than 65% and that 1.25% sisal even exceeded the compression of blocks without fibers; Similarly, Abdelkader et al. (2024) [10] confirmed that adding between 0.1% and 0.4% palm fibers mixed with fiberglass increases compressive strength by up to 29% and reduces thermal conductivity by around 22%. As for palm oil fuel ash (POFA), studies, although still limited, indicate its pozzolanic potential: Tonduba et al. (2021) [8] partially replaced cement with ultrafine POFA, obtaining 6.53 MPa at 28 days and water absorption of 15.44%; however, further research is needed to explore wider dosage ranges and evaluate long-term mechanical behavior.

In response to this lack of integrated analysis, this study combines three complementary approaches: a systematic review, a quantitative descriptive meta-analysis of literature on the incorporation of agricultural waste into CEBs, and a targeted experimental program on the time-dependent mechanical behavior of CEBs stabilized with POFA. It provides three main contributions: it analyzes the last decade of research and, through a meta-analysis of physical and mechanical properties, identifies knowledge gaps; it develops an experimental campaign that addresses these gaps by evaluating compressive strength and flexural strength in CEBs manufactured with POFA controlled production conditions; and it compares the physical and mechanical properties obtained from the meta-analysis with the experimental results for palm ash and other agricultural wastes.

The document is structured into five sections. First, it contextualizes the use of waste as additives in CEBs, briefly reviews its historical evolution, and defines the research objectives. Next, it describes the methodology, including a systematic review of the last decade to analyze research trends (basic, driving, niche and emerging topics) and identify knowledge gaps, the extraction of key quantitative data (particle size, organic matter content, type and percentage of additive) for the meta-analysis, and the experimental campaign, in which only simple compressive strength and flexural strength over time were evaluated in CEBs with different POFA percentages. The results of the meta-analysis and the experimental program are then presented and discussed in light of the key literature, and the final sections summarize the main conclusions, identify current challenges, and outline future perspectives for the sustainable use of palm waste in construction. In this context, the objectives of this study are to: (i) evaluate the effect of POFA content (0–10%) and curing age (14–90 days) on the compressive and flexural strength of CEBs manufactured from an ML soil; (ii) relate the mechanical response to the physical, chemical, mineralogical, and microstructural characteristics of POFA to interpret the dominant stabilization mechanisms; and (iii) identify a practical and reproducible POFA dosage window for mix design under the investigated materials and processing conditions.

2. Methodology

This study integrates a PRISMA-based systematic review, a meta-analysis, and an experimental study. The systematic review covers the last decade on agro-industrial waste ash in CEBs, identifying global advances, research trends, and basic, driving, niche, and emerging topics. The meta-analysis evaluates key parameters, including additive type, density, moisture content, compressive strength, and flexural strength. The experimental study was doneto determine the optimal POFA content in a loamy soil, evaluate its

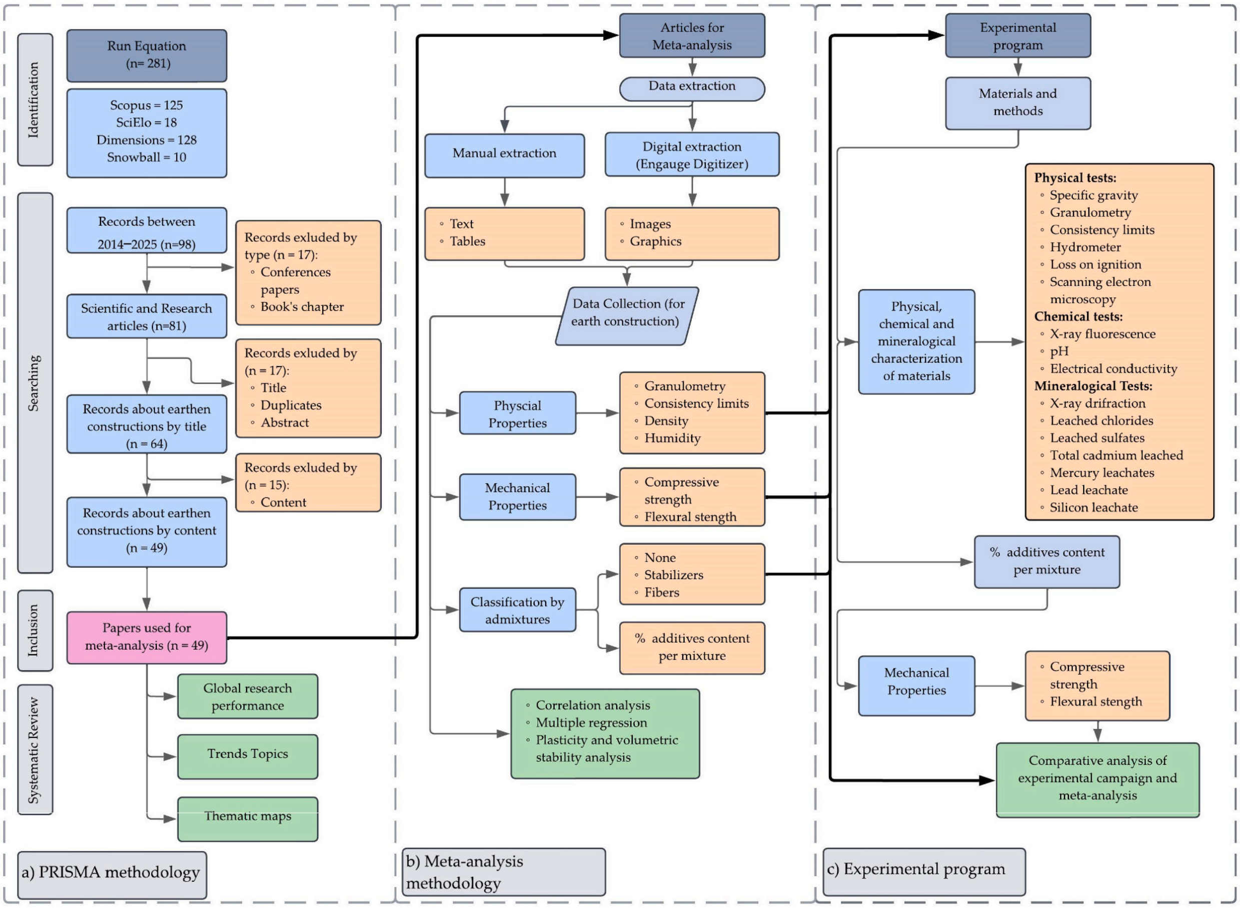

Fig. 1. Research methodology flowchart.

mechanical behavior at different curing ages, and compare it with the meta-analytic results. Durability aspects are addressed only from a literature-based perspective (contextual and comparative discussion), and they are not treated as outcomes of the quantitative synthesis. Fig. 1 presents the overall methodological framework of this study.

2.1. Systematic review

A systematic review was conducted following the PRISMA® (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) methodology, widely used in various fields [14,15]. In addition to the PRISMA flow diagram, a structured study quality/risk-of-bias–oriented appraisal was conducted to strengthen transparency and interpretability of the included evidence. Given that the evidence base consists predominantly of heterogeneous experimental studies in materials engineering (non-randomized designs), a reporting-completeness checklist was used instead of clinical risk-of-bias tools. The checklist evaluates whether each study clearly reports key items that condition internal validity and comparability in CEB research: (i) soil identification and index properties (classification and/or Atterberg limits and PSD), (ii) additive/ash characterization, (iii) mix proportions and replacement definition, (iv) compaction effort/pressure and molding procedure, (v) curing/conditioning regime, (vi) specimen geometry and testing configuration, and (vii) whether replicate number and dispersion/uncertainty information are reported. Appraisal outcomes are summarized in the Supplementary Material (Table S1) and are used to contextualize heterogeneity and identify standardization gaps. The checklist was applied to all included studies (n = 49); studies were not excluded based solely on this appraisal, but the outcomes were used to interpret heterogeneity and reporting gaps. The selected documents were analyzed using Bibliometrix® to characterize the current state of research and identify trends and gaps. To retrieve articles published between 2015 and 2025, the search equations in Table 1 were used in SCOPUS®, SciELO, and Dimensions, supplemented by a snowball search.

2.2. Data selection and cleaning criteria

The data from the databases were exported to CSV and filtered using predefined criteria: i) search terms in title, keywords, or abstract; ii) only scientific articles and reviews; iii) English language; and iv) publication period from January 2015 to August 2025. Following the PRISMA methodology, two search equations yielded 125 documents in Scopus, 18 in SciELO, 128 in Dimensions, and 10 through snowballing. After removing duplicates and screening titles, abstracts, and full texts to retain only studies on agro-industrial waste in CEBs, 49 articles were selected. These were analyzed through a systematic review to identify global research trends and classify fundamental, driving, niche, and emerging topics.

2.3. Data organization, structuring and analysis

The information extracted from the articles was organized in Excel®. Text and table data were collected manually, while graphics and images were digitized using Engauge Digitizer® [14]. This was used to build a comprehensive and systematized database that includes general data (authors, year of publication, country, and abstract) and technical parameters of the materials: particle size distribution, soil consistency limits, type and percentage of additives, density, moisture content, and compressive and flexural strengths of the mixtures studied.

2.4. Information processing with specialized software

The information extracted from the database was processed using open-source software, mainly Bibliometrix® [15], a tool widely used in literature reviews and bibliometric analyses [16,17]. Bibliometrix® was used to construct matrices to evaluate annual scientific output and its geographical distribution, and to generate a thematic map classifying topics as drivers, basic, niche, emerging, and declining, providing a structured framework for analyzing research trends [18].

2.5. Meta-analysis

The information in the database, compiled from various scientific articles, was verified and organized into a table that records, for each mixture of compressed earth blocks, the soil type and its Atterberg limits, the type and percentage of additive, the name of the series, and the dimensions of the test tubes. The systematic review focused on mixtures with similar agricultural and agro-industrial residues (mainly from palm trees) and other lignocellulosic and mineral by-products. The physical-mechanical parameters of interest (maximum dry density, moisture content, dry compressive strength, and flexural strength) were extracted from these mixtures, although the availability of data varies between properties and types of additives, as not all studies report the same set of variables.

Table 1
Search equations used in this research.

Identification	Search equation
1	(“compressed earth blocks" OR CEBs) AND (ash OR waste) AND (“compressive strength" OR "flexural strength" OR durability)

[1] Keywords selected for this study include "Compressed earth blocks", "Compressive strength", "Flexural strength", “durability" The viability of these keywords was determined using ScienceDirect® thesaurus, and they were selected based on previous research on earthen construction.

2.6. Experimental study

2.6.1. Materials and methods

For this research, fine soil classified as low plasticity silt and ash from the controlled combustion of oil palm fruit bagasse (POFA) were used. Both materials were oven-dried at 105 ± 5 °C to constant mass and stored in sealed containers. The particle size distribution of the soil was obtained by sieve analysis for the sandy fraction (ASTM D6913/D6913M [19] and by hydrometer for the fine fraction following ASTM D7928 (with temperature and meniscus corrections) [20]. The Atterberg limits were determined according to ASTM D4318 to define the plastic range and contextualize its behavior in relation to compaction [21].

The particle-size distribution of POFA was determined in suspension according to ASTM D7928 [20]. Its elemental composition was evaluated by X-ray fluorescence (XRF) following practices compatible with ASTM C114 adapted to pozzolanic waste [22] and crystalline mineralogy by X-ray diffraction (XRD, 5°–70° 2θ) in accordance with ASTM C1365 criteria [23]. The microstructure was analyzed by Scanning Electron Microscopy (SEM) in a Vega Tescan microscope. with gold coating and, analyzed with accelerating voltage 10 kV, following the recommendations of ASTM C1723 for cement-based materials [24].

As a complementary characterization of POFA, loss on ignition (LOI) was determined according to ASTM D7348 [25], specific gravity of particles using ASTM C188 [26], pH of the suspension using ASTM D4972 [27], and the electrical conductivity using ASTM D1125 [28], working at 25 ± 2 °C with controlled solid/liquid ratios. Leaching was evaluated by extraction in water according to ASTM D3987 [29].

2.6.2. Manufacture of compressed earth blocks

The compressed earth blocks were manufactured from six mixtures in which POFA replaced dry soil at 0%, 2%, 4%, 6%, 8%, and 10% by weight, as shown in Fig. 2. The selected replacement window (0–10%) was defined as a practical and conservative range supported by both palm-waste ash behavior and material chemistry considerations. First, palm-derived ashes are typically processed as porous, irregular and partially crystalline siliceous powders (quartz-dominated boiler ash with 40.60% SiO_2 and low Al_2O_3), which implies that their contribution is often governed by filler/packing effects and limited secondary cementation unless the ash is further refined [30]. Second, palm-residue ashes used as soil stabilizers are commonly investigated in stepped ranges that extend beyond 10% (0–14% OPEFBA by dry weight), and increasing ash content is consistently associated with higher optimum moisture content and reduced maximum dry density, reflecting increasing water demand and compaction sensitivity at higher dosages [31]. In this context, dosages below 2% were not emphasized because changes are expected to be marginal relative to typical earthen-material variability, whereas dosages above 10% were considered more likely to penalize compaction (increased wopt and reduced γdmax) and amplify variability unless compaction energy and moisture control are concurrently adjusted, as observed for palm-residue ash–soil systems [31]. The materials were pre-dried at 105 ± 5 °C to constant mass and homogenized in the dry state. For each dosage, the optimum moisture content (w_{opt}) and maximum dry density ($\gamma_d$max) were determined by standard Proctor testing in accordance with ASTM D698 [32]. It should be noted that the Proctor test was used only to determine reference compaction parameters (wopt and γdmax) under standardized dynamic compaction energy, and it was not used as the specimen-forming method for the blocks. The mixture was placed in lightly greased metal molds and compacted in a hydraulic press applying 4 MPa to the specified final height. This hydraulic pressing corresponds to static uniaxial compaction to a target height/density, which differs from Proctor compaction in both procedure and objective (block manufacturing versus moisture–density characterization). This pressure corresponds to the nominal molding

Fig. 2. Manufacture of compressed earth blocks.

pressure applied by the Hydraform M7MI press used as reference for CEBs production. The compaction pressure was kept constant across all mixtures to isolate the effects of POFA incorporation and curing. After compaction, the blocks were immediately removed from the molds and stored on wooden trays, indoors at room temperature, protected from rain and direct sunlight.

2.6.3. Mechanical evaluation

From an application standpoint, compressive strength is a primary performance indicator used to classify compressed earth blocks for walls and partitions, while flexural strength (modulus of rupture) is a complementary indicator of cohesion, handling performance, and crack resistance. In this study, these two properties are used to assess the mechanical feasibility of POFA-stabilized CEBs and to enable benchmarking against construction-practice standards and guidance for earth blocks and earthen wall systems DIN 18945, AFNOR XP P13-901, UNE 41410, NZS 4298 ASTM E2392/E2392M [33–37]. However, full qualification for specific construction uses typically also requires durability-related checks (water absorption/erosion resistance) and compliance with local building regulations; therefore, durability is discussed in a contextual/comparative sense based on the literature. The mechanical evaluation of the compressed earth blocks was carried out by means of simple compression and flexural strength tests. For each mixture and each curing age (14, 28, 60, and 90 days), four blocks were manufactured and tested in order to ensure statistical representativeness and limit material variability. Simple compression was performed under deformation control, adapting ASTM C67 to unreinforced masonry units, recording the maximum load and calculating the corresponding strength [38]. The flexural test was performed in accordance with ASTM C348, with a point load applied at the center of the span and the moment of resistance determined from the breaking load and the effective geometry of the specimen [39]. All tests were performed in the laboratory at room temperature, ensuring proper alignment of the support surfaces to achieve uniform load transmission.

3. Results and discussion

3.1. Research trends on compressed earth blocks and agro-industrial waste

The Bibliometrix® thematic map identifies four groups (Fig. 3). The driving themes (high centrality and density) include thermal conductivity, mechanical properties/mechanical strength, and the compressive strength–compressed earth blocks–rice husk ash cluster, confirming an agenda focused on optimizing mechanical and thermal performance with siliceous waste, especially rice husk ash as a partial mineral substitute [5,40]. The literature you provided shows that the incorporation of ash or slag increases dry compressive strength and tends to reduce thermal conductivity, with variations associated with dosage, compaction energy, and curing [5]. In the basic topics (high centrality and low density), compressed earth block, water absorption, and bulk density stand out as cross-cutting quality control parameters, but with protocols that are not very homogeneous in terms of test piece size, optimum humidity, and absorption method, which limits comparability and the performance of robust meta-analyses [41]. Niche topics (high

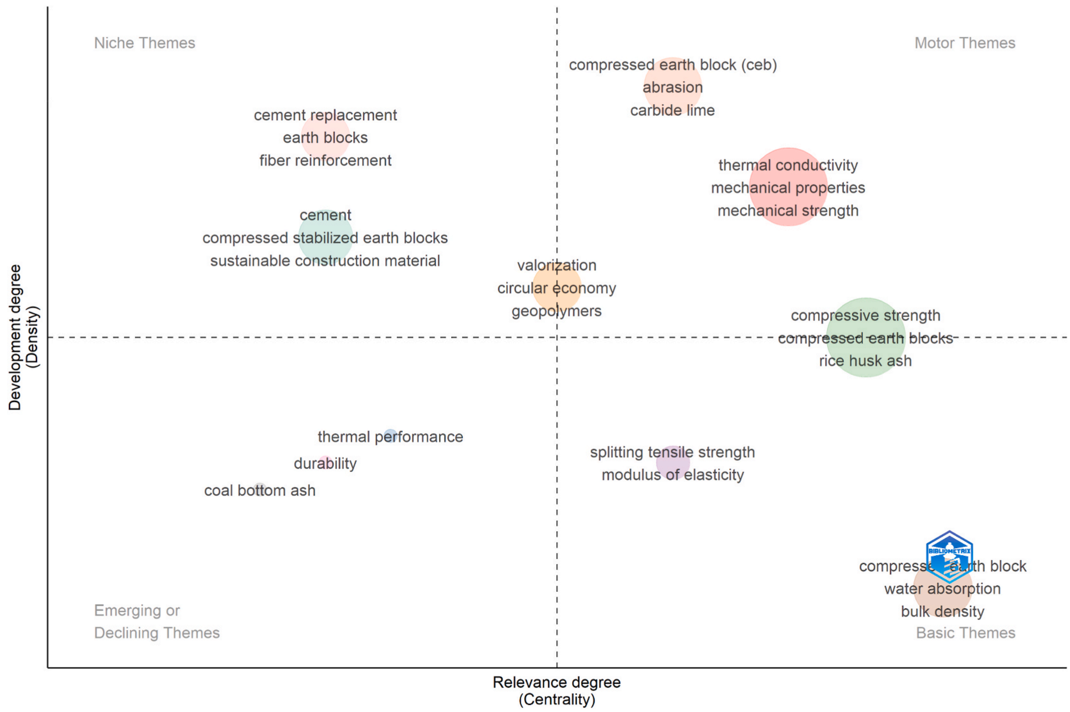

Fig. 3. Thematic map Compress Earth Blocks.

density and low centrality) focus on fiber reinforcement, cement replacement, and compressed stabilized earth blocks, lines of internal development that have not yet converged on the core of the field. The reviewed trials indicate that plant fibers (sisal, bamboo, date palm) improve toughness, flexural strength, and crack control, although excessive contents or suboptimal lengths increase porosity and may reduce compressive strength [42–44]. Experiences with marine bioaggregates (green mussel shell powder and pig hair) have also been reported, achieving increases in compression and good performance against drip erosion, but with limited transfer due to small sample sizes and lack of standardization [7]. Emerging or declining topics include durability, thermal performance, and coal bottom ash. The position of durability indicates that there is still no systematic basis for accelerated aging (wet-dry, salts, abrasion) integrated with the loss of mechanical and thermal properties, despite its relevance for long-term adoption [40,45]. In turn, the lower centrality of coal bottom ash suggests a shift towards agro-industrial waste with a better environmental profile.

The trend map in Fig. 4 shows a sequential evolution in CEBs research lines with agro-industrial waste. Between 2016 and 2019, terms associated with operational and conditioning variables (lime, fibers, curing, bending strength) predominate, reflecting an initial phase focused on adjusting base mixtures and characterizing the primary mechanical response [42]. This is consistent with the position of reinforcement/fiber replacement as a niche topic on the thematic map, where the focus was on local mechanical effects before linking them to the overall performance of the material.

Between 2020 and 2024, the most frequent terms focus on compressive strength, compressed earth blocks, thermal conductivity, and water absorption, evidencing the transition towards thermo-mechanical optimization. This change coincides with studies showing that siliceous wastes such as rice husk ash can reduce thermal conductivity and, at the same time, improve compressive strength in CEBs [46], in line with the driving themes of the thematic map, where compressive strength and thermal conductivity articulate the main axis. The recurring presence of water absorption (2021–2023) confirms the need to integrate hygrothermal variables into the design, as indicated by research with alkali-activated sediments and fly ash, where mechanical improvements are not always maintained if absorption and capillary suction are not controlled [40,45].

The late and less frequent appearance of durability indicates that, although mechanical and thermal efficiency has dominated the agenda, studies on accelerated aging, water resistance, wet-dry cycles, and abrasion remain scarce and heterogeneous, an aspect already highlighted by the meta-analytic review by Mora-Ruiz et al. (2025) [17]. This lack of longitudinal follow-up explains why durability is ranked as an emerging/declining topic on the thematic map and has a low frequency on the trend map.

A joint reading of Fig. 3 (thematic map) and Fig. 4 (trend map) suggests that the field is advancing in a cumulative but fragmented manner: first, compressive strength and thermal conductivity are optimized, and only at a later stage is long-term stability questioned. This methodological sequence helps explain the wide ranges observed in the meta-analytical table, where the same type of additive can improve thermal performance and, at the same time, compromise strength (or vice versa) depending on the experimental protocol applied [44]. The current trend points to a phase in which it is essential to articulate mechanics, thermal properties, and durability within the same experimental framework, especially when agro-industrial waste is used to replace conventional cementitious materials.

3.2. Meta-analysis results

The study-level dataset is provided in the Supplementary Material (Supplementary Table S1). It summarizes the mechanical behavior of CEBs according to the type of additive, grouping the waste into: no additives, cementitious (industrial and agro-industrial), cellulosic, fibers (agricultural, agro-industrial, wood, and animal), and mixed combinations (cementitious + fiber and cementitious + fiber + cellulose). This classification highlights how the nature of the waste influences compressive strength and density across studies,

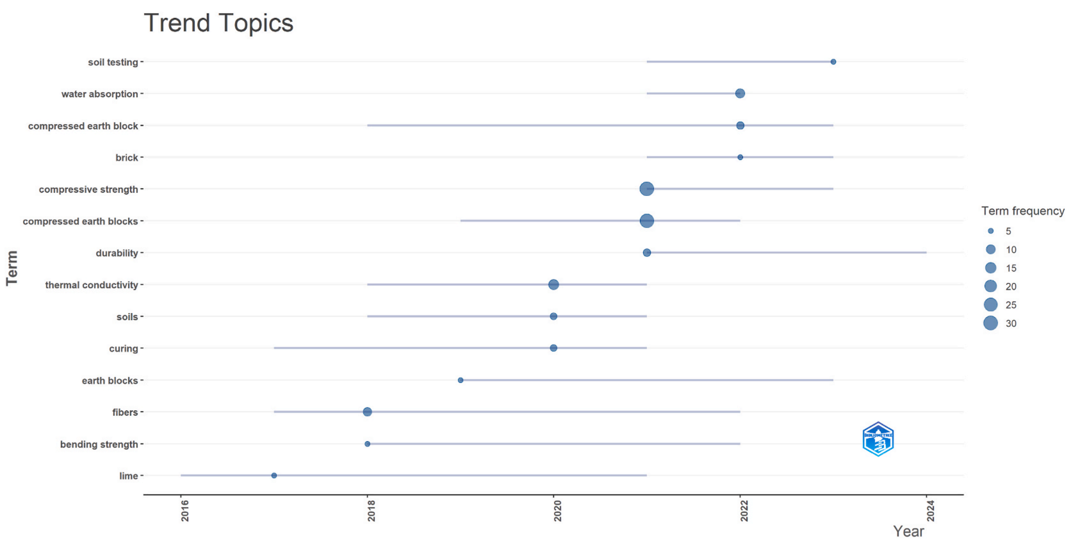

Fig. 4. Keyword trends Compress Earth Block.

while also reflecting variability associated with the soil matrix, the incorporated percentage, and the plasticity ranges (LL, PL, and PI).

Without additives, CEBs have strengths between 1 and 8.75 MPa, confirming the limited performance of unstabilized compacted soil, even with adequate granulometry and SC and CL soils [5]. This behavior is consistent with studies that indicate that, without modifying agents, the minimum regulatory threshold for lightweight structural blocks is rarely exceeded.

Industrial cementitious materials achieve the highest strengths (1–22 MPa), associated with hydration processes and pozzolanic reactions of cements and activated mineral ashes [4,9]. In contrast, agro-industrial cementitious materials show more moderate values (1–12 MPa), but with greater sustainability potential, as in the case of RHA and POFA, which reduce density and moisture and decrease the environmental impact compared to conventional cement [7,47]. This quantitative difference coincides with the thematic map, which shows a priority for combining mechanical performance and eco-efficiency, especially through agro-industrial ash.

Fiber blends exhibit greater dispersion. Agricultural plant fibers achieve strengths between 1.10 and 7.86 MPa, while agro-industrial fibers can reach up to 11.10 MPa, depending on the type of fiber, dosage, and filament length [9,48]. This aligns with

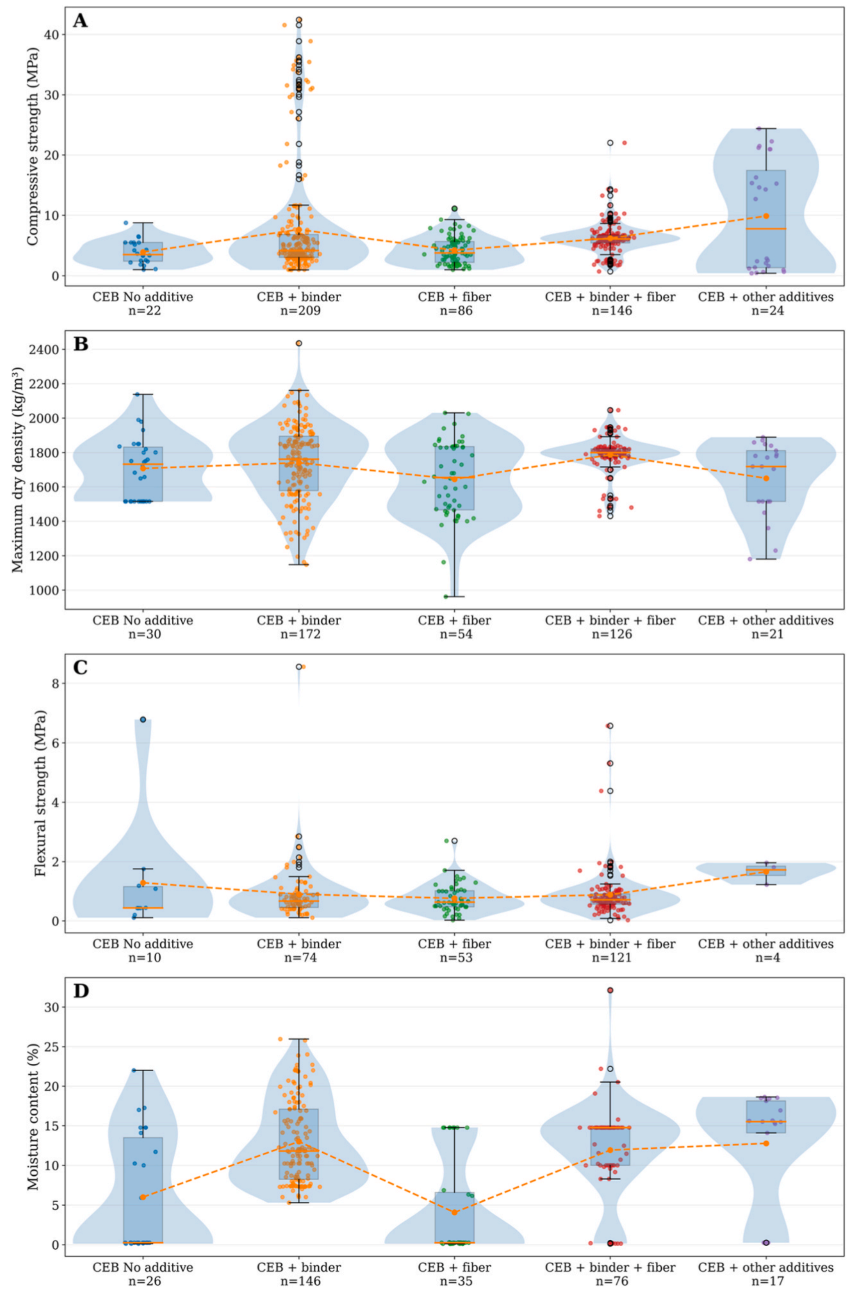

Fig. 5. Quantitative synthesis of mechanical and physical properties of compressed earth blocks as a function of additive type.

the niche cluster of the thematic map, where fiber appears as an advanced but still poorly standardized line of exploration. Animal and marine fibers provide lower compressive strengths (1.74–4.16 MPa), although they improve ductility and resistance to surface erosion when combined with cementitious materials [7].

The best synergies are observed in the hybrid stabilizers + fiber and cementitious + fiber + cellulose systems, with strengths between 0.71 and 22.02 MPa, and up to 24.37 MPa when cellulose nanocrystals are added together with plant fibers [10,43]. This indicates that the multicomponent effect exceeds the performance of each waste separately and suggests that future research should focus less on increasing cement content and more on optimizing the interaction between agro-industrial ash, natural fibers, and small structuring fractions, keeping costs and environmental impact low without sacrificing strength.

The quantitative synthesis presented in Fig. 5 integrates mechanical and physical properties of CEBS grouped by additive system (no additive, binder, fiber, and binder + fiber) and reflects both central tendencies and dispersion arising from a wide range of experimental practices. Given the heterogeneity of soils, stabilizing agents, dosages, compaction pressures, curing regimes and testing protocols reported in the literature, the figure is intentionally designed to combine distributional visualization with the explicit reporting of key descriptive statistics (n, mean, median and coefficient of variation) within each panel. This approach replaces a separate numerical table and allows readers to directly associate statistical descriptors with the underlying distributions, facilitating transparent interpretation of variability, skewness and outliers in a research field where standardized reporting is still evolving.

In compression, the data show a consistent upward shift in central values for binder-stabilized systems compared to unstabilized CEBs. This trend is robust despite high coefficients of variation and is consistent with the extensive use of hydraulic and pozzolanic binders in CEBs technology, including Portland cement, lime, fly ash, rice husk ash, coal bottom ash, phosphogypsum and alkali-activated by-products. Reported binder contents typically range from 3 to 10% by mass of dry soil for cement and lime-based stabilization, with higher dosages occasionally adopted for industrial by-products or alkali-activated systems to compensate for lower early reactivity [5,49,50]. Studies incorporating cement–fly ash blends or alkali-activated binders derived from dredged sediments or glass waste consistently report significant gains in compressive strength, although the magnitude of improvement is highly sensitive to curing temperature, moisture control and compaction energy [40,51]. The wide dispersion observed within the “binder” category therefore reflects genuine inter-study heterogeneity rather than statistical noise, as the term encompasses chemically distinct binders with different reaction mechanisms and processing windows.

Fiber-only systems typically show moderate compressive performance, since fibers rarely contribute as primary load-bearing elements in compression. Natural fibers (e.g., banana, sisal, kenaf, doum palm, bamboo, pig hair) are commonly used at about 0.25% to 2.0% (by mass or volume), and their effect on compressive strength is generally secondary to crack-control mechanisms [7,12,52,53]. Excessive fiber contents or inadequate dispersion have been shown to increase porosity and reduce compressive strength, particularly when fiber length and moisture conditioning are not optimized [53]. The binder + fiber category combines these mechanisms: binders govern peak compressive resistance through matrix strengthening, while fibers contribute to damage control and post-peak stability, provided that fiber dosage and workability allow effective compaction [43].

Flexural strength exhibits less pronounced separation between categories, a result that is consistent with the strong sensitivity of bending response to specimen geometry, span-to-depth ratio, loading configuration and moisture state at testing. Nevertheless, fiber-reinforced systems show patterns compatible with improved flexural behavior when compared in terms of distribution shape and variability rather than mean values alone. Experimental studies report that natural fibers enhance crack-bridging capacity and energy absorption, with optimal performance observed at specific fiber lengths and contents (e.g., 20–40 mm for kenaf fibers, $\leq$1% for banana or sisal fibers), beyond which mechanical benefits may diminish due to fiber agglomeration or poor matrix adhesion [10,52,53]. These findings support the interpretation that flexural strength, as reported across studies, captures only part of the mechanical benefit of fiber reinforcement and should be interpreted in conjunction with variability indicators and qualitative failure modes.

Dry density shows comparatively narrow distributions across all additive systems, confirming that density is a more stable descriptor at the literature scale. Binder-stabilized systems tend to exhibit slightly higher median densities, although several studies demonstrate that strength gains can occur even with modest density reductions when reactive binders or fine by-products refine the microstructure and improve bonding efficiency [49,50]. Fiber incorporation often induces slight density reductions due to the introduction of low-density phases and increased porosity, a trend reported for vegetal and agro-industrial fibers across multiple studies [12,41]. These observations reinforce the notion that density alone is not a reliable proxy for mechanical performance in CEBs systems.

Moisture content shows the highest dispersion and asymmetry, reflecting a key limitation of the literature: studies often report moisture under non-equivalent definitions (molding/compaction or optimum moisture, curing moisture, or service/conditioning moisture) without stating the stage. Binder-stabilized mixes typically require more water to support hydration or activation, while fiber-reinforced mixes are strongly affected by the hygroscopicity of lignocellulosic fibers and their preconditioning [12,43]. Therefore, moisture variability is interpreted mainly as methodological rather than anomalous, reinforcing the need for clearer reporting to enable future inferential synthesis.

In this work, “meta-analysis” is used in a descriptive, non-pooled sense. We systematically extract and aggregate reported outcomes and compare additive systems using robust descriptive and distributional statistics. Effect-size pooling, heterogeneity indices, and weighting were not applied because variance data and comparable testing configurations are inconsistently reported, making formal pooling potentially misleading. Accordingly, the quantitative synthesis maps realistic ranges, characterizes dispersion, and identifies standardization gaps. Here, meta-analysis denotes a quantitative evidence synthesis that maps realistic ranges, characterizes dispersion, and identifies standardization gaps [16].

3.3. Experimental results

3.3.1. Characterization of materials

Following a systematic review and meta-analysis of studies on the use of agricultural waste in CEBs, a specific gap was identified: the mechanical behavior of ash derived from palm waste has been little addressed. This section evaluates how this behavior evolves when POFA is incorporated into CEBs manufacturing.

Soil selection is crucial to ensure strength and durability. The meta-analysis showed that the soils used typically contain 2–25% gravel, 50–80% sand, 20–40% silt, and 5–30% clay [47], with consistency limits ranging from LL = 24–70% [43,54], PL = 15–55% [55], and IP = 1,5–29 % [5,56]. Fig. 6 shows the particle size distribution of soil and POFA. The soil is classified as low plasticity silt (ML), with 1.5% gravel, 12.9% sand, and 85.6% fines, and values of LL = 36.39%, PL = 24.47%, and IP = 8.91%. Coco shell ash, on the other hand, has particle sizes between 1 mm and 0.01 mm.

The chemical characterization of POFA (Table 2) indicated $\Sigma(SiO_2+Al_2O_3+Fe_2O_3$ = 34.4%, CaO = 5.35%, and LOI = 40%. Although technical references often consider ~50% (and even ≥70% in conventional pozzolans) as indicative thresholds for a clearly pozzolanic chemical profile, these values do not preclude the use of the material, especially in non-structural CEBs [57]. In this type of application, in addition to chemistry, fineness, degree of crystallinity, and surface reactivity also influence secondary strengthening mechanisms, as does the contribution of basic oxides such as CaO [57]. Mechanical improvements have been reported with POFA of modest reactive fraction when dosage, compaction, and curing are optimized, activating the filler effect and microstructural densification [31]. Similarly, in palm boiler ash, it has been observed that grinding and better combustion control increase the reactive surface area and open the door to alkali-activated or stabilized matrices [30]. In contrast, formulations with $\Sigma(SiO_2+Al_2O_3+Fe_2O_3 >$ 50% tend to exhibit a more favorable chemical profile for marked pozzolanicity, especially when combined with grinding and/or activation [8]. Overall, the data from this study suggest the viability of POFA as an addition to CEBs, prioritizing its physical contribution and considering, when seeking a greater cementing effect, conditioning to reduce LOI and increase fineness, as well as reactivity adjustments [30,57].

The POFA diffractogram (Fig. 7) shows a clearly crystalline response. The peak of highest intensity is located around $2\theta \approx 26^\circ$, characteristic of quartz, accompanied by other reflections of quartz and cristobalite in the approximate range of 20–35° and in the 40–50° zone. Quantitative refinement indicates approximately 45% quartz and about 5% cristobalite, which is consistent with the SiO_2 and glass-forming oxide content measured by X-ray fluorescence. This behavior is similar to that described for other biomass ashes, in which silica is mainly organized into crystalline polymorphs of SiO_2 [2].

In addition to the siliceous phases, the XRD pattern allows the identification of sylvite (KCl), nitrate (KNO_3), elemental sulfur, and a Ca–Mg–Fe phosphate in appreciable proportions. These phases explain the presence of K_2O, P_2O_5, CaO, MgO, Cl, and S recorded by XRF and are typical in agro-industrial ash, where crop nutrients and fertilization residues are concentrated [30]. In the context of compressed earth blocks, these types of salts can modify pore chemistry and ionic conductivity, and under particular humidity conditions, they can promote efflorescence. Therefore, their presence should be considered when analyzing durability results, rather than being interpreted solely in a negative light.

The bottom of the diffractogram shows a smooth amorphous hump in the 20–35° 2θ range, indicating that POFA combines a vitreous fraction with a significant crystalline fraction. This combination suggests a rather moderate pozzolanic activity: the ash does not behave like a highly reactive pozzolan, as is the case with some rice husk ashes or biomass mixtures rich in amorphous silica, but it does contribute reactive silica to a certain extent [2,58]. In practical terms, this means that POFA does not have a very high cementing potential, but it can participate in secondary gel formation reactions and contribute to the densification of the microstructure when combined with good compaction and adequate curing.

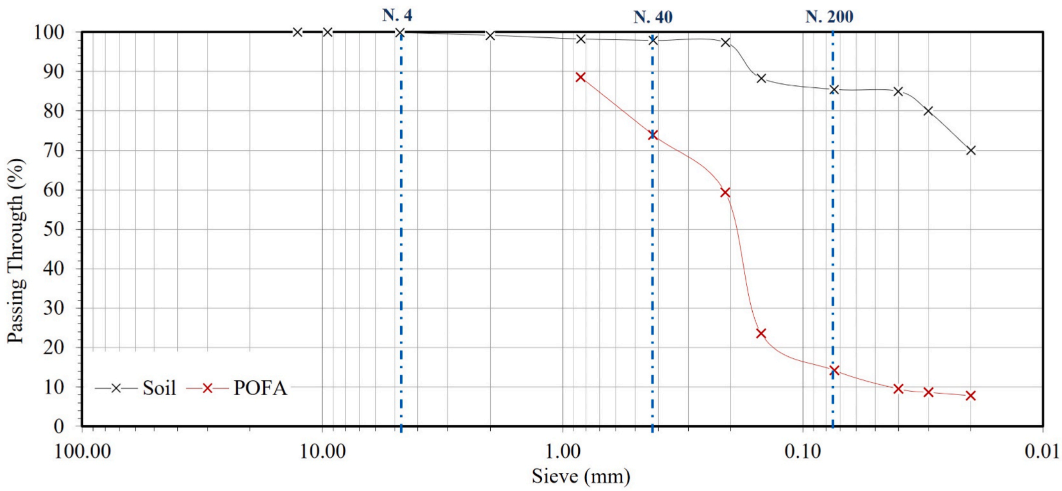

Fig. 6. Particle size distribution of soil and POFA.

Table 2
Chemical properties of POFA.

Chemical Compound	Concretration by weight (%)										
	SiO_2	K_2O	CaO	P_2O_5	MgO	ClO_2	Al_2O_3	Fe_2O_3	MnO_2	LoI	Others
Palm Oil Fuel Ash (POFA)	32.5	5.52	5.35	4.13	2.44	1.88	0.92	0.997	0.107	40	6.156

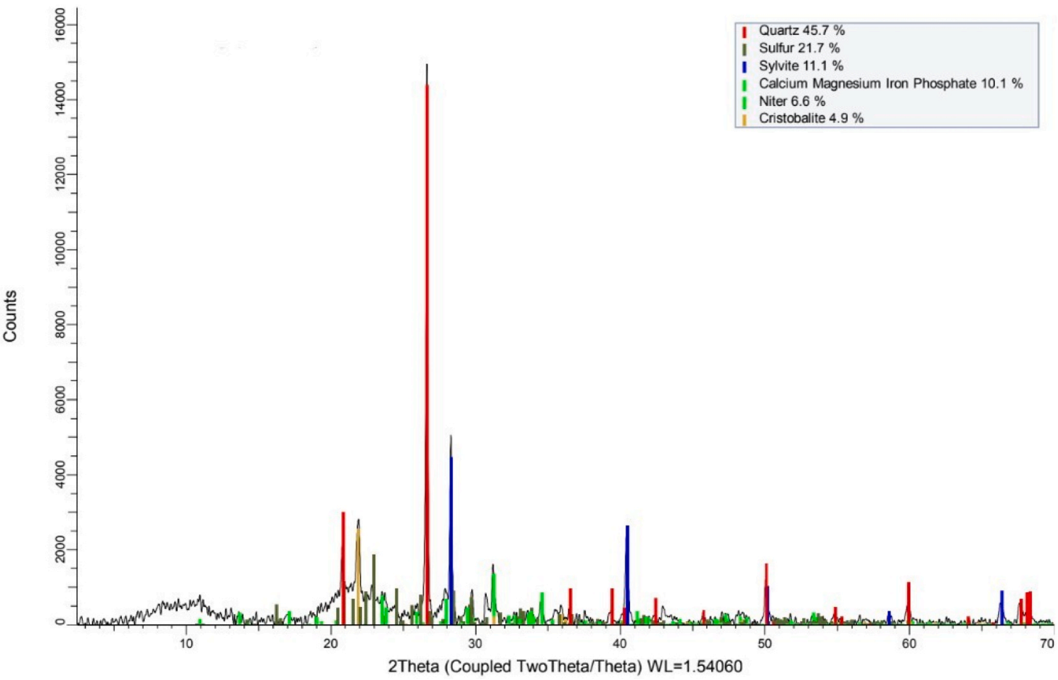

Fig. 7. POFA X-ray diffraction.

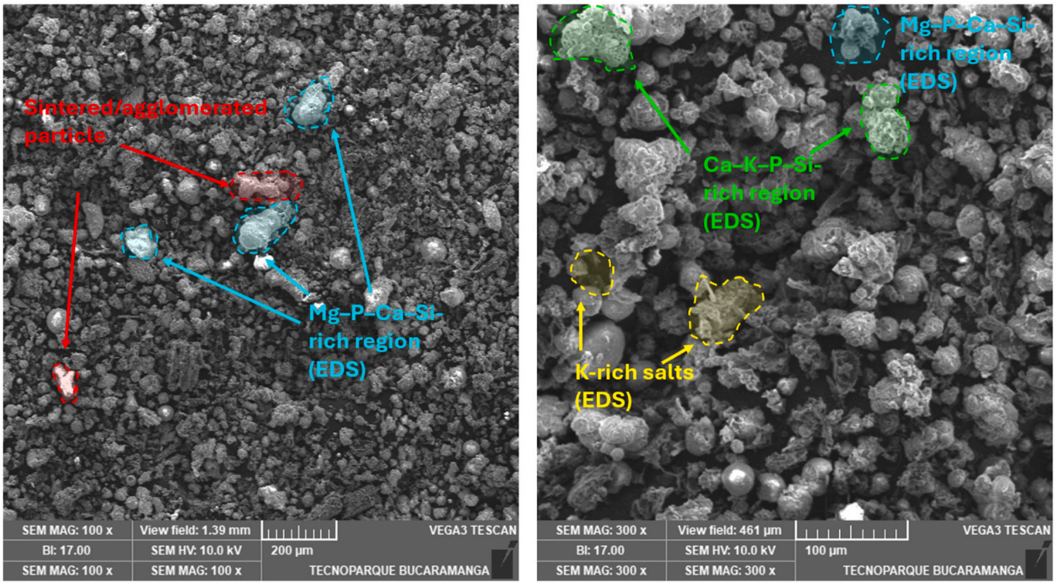

Fig. 8. Microstructure and Elemental Composition POFA.
Note: EDS provides localized elemental signatures and does not directly identify crystalline or amorphous phases.

The SEM micrographs of palm ash (POFA) in Fig. 8, at 100 × and 300 × magnification, show a heterogeneous microstructure with spherical and sub-spherical particles, irregular agglomerates, porous areas, and dark fragments with a carbonaceous appearance. The labels in Fig. 8 indicate EDS-based elemental enrichments from selected spots/areas (Mg–P–Ca–Si-rich and Ca–K–P–Si-rich regions, and K-rich salts), rather than definitive phase identification. At 100 × magnification, a dense "carpet" of fine particles with a wide particle size range can be observed, while at 300 × , smooth spheres, scoriaceous structures, and highly porous regions associated with residual organic material are more clearly distinguished, a morphology consistent with boiler biomass ash, especially from the palm oil industry [2,30].

EDS elemental analysis at both scales shows similar compositions, indicating that the images are representative. A high content of C and O is observed, around 11% by weight of Si and lower proportions of K, Ca, Mg, P, Cl, S, Al, Na, and Fe. These results are consistent with the XRF, which shows a moderate amount of SiO_2, appreciable contents of K_2O, CaO, MgO, and P_2O_5, and a high loss on ignition associated with organic and volatile compounds, a pattern typical of palm ash and other agricultural biomass where crop nutrients are concentrated in the inorganic fraction [30]. As EDS is a localized technique, these values are used to support the trends observed by XRF and the mineralogical interpretation, rather than to quantify bulk composition. Accordingly, EDS signatures are interpreted as indicative elemental associations at selected spots/areas, and they should not be taken as direct proof of specific crystalline or amorphous phases.

The XRD diffractogram reinforces this interpretation by showing intense signals from quartz and cristobalite, indicating that much of the silicon is in crystalline form and has limited reactivity. Saline phases such as sylvite (KCl), niter, elemental sulfur, and a calcium-magnesium-ferric phosphate are also identified. These phases coincide with bright areas in SEM where EDS shows local enrichments of K, Ca, P, and Cl. Following the usual recommendations for microstructural interpretation, it is most prudent to refer to "regions compatible with K- and Ca-rich phases" or "Si-associated zones," using XRD and XRF as a basis for inferring probable phases, without attributing absolute compositions to individual particles [2].

In the case of compressed earth blocks (CEBs), this microstructure suggests that POFA will primarily play a role as a rough siliceous filler and stabilizing additive, rather than as a direct substitute for a highly reactive cement. Hard and rough particles can improve the packing of the mixture and internal friction, while K^+ and Ca^{2+} cations favor flocculation and stabilization processes of the clay fraction, as has been noted in studies on soil stabilization with mineral additives of limited reactivity. In materials where very high strength values are not required, such as many non-structural CEBs, this combination can result in reasonable increases in strength and volumetric stability, along with a possible improvement in thermal behavior linked to the internal porosity of the carbonaceous fragments and porous ash particles.

As summarized in Table 3, POFA has an electrical conductivity of 432.8 μS/cm and a pH of 9.93, values that describe a clearly alkaline and strongly ionic medium, although less caustic than lime or cement (pH > 12). These results are consistent with the composition obtained by XRF for date palm ash, which reports significant contents of SiO_2 (32.5%), CaO (5.35%), K_2O (7.65%), MgO (2.44%), and P_2O_5 (4.13%), together with S and Cl, which explains both the alkalinity and the high concentration of charged species in solution. This profile is similar to that described for other palm ashes with high SiO_2 and the presence of CaO and K_2O, considered viable raw materials for supplementary cementitious materials and geopolymers [30].

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The combination of a pH close to 10 with high conductivity and an appreciable content of dissolved silica indicates that POFA can act as a supplementary cementing agent in CEBs, providing alkalinity and potentially reactive silica, in a manner comparable to, although less intense than, high-purity RHA [46]. However, Table 3 also shows that the critical factor is not heavy metals, but common salts (Cl^- and SO_4^{2-}), whose presence at high levels requires consideration of aspects such as ash dosage, the curing regime, and possible control measures against efflorescence and sulfate-type processes described in cementitious matrices exposed to sulfate-rich solutions [59].

3.3.2. *Effect of POFA on compaction*

Fig. 9 shows that ML soil without additives reaches a maximum dry density of approximately 1.40 g/cm^3 (≈1400 kg/m^3) with an

Table 3
Physical and chemical properties of POFA.

Property type	Parameter	Unit	POFA
Physical chemistry	Electrical conductivity	μS/cm	432.8
	pH/temperature	pH/°C	9.93/24.8
Lixiviates	Chlorides	mg Cl/L	660
	Sulfates	mg SO_4^{2-}/L	297
	Total cadmium	mg Cd/L	<0.005
	Total mercury	mg Hg/L	<0.0005
	Total lead	mg Pb/L	0.132
	Total silicon	mg Si/L	195

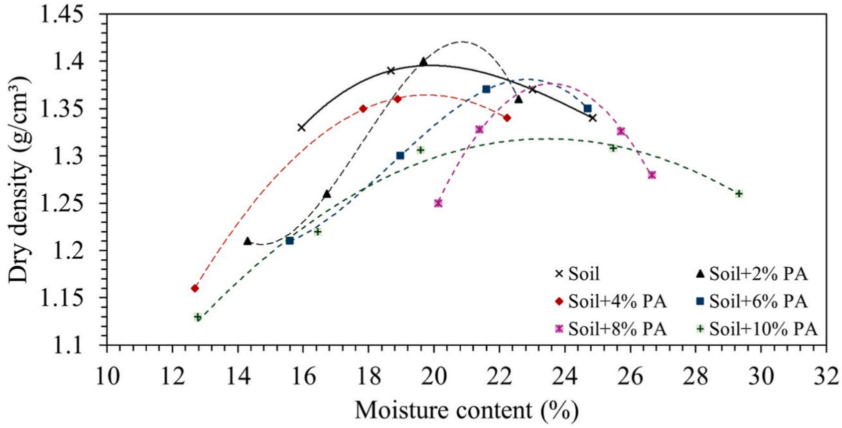

Fig. 9. Proctor test.

optimum moisture content of 20%. When POFA ash is incorporated, the maximum dry density ranges between 1.33 and 1.43 g/cm^3 (1330–1430 kg/m^3) and the optimum moisture content increases from 21% (2% POFA) to 25–26% (10% POFA). A POFA content of 2% produces the highest density (1.42–1.43 g/cm^3), while from 4 to 10% POFA the density decreases slightly and more water is required to achieve the optimum compaction state, indicating a beneficial filling effect at low dosages and a progressive lightning of the mixture when ash replaces a larger fraction of the soil.

Compared to the systematic review, these densities (1330–1430 kg/m^3) are below the typical values for CEBs without additives, which have maximum dry densities of 1658–1990 kg/m^3 and optimum moisture contents of 6–22% [40,47,60], and at the lower end of the range for blocks with agro-industrial binders (1195–1960 kg/m^3, wopt ≈12–19%) [40,45,47,50,61,62]. In turn, CEBs with industrial cementing agents achieve even higher densities (1488–2435 kg/m^3, wopt 7–18%) [9,11,55]. In this context, the behavior observed with POFA is consistent with that reported for other agro-industrial ashes: the optimum moisture content increases and the dry density decreases moderately as the ash content increases, due to its lower specific gravity and higher porosity, but without leaving the compaction range considered suitable for the manufacture of compressed earth blocks.

3.3.3. *Mechanical performance of CEBs*

Fig. 10 shows the evolution of the compressive strength of CEBs with 0–10% POFA between 14 and 90 days; the red line represents the mean value and the black bars represent the dispersion. At 28 days, the reference block (0% POFA) reaches approximately 2.2 MPa, within the range reported for CEBs without additive (1.0–3.38 MPa) in the database [5,40,47,60,63]. When POFA is incorporated, the strength increases significantly: with 4–6% ash, values in the range of 3.8–4.0 MPa are obtained, while for 8–10% the strengths remain in a similar range, but with a slight decrease in the mean and an increase in dispersion. This indicates that moderate dosages (4–6%) offer the best compromise between increased strength and reproducibility, and that higher POFA contents do not provide significant additional gains. Accordingly, the 4–6% POFA interval should be interpreted as a practical and reproducible mix-design window under the investigated materials and processing conditions, rather than as an absolute optimization value transferable to other POFA sources

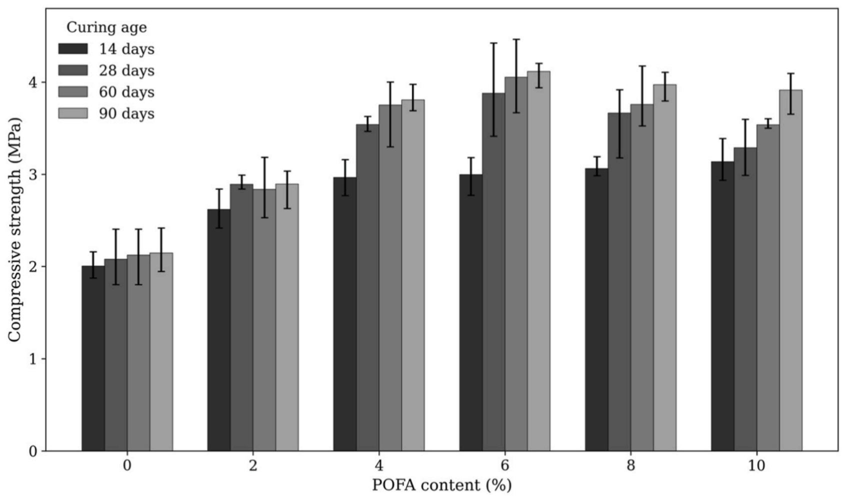

Fig. 10. Average compressive strength of CBEs.

or soils. Based on the achieved strength levels and in line with practice-oriented standards and guidance [33–37], the POFA-stabilized mixtures in the intermediate dosage range are primarily intended for non-structural masonry units (einfill blocks or protected wall systems), whereas structural or exposed applications would require additional durability assessment and code-specific verification.

When these results are compared with data from meta-analyses using similar residue percentages, it can be seen that CEBs with rice husk ash (RHA) with 6.25% cement and 5–7.5% RHA develop strengths of 3.44–3.99 MPa at 28 days, while increasing the RHA to 15–20% reduces the strength to 3.19–2.85 MPa [46]. In other words, with residue contents in the range of 5–7.5%, RHA provides values very close to those obtained in this study with 4–6% POFA (3.8–4.0 MPa), which places POFA at a comparable performance level within the family of agro-industrial ashes. In the case of ultra-fine palm oil fuel ash (UfPOFA), Article 17 uses 6–9% cement and 1–4% UfPOFA, obtaining strengths of 6.49 MPa (9% C + 1% UfPOFA), 3.74 MPa (8% C + 2%), 5.23 MPa (7% C + 3%), and 2.15 MPa (6% C + 4%) [8]. For residue contents in the range of 2–4%, these values are distributed among mixtures above and below the strengths achieved here with 4–6% POFA, indicating that the response of UfPOFA is more sensitive to the specific cement–ash combination.

For their part, the combinations of calcium carbide residue (CCR) and RHA in article 19 use RHA percentages of 2–8% associated with CCR fractions of 12–18%, achieving strengths of 6.0–7.0 MPa [49]. These values are clearly higher than those obtained with 4–6% POFA, but they require a much higher total cementitious material content, so they are not directly comparable from an eco-efficiency standpoint. Something similar occurs with mixtures incorporating bottom ash (BC) in article 49, where BC percentages of around 4–9% combined with cement (and, in some cases, lime) produce strengths between 2.3 and 5.11 MPa [50]; under these conditions, the values overlap with the range achieved by CEBs with 4–6% POFA.

Fig. 11 shows the flexural strength of CEBs with 0–10% POFA ash between 14 and 90 days. In each graph, the red line corresponds to the mean value and the black bars represent the dispersion of the results. At all ages, the reference block (0% POFA) remains around 0.4–0.45 MPa, while the mixtures with ash reach values close to 0.6–0.7 MPa, especially for contents of 10%. However, at these high dosages, the error bars are longer and partially overlap with those of other mixtures, indicating that, although the mean increases, the response is more variable and strongly conditioned by small differences in compaction, water content, and mixture homogeneity.

This behavior is consistent with the role of POFA in the microstructure of CEBs. At low to moderate contents (2–6%), ash acts mainly as a fine filler, improving packing and contact between soil particles; this favors the transmission of tensile/flexural stresses and explains the systematic increase in the red line relative to the control. When the dosage is increased to 8–10%, part of the mineral skeleton is replaced by a more porous and heterogeneous material, which can generate locally weak areas and facilitate the appearance of cracks associated with voids or variations in compaction. Hence, 10% POFA shows the highest average strengths, but accompanied by larger dispersions, reflecting greater sensitivity of flexural behavior to local defects.

Ash-free CEBs are above the typical value reported for blocks without additives, whose average flexural strength is around 0.2 MPa [5], while mixtures with 4–10% POFA (0.5–0.7 MPa) are within the characteristic range of CEBs with agro-industrial cementing agents (0.1–1.3 MPa) [8,46,49,61,64–66]. Compared to systems with industrial binders, which reach approximately 0.2–2.9 MPa [4,9–11,55,67], POFA-based CEBs are at the lower end of the range, which was to be expected when using an agro-industrial waste product as the main improving agent. Taken together, the red line and black bars in Fig. 10 indicate that POFA increases the flexural strength of the material to levels comparable to other eco-efficient CEBs in the literature, but also introduces appreciable variability that must be controlled through careful dosing and compaction.

The strength gains observed in compression and bending (Figs. 10 and 11) can be explained by a combined stabilization mechanism based on the interaction between ML soil and POFA at the physical, chemical, and mineralogical levels. From a physical point of view, SEM micrographs show that POFA is made up of fine, rough, spherical and sub-spherical particles, together with scoriaceous agglomerates and highly porous regions with carbonaceous remains [2,30]. At intermediate dosages, these particles act as filler within a

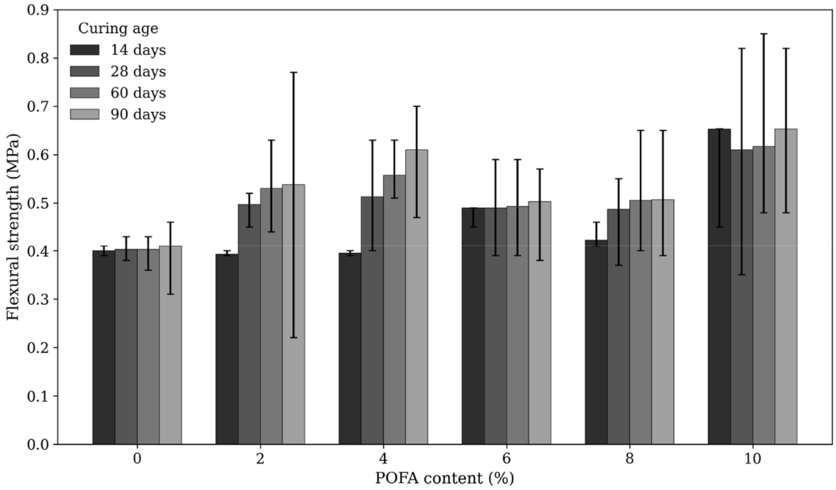

Fig. 11. Average flexural strength of CEBs.

matrix rich in fines, reducing pores, improving packing, and increasing internal friction, which reinforces the granular skeleton against compression and hinders the propagation of cracks under bending. When the POFA content increases, the replacement of soil by porous agglomerates and carbonaceous fragments introduces heterogeneities and possible weak points, consistent with the increase in mechanical dispersion observed for mixtures richer in ash. This dispersion is also consistent with the known variability of POFA properties across sources, as differences in combustion conditions, fineness, and feedstock can modify residual carbon content, particle morphology, and water demand, thereby affecting packing efficiency and the mechanical response. Overall, the combined filler/-packing effect, clay flocculation under an alkaline/ionic medium, and limited secondary cementation explain the strength increase at intermediate POFA dosages, whereas porous agglomerates and carbonaceous residues at higher contents increase heterogeneity and dispersion. Accordingly, given the high loss on ignition and the predominantly crystalline silica content of POFA, the strength development is interpreted as being primarily governed by physical densification and packing effects, while chemical or secondary cementation mechanisms play a subordinate role.

Chemically, POFA has a relatively moderate $\Sigma(SiO_2+Al_2O_3+Fe_2O_3)$ sum and a high LOI, which points to limited but not negligible pozzolanicity [57]. The ash leachate shows a clearly alkaline and strongly ionic medium, with the presence of K^+, Ca^{2+}, Mg^{2+}, and chloride and sulfate species [30,59]. This alkalinity favors the flocculation and stabilization of the clay fraction of the soil, reducing plasticity and increasing the rigidity of the granular skeleton [50]. At the same time, the vitreous fraction identified by XRD contributes, albeit moderately, to secondary pozzolanic reactions with available calcium, generating small volumes of C–S–H/C–A–S–H gels that locally densify the microstructure and explain the gradual improvement in mechanical properties over time [2,30]. However, the high LOI and the presence of organic compounds and soluble salts also favor the existence of residual porosity and sensitivity to curing conditions, which is reflected in the greater variability of the results when the POFA dosage increases.

Mineralogically, XRD indicates that the ash is dominated by quartz and cristobalite, with a smooth amorphous hump and the presence of saline phases such as sylvite (KCl), niter (KNO_3), elemental sulfur, and calcium-magnesium-ferric phosphates [2,30]. The crystalline polymorphs of SiO_2 basically act as a rigid microaggregate that increases the shear strength and stiffness of the matrix, reinforcing the physical filling effect in both compression and bending. The K- and Ca-rich phases are consistent with the alkalinity and high conductivity measured in the leachates [30,59], and support the stabilizing role on clays. On the other hand, soluble salts and carbonaceous residues associated with high LOI introduce a more porous and heterogeneous microstructure, which explains why, at high POFA dosages, strength gains are attenuated and variability increases. Taken together, the combination of rigid siliceous filler, slight pozzolanic cementation, and a partially porous matrix allows us to understand the increases observed in compression and flexural strength for intermediate POFA contents, as well as the tendency toward greater dispersion when the amount of ash is increased.

4. Recommendations

The results indicate that the incorporation of POFA in CEBs made with silty soils performs optimally at intermediate dosage ranges, in the order of 4–6% by weight, where the best compromise between strength gain and low dispersion of results is achieved. For full-scale applications, it is recommended to rigorously control the molding moisture, compaction energy, and ash homogenization, especially when high dosages are used, in order to limit microstructural and mechanical variability. Given the identified soluble salt content, it is suggested that pre-treatments be implemented on the POFA (combustion optimization, fine grinding, and/or washing) when the CEBs are exposed to humid environments or will be exposed, to mitigate the risk of efflorescence and potential durability problems. Finally, it is considered a priority that future work adopts standardized testing protocols for compression, bending, absorption, and durability, so that the results can be comparable and transferable to future sustainable construction standards.

5. Conclusions

The systematic review and meta-analysis show that research on CEBs with agro-industrial waste has focused mainly on improving compressive strength, thermal conductivity, and water absorption, while durability remains a less developed and methodologically fragmented area. This heterogeneity is manifested in notable differences in specimen geometry, compaction energies, test ages, and curing conditions, which limits comparability between studies and hinders the formulation of robust predictive models based on the existing literature.

Within this landscape, CEBs without additives generally have relatively low strengths, while systems stabilized exclusively with industrial cementing agents achieve the highest values, albeit at the cost of a greater environmental impact. Mixtures incorporating agro-industrial ash show moderate but technically competitive strengths, with reductions in density and a potential thermal benefit. Hybrid systems (ash + fibers or other lignocellulosic fractions), on the other hand, tend to offer the most favorable mechanical synergies, confirming that combining waste at different scales is more effective than simply increasing the cement content.

The physical, chemical, mineralogical, and microstructural characterization of the POFA developed in this work reveals an ash with a moderate vitreous fraction, an appreciable presence of crystalline SiO_2, high loss on ignition, and alkaline leachates with soluble salts. This profile suggests limited but sufficient pozzolanicity to generate a certain degree of secondary cementation, which acts in a complementary manner to a marked physical filling effect and stabilization of the clay fraction, consistent with the increases in strength observed for intermediate dosages.

Mechanical tests on CEBs with POFA show that contents in the range of 4–6% produce consistent increases in compressive and flexural strength compared to the control without ash, reaching values comparable to those reported for other eco-efficient blocks with agricultural ash and falling within the usual ranges for non-structural elements. At higher dosages (8–10%), mechanical gains tend to stabilize, and the dispersion of results increases, indicating that excessive replacement of soil with a more porous and heterogeneous ash introduces weak areas and makes the material more sensitive to variations in compaction and water content.

The experimental case study indicates that POFA can be a technically feasible additive for low-impact, non-structural CEBs when intermediate dosages are used under controlled production conditions; however, transferability across different soils, POFA sources, manufacturing energies, and exposure conditions requires further validation. The systematic review and the descriptive quantitative synthesis position these experimental results within the broader evidence base on agro-industrial ashes used in CEBs and highlight the need to move towards experimental programs that jointly evaluate mechanical, thermal, and durability performance. The novelty of this work lies in combining PRISMA-based evidence synthesis with a targeted experimental programme and complementary chemical/mineralogical/microstructural characterization to derive a mechanism-informed, practically reproducible dosage window for POFA-stabilized CEBs. Accordingly, recommendations regarding harmonized testing and potential regulatory incorporation are derived primarily from the synthesis evidence and should be interpreted as research and policy implications rather than experimentally demonstrated outcomes.

CRediT authorship contribution statement

Viviana Mora-Ruiz: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cristian Mejía-Parada:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Claudia Tavera:** Supervision, Investigation.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2026.115804.

Data availability

Data will be made available on request.

References

[1] S. Sharma, S. Basu, N.P. Shetti, M. Kamali, P. Walvekar, T.M. Aminabhavi, Waste-to-energy nexus: a sustainable development, Environ. Pollut. 267 (2020), https://doi.org/10.1016/j.envpol.2020.115501.
[2] S. Šupić, M. Malešev, V. Radonjanin, V. Bulatović, T. Milović, Reactivity and pozzolanic properties of biomass ashes generated by wheat and soybean straw combustion, Materials 14 (2021) 1–20, https://doi.org/10.3390/ma14041004.
[3] D. Tonini, P.F. Albizzati, T.F. Astrup, Environmental impacts of food waste: learnings and challenges from a case study on UK, Waste Manag. 76 (2018) 744–766, https://doi.org/10.1016/j.wasman.2018.03.032.
[4] Y. Li, L. Li, V. Bindiganavile, Constitutive model of uniaxial compressive behavior for roller-compacted concrete using coal bottom ash entirely as fine aggregate, Buildings 11 (2021), https://doi.org/10.3390/buildings11050191.
[5] T.E. Elahi, A.R. Shahriar, M.S. Islam, Engineering characteristics of compressed Earth blocks stabilized with cement and fly ash, Constr. Build. Mater. 277 (2021), https://doi.org/10.1016/j.conbuildmat.2021.122367.
[6] P. Poullain, N. Leklou, A. BabatoundéLaibi, M. Gomina, Properties of compressed Earth blocks made of traditional materials from Benin, Rev. Compos. Matériaux Avancés 29 (2019) 233–241, https://doi.org/10.18280/rcma.290407.
[7] B.A. Lejano, R.J. Gabaldon, P.J. Go, C.G. Juan, M. Wong, Compressed Earth blocks with powdered green mussel shell as partial binder and pig hair as fiber reinforcement, Int. J. GEOMATE 16 (2019) 137–143, https://doi.org/10.21660/2019.57.8138.
[8] Y.W. Tonduba, A.K. Mirasa, H. Asrah, Utilization of ultrafine palm oil fuel ash in interlocking compressed Earth brick, Int. J. GEOMATE 21 (2021) 70–78, https://doi.org/10.21660/2021.87.j2245.

[9] B.M. Ganou Koungang, J.O. Tchamdjou Mbouendeu, D. Ndapeu, Z. Zhao, G. Tchemou, F. Michel, E. Njeugna, A. Messan, L. Courard, Experimental thermophysical dependent mechanical analysis of Earth bricks with Canarium schweinfurthii and Cocos nucifera bio-aggregates - a case study in Cameroon, Cogent Eng. 10 (2023), https://doi.org/10.1080/23311916.2022.2159159.

[10] F. Abdelkader, R. Mohamed, K. Cheikh, A.H.M. Amine, Improving the mechanical and thermal behavior of a compressed Earth block using fibers, Journal of Engineering and Sustainable Development 28 (2024) 702–709, https://doi.org/10.31272/jeasd.28.6.2.

[11] K. Mouih, R. Hakkou, M. Mansori, J. Ghanbaja, Y. Taha, H. Kaddami, Synergistic effect of micro and nano cellulosic fillers on thermal insulation and mechanical strength properties of compressed Earth bricks from phosphate mining by-products, J. Build. Eng. 102 (2025), https://doi.org/10.1016/j.jobe.2025.112023.

[12] B. Taallah, A. Guettala, The mechanical and physical properties of compressed Earth block stabilized with lime and filled with untreated and alkali-treated date palm fibers, Constr. Build. Mater. 104 (2016) 52–62, https://doi.org/10.1016/j.conbuildmat.2015.12.007.

[13] F.B. Ebanda, A.E. Mewoli, A.E. Njom, M.T. Kibong, P.M. Anicet Noah, B. Ndiwé, M.J. Ndengue, S.O. Biloa Otiti, J.R. Lucien Meva'a, A. Ateba, Towards sustainable construction in Cameroon : impact of tropical plant fibers on the performance of compressed Earth bricks, Innovative Infrastructure Solutions 9 (2024), https://doi.org/10.1007/s41062-024-01797-8.

[14] Mark Mitchell, Engauge Digitizer, 2020.

[15] M. Aria, C. Cuccurullo, Bibliometrix, 2017.

[16] M. Borrego, M.J. Foster, J.E. Froyd, Systematic literature reviews in engineering education and other developing interdisciplinary fields, J. Eng. Educ. 103 (2014) 45–76, https://doi.org/10.1002/jee.20038.

[17] V. Mora-Ruiz, J. Soto-Paz, S. Attia, C. Mejía-Parada, Sustainable earthen construction: a meta-analytical review of environmental, mechanical, and thermal performance, Buildings 15 (2025), https://doi.org/10.3390/buildings15060918.

[18] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the fuzzy sets theory field, J. Informetr. 5 (2011) 146–166, https://doi.org/10.1016/j.joi.2010.10.002.

[19] ASTM International, Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, West Conshohocken, PA, 2017, https://doi.org/10.1520/D6913_D6913M-17.

[20] ASTM International, Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, ASTM International, West Conshohocken, PA, 2021, https://doi.org/10.1520/D7928-21E01.

[21] ASTM International, Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2017, https://doi.org/10.1520/D4318-17E01.

[22] ASTM International, Test Methods for Chemical Analysis of Hydraulic Cement, ASTM International, West Conshohocken, PA, 2024, https://doi.org/10.1520/C0114-24.

[23] ASTM International, Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-Ray Powder Diffraction Analysis, ASTM International, West Conshohocken, PA, 2018, https://doi.org/10.1520/C1365-18.

[24] ASTM International, Standard Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-Ray Powder Diffraction Analysis, ASTM International, West Conshohocken, PA, 2022, https://doi.org/10.1520/C1723-16R22.

[25] ASTM International, Test Methods for Loss on Ignition (LOI) of Solid Combustion Residues, ASTM International, West Conshohocken, PA, 2021, https://doi.org/10.1520/D7348-21.

[26] ASTM International, Test Method for Density of Hydraulic Cement, ASTM International, West Conshohocken, PA, 2017, https://doi.org/10.1520/C0188-17.

[27] ASTM International, Test Methods for Ph of Soils, ASTM International, West Conshohocken, PA, 2019, https://doi.org/10.1520/D4972-19.

[28] ASTM International, Test Methods for Electrical Conductivity and Resistivity of Water, ASTM International, West Conshohocken, PA, 2023, https://doi.org/10.1520/D1125-23.

[29] ASTM International, Practice for Shake Extraction of Solid Waste with Water, ASTM International, West Conshohocken, PA, 2020, https://doi.org/10.1520/D3987-12R20.

[30] Z. Yahya, M.M. Al, B. Abdullah, H. Kamarudin, K. Nizar, Chemical and physical characterization of boiler ash from palm oil industry waste for geopolymer composite, Rev. Chem. (2013). https://www.researchgate.net/publication/264081382.

[31] O.A. Joy, O.J. Kolawole, Effects of compactive effort on laterite-oil palm empty fruit bunch ash mixture, Covenant Journal of Engineering Technology (CJET) 4 (2020). http://journals.covenantuniversity.edu.ng/index.php/cjet.

[32] ASTM International, Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3)), ASTM International, West Conshohocken, PA, 2021, https://doi.org/10.1520/D0698-12R21.

[33] DIN 18945:2024-03, Lehmsteine_- Anforderungen, Prüfung Und Kennzeichnung, 2024, https://doi.org/10.31030/3517954.

[34] Standard XP P13-901. https://www.boutique.afnor.org/en-gb/standard/xp-p13901/earth-bricks-and-earth-blocks-for-walls-and-partitions-definitions-specific/fa202221/321764?utm_source=chatgpt.com. (Accessed 31 January 2026).

[35] UNE 41410:2023 Bloques de Tierra Comprimida (BTC) para muros y. https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0072146&utm_source=chatgpt.com. (Accessed 31 January 2026).

[36] NZS 4298, Nzs 4298: materials and workmanship for Earth buildings, New Zeal. Tech. Committe 4298 (1998) 91.

[37] E2392/E2392M, Standard Guide for Design of Earthen Wall Building Systems. https://store.astm.org/e2392_e2392m-24.html?utm_source=chatgpt.com. (Accessed 31 January 2026).

[38] ASTM International, Test Methods for Sampling and Testing Brick and Structural Clay Tile, ASTM International, West Conshohocken, PA, 2021, https://doi.org/10.1520/C0067_C0067M-21.

[39] ASTM International, Test Method for Flexural Strength of Hydraulic-Cement Mortars, ASTM International, West Conshohocken, PA, 2021, https://doi.org/10.1520/C0348-21.

[40] M. Brahim, K. Ndiaye, S. Aggoun, W. Maherzi, Valorization of dredged sediments in manufacturing compressed Earth blocks stabilized by alkali-activated fly ash binder, Buildings 12 (2022), https://doi.org/10.3390/buildings12040419.

[41] H. Limami, I. Manssouri, O. Noureddine, S. Erba, H. Sahbi, A. Khaldoun, Effect of reinforced recycled sawdust-fibers additive on the performance of ecological compressed Earth bricks, J. Build. Eng. 68 (2023), https://doi.org/10.1016/j.jobe.2023.106140.

[42] A. Thennarasan Latha, B. Murugesan, B. Skariah Thomas, Compressed Earth block reinforced with sisal fiber and stabilized with cement: manual compaction procedure and influence of addition on mechanical properties, Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.04.373.

[43] D. Abessolo, A.B. Biwole, D. Fokwa, B.M. Ganou Koungang, B.B.A.A.H. Yembe, Physical, mechanical and hygroscopic behaviour of compressed Earth blocks stabilized with cement and reinforced with bamboo fibres, Int. J. Eng. Res. Afr. 59 (2022) 29–41, https://doi.org/10.4028/p-spbskv.

[44] I. Bouchefra, F.Z. EL Bichri, H. Chehouani, B. Benhamou, Mechanical and thermophysical properties of compressed Earth brick rienforced by raw and treated doum fibers, Constr. Build. Mater. 318 (2022), https://doi.org/10.1016/j.conbuildmat.2021.126031.

[45] M. Brahim, K. Ndiaye, S. Aggoun, Durability and stability performance of compressed earth blocks (CEB) made with sediment and FA, Front. Eng. Built Environ. 5 (2025) 173–191, https://doi.org/10.1108/FEBE-10-2024-0068.

[46] M. Yatawara, S. Athukorala, Potential of replacing clay soil by rice husk ash (RHA) in enhancing the properties of compressed Earth blocks (CEBs), Environ. Dev. Sustain. 23 (2021) 3474–3486, https://doi.org/10.1007/s10668-020-00727-9.

[47] S. Djadouf, N. Chelouah, A. Tahakourt, The influence of the addition of ground olive stone on the thermo-mechanical behavior of compressed Earth blocks, Matériaux Tech. 108 (2020), https://doi.org/10.1051/mattech/2020023.

[48] S. Cabrera, K. Elert, A. Guilarducci, A. Margasin, The effect of local pozzolans and lime additions on the miner-alogical, physical and mechanical properties of compressed Earth blocks in Argentina, Revista de La Construccion 21 (2022) 248–263, https://doi.org/10.7764/RDLC.21.2.248.

[49] P. Nshimiyimana, A. Messan, L. Courard, Physico-mechanical and hygro-thermal properties of compressed Earth blocks stabilized with industrial and agro by-product binders, Materials 13 (2020), https://doi.org/10.3390/ma13173769.

[50] A. Lawane, J.R. Minane, R. Vinai, A. Pantet, Mechanical and physical properties of stabilised compressed coal bottom ash blocks with inclusion of lateritic soils in Niger, Sci. Afr. 6 (2019), https://doi.org/10.1016/j.sciaf.2019.e00198.

[51] J. Rivera, J. Coelho, R. Silva, T. Miranda, F. Castro, N. Cristelo, Compressed Earth blocks stabilized with glass waste and fly ash activated with a recycled alkaline cleaning solution, J. Clean. Prod. 284 (2021), https://doi.org/10.1016/j.jclepro.2020.124783.

[52] M. Mostafa, N. Uddin, Experimental analysis of Compressed Earth Block (CEB) with banana fibers resisting flexural and compression forces, Case Stud. Constr. Mater. 5 (2016) 53–63, https://doi.org/10.1016/j.cscm.2016.07.001.

[53] A.B. Laibi, P. Poullain, N. Leklou, M. Gomina, D.K.C. Sohounhloué, Influence of the kenaf fiber length on the mechanical and thermal properties of Compressed Earth Blocks (CEB), KSCE J. Civ. Eng. 22 (2018) 785–793, https://doi.org/10.1007/s12205-017-1968-9.

[54] A. Jiménez-Montoya, J.B. Pascual-Francisco, G. Sánchez-Cruz, M.G. Ríos-Ledezma, J.K. Novelo-Ramos, A.L. Matías-Molina, Soil and cement bricks with diverse reinforcements: a Review, Revista Politecnica 53 (2024) 97–113, https://doi.org/10.33333/rp.vol53n2.10.

[55] S. Oubaha, R. Hakkou, Y. Taha, M.O. Mghazli, M. Benzaazoua, Elaboration of compressed Earth blocks based on phosphogypsum and phosphate mining by-products, J. Build. Eng. 62 (2022), https://doi.org/10.1016/j.jobe.2022.105423.

[56] S. Paul, M.S. Islam, T.E. Elahi, Potential of waste rice husk ash and cement in making compressed stabilized Earth blocks: strength, durability and life cycle assessment, J. Build. Eng. 73 (2023), https://doi.org/10.1016/j.jobe.2023.106727.

[57] F.M. Lea, P.C. Hewlett, Martin Liska, Lea's Chemistry of Cement and Concrete, Butterworth-Heinemann, 2019.

[58] F. Pacheco-Torgal, S. Jalali, Earth construction: lessons from the past for future eco-efficient construction, Constr. Build. Mater. 29 (2012) 512–519, https://doi.org/10.1016/j.conbuildmat.2011.10.054.

[59] Karen Scrivener, Ruben Snellings, Barbara Lothenbach, A Practical Guide to Microstructural Analysis of Cementitious Materials, CRC Press, 2016.

[60] I. Dabakuyo, R.N.N. Mutuku, R.O. Onchiri, Mechanical properties of compressed Earth block stabilized with sugarcane molasses and Metakaolin-based geopolymer, Civil Engineering Journal (Iran) 8 (2022) 780–795, https://doi.org/10.28991/CEJ-2022-08-04-012.

[61] M.A. Gómez-Casero, F.J. Moral-Moral, L. Pérez-Villarejo, P.J. Sánchez-Soto, D. Eliche-Quesada, Synthesis of clay geopolymers using olive pomace fly ash as an alternative activator. Influence of the additional commercial alkaline activator used, J. Mater. Res. Technol. 12 (2021) 1762–1776, https://doi.org/10.1016/j.jmrt.2021.03.102.

[62] F. Belayali, W. Maherzi, M. Benzerzour, N.E. Abriak, A. Senouci, Compressed Earth blocks using sediments and alkali-activated byproducts, Sustainability 14 (2022), https://doi.org/10.3390/su14063158.

[63] A.F. Minguela, Bio-composites to tackle UK built environment carbon emissions: comparative analysis on load-bearing capacity, hygroscopic and thermal performance of compressed Earth blocks with addition of industrial Hemp waste, Open Construct. Build Technol. J. 11 (2017) 395–412, https://doi.org/10.2174/1874836801711010395.

[64] A.A. Mohammed, H.A.M. Yahia, H.A. Mohammed, I.M. Abdulhadi, O.A. Alelweet, M.M. Maseer, The durability of innovative blocks through cyclic testing and actual climate exposure, Progress in Engineering Science 2 (2025), https://doi.org/10.1016/j.pes.2025.100050.

[65] P. Nshimiyimana, A. Messan, Z. Zhao, L. Courard, Chemico-microstructural changes in earthen building materials containing calcium carbide residue and rice husk ash, Constr. Build. Mater. 216 (2019) 622–631, https://doi.org/10.1016/j.conbuildmat.2019.05.037.

[66] E. Hany, N. Fouad, M. Abdel-Wahab, E. Sadek, Investigating the mechanical and thermal properties of compressed earth bricks made by eco-friendly stabilization materials as partial or full replacement of cement, Constr. Build. Mater. 281 (2021), https://doi.org/10.1016/j.conbuildmat.2021.122535.

[67] M. Mostafa, N. Uddin, Effect of banana fibers on the compressive and flexural strength of compressed earth blocks, Buildings 5 (2015) 282–296, https://doi.org/10.3390/buildings5010282.