Renewable and Sustainable Energy Reviews 144 (2021) 110951

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Life cycle assessment (LCA) of natural vs conventional building assemblies

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ARTICLE INFO

Keywords:
LCA
Natural building materials
Earthen building materials
Earth architecture
Environmental performance
Thermal simulation

ABSTRACT

Natural earthen and bio-based building materials are critically needed to dramatically reduce energy-intensive and extractive construction practices that are the hallmark of the modern building industry. Building assemblies such as cob, light straw clay and rammed earth were shown to provide an optimal indoor environment for occupant comfort and health. Despite these advantages, natural materials are still not widespread in mainstream construction for two primary reasons: technical data is inadequate to quantify their energy performance in different climates, and environmental measures are missing to perform decision making throughout the design process. This paper presents an environmental life cycle assessment (LCA) of natural earthen and bio-based materials compared to conventional building materials in 6 climates: hot desert, desert, semi-arid, Mediterranean, temperate, and continental. Results show that, when coupling the embodied and operational environmental impacts, the natural assemblies reduce energy demand by 32–59% in the hot desert climates, 29–55% in semi-arid climates, 46–73% in Mediterranean climates, 34–57% in temperate climates and 27–50% in continental climates as compared to conventional assemblies. The operational impacts are shown to be highly dependent on the thermal properties and climate zone, but in all cases natural assemblies outperform conventional assemblies. In particular, light straw clay and insulated rammed earth are the top performers for all 6 climates. The work presented in this paper contributes critically needed environmental quantifications to catalyze the advancement of healthier and more environmentally sound commitments to ecological construction worldwide.

1. Introduction

In contrast with other building materials, earthen and bio-based materials exhibit a number of advantages: a) high thermal inertia and structural capacity in compression; b) a better resistance to fungi, insects and rodents, compared to exposed cellulose-based materials; c) potential abundance in and around the construction site; d) a diversity of building forms and construction techniques, from sculptural monolithic assemblies to modular components [1].

Due to their high thermal inertia, earthen materials are particularly advantageous in warmer climates, especially when diurnal changes offer warm days and cool nights. When combined with bio-based fibers, earthen assemblies can provide both thermal inertia and thermal resistance to the building envelope [2]. Additionally, the advantages of earthen assemblies as a thermal mass can be used in cold climates by placing it within an insulated envelope or by using Trombe walls; the assembly can store and retain heat from passive solar or active indoor sources and release this heat slowly over a period of time (e.g., over a cold night) [1,3].

In addition to their thermal properties, earthen and bio-based building materials exhibit good hygrothermal properties due to their porosity. Recent research has shown that various earthen building assemblies are able to regulate indoor humidity to achieve optimal levels for occupant health [4–7]. Furthermore, clay-based materials were shown to act effectively as passive removal materials (PRMs) for ozone [8].

Given these numerous environmental and health benefits, earthen and bio-based building materials should be analyzed and demonstrated through environmental product declarations (EPDs) and product category rules (PCRs) [9,10] based on a life cycle assessment (LCA) methodology [11,12]. In particular, EPDs are used to "enable comparisons between products fulfilling the same function" and could bridge the gap between policymakers, product developers, field practitioners and homeowners, by providing measures that can be used for design decision

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https://doi.org/10.1016/j.rser.2021.110951
Received 9 September 2020; Received in revised form 15 February 2021; Accepted 6 March 2021
Available online 1 April 2021
1364-0321/

Fig. 1. (a) Example of light straw clay installation and (b) finished product [28,29].

making [13]. Earthen building codes and standards should be better represented in codes and standards worldwide, a task that requires enumerated technical data and awareness about their benefits [14].

To address this need, the main goal of this research is to enumerate the potential environmental impacts of incorporating natural wall assemblies and comparing those assemblies to various conventionally built walls. This LCA compares different natural building assemblies (light straw clay, cob, insulated and uninsulated rammed earth) to conventional building assemblies (light timber frame, insulated and uninsulated concrete masonry).

This paper is structured as follows: Section 2 overviews previous LCA studies on natural building assemblies and Section 3 provides background on the natural assemblies considered in this work. Thereafter, Section 4 outlines the LCA materials and methods incorporated in this work and Section 5 provides the results of the LCA phases. Finally, Section 6 presents the conclusions of this work as well as the limitations and future research recommendations.

2. Existing life cycle assessment studies on natural building assemblies

Existing LCA studies of natural building materials, most of which are focused on inventory analysis, provide an important first step in comparing the life cycle impacts of earthen versus conventional assemblies. Existing studies assess individual construction techniques such rammed earth [15–18], cob [19,20], adobe bricks [21,22], earth plasters [23], earthships [24,25], compressed earth blocks [18], and earthbags [26]. To the best of found knowledge of the authors, a complete LCA for light straw clay is still missing from the literature.

For rammed earth and cob, existing LCA studies include preliminary inventory data, each for an individual location, with missing comparative studies for the US. Studies on rammed earth include an impact assessment for the manufacturing phase that was conducted using eco-indicator impact points in a European context [15]. Another study accounts for the energy expenditures during the manufacturing and transportation to the building site of rammed earth, stone masonry, and concrete housing construction in South France [16]. Additionally, an input-output embodied energy analysis for a residential building in Australia [17], and an EPD-oriented cradle to gate analysis in the context of Portugal [18] have been developed. For cob, an embodied energy evaluation was conducted for Canada using secondary online resources [19], and an embodied CO_2 inventory analysis for a small cob structure was developed for rural Nicaragua [20].

To the best of authors' knowledge, these individual natural building LCA studies are not readily comparable due to the location-specific and material/process-specific data used in each study. Most studies do not include a comparison to conventional materials and methods, making it challenging to use these studies to extract environmental management recommendations or to determine design change requirements. Finally, many studies use a functional unit of 1 kg of material, which may not allow for a readily available comparison between various structural systems because of the need to translate weight into square footage for numerous building materials within a building assembly.

To address these gaps, this work presents a comparative LCA of a suite of natural and conventional residential building wall assemblies. The presented LCA incorporates location-specific data from existing database inventories, as well as develops critically missing inventory data for earthen assemblies for the context of the US. Using a functional unit of 1 square meter (m^2) of a typical one- or two-story wall system, this study allows for a readily available comparison between complete assemblies, as well as future analyses that accounts for operational considerations of other typical wall assemblies.

3. Background on the natural assemblies considered in this study

The following section includes an overview of the natural building assemblies considered in this work: light straw clay, cob, and rammed earth.

3.1. Light straw clay

Light straw clay, also referred to as light clay, straw clay, slip straw, rammed straw and leichtlehmbau (in Germany), is an earthen and bio-based infill method comprised of fiber (usually straw) as its predominant component that is wetted with clay slurry (very wet clay). The loose straw is lightly coated in clay and then packed into temporary or permanent formwork (shuttering), serving as an insulating assembly, as

Fig. 2. (a) Vernacular cob structure, and (b) successfully code-permitted cob structure [34,35].

Fig. 3. (a) The Great Wall of China, Jiayuguan Gate, built by the Ming Dynasty around 1372, and (b) rammed earth residential house in Mexico [37].

shown in Fig. 1. Light straw clay can be mixed and packed to a variety of densities [27], but is not, itself, load bearing.

Beyond being an excellent insulation assembly, light straw clay exhibits additional advantages. It is compatible with conventional framing systems, making it a viable retrofit insulation, especially where existing walls can be furred out to any thickness. Additionally, the light straw clay mixture is very workable and is compatible with other wall assemblies; it can be easily worked around windows, door and other openings. Lastly, light straw clay is considered a healthy building material that is often offered as a viable alternative for occupants with sensitivity to mold and chemicals [28].

3.2. Cob

Cob is an earthen building material consisting of clay-rich soil mixed with natural fibers, such as straw and water. This mixture is produced in a plastic state and implemented wet to build monolithic load bearing walls without formwork (Fig. 2). The term cob comes from England, and it is sometimes referred to as monolithic adobe, as well as Bauge (France), Lehmweller (Germany), Pasha (Turkey) and Zabour (Yemen) [30,31]. Cob easily lends itself to form different curves, shapes, and sculptural details [32]. The presence of straw in cob was shown to impart a ductile failure mechanism, a quality that suggests appropriate behavior in seismic areas [33].

3.3. Rammed earth

Rammed earth, also referred to as Pisé (France), Tapial (Spain) and Stampflehmbau (Germany), combines small gravel aggregates, silt, sand, clay and a small amount of water, all compacted by ramming into formwork, similar to those used for concrete. Rammed earth has been used since ancient times, including well-known, monumental architecture, such as the Alhambra in Spain, the Pyramid of the Sun in Mexico and portions of the Great Wall of China. In recent decades, rammed earth has experienced a revival; its reassessment began in the 1970s, shifting towards more high-end contemporary architecture [36]. Today, rammed earth can be found in various projects, from residential to commercial structures (Fig. 3).

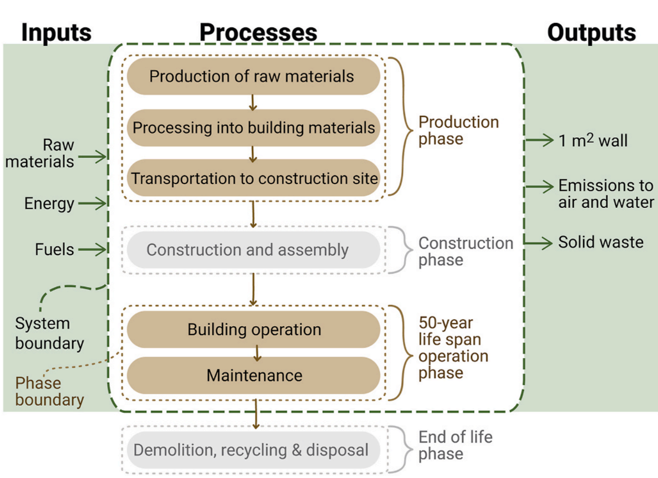

Fig. 4. The system boundaries diagram of this life cycle assessment study, which includes the production (embodied) and operational phases.[11]

4. Materials and methods for the comparative life cycle assessment

This environmental impact assessment used the environmental LCA methodology as defined by the ISO series of LCA standards [11,12]. The ISO describes a four-stage process: (1) Goal and scope definition; (2) Life cycle inventory (LCI), which enumerates system inputs (e.g., materials, energy use) and outputs (e.g., emissions to air, water, soil); (3) Life cycle impact assessment (LCIA), which analyzes the LCI data using environmental impact indicators to predict potential impacts to human health and the environment; (4) Interpretation of the results.

The embodied phase was modeled using SimaPro version 8.5 [38] for US-LCI [39] and EcoInvent [40] inventory data that are relevant to North America [41]. The study presented in Ref. [42] includes an early assessment for the embodied inventory and environmental impacts of cob as a basis for the presented analysis. For the operational phase, the thermal performance of the walls was assessed using EnergyPlus version 9.2.0 [57] and DesignBuilder version 6.1.3 [58] to determine heating and cooling loads for six climate regions.

4.1. Goal and scope

This work considered four natural wall assemblies (cob, light straw clay, and insulated and uninsulated rammed earth) and three conventional assemblies (light timber frame, insulated and uninsulated concrete masonry). The environmental impacts accounted for energy savings and emissions reductions of natural assemblies for a single-family housing unit in warm-hot climates in the US as defined by ASHRAE [43]: warm-hot climate zones 2B (e.g., Tucson, AZ), 3B (e.g., El Paso, TX), and 3C (e.g., Los-Angeles, CA). Additionally, due to the traditional use of earthen materials in temperate and colder climates, climate zones 4B (e.g., Albuquerque, NM), 4C (e.g., Portland, OR) and 5B (e.g., Denver, CO) were also considered.

4.2. Functional unit

The functional unit selected is 1 m^2 (10.75 ft^2) of load bearing exterior wall suitable for up to two-story residential construction that has an insulation value meeting or exceeding the requirements of the

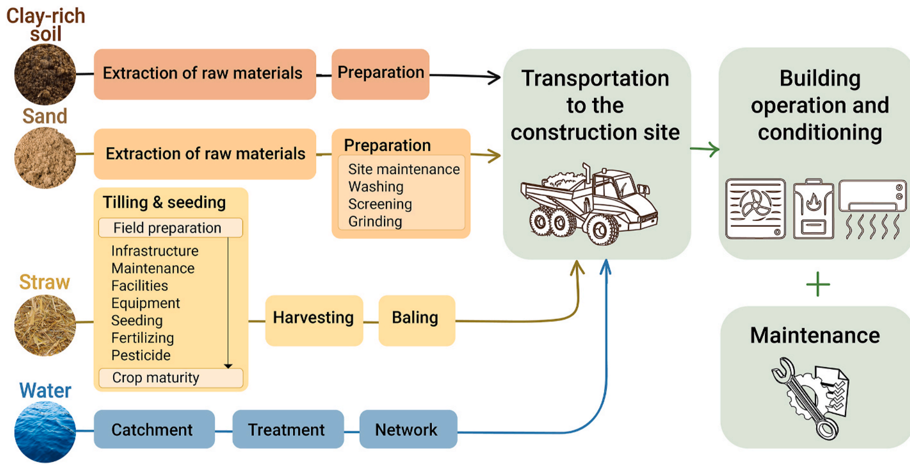

Fig. 5. The system boundaries and processes incorporated in the developed cob life cycle inventory.[1]

International Energy Conservation Code [43] for climatic zones 1–4. The functional unit was selected to provide an applicable and multipliable measurement that allows for results to be extrapolated to different scales of design and construction. To further ensure that results are transferable to different scales, the functional unit for each wall – described in 4.7 – was designed according to construction guidelines and common practice.

4.3. System boundaries

The system boundaries considered extraction and processing of raw materials, manufacture of building materials, transportation to the construction site, operation of HVAC for space conditioning, and maintenance for a 50-year lifespan. Onsite construction as well as demolition and disposal energy and emissions are beyond the system boundaries, as shown in Fig. 4.

Given the lack of information about maintenance of the various earthen and bio-based walls, the maintenance phase was limited to the application of embodied values for component renewal, such as surface plaster, every 10 years (as seen in Ref. [44], for instance).

4.4. Life cycle assessment approach

The approach taken in this LCA is a "Meso/macro-level decision support" approach [11], which matches the aim of stimulating strategic policy advancement. To support this approach, this LCA used system expansion and allocation. For example, as detailed in Ref. [42], straw was modeled using a market-based economic allocation between wheat grain and wheat straw to best capture a viable future scenario where straw could be used as a valuable building material rather than a less valuable byproduct of cereal production [45,46].

Due to the significant impact that heating and cooling energy can have on environmental impacts of a home, this study included a thermal analysis of each wall assembly for each climatic context. Thus, the operational stage was informed by a simulation model that predicts indoor air temperature and energy loads of both natural and conventional residential structures in the different climate zones. Significantly, whereas many thermal performance studies include static calculations and account for the thermal resistance of the envelope, this study includes a dynamic simulation that accounts for thermal and hygrothermal (vapor resistivity) characteristics of each assembly, as well as air temperature, radiant temperature, and relative humidity for each climatic context [13].

[1] Image made by the authors.

4.5. Life cycle inventory analysis

The study includes both previously studied and unstudied wall systems. For the concrete masonry unit (CMU) and lightweight wood frame systems, existing LCA studies are used from which LCI data was obtained. The existing database were used for lumber and plywood sheathing [47], gypsum board [48], fiberglass batt and rigid polystyrene insulation [49], Portland cement stucco [50], and concrete masonry blocks [51].

The inventory for the natural assemblies was developed for each constituent material to be shovel ready. As illustrated in Fig. 5 for cob, the developed LCI included the production and transportation of clay-rich soil, sand, straw, and water for on-site mixing and assembly. Constituent materials were represented by inventory databases from US-LCI [39] where possible. Other inventories with relevance to the US geographical context were selected from EcoInvent [40].

4.6. Life cycle impact assessment categories

The life cycle impact assessment (LCIA) used impact categories from the cumulative energy demand (CED) version 1.09 [52] and the tool for reduction and assessment of chemicals and other environmental impacts (TRACI) version 2.1 [53]. Predominantly used in the US, CED and TRACI tools enabled the assessment of environmental impacts using factors that were evaluated based on the US energy grid, water, and land use [52, 53]. The CED impact factors were used to characterize the inventory fuels and sources of energy, including coal, natural gas, diesel, crude oil, and electricity, as well as air emissions. The TRACI impact factors were used to characterize the inventory emissions, while considering a range of airborne emissions. Of the various impact categories, This LCA study adopted primary impact categories of energy use (MJ_{eq}), global warming potential (kg CO_{2eq}), air acidification (kg SO_{2eq}), and Human Health (HH) respiratory effects (kg $PM_{2.5eq}$).

4.7. Thermal performance assessment through dynamic simulations

The operational LCA phase of the wall assemblies was assessed using a thermal performance simulation that accounts for heating and cooling demand. A full year heat balance was simulated in each of the climates detailed in 4.1. The simulated annual energy loads were then used to estimate the operational environmental impacts for a 50-year lifespan using US-LCI database [39].

The wall assemblies were modeled using EnergyPlus version 9.2.0 [57] and DesignBuilder version 6.1.3 [58], and climate data was modeled using Typical Meteorological Year version 3 (TMY3) [59]. The simulation model incorporated a small test chamber that was designed

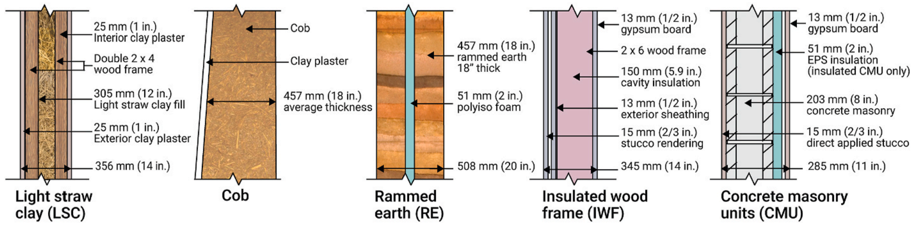

Fig. 6. Section drawings of the assessed wall systems.[3][1].

according to field chamber tests, as recorded by (Heathcote, 2002; Peng & Wu, 2008). The interior air and surface temperature for representative winter and summer periods were recorded for the building while maintaining indoor comfort set points of 20 °C (68 °F) for winter and 24.4 °C (76 °F) for summer, as recommended by ASHRAE (2017). For the purpose of generating heat gains, it was assumed that the chamber was occupied by one person for 24 h per day, every day. The model infiltration was set at a constant rate of 0.300 Air Changes per Hour (ACH). Apart from the walls, the construction assemblies of the chamber were taken from the DesignBuilder energy code standard templates [54], with an insulated 100 mm thick concrete floor slab with timber and insulated and asphalt-protected concrete roof. Each of the four walls was designed with a 2% glazed area, using double-glazed clear windows.

The main goal of this step was to isolate the relative impacts associated with the walls rather than to extrapolate the results to a real building. The contributions of the walls to the overall heat gains and losses in the simulated chamber were used to scale the simulation results to the heating and cooling loads that were attributable to the wall construction only. An average annual fuel utilization efficiency (AFUE) of 80% for the gas furnace heating system, energy efficiency ratio (EER) of 9.5 and coefficient of performance (CoP) of 2.78 for the electric cooling system were used to convert loads to site energy, as recommended by Ref. [55]. Finally, inventory fuels from the US-LCI database for US Southwest geographical context were used to convert the site energy to source energy [39]. The site-to-source conversion for energy use for this analysis resulted in a mean 1:3 site-to-source ratio, which corresponds with the ratios provided by Ref. [56].

4.8. Constituent materials and technical details of the wall systems

Each of the wall systems included in this LCA were analyzed according to the constituent materials, as detailed in the following subsections.

4.8.1. Light straw clay

The light straw clay wall section, illustrated in Fig. 6a, was designed based on the IRC light straw clay appendix [57]. The incorporated section includes light straw clay infilling a 38 × 89 mm (2 × 4 in.) double stud timber frame as described in section AR103.2.4 in Ref. [57]. The overall core density of the 305 mm (12 in.) thick light straw clay was selected as 192 kg/m^3 (12 pcf) based on an 85% straw content [51,52]. The insulation value of this wall is 3.84 m^2 K/W (R-21.8 °F·ft^2·hr/Btu).

4.8.2. Cob

The cob wall section (Fig. 6b) was designed according to typical sections recommended by Ref. [58] and for adobe structures in seismic areas [59]. It was assumed that the minimum thickness of the cob wall is 305 mm (12 in.) at the top of the wall, and 610 mm (24 in.) at its base, resulting in an average wall thickness of 457 mm (18 in.) [55]. The insulation value of this wall is 2.01 m^2 K/W (R-11.4 °F·ft^2·hr/Btu).

4.8.3. Rammed earth

The rammed earth wall section, illustrated in Fig. 6c, was designed according to common practice and code requirements [60,61]. Rammed earth mainly requires clay-rich soil, sand and gravel, with no added fiber, to which a small amount of water is added to achieve optimal compaction. This study assumed 20% gravel and 8% water content [62]. Additionally, the 457 mm (18 in.) thick rammed earth wall was assumed to have no plaster, which is the common practice to achieve the desirable aesthetic effect of rammed earth components. The insulation value of this wall is 1.58 m^2 K/W (R-9 °F·ft^2·hr/Btu). A variation of the plain rammed earth wall section also considered was insulated rammed earth (IRE) into which 51 mm (2 in.) R-12 polyisocyanurate (polyiso) insulation was added at the midplane of the wall. The insulation value of the insulated rammed earth wall is 3.70 m^2 K/W (R-21 °F·ft^2·hr/Btu).

4.8.4. Insulated wood frame

The conventional wood frame wall system, illustrated in Fig. 6d, was selected to represent a typical light-frame wood residential house in the US [63]. To better represent the warmer climates of the Southwestern USA, stucco rendering was used rather than vinyl cladding [64]. The wall included the following layers, listed from interior to exterior: 13 mm (0.5 in.) gypsum board, 38 × 140 mm (2 × 6 in.) dimensional lumber, cavity insulation in the form of a 150 mm (5.9 in.) R-21 fiberglass batt [56], 13 mm (0.5 in.) plywood sheathing, and 15 mm (0.6 in.) stucco. The insulation value of this wall is 3.06 m^2 K/W (R-17.4 °F·ft^2·hr/Btu).

4.8.5. Concrete masonry units

The benchmark concrete masonry unit (CMU) system, illustrated in Fig. 6e, was selected from Ref. [59]. The CMU wall included the following layers, listed from interior to exterior: 13 mm (0.5 in.) gypsum board, 203 mm (8 in.) CMU blocks, and 15 mm (0.6 in.) Portland cement-based stucco. Two alternatives were considered: an uninsulated CMU assembly and an insulated CMU assembly (ICMU) that provided an additional 51 mm (2 in.) of R-15 extruded polystyrene insulation between the CMU and interior gypsum board. Although the uninsulated CMU wall does not adhere to energy code requirements in the US [43], it was still considered in this research due to its relevance to other geographical and building practice contexts, such as those prevalent in Central America and the Middle East. The insulation value of the uninsulated wall is 1.41 m^2 K/W (R-8 °F·ft^2·hr/Btu) and 4.19 m^2 K/W (R-23.8 °F·ft^2·hr/Btu) for the insulated assembly.

5. Life cycle assessment results and discussion

The following section portrays the LCA results for each phase, as well as the combined embodied and operational results and the tradeoffs between the life cycle phases.

5.1. Life cycle inventory results for each wall system

Each of the light straw clay, cob, and rammed earth wall systems incorporated clay-rich soil and, depending on the assembly, gravel, sand, fibers, and water are used in the mixture. Cob and light straw clay required additional layers of clay plaster render. Additionally, light

[2] Image made by the authors.

Table 1
Life cycle inventory results for each constituent material showing totals to construction site [42].

Inventory item	units	Straw	Sand/ gravel	Clay-rich soil	Clay plaster	Tap water	Lumber	Gypsum board, 13 mm	CMU blocks	Portland cement stucco, 60 mm	Plywood, 13 mm	Fiberglass batt, R21	EPS insulation, R15, 51 mm
		/bale	/kg	/kg	$/m^2$	/kg	$/m^3$	$/m^2$	/100 ct	$/m^2$	$/m^2$	$/m^2$	$/m^2$
coal	MJ	2.14	0.0205	0.0012	1.14	0.0030	240	–	481	2.91	–	0.72	26.4
natural gas	MJ	11.4	0.0105	0.0108	2.57	0.0015	796	28.6	109	10.30	4.95	3.69	121
oil	MJ	11.8	0.0619	0.0876	8.02	0.0008	329	9.80	1	0.47	–	0.42	117
diesel	MJ	–	–	–	–	–	–	8.89	279	1.38	12.2	–	–
electricity	MJ	–	–	–	–	–	–	2.92	137	1.79	25.7	55.6	–
other	MJ	0.07	0.0027	0.0177	–	0.0006	–	–	219	0.40	0.75	–	–
total	MJ	25.3	0.0956	0.1170	11.70	0.0058	1366	50.2	1225	17.2	43.6	60.5	265
CO_2	kg	0.85	0.0042	0.0070	0.428	0.0004	52	2775	0.39	2628	2.80	15.3	9.98
SO_2	kg	0.0060	2.9e-6	6.1e-6	0.0004	1.7e-6	0.342	8.08	0.523	2.21	–	0.0014	0.0816
NO_x	kg	0.0116	3.6e-5	3.7e-5	0.0030	1.0e-6	0.288	11.4	0.0222	11.2	0.0452	0.0586	0.0371
VOC	kg	2.4e-5	9.4e-7	1.0e-5	6.6e-5	3.1e-10	0.054	1.77	0.0080	0.196	–	0.0096	0.0002
CH_4	kg	0.0035	4.0e-6	4.2e-6	0.0004	2.3e-13	0.173	0.324	0.226	0.052	0.0136	0.0069	0.0027
CO	kg	0.0007	2.3e-5	3. 9e-5	0.0023	3.0e-7	0.114	3.94	0.748	1.08	–	0.0348	0.0207
TPM	ppm	0.0004	2.2e-6	3.5e-7	0.0004	1.6e-6	0.366	6.39	0.390	4.12	–	0.0005	0.0061

Table 2
Constituent material quantities and proportions.

Wall	Constituent material	Bulk density (kg/m^3)	Proportion by volume	Mix weight (kg/m^3)	Weight per m^2 wall (kg)	Proportion by weight
		A	B	C = AxBxα	Cxd	C/C_{total}
Light straw clay	straw	110 [62]	0.85	94	29	0.35
	clay-rich soil	1400 [63]	0.06 [65]	84	26	0.32
	water	1000	0.09	90	27	0.33
	total		1.00	C_{total} = 268	82	1.00
Cob	straw	110 [62]	0.20	22	10	0.02
	sand	1600 [64]	0.40	640	292	0.52
	clay-rich soil	1400 [63]	0.40	560	256	0.46
	dry total		1.00	C_{total} =1222	558	1.00
	water	1000			+134	+0.24 [66]
Rammed earth	gravel	1500	0.20	360	165	0.20
	sand	1600	0.40	768	351	0.43
	clay-rich soil	1400	0.40	672	307	0.37
	dry total		1.00	C_{total} =1800	823	1.00
	water	1000			+66	+0.08 [67]

α accounts for compaction of final wall; α = 1 of light straw clay and cob; α = 1.2 for rammed earth.
d is the wall thickness; d = 305 mm for light straw clay; d = 457 mm for cob and rammed earth.

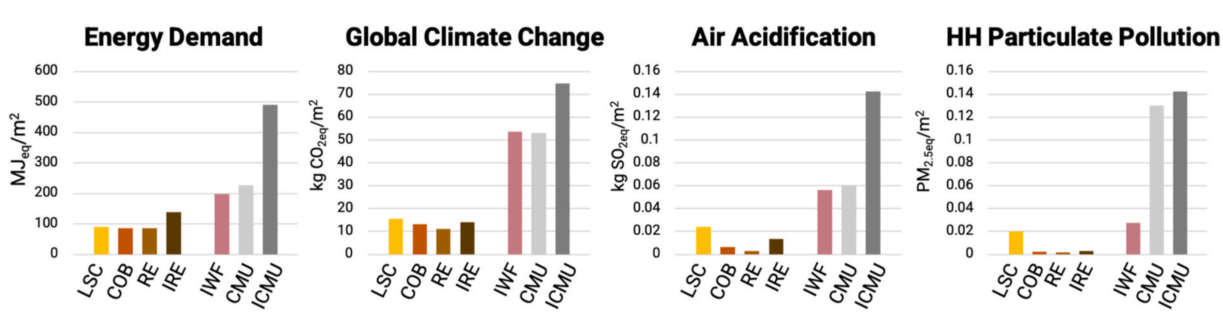

Fig. 7. Environmental impacts comparison overview for each wall system. Abbreviations: light straw clay (LSC), cob (COB), rammed earth (RE), insulated rammed earth (IRE), insulated wood frame (IWF), concrete masonry units (CMU), insulated concrete masonry units (ICMU).

straw clay was incorporated within a timber frame. The inventory analysis for each constituent material, as well as the sensitivity and uncertainty analysis were developed as a first step for this work [13,65] and is summarized in Table 1.

Table 2 details the inventory quantities for each of the constituent materials in each of the natural assemblies. The material volumes calculated for earth construction include only those required for the 1 m^2 wall assembly; additional materials required for a thorough mix, or 'spoil', is not included. The amount of spoil will depend to some extent on the mixing process adopted but will generally fall in the range of 10% of the volume required. On the other hand, for rammed earth, the effect of compaction, accounting for *in situ* density, is accounted for through the compaction factor, α = 1.2 based on the recommendation of [57].

[3] Image made by the authors.

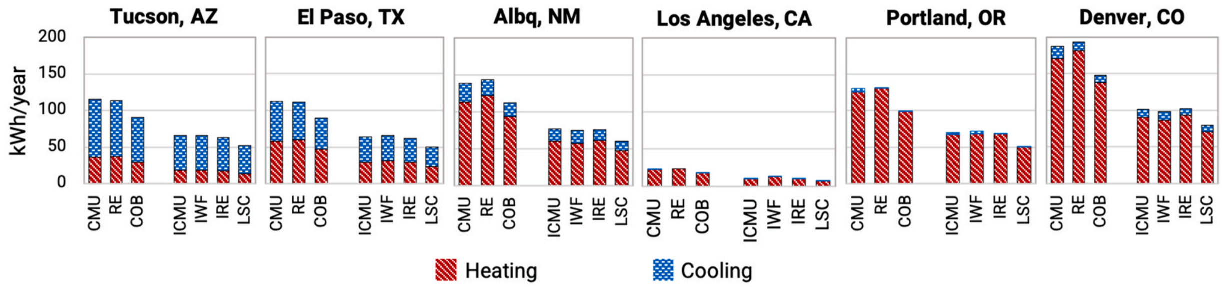

Fig. 8. Chamber annual heating and cooling loads for each wall assembly in each location. Abbreviations: concrete masonry units (CMU), rammed earth (RE), cob (COB), insulated concrete masonry units (ICMU) insulated wood frame (IWF), insulated rammed earth (IRE), light straw clay (LSC).

5.2. Life cycle impacts for the embodied phase

The comparison of embodied environmental impacts among all six wall systems is shown in Fig. 7. As expected, the natural wall systems exhibit significantly better embodied environmental performance than the conventional insulated wood frame and CMU wall systems, for all impact categories.

For the embodied energy demand, processing and transportation require more energy than the extraction of raw materials and forestry operations [40]. For global climate change impacts, cement manufacturing is the dominant contributor to the footprint of the CMU wall. The manufacturing of fiberglass insulation also has a high impact due to quartz extraction and cullet processing. In terms of air acidification, processes that involve fossil fuel burning and agriculture activities are the primary source of impacts; in other words, walls made from rammed earth and cob show the lowest acidic emissions, due to their minimally processed geological components coupled with the absence of biological constituent materials. Lastly, when considering human health particulate pollution, the impacts are most significant for the CMU walls due to the amounts of pollutants emitted during cement manufacture, as well as from the fugitive emissions generated during the transfer and processing of raw materials.

In summary, the environmental impacts of the external wall functional units vary considerably and support the environmental urgency of earthen and bio-based construction. Insulated rammed earth outperforms the insulated CMU assembly, with embodied reductions of 78% for global climate change, 72% for energy demand, 90% for air acidification and 98% for air particulate pollution impacts. Light straw clay results in reduced embodied impacts as compared to conventionally insulated wood frame construction, with 71% reductions in global climate change impacts, 55% in energy demand, 57% in air acidification and 27% in air particulate pollution. Overall, the natural assemblies reduce the embodied energy demand by 30–83%, climate change potential by 60–82%, air acidification by 57–98% and particulate pollution by 27–99% as compared to the conventional assemblies. In particular, cob and uninsulated rammed earth exhibit the lowest embodied impacts and CMU construction exhibits the highest embodied impacts.

5.3. Life cycle impacts for the operational phase

The annual mean load results, illustrated in Fig. 8, show that the light straw clay outperforms the other assemblies in the majority of cases. Insulated rammed earth is shown to result in the least heating load for Portland winter and the least cooling loads for Denver summer. It is only in the mildest conditions that the complete suite of natural assemblies performs best. This is evident for Los Angeles summer cooling loads, although due to its mild climate, the overall loads for this location are lower and less significant compared to other locations. A comparison with US EIA (2018) field data [66] shows excellent correlation of the extrapolated data [13].

Of the overall heat gains and losses, the portions attributed to the walls ranged between 15% and 35% for the lightweight assemblies (IWF, LSC) and 30%–50% for the mass assemblies (RE, IRE, COB, CMU, ICMU). Fig. 9 shows the environmental LCIA results for the operational phase, using the heating and cooling energy use for a 50-year lifespan, showing that the operational energy demand in the light straw clay chamber was lower for all climates, followed by the insulated rammed earth and insulated wood frame chambers. Additionally, the results highlight the significance of the heating energy demand, which proves dominant in all climates except hot desert and desert.

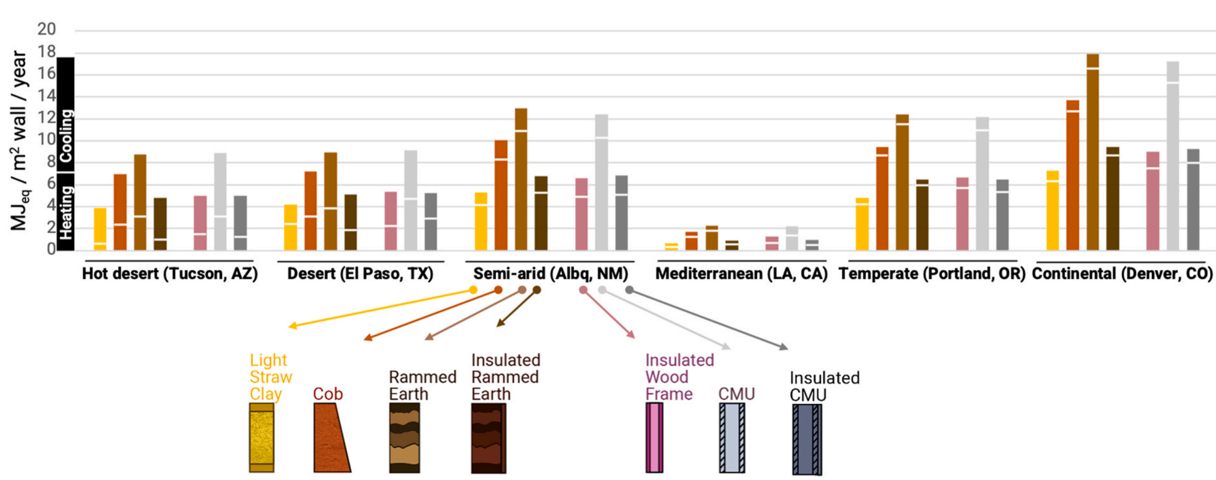

Fig. 9. Annual operational impacts for heating and cooling energy demand for each assembly in each of the 6 tested locations. Divided by a white line, the lower bars signify heating impacts and upper bars signify cooling impacts.

Table 3
Environmental impacts for the maintenance phase over a 50 year lifespan for the incorporated external rendering materials.

		Energy demand [MJeq]	Global warming [kg CO2eq]	Acidification air [kg SO2eq]	HH particulate air [PM2.5eq]
Clay plaster: required 5 times in a 50-year life	Production	8.88	0.727	0.000314	0.000477
	Transportation	2.86	0.616	0.0000954	0.0000364
	Total	11.7	1.34	0.000409	0.000513
Portland-cement stucco: required 1.5 times in a 50-year life	Materials extraction	0.487	0.152	0.0000497	0.00261
	Materials transportation	0.182	0.0270	0.0000747	0.00000457
	Processing	15.7	5.51	0.00200	0.00258
	Transportation	0.873	0.272	0.0000890	0.00000558
	Total	17.2	5.96	0.00221	0.00520

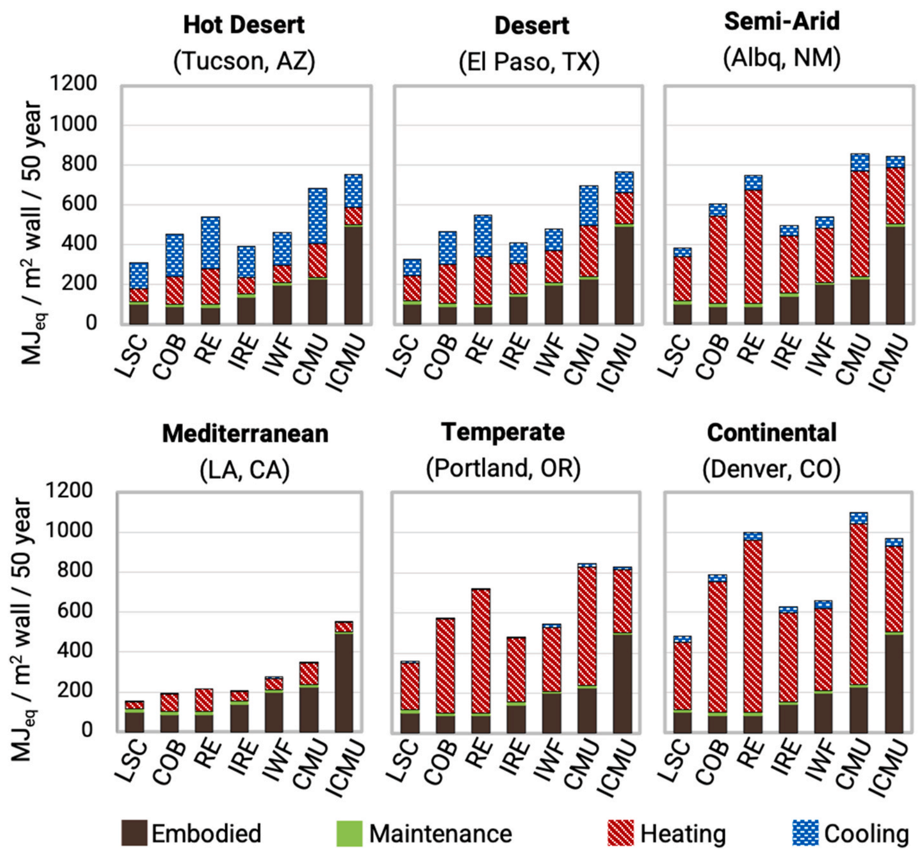

Fig. 10. Embodied and operational (heating and cooling) energy demand impacts for each wall alternative in each climate. Abbreviations: light straw clay (LSC), cob (COB), rammed earth (RE), insulated rammed earth (IRE), insulated wood frame (IWF), concrete masonry units (CMU), insulated concrete masonry units (ICMU).

5.4. Embodied and operational life cycle impact assessment tradeoffs

5.4.1. Ongoing investments for maintenance

The energy and environmental costs of maintaining homes of different construction materials was factored into the operational energy and environmental footprint assessment. Maintenance requirements for different wall assemblies include many uncertainties because they are highly dependent on various aspects such as the design details, original construction quality, quality of the materials and products, climate and weathering, as well as occupant behavior. In particular, for natural assemblies, maintenance requirements may be substantially reduced or avoided altogether, depending upon design features that reduce erosion, such as having a wide roof overhang that keeps rain off the walls.

Due to lack of maintenance records regarding various wall assemblies and the likelihood that the significance of the impacts of maintenance would be relatively low [44], the maintenance impacts in this research are limited to exterior finish replacement. The following were considered:

i The cob and light straw clay were assumed to be re-plastered every 10 years.
ii The rammed earth assembly was assumed to require repairs using the original soil mix equivalent in impact to a 25 mm (1 inch) plaster coat, every 10 years.
iii The Portland cement stucco rendering of the conventional assemblies was assumed to be renewed every 20 years.

Over a 50-year operational life, the environmental impacts of these maintenance tasks would still support earthen and bio-based construction, as shown in Table 3 for two render types.

5.4.2. Combined embodied and operational impacts

The operational life cycle impacts for space heating, cooling, and

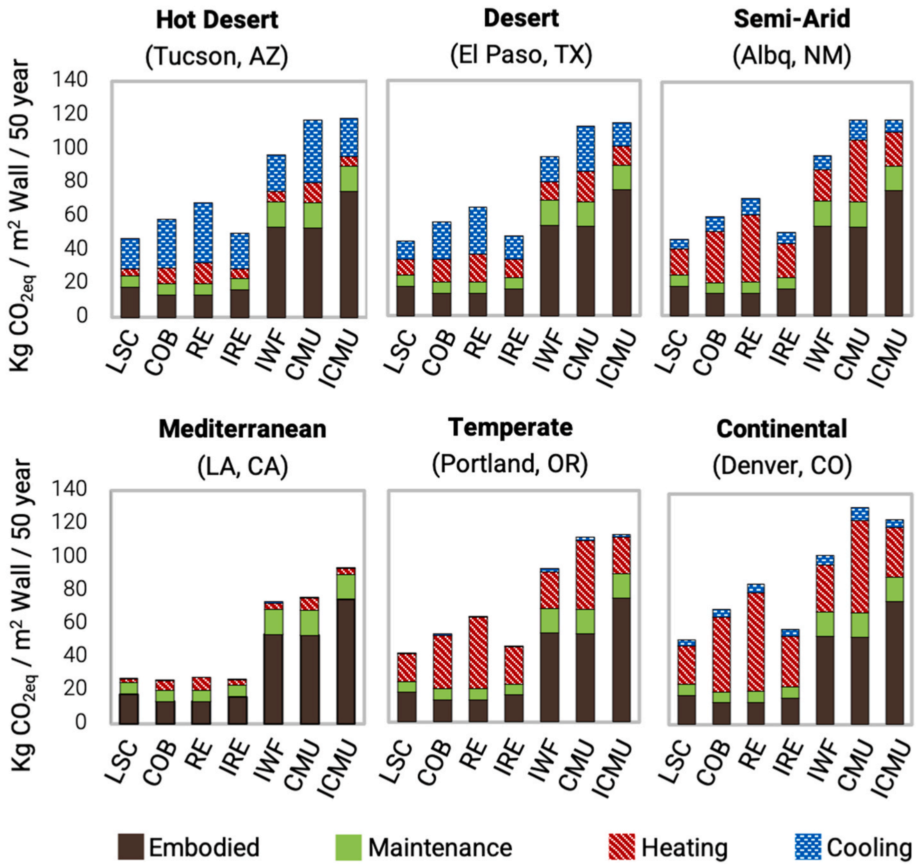

Fig. 11. Embodied and operational (heating and cooling) global climate change impacts for each wall alternative in each climate. Abbreviations: light straw clay (LSC), cob (COB), rammed earth (RE), insulated rammed earth (IRE), insulated wood frame (IWF), concrete masonry units (CMU), insulated concrete masonry units (ICMU).

maintenance for a 50-year building life were analyzed against the embodied life cycle impacts of the walls. The overall environmental impacts, depicted in Fig. 10 and Fig. 11, show that the energy impacts of the embodied phase can dominate for the natural assemblies and provide a significant advantage over conventional wall construction, even with a 50 years of operational energy use.

For all climates except the mildest, light straw clay is shown to achieve the best performance as opposed to conventional assemblies, reducing energy demand by 32–59% in hot desert climates, 29–55% in semi-arid climates, 46–73% in Mediterranean climates, 34–57% in temperate climates and 27–50% in cold continental climates. Insulated rammed earth is shown to reduce energy demand by 14–48% for hot desert climates, 9–41% in semi-arid climates, 27–64% in Mediterranean climates, 12–42% in temperate climates and 5–35% in cold continental climates, as opposed to the conventional assemblies. Cob is shown to be outperformed by insulated wood frame construction in semi-arid, temperate and continental climates. The climates where cob is shown to be most advantageous are hot desert and Mediterranean climates.

The earthen assemblies also demonstrate a dramatic reduction in global climate change impacts when accounting for both embodied and operational values. The reduced emissions are shown to be more dramatic than the energy reductions for the natural assemblies due to the chemical reactions during materials processing and fugitive emissions during quarry operations of conventional materials. The overall climate change impact reductions achieved by implementing natural materials range between 20 and 80%, with the highest reductions for Mediterranean climates (Los Angeles, CA) and temperate climates (Portland, OR). The reductions in air acidification impacts are shown to be the most significant in hot desert climates (Tucson, AZ) due to the reduced need for cooling. The overall human health particulate pollution impacts reductions achieved by implementing earthen and bio-based materials ranges between 45 and 98%.

6. Conclusions and future research

This research developed a life cycle inventory (LCI) and life cycle assessment (LCA) to evaluate the embodied and operational environmental impacts of three natural assemblies (light straw clay, cob and rammed earth), comparing them to conventional assemblies (wood frame and insulated and uninsulated concrete masonry units). The impacts assessment accounted for energy demand, global climate change impacts, air acidification and human health particulate pollution. For the embodied phase, existing inventories of the constituent materials were used to develop the LCI of each of the wall assemblies. For the operational phase, thermal performance was assessed using dynamic TMY simulations to determine heating and cooling loads for a 50-year lifespan for six climate regions: hot desert (ASHRAE 2B, represented by Tucson, AZ); subtropical desert (3B, El Paso, Texas); mild semi-arid (3C, Albuquerque, NM), mild Mediterranean (4B, Los Angeles, CA), temperate oceanic (4C, Portland, OR) and continental semi-arid (5B, Denver, CO).

The embodied LCIA results indicate that the environmental impacts of the eight external wall assemblies vary considerably although universally demonstrate the environmental urgency of earthen and bio-based building materials. The natural building assemblies were shown to reduce embodied energy demand by 38–83%, embodied climate change potential by 60–82%, embodied air acidification by 57–98% and embodied particulate pollution by 27–99% as opposed to the conventional wall assemblies.

Furthermore, the operational LCIA results indicates that the light straw clay outperforms all other assemblies for all climate conditions, due to its high thermal resistance and moderate internal heat capacity. For mild climate conditions, insulated rammed earth, with the highest heat capacity and moderate thermal resistance, performs better than the conventional assemblies. The uninsulated mass assemblies were shown to be preferable only for very mild climate conditions, where the outdoor thermal conditions provide comfortable temperature levels, such as in Los Angeles and summers in Portland.

When coupling the embodied and operational environmental impacts, the natural assemblies result in lower environmental impacts than the conventional assemblies in the range of arid and semi-arid climates. The combined embodied and operational results revealed that the energy impacts of the embodied calculations can dominate insulated conventional assemblies, even with 50 years of operational energy use. For all climates except the mildest, light straw clay is shown to achieve the best performance with the least energy use and environmental impacts, reducing energy demand by 32–59% in hot desert climates, 29–55% in semi-arid climates, 46–73% in Mediterranean climates, 34–57% in temperate climates and 27–50% in continental climates as compared to conventional residential building assemblies. Furthermore, the natural assemblies are shown to reduce emissions substantially as opposed to conventional assemblies, reducing climate change impacts by 20–80%, air acidification by 30–80% and health particulate pollution by 45–98%.

Future research should expand this work to a whole-building LCA of natural vs conventional buildings. Additional thermal and hygrothermal studies should expand this work into complete structures with architecture driven by the specific characteristics of earth, including its limitations and assets. Furthermore, this comparative LCA should be expanded to additional natural and bio-based building assemblies, such as compressed earth blocks, earthbags, and fungi-based blocks, as well as insulation materials, both conventional (e.g., rock wool and polyurethane foam) and eco-friendly (e.g., cellulose, straw, and hemp). Lastly, strategies to help reduce heating and cooling loads should be examined and predicted future TMY climate data should be used to investigate resiliency in the face of climate change.

This research hopes to catalyze the broader adoption of earthen and bio-based materials by providing a framework that should be adopted for analyzing other promising natural and living materials; the integration of natural and low-carbon building materials is critically dependent on future LCA work that can inform EPDs for sustainable building materials and methods.

Author statement

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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.

Acknowledgements

Dr. Lola Ben-Alon wishes to warmly thank Dr. Gwen DePietro for her contribution in reviewing the initial versions of this work and for providing technical support at the early stages of this project.

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