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Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material

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A B S T R A C T

Cob is an earthen building material that offers a minimally processed, low carbon, and locally available alternative to conventional building materials and methods. This paper provides a framework for a comparative Life Cycle Assessment (LCA) from an embodied perspective of energy and air emissions, using cob earthen wall construction as well as benchmark wall assemblies of concrete masonry and wood frame. The results of the study show that cob production requires only 18–38% energy and reduces 75–82% of global climate change impacts when compared to conventional materials. Significantly, the embodied environmental impacts of cob were shown to be lower than conventional materials in all aspects. Further, sensitivity analysis shows that impacts can be further reduced by maximizing the use of local materials.

1. The importance of modern earthen construction

The vast majority of modern buildings are constructed from highly processed materials, critically depleting global natural resources [1]. As a consequence, there has been a growing interest in using natural building materials – specifically locally available earthen building materials, that are minimally processed and inherently low carbon [2,3]. As with other earthen construction materials and methods, cob was once a commonly used “vernacular” material in which renewed interest is growing and new applications in modern construction are realized largely due to its various sustainability benefits [4–6]. Cob consists of clay-rich soil, sand, straw, and water, mixed in a plastic state to achieve load bearing walls for up to 2-story structures. In addition to its environmental benefits, cob also exhibits excellent health, indoor air quality, social, and affordability advantages [4,7].

Despite the benefits and the bottom-up attempts to implement cob construction, there are many barriers and unrealized opportunities for the use of this technique in mainstream construction. Significantly, the available literature lacks synthesized technical and environmental performance data for cob, a gap that was shown to be limiting policy makers from advancing regulations and building guidelines for cob construction [8].

The aim of this paper is to enumerate the environmental performance of cob construction from a life cycle perspective. The study includes results of a comparative Life Cycle Assessment (LCA) of cob and benchmarks for conventional materials (concrete masonry and wood wall assemblies). The framework for the presented LCA is a single-family residential construction project located in a warm-hot climate zone in the US.

2. Background on cob construction

Cob is an earthen building material that combines earth, natural fibers such as straw, and water. This mixture is produced in a plastic state and implemented wet to build monolithic load bearing walls. The term cob comes from England, and it is sometimes referred to as monolithic adobe, as well as Bauge (France), Lehmweller (Germany), Pasha (Turkey), Terre Crue (Italy), and Zabour (Yemen) [4,9]. Previous literature on cob mainly dealt with cob in the context of building restoration (mainly in the UK, e.g. Refs. [10,11]). However, recent research has focused on new ways to implement cob in contemporary practices although focusing on vernacular construction [7,12]. To date only a few mainstream cob structures have been built that are deemed to comply with building codes (Fig. 1).

Cob construction has been shown to be an affordable building method due to its (often) locally available constituent materials and approachable construction method that can be implemented by community effort and sweat equity of homeowners [13]. Cob construction methods require little training. The material itself can be easily assembled, lending itself to form different curves, shapes, and sculptural

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Fig. 1. Vernacular cob structure (left) and successfully permitted cob structure (right) [14,15].

Fig. 2. Manual cob production (left) and tractor-cob (right) [9].

details [7].

Nonetheless, cob construction has several disadvantages. When implemented manually, cob construction can be labor intensive and slow. It was traditionally considered in England as "the slow process" [9]. One way to address this disadvantage is to spread the labor across many workers by making cob-building a community effort in which everyone can contribute – from expert builders to children and elders [7]. Cob construction can also be implemented using machinery and accessories, such as in the case of 'tractor-cob' that uses machinery for the cob mixing (Fig. 2), and shuttered-cob that uses formwork (Fig. 3). Incorporating these latter techniques, however, detracts from the environmental benefits and sculptural features of cob construction.

3. Previous LCA studies of earthen construction

Environmental LCA has become a common tool in the building sector to evaluate building products and processes. It is considered a powerful tool for the evaluation of and contribution to sustainable building development [17]. Specifically for earthen construction, previous research stresses the need for an environmental LCA in order to evaluate earthen construction action strategies [18], as well as "Cost/benefit analyses … including life-cycle analysis of construction assemblies" in order to enhance codes and practice of earthen construction in North America [19].

Although earthen construction (and particularly cob) has been extensively argued as being better environmentally, few studies have rigorously examined its environmental impacts. Existing earthen construction LCA studies include environmental impact evaluations of adobe bricks [20,21], rammed earth [22,23], and earth plasters [2,24]. These existing studies exhibit various limitations: they often do not include a comparison to conventional materials and methods, making it hard to use these studies to extract environmental management recommendations or to determine design change requirements. In addition, individual LCA studies are not readily compared, due to the location-specific and material/process-specific data used in each study. Lastly, many studies use a functional unit of 1 kg of material, which does not allow comparison between various structural systems. There has been limited work focused on the environmental impacts of cob, specifically from a life cycle perspective. For instance, existing studies present a simplified breakdown of the embodied energy of cob in Canada, using secondary online resources [25] and embodied CO_2 inventory emissions of a small cob structure in rural Nicaragua that was not extended to a full impact assessment [26].

To address the missing body of knowledge about the environmental impacts of cob, this study develops a Life Cycle Inventory (LCI) for cob and presents a comparison of cob to conventional materials. Using a functional unit of 1 square meter of a wall system, this study allows for a future comparison as well as future analyses that account for operational considerations among other typical wall assemblies.

4. Methodology for the comparative cob LCA

This study was implemented based on the environmental Life Cycle Assessment methodology, as described in the ISO 14040 series of standards [27,28]. Accordingly, the SimaPro software [29] was used to model inventory data that is relevant to North America.

Fig. 3. Sculptural cob wall (left) and shuttered-cob (right) [9,16].

4.1. Goal and scope definition

The goal of the study was to understand whether, and to what extent, energy savings and greenhouse gas (GHG) emission reductions can be achieved through using cob construction for a single-family housing dwelling in warm-hot climates in the continental US, defined as IECC climate zones 1 through 4 [30]. The study compares cob wall assembly with three benchmark wall assemblies: 1) insulated lightweight sheathed timber platform frame, 2) uninsulated Concrete Masonry Units (CMU), and 3) CMU with internal rigid insulation.

4.2. Functional unit

The chosen functional unit is 1 m^2 of load bearing exterior wall suitable for up to 2-story construction having an insular value meeting or exceeding the requirements of the International Energy Conservation Code® in climatic zones 1–4 [30]. The functional unit was designed according to construction guidelines and was assumed to meet practice requirements as further detailed in Section 4.6.

4.3. System boundaries

The study accounts for the cradle to construction site portion of the life cycle and considers embodied environmental impacts. Specifically, the system boundaries for each of the three wall systems include the extraction and processing of raw materials, manufacturing of building materials, and transporting those materials to the construction site. Onsite mixing, construction, use phase (e.g., occupation of the residence), demolition, and disposal are beyond the system boundaries (Fig. 4).

4.4. Life Cycle Inventory (LCI) analysis

The LCI data for the conventional wall assemblies was extracted from existing inventories that were selected according to their cradle to gate scope as well as North American geographical context that resemble to the scope of this study. Specifically, LCI results of lumber and plywood sheathing [31], gypsum board [32], fiberglass batt and rigid polystyrene insulation [33], Portland cement stucco [34], and concrete masonry blocks (CMU) [35] were used.

The cob LCI, which is not available in existing literature, was developed for each constituent material to be shovel ready. As illustrated in Fig. 5, the cob LCI included the production and transportation of clay-rich soil, sand, straw, and water for on-site for mixing and assembly. Existing inventory databases were selected from US-LCI [36] where possible. Other inventories were selected from EcoInvent with relevance to the US geographical context [37].

The flows of substances were allocated for each component of the wall assemblies, accounting for energy inputs that include coal, natural gas, diesel, crude oil, and electricity, as well as emissions to air that include carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), oxides of nitrogen (NO_x), methane (CH_4), volatile organic compounds (VOCs), and particulate matters (PM).

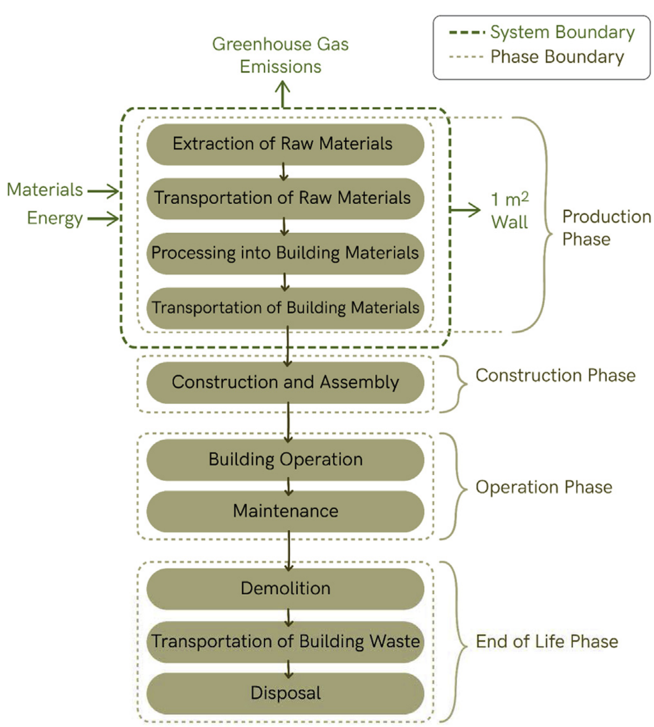


Fig. 4. The system boundaries of the proposed study, which includes the production phase from cradle to construction site.

4.5. Life cycle impact assessment (LCIA) categories

The LCIA compares the environmental impacts and risks that are associated with the inventory results. This impact assessment is conducted using environmental impact factors that were chosen according to their relevance to the goal and scope of the study. Due to their representation of the US environment, Cumulative Energy Demand (CED Version 1.09) impact factors are used to characterize the inventory fuels and sources of energy and the TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) method is used to categorize and characterize the inventory emissions [38,39]. The primary impact categories of interest are energy use (MJ_{eq}) and global warming potential (kg CO_{2eq}). Additional (secondary) impact categories are briefly investigated and include acidification potentials for air emissions (kg SO_{2eq}) and Human Health (HH) particulate potentials for air emissions (kg $PM_{2.5eq}$).

4.6. Details of the cob and conventional wall systems

4.6.1. Cob wall

The selected cob wall system uses a typical section as implemented by cob practitioners [40]. As depicted in Fig. 6, the 4.3 m (14 ft) tall prototype cob wall is tapered, with a minimum of 305 mm (12 in.) thickness at the top of the wall. The base thickness tapers from 610 mm to 305 mm, corresponding the recommended height to base thickness ratio of 7 by Getty Report on adobe structures in seismic areas [41] (Fig. 6). A 25 mm (1 in.) clay plaster render is applied to the exterior wall and no finishing is provided on the interior. For the purpose of simplification, the assessment calculations consider an average wall thickness of 460 mm (18 in.). Cob walls were shown to have an R-value of 0.106 K m^2/W per 25.4 mm (R-0.6 ft2°Fh/Btu per inch) [42], resulting in an average R-1.91 K m^2/W (R-10.8 ft^{2}°Fh/Btu) for the complete wall. This value complies with the R-1.41 K m^2/W (R-8 ft^{2}°Fh/Btu) required by International Code Council energy requirement for climate zones 1–4 [30].

4.6.2. Concrete masonry block (CMU) wall

The benchmark concrete masonry wall system includes 13 mm (0.5 in.) gypsum board, 203 mm (8 in.) CMU blocks, and three-coat Portland cement stucco (Fig. 6). The CMU blocks are unfilled and unreinforced, with a density of 1360 kg/m^3 (85 lb/ft^3). Two scenarios were tested: uninsulated CMU and insulated CMU with an internal 50 mm (2 in.) rigid polystyrene insulation that was considered to achieve the required R-2.3 K m^2/W (R-13 ft^{2}°Fh/Btu) for mass walls with internal insulation as specified in ICC, 2018 (Table R402.1.2, i). Both scenarios include an exterior stucco render and interior 13 mm gypsum board on metal channels or wood furring [43].

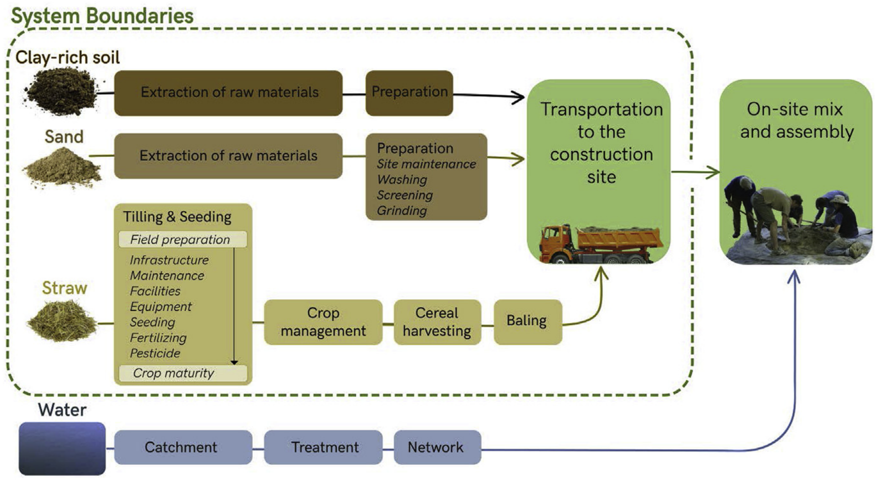


Fig. 5. The system boundaries and processes incorporated in the developed cob LCI.

4.6.3. *Light-frame wood wall*

The benchmark insulated wood frame wall system includes 13 mm gypsum board, 2 × 4 in. (51 × 102 mm) softwood dimensional lumber, cavity insulation in the form of a 150 mm (6 in.) fiberglass batt, 13 mm plywood sheathing, and three-coat Portland cement stucco (Fig. 6). This chosen wall system represents a typical platform light-frame wood residential house in the US [44].

5. Developing the Life Cycle Inventory (LCI) of cob earthen construction

The cob LCI depicts the flow of substances crossing the cob wall production system boundary, developed using existing inventory databases and field data. Existing databases include US-LCI [36] as well as Ecoinvent inventories for North America [37]. Interviews with cob practitioners helped determine field data related to costs and transportation distances of raw materials, which are further specified according to their approximate ranges in the sensitivity analysis (section 5.3). All transportation processes were assumed to utilize diesel-powered combination trucks. Lastly, on-site mixing was considered using tap water with conventional treatment.

Weight distributions were calculated for the wall dry components: straw, sand, clay-rich soil, and clay plaster. Table 1 shows the weight distribution of these components for a 1 m^3 cob mix, calculated using the volume distribution as recorded in a previous study on cob properties [45]. An approximate 24% water content was considered [46], and a drying losses ratio of 20% [20]. The overall bulk density of the mixture is therefore 1462 kg/m^3, corresponding with previous tests who showed 1400–1600 kg/m^3 bulk density range for cob [45–47].

5.1. *Straw*

For the straw modeling, four main stages were assessed: producing the straw (tilling and seeding, crop managing), cereal harvesting, baling, and transporting the bales to the construction site (Fig. 5). Straw production is a co-product of wheat production, and thus the associated inputs and outputs must be allocated between the two products. Economic allocation was chosen in order to best capture the scenario of straw as a valuable building material rather than an invaluable by-product of cereal production [51,52]. Wheat straw prices were drawn from both the field and literature (Table 2) and represent the average experienced wheat straw price according to four cob experts located in southwest USA. This average price reflects how, according to experts, straw is typically purchased directly from local farmers, and prices often vary according to availability.

5.2. *Sand*

The sand was assumed to be extracted in a quarry, and the modeling of the sand production included digging and extracting of raw materials, internal processing (transporting, washing, screening, grinding), machinery, and the land-use of the quarry.

5.3. *Clay-rich soil*

According to field experts, clay-rich soil can often be extracted on-site, as the byproduct soil from digging the foundation level. This study, though, accounts for a scenario of having no suitable construction soil on site. This scenario requires purchasing clay-rich soil from a quarry, with at least 50% clay, to provide the approximate recommended clay content of 20% in a cob mixture.

5.4. *Clay plaster*

A layer of 1 in. (25 mm) clay plaster is typically used as the finish material for the exterior cob wall surface. It is assumed that an

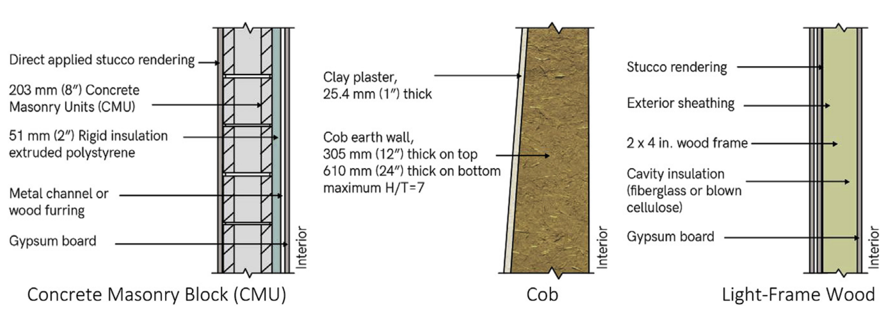


Fig. 6. Section drawings of the assessed wall systems.

Table 1
Bulk density, volume distribution, and weight per componenet for a m^3 cob mix. Values retrieved from[1] [48][2] [49][3] [50][4] [45].

Component	(A) Bulk Density (kg/m^3 component)	(B) Volume Distribution[4] (%)	(C) = (A)*(B) Weight (kg/m^3 mix)	(D) = (C)*0.457 wt per 1 m^2 wall	(E) = (C)/(C_{total}) Weight distribution (%)
Straw	110[1]	20	22	10	2
Sand	1,600[2]	40	640	292	52
Clay-rich soil	1,400[3]	40	560	256	46
Total	–	100	(C_{total}) = 1222	558	100

additional layer of lime stucco is not needed to protect the clay from moisture in the warm-hot climate context [55]. A scenario of purchasing a clay plaster product was considered to achieve optimal surface aesthetics and performance. The modeling of the clay plaster product includes extracting and mixing raw materials, transporting the raw materials to the packing site, packing, storing, and transporting to the construction site.

5.5. Inventory results

The inputs and outputs of the developed inventory for cob include raw materials, energy, product outputs, as well as inorganic emissions and particulates to air. Summarized in Table 3, the cob data inventory captures the flow of substances during the production and transportation of the required cob components from cradle to construction site. These results account for a total of 735 kg wet cob mixture, which produces 617 kg of dried plastered cob wall for the 1 m^2 functional unit (or 0.46 m^3 at an average thickness of 460 mm).

6. Results of the comparative LCA of cob vs. benchmark wall assemblies

6.1. Life cycle impact assessment (LCIA) results of cob earthen construction

Using the LCI results, the environmental LCIA of a 1 m^2 cob wall are presented in Table 4 and Fig. 7, showing the contributions of each mixture component. Overall, Table 4 shows that each of the cob components contribute meaningfully to the modeled environmental impacts. Specifically, the straw production (including tilling, seeding, and crop managing) accounts for relatively high air acidification impacts, due to the use of fertilizers and pesticides. Where possible, sourcing fibers from local farms that utilize low impact practices may further reduce environmental impacts associated with cob construction. Sand impacts are relatively high for particulate impacts. The clay rich soil has the highest rank for energy demand and climate change impacts. As discussed previously, however, clay rich soil can be produced on site during excavation, thus minimizing impacts associated with this input and lowering overall impacts significantly. Similarly, the clay plaster is assumed to be manufactured off site – a cob finish would change these impacts.

Fig. 7 illustrates that the environmental impact distributions of the cob components are different from their weight and volume distributions. The straw and the clay plaster, while relatively small mass and volume components, contribute relatively higher than the clay-rich soil and sand.

Table 3
Data inventory for the production of a 1 m^2 of cob wall with an average thickness of 457 mm.

Inputs		Outputs	
		Product (cob mixture) (kg)	735
Raw materials		Product (plaster mixture) (kg)	36.9
Straw (kg)	10.1	Mixing spoil (cob and plaster mixture) (kg)	77.2
Sand (kg)	292	Drying losses (kg)	154
Clay-rich soil (kg)	256	Dried cob wall with clay plaster skim (kg)	617
Clay plaster (kg)	28.1	Cob wall (m^2)	1.00
Water (for on-site mixing) (kg)	185	**Emissions**	
Water (from the off-site production of the constituent materials) (kg)	685	*Inorganic emissions to air (kg)*	
		Carbon monoxide (CO)	0.0195
Energy		Carbon dioxide (CO_2)	4.06
Coal (kg)	0.527	Nitrogen oxides (NO_x)	0.0304
Natural gas (m^3)	0.409	Sulphur dioxide (SO_2)	0.00647
Crude oil (kg)	1.22	Methane (CH_4)	0.00479
Electricity (kWh)	1.26		
Others (MJ_{eq})	0.954	*Particle to air (kg)*	
		Dust ($PM_{2.5-10}$)	0.217
		Dust ($PM_{<2.5}$)	0.000728
		VOCs	0.00300

6.2. Comparative assessment results

The comparative inventory assessment results, including fuel demand and air emissions are presented in Fig. 8 and Fig. 9, showing that cob accounts for the lowest amounts of inventory flows. Furthermore, the impact assessment results shown in Table 5 and Fig. 10 illustrate the significantly low energy demand and air emissions that are associated with the production of cob. In contrast, the insulated CMU wall has the overall highest environmental impacts. It requires the highest amount of energy, which is mainly due to the production of the rigid insulation layer. Moreover, it results in the highest global warming potential and air particulate pollution that results from the production of the cement.

According to the results presented in Table 5 and Fig. 10, the cob wall alternative accounts for the lowest energy demand, as well as the lowest air emissions. In contrast, the insulated CMU wall has the overall highest environmental impacts. It requires the highest amount of energy, which is mainly due to the production of the rigid insulation layer. Moreover, it results in the highest global warming potential and air particulate pollution that results from the production of the cement.

The modeling results allow for the comparison of clay plaster and Portland cement stucco. The clay plaster performs better

Table 2
Prices used for the market-based economic allocation of the wheat and straw production and harvesting processes.

Component	Unit	Price from primary source	Price from field experts	Price used for the LCI (average)
Wheat Straw	$/square bale	3.30 [53]	13.0, 3.50, 12.0, 7.50	7.96
Wheat Grain	$/bushel	6.10 [54]	–	6.10

Table 4
Environmental impacts for a 1 m^2 cob wall assembly according to each constituent material.

	Weight per 1 m^2 wall (kg)	Stage	Energy Demand [MJ_{eq}]	Global Warming [kg CO_{2eq}]	Acidification Air [kg SO_{2eq}]	HH Particulate Air [$PM_{2.5eq}$]
Straw	10.1 (0.61 bales)	Production	13.4	2.59	3.62E-03	4.99E-04
		Harvesting	1.79	0.0238	3.36E-05	2.41E-05
		Baling	0.00	0.00	8.41E-12	6.61E-12
		Transportation	0.409	0.0874	1.37E-05	5.22E-06
		Sub-Total	**15.6**	**2.70**	**3.67E-03**	**5.28E-04**
Sand	292	Production	16.1	1.83	4.39E-04	6.91E-04
		Transportation	11.9	2.57	3.98E-04	1.52E-04
		Sub-Total	**28.0**	**4.40**	**8.36E-04**	**8.43E-04**
Clay-rich soil	256	Production	19.6	2.43	1.21E-03	7.63E-05
		Transportation	10.4	2.25	3.48E-04	1.33E-04
		Sub-Total	**30.0**	**4.68**	**1.56E-03**	**2.09E-04**
Clay plaster	28.1	Production	8.88	0.727	3.14E-04	4.77E-04
		Transportation	2.86	0.616	9.54E-05	3.64E-05
		Sub-Total	**11.7**	**1.34**	**4.10E-04**	**5.13E-04**
Water	185	Conventional Treatment	**1.09**	**13.2**	**3.19E-04**	**3.78E-04**
Total	**772**		**86.4**	**13.2**	**6.79E-03**	**2.47E-03**

environmentally than the Portland-cement based stucco in terms of global warming and air acidification impacts. However, clay plaster produces more air particulates that affect human health. Packaged plaster is often chosen because its consistency corresponds to increased durability. One alternative to using packaged plaster is mixing the cob constituent materials to achieve an on-site plaster mixture [56].

Overall, the cob wall accounts for significantly lower impacts for all the tested environmental performance parameters compared to the CMU and wooden wall systems. Specifically, the production of the cob wall assembly requires only 18–38% of the life cycle energy demand of the other assemblies. Additionally, the production of cob accounts for only 18–25% of global warming impacts and 5% or less of air acidification and particulate pollution than the other wall assemblies. Furthermore, cob impacts are lessened further by the on-site sourcing of clay soil when possible.

6.3. Sensitivity and uncertainty analysis

The sensitivity of the impact results of the cob wall assembly were simulated using @Risk software [57]. Using triangular input distributions and modeled over 1000 iterations, the sensitivity analysis illustrates the effects of transportation distances, wheat grain and straw market prices, average wall thickness, amount of clay-rich soil required, straw density, and average wheat yield at field. The transportation distances for the clay-rich soil, sand, and straw ranged between 10 and 50 km, according to interviews with experts [8]. The transportation distance of the clay plaster ranged between 0 and 100 km, reflecting the possible application of plaster made from the on-site cob mixture. Likewise, the required clay-rich soil ranged between 0 and 560 kg in order to account for the scenario of available clay-rich soil on site. Lastly, other outputs ranges were varied by ± 10%. As depicted in Fig. 11, Fig. 12, and Fig. 13, the inputs with the greatest influence on the cob LCIA are the average wall thickness, the amount of acquired clay-rich soil, as well as the transportation distances of constituent materials. Other modeled factors have markedly less effect on overall results.

7. Discussion and future research

The high dependence of the environmental impacts of cob on the amount of acquired clay-rich soil on demonstrates the benefits of using on-site subsoil, which can be made available from foundation excavation, or from nearby excavation projects. This scenario adds the benefit of avoiding the transportation or re-grading impacts of otherwise unused excavated soils. For example, the sensitivity analysis shows that use of on-site clay soil may reduce energy requirements from 82.9 MJ/m^2 to 67 MJ/m^2. Lastly, the effects of transportation distances on the results indicate that the environmental benefits of cob are highly

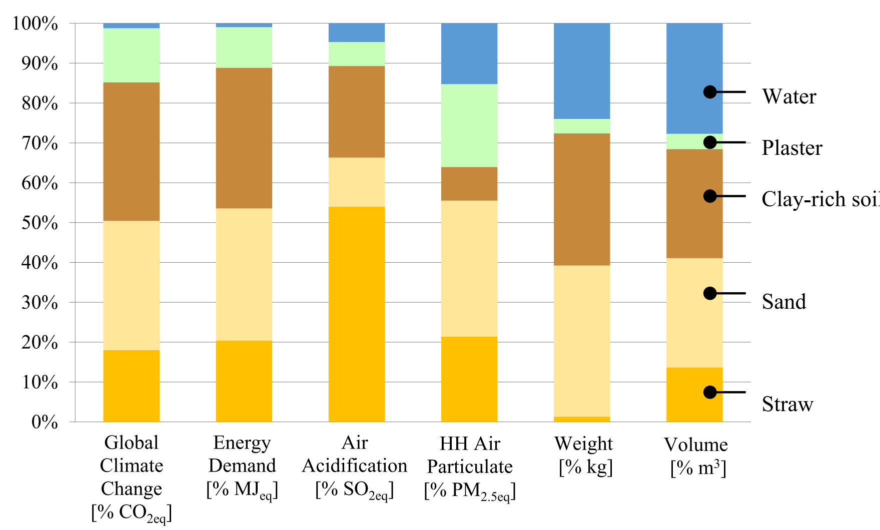


Fig. 7. Distribution of global climate change, energy demand, air acidification, and air particulate impacts, as well as the weight and volume for each constituent component of the cob mixture.

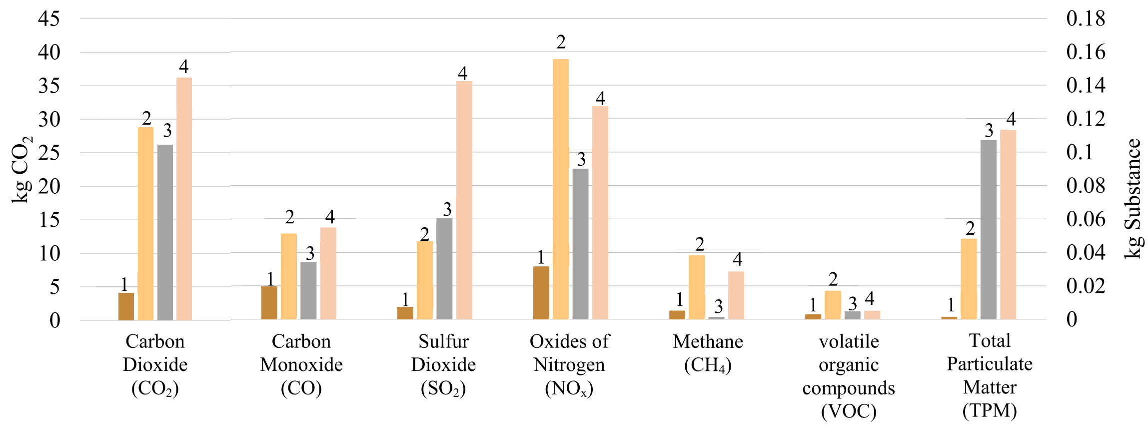


Fig. 8. LCI air emissions for each of the assessed wall systems: (1) cob, (2) wood frame, (3) uninsulated CMU, and 4) CMU with internal rigid insulation.

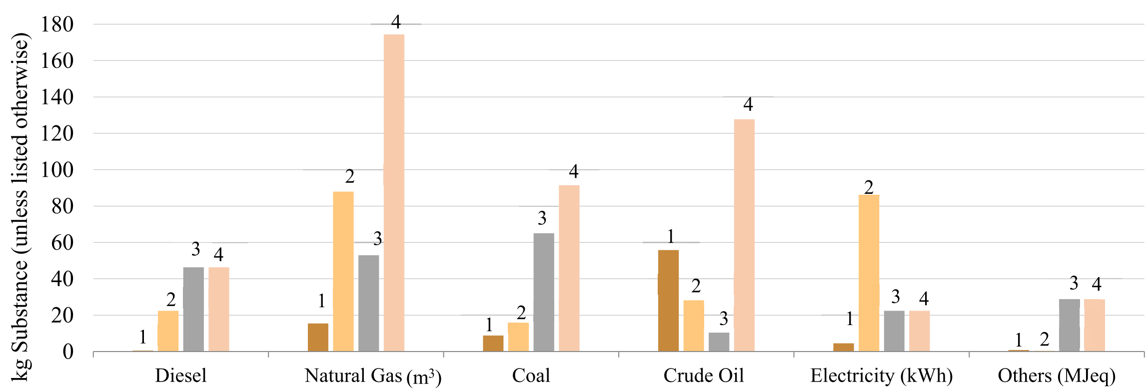


Fig. 9. LCI energy and fuels demand for each of the assessed wall systems: (1) cob, (2) wood frame, (3) uninsulated CMU, and 4) CMU with internal rigid insulation.

dependent on the local availability of its constituent materials, especially the sand and clay-rich soil that are highest in weight.

The effect of the wall thickness on the environmental impacts of cob may encourage research and field efforts towards an optimal mixture that could provide a wall thickness that is minimal as possible. Increasing the R-value of cob might also allow a smaller thickness. As the wall thickness effects the operational impacts of the wall assembly, not evaluated in this analysis, a next level analysis should include the associated HVAC requirements driven by climate conditions. Additionally, future analysis should include other types of insulation materials, both conventional (e.g., rock wool and Polyurethane Foam) and eco-friendly (e.g., cellulose and light straw clay), as well as the application of an insulated cob wall assembly. Although not modeled in this study, it has been shown that a 30% pumice addition increased the

Table 5
Comparative environmental embodied impacts results for the four wall alternatives.

		Impact Categories			
	Component	Energy Demand [MJ_{eq}]	Global Warming [kg CO_{2eq}]	Acidification Air [kg SO_{2eq}]	HH Particulate Air [$PM_{2.5eq}$]
Cob	Straw	15.6	2.70	0.00367	0.000528
	Sand	28.0	4.40	0.000836	0.000843
	Clay-rich soil	30.0	4.68	0.00156	0.000209
	Clay plaster	11.7	1.34	0.000410	0.000513
	Water	1.08	0.132	0.000319	0.000378
	Total	**86.4**	**13.2**	**0.00679**	**0.00247**
Wood frame	Gypsum board	50.22	6.17	0.00808	0.00834
	Lumber	69.37	14.4	0.0347	0.0478
	Fiberglass	60.46	33.0	0.00143	0.000735
	Plywood	43.70	3.14	0.0316	0.000326
	Stucco	17.22	5.96	0.00221	0.000136
	Total	**241**	**62.7**	**0.0781**	**0.0574**
Non-insulated CMU	Gypsum board	50.2	6.17	0.00808	0.00834
	CMU	158	41.0	0.0504	0.122
	Stucco	17.2	5.96	0.00221	0.000136
	Total	**226**	**53.1**	**0.0607**	**0.130**
Insulated CMU	Gypsum board	50.2	6.17	0.00808	0.00834
	Rigid insulation	265	21.7	0.0816	0.0125
	CMU	158	41.0	0.0504	0.122
	Stucco	17.2	5.96	0.00221	0.000136
	Sub-Total	**491**	**74.8**	**0.142**	**0.143**

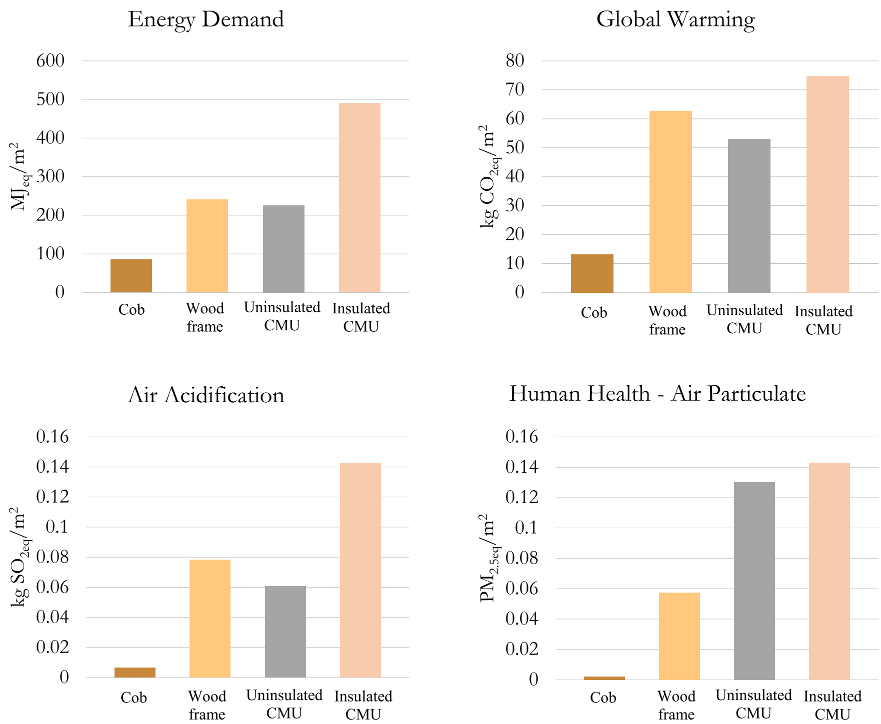


Fig. 10. Environmental embodied impacts comparison among the different wall systems.

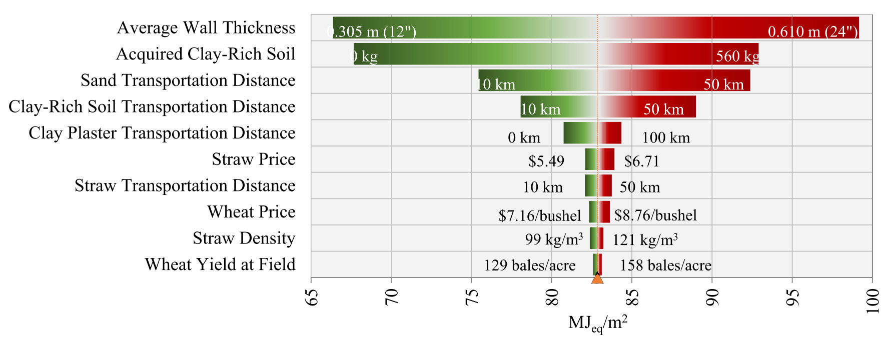


Fig. 11. Sensitivity analysis of the energy demand of cob production, ranked by the input effect on output mean.

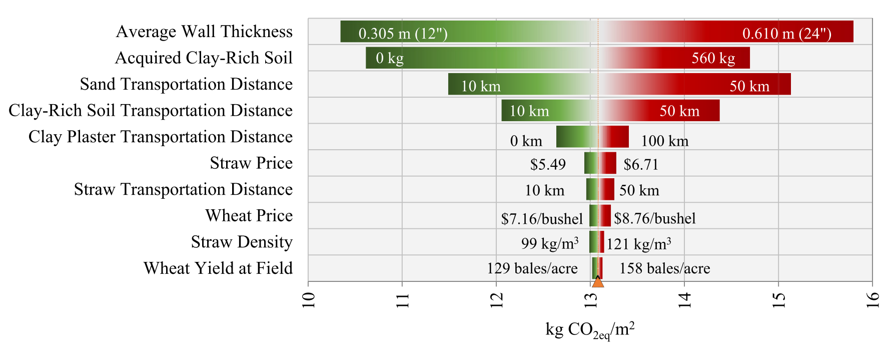
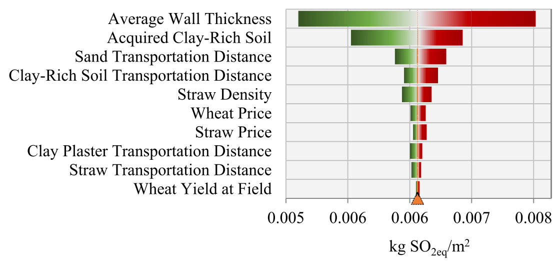


Fig. 12. Sensitivity analysis of the global climate change impacts of cob production, ranked by the input effect on output mean.

R-value of cob to R-1.6 K m^2/W per 25.4 mm (R-0.9 ft^2°Fh/Btu per inch) [42], achieving an average R-2.85 K m^2/W (R-16.2 ft^2°Fh/Btu) for the total cob wall.

The presented paper is part of a larger study that aims to evaluate the environmental impacts of various earthen building techniques from a cradle to grave perspective. Future research of a complete LCA will demonstrate the environmental impacts while taking into account both embodied impacts, as well as construction, occupancy, and end-of-life stages. Due to their low thermal resistance, the operational impacts of earthen materials should be evaluated not only according to their insulation properties, but also according to their thermal storage capacity. In addition to including other types of earthen construction, future research should also include a full LCA of 3 types of functional units (kg, 1 square foot of wall, a typical wall), to allow transparency of data for future use by researchers and decision makers.



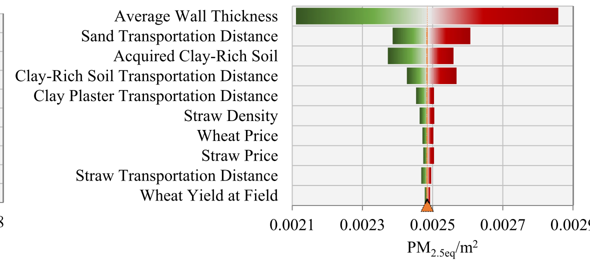


Fig. 13. Sensitivity analysis results of the air acidification (left) and HH air particulate (right) impacts of cob production, ranked by the input effect on output mean.

8. Conclusions

This study develops an environmental LCI for cob and compares the environmental impacts of cob with conventional wall assemblies from cradle to construction site stages, using 1 m^2 residential wall assembly as a functional unit. The results of the developed cob LCI show that off-site sourcing of clay soil contributes significantly to cob impacts. Straw, despite its small volume and mass contribution to a cob assembly, can account for a relatively large proportion of the overall energy demand and air emissions due to upstream impacts from production and the use of fertilizers and pesticides. Similarly, using a packaged product for the clay plaster increases the environmental impacts of cob due to its longer transportation distance, packaging, and storing.

Three benchmark conventional wall assemblies were selected: light frame wood, concrete with CMU infill, and insulated concrete with CMU infill. The comparative results between cob and these benchmark assemblies show that the production of cob wall has significantly lower environmental impacts as opposed to conventional wall assemblies. Specifically, the production of cob decreases energy demand by 62–82%, global warming potential by 75–82%, air acidification by 89–95%, and air particulate pollution by 96–98%, when compared to conventional assemblies. By adjusting the functional unit, these results can be applied to future studies of various building components, such as floors, internal partitions, mass heaters, etc., or extended to whole building analyses to account for heating and cooling requirements.

A sensitivity analysis of the various cob modeling parameters was performed, showing that the variability of the modeled environmental impacts of cob depends mostly on the wall thickness, the amount of acquired clay-rich oil, and transportation distances of raw materials. These results indicate that the environmental benefits of cob could be enhanced by minimizing wall thickness (e.g., by achieving an optimal mixture in terms of strength, durability, and operational functionality), by utilizing onsite clay-rich soil (e.g., by using subsoil from foundations excavation), as well as by using locally available constituent materials.

The contribution of this study lies the development of environmental measures that could be used by policy makers and cob advocates in their endeavors to catalyze the use of cob in mainstream construction projects. Future research directed towards comparative LCA of natural building vs. benchmark conventional building should include a myriad of natural building techniques that range from high insulative assemblies (e.g., straw bale construction and light straw clay) to high thermal mass assemblies (e.g., rammed earth and compressed earth blocks). The operational impacts associated with variable R-values should also be included to account for occupants use phase. The long-term implications that this LCA study hopes to achieve are the enumeration of earthen construction environmental benefits to catalyze the implementation of mainstream earthen construction projects.

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