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The state of earthen housing worldwide: how development affects attitudes and adoption

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ABSTRACT
Housing is a cross-cutting issue that is crucial to achieving several of the Sustainable Development Goals. Earthen housing is found across the globe, particularly in developing countries, but there is a lack of up-to-date information about its distribution and trends. This knowledge gap is a barrier to developing more effective research and policy for earthen housing. In this study, national demographic datasets were used to investigate the distribution, trends and attitudes towards earthen housing worldwide. Data was collected and analysed for the most populous 26 countries, which make up >75% of the global population. Globally, earthen housing is in decline relative to non-earthen housing, driven by demographic changes and negative perceptions of earthen materials in developing countries. The proportion of households living in earthen dwellings worldwide is estimated to be 8–10%, and the average across developing countries to be 20–25%. There is a negative correlation between countries' level of development and prevalence of earthen housing. Whilst data is more sparse for highly developed countries, the development of standards and commercial interest suggests more favourable attitudes to earthen housing. A focus is encouraged on high-quality earthen dwellings which can help meet housing needs in both developing and developed countries.

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Housing design; earth construction; development; census; Sustainable Development Goals

Introduction

Earthen construction has a long history in human habitats, including cultural or communal buildings as well as housing (Houben & Guillaud, 1994). It has been (and still is) used in many regions around the world. There is great diversity in both the form and quality of earthen buildings, ranging from poor quality housing (Kulshreshtha et al., 2020) to luxury developments and showpiece 'starchitecture' buildings (Ramage et al., 2019).

Housing is a key part of the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015), particularly SDG 11 'Sustainable cities and communities' (Smets & Van Lindert, 2016). It also strongly relates to numerous other SDGs, including SDG 1 'No Poverty', SDG 3 'Good Health and Wellbeing', and SDG 13 'Climate Action'. Hereafter, 'housing' will be used to refer to residential building stock in general, and 'dwelling' will be used to refer to an individual residential unit occupied by a single household. Over recent decades, the world housing stock has undergone rapid change in both scale and material use (Okpala, 1992). In developing countries, there is a widely held aspiration to replace traditional and/or indigenous materials (including earth) with 'modern' materials (e.g. fired bricks, concrete) in order to improve dwellings' robustness and their occupants' quality of life. In contrast, in developed countries there has been a renewed interest in traditional and/or indigenous materials (again, including earth) for a range of motivations including culture, aesthetics, environmental impacts and health (Hall et al., 2012).

Despite earth being a major construction material for housing, the global distribution of earthen housing is poorly understood. So far, understanding is limited to certain regions, including India (Kulshreshtha et al., 2020), France (Leylavergne, 2012; Antoine & Carnevale, 2016), Germany (Lehmbau Atlas, 2012) and Europe as a whole (Akermann et al., 2011). A wide range of earthen buildings (not limited to housing) were included within a study on earthen structures in the UNESCO World Heritage List, but this was restricted to 150 sites (Gandreau & Delboy, 2012). The majority of these previous studies focussed on describing construction method and architecture of the earthen dwellings, rather than

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a quantitative description of their numbers. Within SDG 11, earthen housing is crucial to achieving targets 11.1 (universal access to adequate housing) and 11.c (maximizing use of local materials in construction). However, one of the barriers to achieving these targets is information – and in particular, these two key knowledge gaps: a quantitative understanding around the worldwide distribution of earthen housing; and, the trends of adoption for earthen housing in both highly developed and developing countries. Addressing these knowledge gaps will enable more effective work on earthen housing by many actors, such as researchers, policymakers and standards bodies.

The most commonly quoted global estimate is that 1/3rd of the world's population lives in earthen dwellings, with that figure rising to ~50% for the population of developing countries (Houben & Guillaud, 1994). These estimates were first given in 1983, and continue to be regularly restated, often without indicating whether the whole world or just the developing world is referred to (Rael, 2008). Other sources give worldwide values of around 50% or above (Agarwal, 1982; Avrami & Guillaud, 2008). While the estimate from 1983 may have been a representative 'ballpark' figure at the time, substantial changes in global demographics and housing stock have taken place in the subsequent >35 years. The use of the best available data to revise these values for the 21st century is long overdue.

The approach of this study was to use national demographic datasets in order to interrogate the status and trends of earthen housing. The aim was to fill knowledge gaps around: the distribution of earthen dwellings around the world and within countries; the changes in prevalence of -and attitudes towards-earthen housing at different developmental stages; and, the overall prevalence of earthen dwellings around the world.

Methodology

Countries investigated

A 'fat tail' exists in the distribution of global population over the number of countries – >75% of the world's population lives within just 26 countries (Figure 1). National demographic datasets offer an efficient way to assess a large proportion of the global population from a relatively small number of countries. The scope of this study is therefore focussed on the 26 most populous countries. These countries span a range of income groups and stages of development (Table 1), and hence provide the opportunity to make comparisons between countries based on these attributes.

This approach was used in order to obtain a balance between assessing a substantial proportion of the global population, whilst also limiting the scope to a feasible number of national datasets. It was also sought to

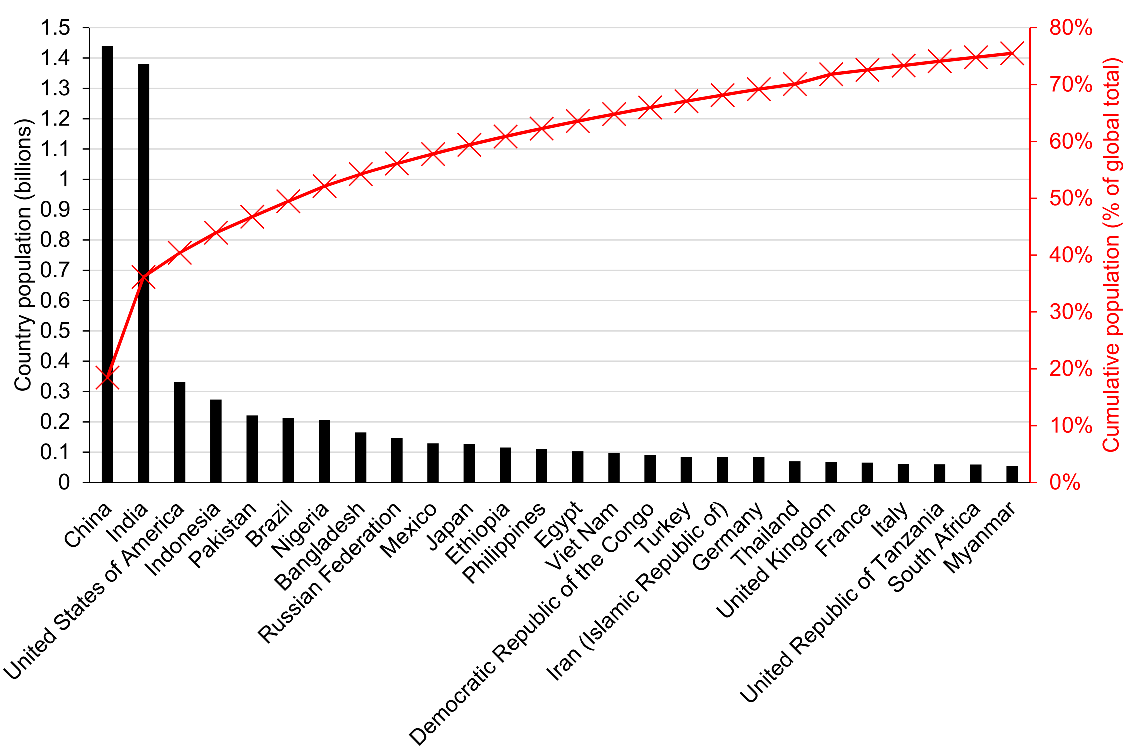

Figure 1. Individual and cumulative populations for the 26 most populous countries. 2020 population data from United Nations (2019).

Table 1. Key demographic data for selected 26 countries.

Country	Population ranking	Population (millions)	HDI group	HDI score	Income group	MDPI score
China	1	1439.3	High	0.758	Upper middle	0.016
India	2	1380.0	Medium	0.647	Lower middle	0.123
United States of America	3	331.0	Very high	0.92	High	n/a
Indonesia	4	273.5	High	0.707	Lower middle	0.028
Pakistan	5	220.9	Medium	0.56	Lower middle	0.198
Brazil	6	212.6	High	0.761	Upper middle	0.016
Nigeria	7	206.1	Low	0.534	Lower middle	0.291
Bangladesh	8	164.7	Medium	0.614	Lower middle	0.198
Russian Federation	9	145.9	Very high	0.824	Upper middle	n/a
Mexico	10	128.9	High	0.767	Upper middle	0.025
Japan	11	126.5	Very high	0.915	High	n/a
Ethiopia	12	115.0	Low	0.47	Low	0.489
Philippines	13	109.6	High	0.712	Lower middle	0.024
Egypt	14	102.3	High	0.7	Lower middle	0.019
Viet Nam	15	97.3	Medium	0.693	Lower middle	0.019
Democratic Republic of the Congo	16	89.6	Low	0.459	Low	0.389
Turkey	17	84.3	Very high	0.806	Upper middle	n/a
Iran (Islamic Republic of)	18	84.0	High	0.797	Upper middle	n/a
Germany	19	83.8	Very high	0.939	High	n/a
Thailand	20	69.8	High	0.765	Upper middle	0.003
United Kingdom	21	67.9	Very high	0.92	High	n/a
France	22	65.3	Very high	0.891	High	n/a
Italy	23	60.5	Very high	0.883	High	n/a
United Republic of Tanzania	24	59.7	Low	0.528	Low	0.273
South Africa	25	59.3	High	0.705	Upper middle	0.025
Myanmar	26	54.4	Medium	0.584	Lower middle	0.176

Note: 2020 population data from United Nations (2019); groups and scores for HDI and MDPI from UNDP (2020); income groups from The World Bank (2020b).

provide a balanced assessment for the world as whole, rather than risk a positive selection bias by intentionally focussing on countries where earthen construction is widespread and/or well-documented. It is acknowledged that this sample of countries excludes several countries (i.e. those in the remaining <25% of world population) in which earth construction is widely adopted and/or very well documented (e.g. Mali, Sudan, Yemen); at the same time, the sample also excludes many countries in which earth construction is not widely adopted (e.g. Malaysia, Poland, Canada).

Sources and limitations of national demographic data

Censuses and other national demographic datasets provide valuable information but also present challenges. Census reports are not always publicly available, and are not always translated into English. To overcome the challenges of limited access to census reports, three types of sources were used to provide national demographic data around housing materials and housing quality:

1. Census reports
2. IPUMS census data
3. Demographic and Health Surveys (DHS) questionnaire data

A national census is the most wide-ranging and in-depth recording of data about a country's population. Census reports are published by countries' statistics authorities, and data are typically presented by the number of dwellings (rather than population). This was the first preference of data source as it offers the most comprehensive data with minimal subsequent processing. Within the housing and health research area, census data has previously been used to analyse trends in housing in Sub-Saharan Africa from 2005 to 2015 (Tusting et al., 2019).

IPUMS is an open database which provides a sample of census data (typically in the range of 10–15% of the population), including for some countries whose census reports are not readily accessible or available in English (Minnesota Population Center, 2019). However, the raw census data are processed into universal categories and so does not necessarily accurately represent the exact questions used in the original survey. It also sometimes includes a conversion to numbers of people rather than numbers of dwellings. This was the second preference of data source when census reports were not accessible. In the use of IPUMS data, it was assumed that the number of households and number of people are directly proportional, so that values reported in terms of 'proportion of people living in earthen dwellings' were equivalent to 'proportion of households living in earthen dwellings'. Consequently, the latter term will be used throughout.

Demographic and Health Surveys (DHS) data are generated from household surveys undertaken every 5 years, which include questions about housing characteristics and materials. They provide a snapshot of a country, given that they collect data from a small sample of the population. DHS data were used in a different way to the previous two sources, as described in the following paragraphs.

These three source types have advantages and disadvantages in terms of availability, comparability and transparency of data. To make best use of the data available, the different source types were used for different aspects of the analysis (Table 2). For comparing between countries, the most recent census reports were used. When this was not accessible, the census data provided by IPUMS was used as the best available substitute. For countries for which either census data were not available, or census data did not contain any data relevant to the construction material of dwellings, other sources of national or regional level data were obtained where possible. For comparing trends over time, DHS surveys were used, along with the census and IPUMS data. Whilst DHS surveys only represent a small sample of each country's population (typically <0.01% of the population), these have the advantages of being carried out at regular intervals, and having a set of questions which are common across all countries and across years as the surveys were carried out by a single organization. Historical population estimates from the United Nations World Population Prospects (2019) were used to convert the historical values for the proportion of population living in earthen dwellings into absolute numbers of people (see Appendix B in Supplementary Information).

Classification of earthen construction

For the purposes of this study, an earthen dwelling was defined as a dwelling in which a majority of the external walls of the building are constructed using unfired earth as a major component. This included wholly earthen wall construction (e.g. adobe blocks, rammed earth, compressed earth blocks) as well as part-earthen wall construction (e.g. wattle and daub). Stabilized and unstabilized earth construction techniques were both included. Flooring material was considered separately, as earthen floors have distinct functional requirements and risks compared to walls – this distinction is explored in the section 'Reduced prevalence of earthen housing and higher development – correlation or causation?'.

Table 2. Data sources used for different aspects of analysis.

Comparison between countries	Comparison within each country over time
Census reports	Census reports
IPUMS census data	IPUMS census data
	DHS surveys

Analysis methods

The analysis of national demographic data is a novel approach for interrogating the current state and historical trends of global earthen construction, which has not previously been used. Given that census questions and response options are unique to each country, using census data presents challenges of making fair comparisons between different countries' data. On the other hand, a given country's choice of questions and response options itself provides information about that country's attitudes towards construction materials. In order to identify common points of comparison and trends in countries' surveys, a cascade of questions was used to assess how each census presented the relevant data (see Appendix A in Supplementary Information).

The following developmental indicators were also used to compare between countries:

- Human Development Index (HDI) – a compound measure of a country's development (higher value = higher degree of development) (UNDP, 2020).
- Multidimensional Poverty Index (MDPI) – a compound measure of a country's poverty (higher value = higher degree of poverty). Scores are only calculated for countries outside of the highly developed HDI grouping (UNDP, 2020).
- Gross Domestic Product per capita (GDP) – an overall measure of the average wealth of a country's citizens (The World Bank, 2020a).

Estimate of number of households living in earthen dwellings

In order to test the validity of widely-used estimates about the proportion of the global population living in earthen dwellings, an approximate estimate was made for these 26 countries. Depending on the availability of data for a given country, the following procedures were used to make an estimate, in order of preference:

1. Use of census data.
2. Use of other national statistical data.
3. Estimation on the basis of partial or regional data in research articles.
4. Estimation based on benchmark data available for comparable countries (in terms of region and development level)

To aid sourcing of non-census data sources for the numbers of earthen housing and the availability of standards, experts in the fields of earthen construction and local building materials in the respective countries were contacted. When the lack of other data required the use of the latter two methods, an upper limit and lower limit were also estimated, to provide a range of uncertainty. Full descriptions of the estimation procedures used for each country are provided in Appendix C in Supplementary Information. Estimates were described in terms of households, rather than the dwellings themselves, to reflect the fact that census data reports in terms of the number of households.

Availability of standards and qualitative information on earth construction trends

As part of the investigation into trends in adoption of earthen housing, experts in the fields of earthen construction and local building materials in the respective countries were contacted. All were asked about the availability of standards, and experts in highly developed countries were also asked to provide other qualitative or anecdotal evidence. This included the existence of policies to promote earthen construction and the number of companies specifically working with earthen construction. These extra questions were asked for highly developed countries because of their widespread lack of quantitative data, which will be explained in the section 'Availability of earth construction data in censuses'.

Results

Availability of earth construction data in censuses

A large proportion of the 26 countries enquired about the type of walling materials in their census survey. However, this was not evenly distributed between HDI groups – the majority of very high HDI countries did not enquire about construction material (Figure 2). For the countries which did enquire about construction material, a majority included earth as an individual response option. This included most of the low or medium HDI countries.

For those countries which included earth as a response option, there were differences in the number of options provided (Table 3). Several countries only included a single generic option for earth construction, whilst others (e.g. Tanzania, Ethiopia, South Africa) differentiated between earth blocks and wattle & daub.

For other countries, earth was not included as an individual response option. In some cases, earth could potentially have been included in broader categories (e.g. non-permanent materials). This seemed to be the case in countries where earth is not a strong part of vernacular architecture (e.g. Philippines, Thailand).

Relative prevalence of earthen walling and earthen flooring

For countries which obtained data for both floor and wall materials, the overall trend was that earthen

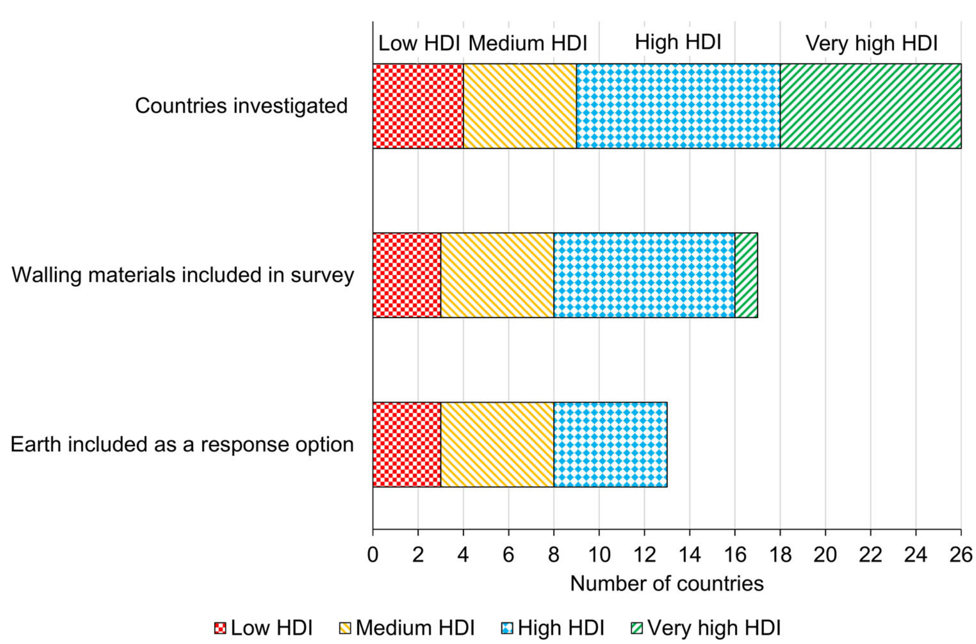

Figure 2. Breakdown of how many countries census data provided relevant information to earth dwellings, grouped by Human Development Index (HDI) group.

Table 3. Response options for countries which included earth as a survey option for construction material of dwellings.

Country	Data source	Earth response options	Non-earth response options
India	Census 2011	Mud/unburnt brick	Grass/thatch/bamboo; plastic/polythene; wood; stone not packed with mortar; stone packed with mortar; G.I./metal/asbestos sheets; burnt brick; concrete; any other walling material
Pakistan	Census 1998	Unbaked bricks/earth bound	Baked bricks/blocks/stone; wood/bamboo; others
Brazil	Census 2010	Rammed earth (without coat/plaster), rammed earth (with coat/plaster),	Brick masonry (coated), Brick masonry (uncoated), Equipped wood, harnessed wood. straw, other material (plastic etc)
Nigeria	Census 2006	Mud/reed	Wood/bamboo; stone; cement/blocks/bricks; metal/zinc sheet; other
Bangladesh	Census 2011	Mud/un-burnt bricks	Straw/Bamboo/Polythene/Plastic/Canvas, Tin (C.I Sheet), Wood, Brick/cement, others
Mexico	Census 2010 (IPUMS)	Adobe; Mud or Adobe	Cardboard, scrap, and miscellaneous materials; Waste, scrap, or discarded material; Cardboard sheet; Wood; Reed, bamboo, or palm; Brick, block, stone, or cement; Metal or asbestos sheet
Ethiopia	Census 2007 (IPUMS)	Unburnt brick with mud; Mud or adobe; Mud with wood/wattle	Wood; Bamboo or cane; Brick, block, stone, or cement; Brick with plaster exterior; Brick; Cemented stone; Metal or iron sheet; Others
Egypt	Census 2017	Bricks or clay (i.e. earth)	Red bricks or their alternatives and other ceils; red bricks or their alternatives and concrete ceils; prefabricated materials; concrete ceils and pillars
Vietnam	Census 2009 (IPUMS)	Wood and earth adobe; Netted bamboo or cane with mud;	Brick, stone, concrete; Concrete; Mixed material; Others
Iran	Census 2016	Adobe and wood; Adobe and clay	Reinforced concrete; Brick and steel or stone and steel; Brick and wood or stone and wood; Cement block (kinds of roof); All brick or stone and brick; All wood; others
Tanzania	Census 2012	Poles and Mud; Sundried bricks;	Stones; Cement bricks; Timber; Timber and Iron sheets; Grass; tent
South Africa	Census 2011 (IPUMS)	Cement and adobe bricks; Mud with wood/wattle	Cardboard sheet; Plastic sheeting, cardboard; Wood, formica, and other; Wood or bamboo; Grass, straw or reed; Bricks; Cement blocks; Asbestos; Metal or Iron sheet; Others
Myanmar	Census 2014	Earth	Tiles; Concrete; bricks; Wood; Bamboo; Corrugated sheeting; Non-woody vegetation

flooring was at least as widespread as earthen walling in each country (Figure 3). The exception to this is Mexico – however, it only deviated by a small amount.

Rural–urban distribution of earthen dwellings

Several censuses made a distinction between dwellings in rural and urban areas. However, only a small number included data for earthen dwellings as well as a rural–urban breakdown. Within this sample (Figure 4), earth construction was consistently more prevalent in rural areas. The overall distributions within the South Asian region (i.e. India, Pakistan, Bangladesh) demonstrated a high degree of similarity. In Brazil, a similar trend of earth construction mostly being in rural areas was also seen, albeit this was much less obvious given that for the country as a whole, the majority of the population is urban (85.9%).

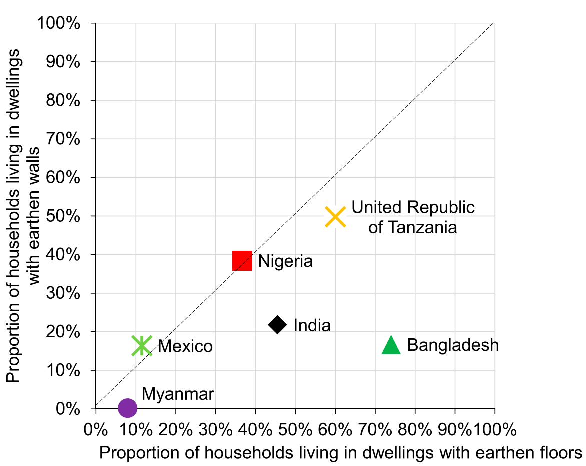

Figure 3. The proportion of households living in dwellings with earth floors and earth walls (for countries which provided both sets of data).

Earthen construction and development status

For the countries reporting data for earthen dwellings, a weak negative correlation was observed between HDI and the proportion of earthen dwellings (Figure 5), meaning that higher levels of development are associated with a lower proportion of a country's population living in earthen dwellings. For MDPI, a weak positive correlation was observed (Figure 6), meaning that lower levels of poverty are associated with a lower proportion of a country's population living in earthen dwellings. The overall narrative trend observed is hence the same for both metrics. The clearest outlier on both plots is Myanmar, which has a very low proportion of households living in earthen dwellings (0.2%) and a relatively low level of development (i.e. low HDI and high MDPI scores).

Changes in earthen dwellings with time and wealth

For some countries, comparable earthen data were available for different time points (Figure 7(a)), which was then plotted against changes in each country's wealth

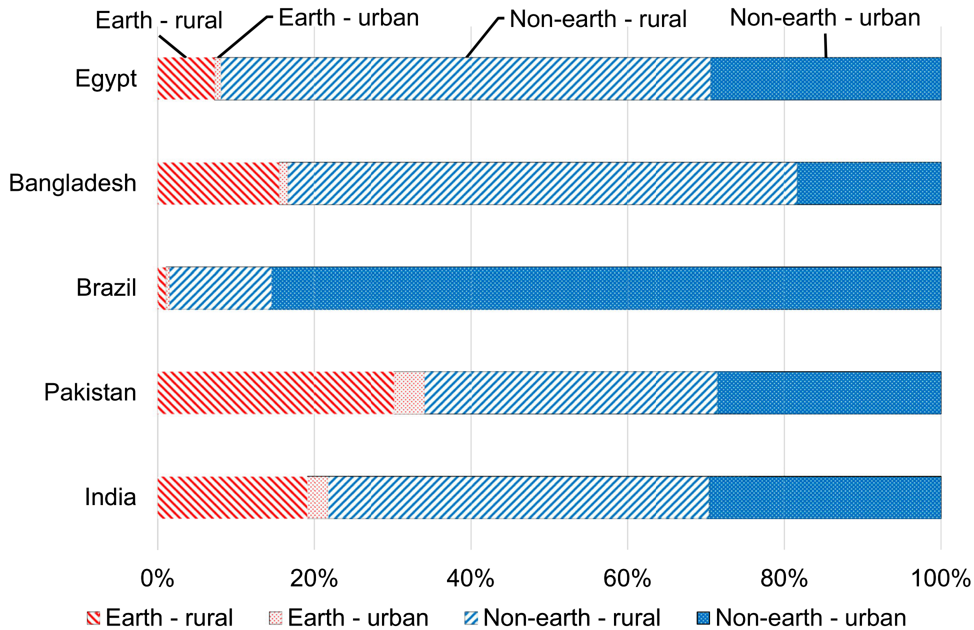

Figure 4. The proportion of households living in earthen and non-earthen dwellings in urban and rural areas.

(using GDP per capita as an indicator) for the same years (Figure 7(b)). A clear overall trend was observed between increasing wealth and a decreasing proportion of the overall population living in earthen dwellings over recent decades. Despite differences in absolute values between countries, the overall trend is common for all the countries for which data were available.

Presentation of these values in terms of absolute population, rather than simply proportions, revealed more nuanced trends (Figure 8). With the exception of South Africa, the populations living in earthen dwellings in these countries have remained fairly constant over time (India, Mexico), or have even undergone a fairly modest increase (Bangladesh, Tanzania). In contrast, all these countries underwent large increases in the population living in non-earthen housing.

Current global prevalence of earth construction

The number of households living in earthen dwellings was estimated for the 26 countries (together representing >75% of the world population), in order to interrogate the validity of two widely used statements around the global prevalence of earthen dwellings.

The first widely used statement, that ‘one third of the world’s population lives in earthen dwellings’ is now shown to be a substantial overestimate. From estimates for the 26 countries, the real range is expected to be 8–10% (Figure 9(a)). Whilst this is a small proportion relative to the remainder of the population living in non-earthen dwellings, earthen dwellings are nonetheless estimated to provide shelter for around 650–700 million people worldwide. The second widely

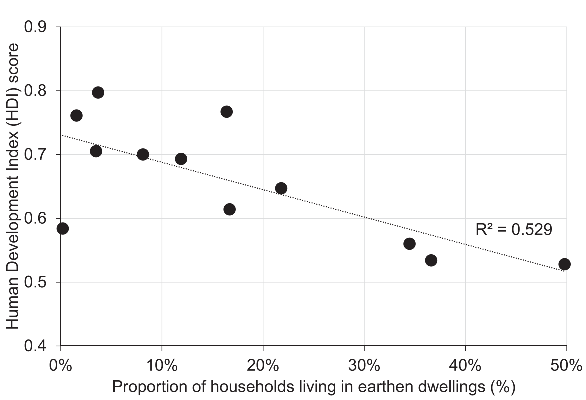

Figure 5. Correlation between human development index (HDI) and proportion of households living in earthen dwellings.

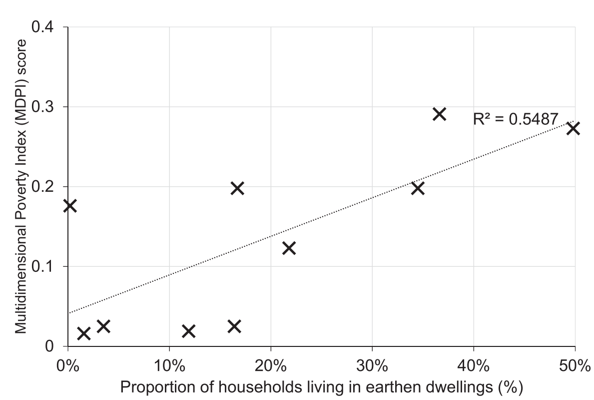

Figure 6. Correlation between multi-dimensional poverty index (MDPI) and proportion of households living in earthen dwellings.

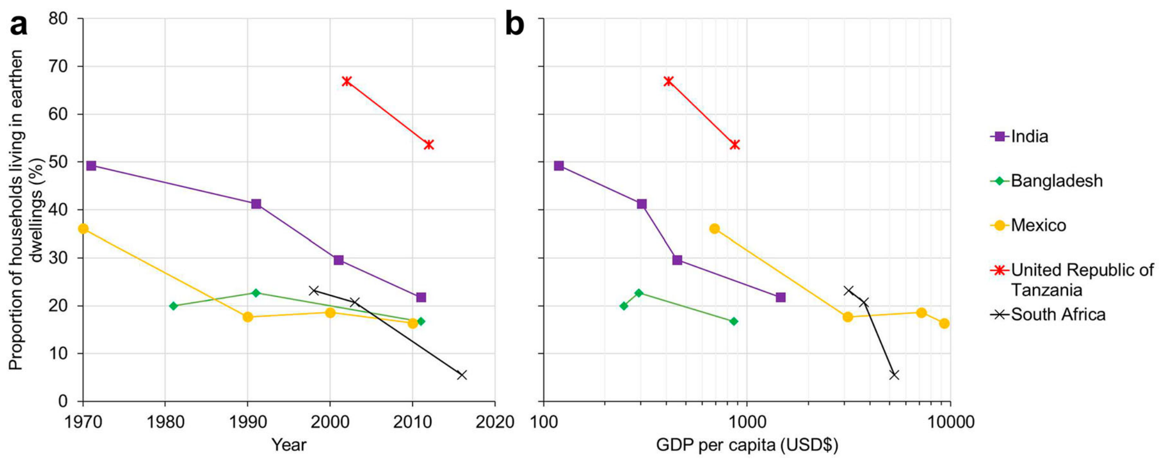

Figure 7. Changes in proportion of households living in earthen dwellings for India, Bangladesh, Mexico, Tanzania and South Africa plotted against: (a) time, (b) GDP per capita (current USD$).

used statement, that 'half of the population of developing countries lives in earthen dwellings' is also a substantial overestimate. Choosing here to classify developing countries as either low or medium HDI group, the real range is expected to be 20–25% (Figure 9(b)). Nonetheless, there is still a clear difference in prevalence between the 'Global North' and the 'Global South' (Figure 10).

Despite the difficulties involved in some of these estimates, the magnitude of uncertainties are relatively small. This arises from the fact that quantitative data exist for several of the world's most populous countries, namely China (4.2%), India (28.2%), Pakistan (34.5%), Brazil (1.6%), Nigeria (36.6%), Bangladesh (16.7%) and Mexico (16.4%). This helps to compensate for the higher levels of uncertainty in other, less populous countries. Furthermore, many of the census datasets are now over 10 years old, and there is a historical trend of much faster growth in non-earthen housing stock relative to earthen housing stock in some countries (Figure 8) – as a result these estimates are likely to be an over-estimate. It is considered unlikely that the countries which make up the remaining <25% of the global population exhibit a distribution which is substantially different from that presented here. Given that the absolute numbers of earthen housing have been relatively stable for some countries in recent decades (Figure 8), it may well be that the earlier estimate of ∼33% may have been broadly accurate for a time period in the 20th century – perhaps the 1950s or 1960s. Nonetheless, it is concluded that these two widely used statements now over-estimate the proportion of earthen dwellings – they are out of date and therefore should no longer be used.

Availability of national standards for earthen construction

Whilst the census survey questions (Figure 2) indicated attitudes towards earth construction and the importance of construction materials in different countries' surveys, attitudes are also reflected by how well-developed countries' national standards are (Niroumand et al., 2017). Normative documents were excluded from consideration, due to their lesser influence relative to standards and greater difficulty of finding. The most recent review of national standards and normative documents for earth construction was given by Schroeder (2012). The relevant national standards for the countries considered in this study are given in Table 4. Comparing the availability of national standards with the HDI group (Figure 11), it can be seen that these are more widely available for the very high HDI countries compared to other groups.

Discussion

Developing and highly developed countries have different attitudes towards housing walling materials

The divide in census survey questions between low, medium and high HDI countries (whose census surveys did include questions about dwellings' construction material) and very high HDI countries (whose census surveys did not) was shown in Figure 2. In turn, this reflects assumptions about which factors strongly influence citizens' quality of life. In less developed countries, there is a wider palette (and level of quality) of the housing materials themselves, and hence housing materials are a strong indicator for the quality of life and economic status. Earthen materials in particular are

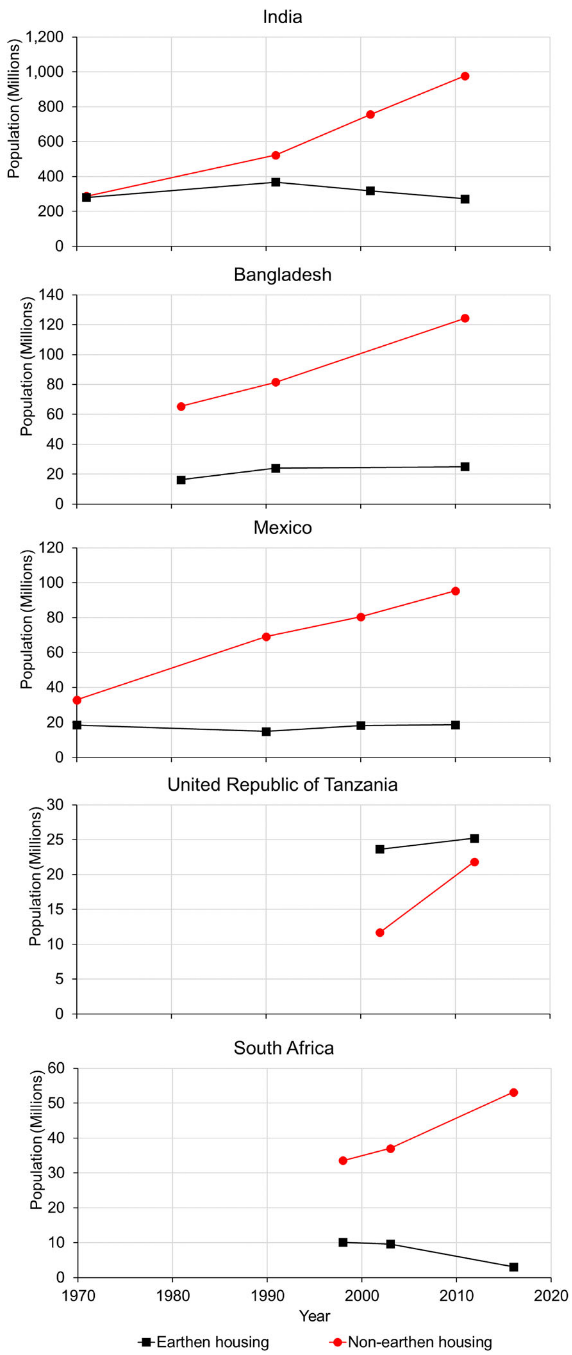

Figure 8. Changes in the populations living in earthen and non-earthen housing for India, Bangladesh, Mexico, Tanzania and South Africa.

considered to indicate low economic status (Hadjri et al., 2007). In contrast, in the very highly developed countries, robustness of housing is taken for granted and there is typically a narrower palette of construction materials. Consequently, other housing factors (e.g. access to heating and cooling) are considered more relevant in determining the quality of life. One aspect of earthen dwellings which is not captured in national demographic data is the quality of those dwellings. For the purposes of this article, high-quality earthen dwellings are defined as possessing both a good architectural design (i.e. roof, foundation, detailing, finishing) and good material quality (i.e. well-graded, sufficiently compacted soil, as appropriate), together leading to a good durability performance for the structure as a whole. In comparison, poor quality earthen dwellings are defined as being deficient in architectural design and/or material quality. A detailed description of these technical requirements can be found elsewhere (Houben & Guillaud, 1994). Quantification of dwelling quality is challenging, and arguably more research is needed in this area. Nonetheless, a broad inference can be made: in very high HDI countries, the construction sector is highly regulated, and hence the durability of dwellings is typically highly satisfactory, and (as stated previously) is taken for granted. In comparison, in less developed countries the construction sector is typically much less regulated and the budgets available for home construction are typically much smaller. As a result, there is a greater prevalence of dwellings (including but not limited to earthen dwellings) which do not demonstrate sufficient durability. An earthen dwelling built in a less developed country is not automatically of low quality, nor is an earthen dwelling built a highly developed country automatically of high quality. Nonetheless, low quality earthen dwellings are far more prevalent in less developed countries, for the reasons outlined above. The implication for attitudes is that in less developed countries, the existing building stock has already shaped attitudes to earthen housing; whilst in very high HDI countries (which do not contain a large number of poor quality buildings to act as a reference point), attitudes towards earthen housing have not been pre-determined in such a negative way.

The trends observed for how the proportion of earthen dwellings has changed with time (Figure 7(a)) agree with general observations made over the previous decades for Sub-Saharan Africa (Tusting et al., 2019), Africa as a whole (Adegun & Adedeji, 2017) and India (Kulshreshtha et al., 2020). However, this analysis has a crucial caveat – the data presented are a biased sample of earthen dwellings. The earthen data available offers far better representation for low and medium HDI countries (Figure 2), and thus prevents comparative analysis with high and very high HDI countries. Whilst some highly developed countries contain a large absolute number of earthen dwellings, these only make up a very small proportion of the national building stock as a whole. Based on values stated in the literature, Germany, France, Italy and the United Kingdom were all estimated to have proportions of households living in earthen dwellings of <1% (full details are included in Appendix C in the Supplementary Information).

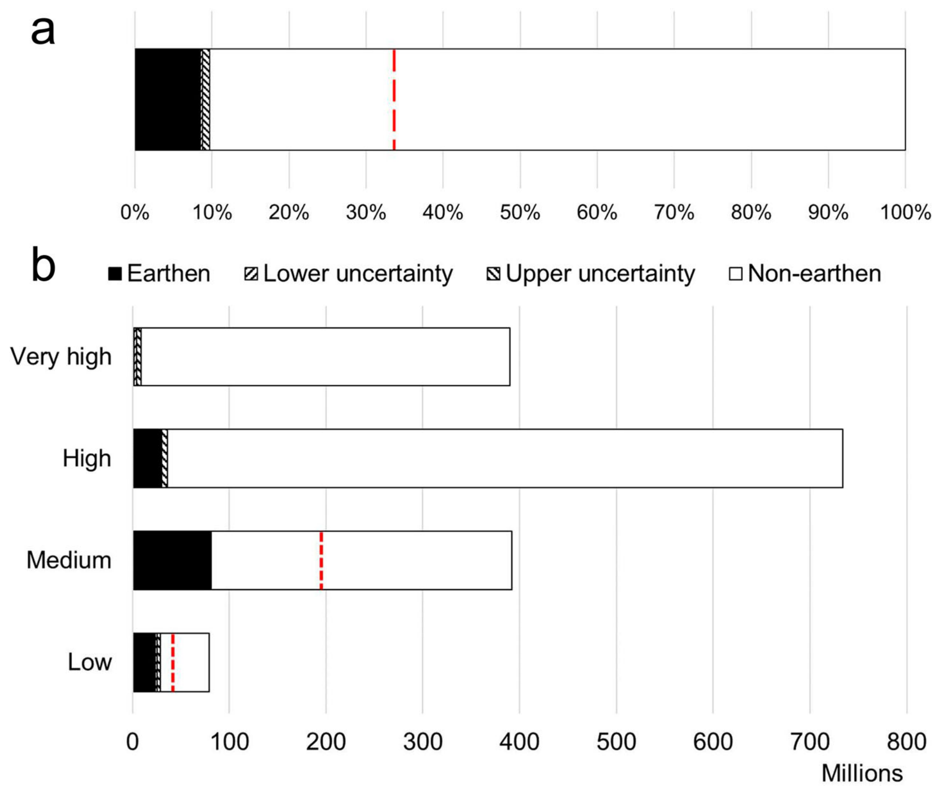

Figure 9. (a) The estimated proportion of households living in earthen dwellings in the 26 countries considered in this study, including estimates of the uncertainty in estimates generated in this study. (b) A breakdown in HDI group of the estimated number of households living in earthen dwellings in the 26 countries considered in this study. Previous widely used estimates are marked in dashed lines.

Anecdotal observations from local experts and other sources suggest that there is a growing interest in earthen construction in several of these countries (e.g. France, U.K., U.S.A.). This interest is largely driven by the desire for sustainable housing with low embodied carbon (Niroumand et al., 2017; Swan et al., 2011). This is also expressed by a growing number of earth-based products and earth construction companies (Leylavergne, 2012; Dachverband Lehm, 2021), and a growing stock (albeit still relatively small) of modern earthen buildings (Akermann et al., 2011; Antoine & Carnevale, 2016). The

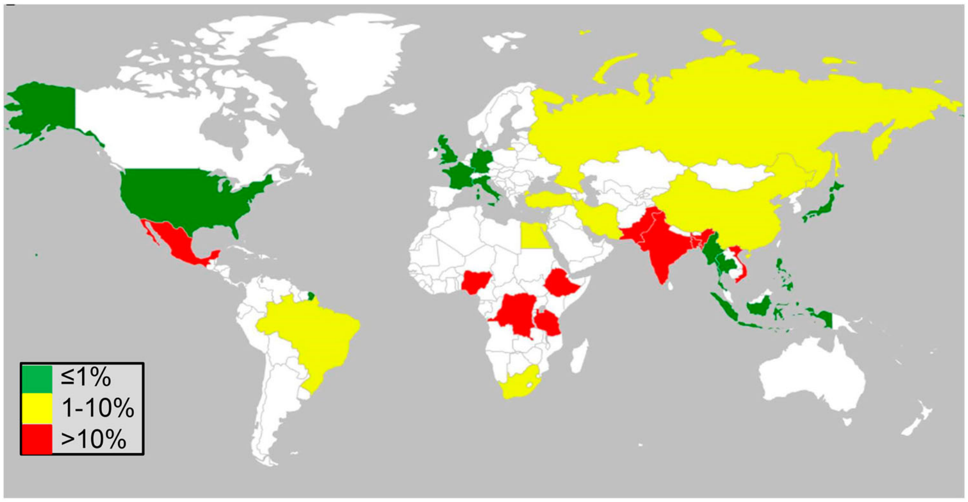

Figure 10. A global choropleth map for the prevalence of earthen dwellings in the countries considered in this study. The colour code is based on the proportion of households living in earthen dwellings.

Table 4. Earth construction standards for the 26 most populous countries.

Country	HDI group	Standard
China	High	None
India	Medium	IS: 4332 (BIS, 1967), 2110 (BIS, 1998a), 13827 (BIS, 1998b), 1725 (BIS, 2013), 17165 (BIS, 2020)
United States of America	Very high	ASTM E2392/E2392M (ASTM, 2010), CID-GCB-NMBC-14.7.4 (CID, 2006)‡
Indonesia	High	–
Pakistan	Medium	None
Brazil	High	NBR 8491 (ABNT, 1984), 10,832 (ABNT, 1989), 12,023 (ABNT, 1992), 13,554 (ABNT, 1996)
Nigeria	Low	NIS 369 (SON, 1997), ARS 670-683 (ARSO, 1996)*
Bangladesh	Medium	None
Russian Federation	Very high	–
Mexico	High	–
Japan	Very high	–
Ethiopia	Low	–, ARS 670-683 (ARSO, 1996)*
Philippines	High	–
Egypt	High	HBRC (HBRC, 2016), ARS 670-683 (ARSO, 1996)*
Viet Nam	Medium	None
Democratic Republic of the Congo	Low	–, ARS 670-683 (ARSO, 1996)*
Turkey	Very high	TS 537 (TS, 1985)
Iran (Islamic Republic of)	High	–
Germany	Very high	Lehmbau Regeln (Dachverband Lehm, 2009), DIN 18945 (DIN, 2018a), DIN 18946 (DIN, 2018b)
Thailand	High	None
United Kingdom	Very high	None
France	Very high	AFNOR XP.P13-901 (AFNOR, 2001)
Italy	Very high	None
United Republic of Tanzania	Low	–, ARS 670-683 (ARSO, 1996)*
South Africa	High	–
Myanmar	Medium	–

– indicates countries in which local experts could not be found who could confirm the existence or absence of national standards.
* ARS 670-683 (1996) is an African Regional Standard, so whilst it is available in African countries it is not considered a national standard *per se*.
‡CID-GCB-NMBC-14.7.4 (2006) is a New Mexico state standard, rather than a USA-wide national standard.

availability of standards for earth construction is still lacking in several very high HDI countries, but standards are still on average more widely available than in the lower HDI group countries (Figure 11). Given the importance of standards in enabling widespread adoption, there are movements to accelerate their development for earthen construction (Swan et al., 2011).

In summary, in very high HDI countries, earth is viewed as perhaps a niche material, but not a 'poor' material – because the quality of earthen buildings is generally high. Hence, earth construction is viewed as

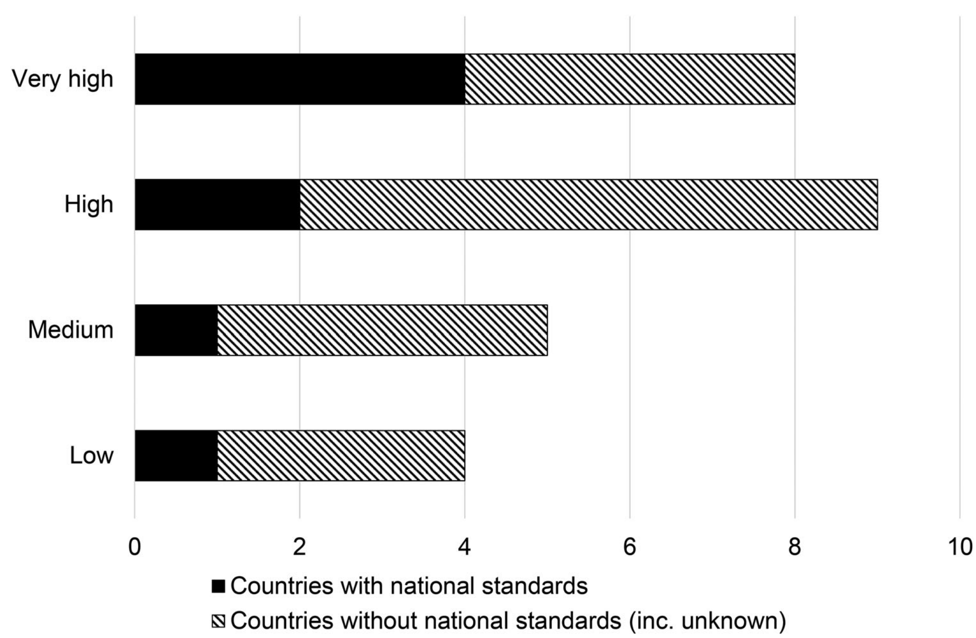

Figure 11. Availability of national earth construction standards and/or normative documents for countries in different HDI groups (very high, high, medium, low).

a respectable and reliable construction material that can provide a decent quality of life. A high-level finding of these observations from the national demographic data and standards is that attitudes towards earth construction are not fixed and immutable. In less developed countries the average quality of earthen dwellings is typically lower, which has informed the prevailing attitudes. In highly developed countries, the much smaller number of earthen dwellings are of much higher quality, and their adoption is supported by a greater availability of national standards (although this is still lacking overall). These arguments are based on the country-scale data analysed in this article, which are highly useful for obtaining a global perspective that is lacking in the existing literature. Nonetheless, future research using a range of methods is needed to obtain a more granular understanding of attitudes towards earthen dwellings in different countries and the different sectors of their populations. How (and how quickly) prevailing negative attitudes towards earth construction in less developed countries could be changed remains a matter for debate.

Reduced prevalence of earthen housing and higher development – correlation or causation?

There is a weak correlation between the proportion of earthen dwellings and HDI and MDPI scores, as shown in Figures 5 and 6 respectively. This correlation appears much stronger if countries without a strong use of earth in traditional construction (e.g. Myanmar) are excluded. On initial inspection, a policymaker might conclude that the way to accelerate a country's development is to replace earthen housing stock with housing made of other materials as quickly as possible. However, correlation does not always mean causation – it is crucial to interrogate to what extent this trend is attributable to the material itself, versus other factors of housing design and the wider urban environment.

An argument can be made that the issue is not earth itself – but rather poor quality dwellings in general, and the use of earth when built within a way that is detrimental to health outcomes. In a study in Sub-Saharan Africa, controlling for poverty and other known health factors, the influence of 'finished' building materials resulted in a reduction in odds of malaria, stunting and underweight of 0–5–year–olds (Tusting et al., 2020). In comparison, the influence of 'finished' building materials had no association with diarrhoea, acute respiratory infections, wasting or anaemia, which were improved by other aspects of higher quality housing (i.e. drinking water and sanitation). Within this, the role of the individual building elements needs to be interrogated. Whilst poorly finished earthen walls can facilitate some disease vectors due to crumbling (Wiese et al., 2017), it is arguably earthen floors which are most directly involved in increasing risk factors, including Visceral Leishmaniasis (Younis et al., 2020) and Tungiasis (Wiese et al., 2017), and also attracting mosquitoes to enter (Wanzirah et al., 2015). Whilst occupants of earthen dwellings do suffer higher malarial risk, this is attributed to poor design and finished quality (e.g. open eaves which allow mosquitoes to enter) rather than the earthen material itself (Ogoma et al., 2010; Lindsay et al., 2002).

In developing countries, the typical preference of upgrading building elements runs in the order of roof, walls and lastly, floor (Tusting et al., 2019). Walls represent the largest volume and typically most expensive element of a dwelling. The available data shows the prevalence of earthen floors is typically higher than the prevalence of earthen walls (Figure 3). Therefore, it is arguable that policymakers and researchers should prioritize the replacement of earth floors, along with low-cost design interventions such as closing eaves, to protect from disease vectors (Wanzirah et al., 2015).

In highly developed countries, the arguments made for earthen housing are the opposite –with an increasing proportion of time spent indoors, the moisture buffering capacity and intangible aspects of earthen dwellings make for healthier indoor environments (Mcgregor et al., 2016). This supports the argument that the problem of poor quality earthen dwellings lies fundamentally in poor design and finishing of the structure and materials and the surrounding environment, rather than the fundamental nature of the material itself. Therefore, housing policymakers should not assume the correlation between lower prevalence of earthen dwellings and higher levels of development is entirely causative. Rather, focus should be on replacing or upgrading poor quality earthen dwellings, whilst not ignoring the potential health benefits that high-quality earthen dwellings can provide.

A conceptual model for understanding the relationship between earthen housing and development

The trends of countries' earthen dwellings with development (Figures 5 and 6) and wealth (Figure 7(b)), together with the attitudes reflected in surveys (Figure 2) and availability of standards (Table 4) altogether suggest that countries' attitudes towards, and adoption of, earth construction changes with their position on the development trajectory. Using the findings in this study, a conceptual model is proposed which broadly characterizes the trajectory of earthen dwellings by four phases, aligned with the HDI development groupings (Figure 12):

1. Low HDI countries – from a starting point of high prevalence, low-quality earthen construction is very common amongst the poor, and uncommon amongst the wealthy.
2. Medium HDI countries – as the country grows richer, the proportion of earthen dwellings decreases (although the absolute number may not actually decrease, or decrease by a smaller amount, due to population growth). Low-quality earthen dwellings are replaced with concrete or brick. Rural-urban migration levels are high.
3. High HDI countries – after the country's housing stock is largely built and population growth starts to decrease, the proportion of earthen dwellings remains low. Rural-urban migration levels are lower.
4. Very high HDI countries – with low levels of population growth and increasing amounts of wealth, there is a renewed interest in building new earthen buildings of high quality.

A caveat to this model is that it only applies to countries in which earth construction is a widely established part of vernacular architecture. Within the perspective of construction in developing countries, it is crucial to assess the construction industry as entwined with the availability of resources, and also the socio-economic environments of that country (Ofori, 1994). Whilst the exact form and rate of these changes cannot be tested with quantitative data (due to the lack of data for highly developed countries previously described), this proposed model nonetheless offers a helpful qualitative way in which to evaluate earthen construction for the range of countries across the development spectrum.

Implications for achieving SDG 11 and SDG 13

The reduction in proportions of earthen dwellings over time (Figure 7(a)) is expected to partly result from dwellings being 'upgraded' or 'improved' to more durable, more expensive materials (e.g. brick, concrete) when it can be afforded. This process is supported by SDG 11, which targets 'adequate housing' for all by 2030. 'Upgraded' materials typically have a much higher environmental impact compared to unstabilized earth construction (Praseeda et al., 2016). Existing earth dwellings can therefore be considered as a 'virtual carbon sink' of sorts – the use of dwellings with such low embodied carbon avoids emissions associated with the production of more carbon-intensive construction materials. Conversely, the number of people who currently live in earthen dwellings can be considered as an emissions 'time bomb' – if and when they 'upgrade' to brick or concrete dwellings, this will collectively cause a large amount of emissions from the manufacture of those materials. Whilst earthen dwellings now make up only a small proportion of buildings worldwide (Figure 9) this is still a large absolute number. When scaled across hundreds of millions of households, the prospect of upgrading dwellings presents a large potential source of carbon emissions which will make it more challenging to meet the 1.5°C target (as well as the targets of SDG 13). Through developing a more accurate, up-to-date estimate of the extent and distribution of earth construction around the world (Figure 9), researchers and policymakers will be better informed to best support the upgrading of dwellings to maximize health benefits and minimize environmental costs.

The trends observed around earthen dwellings and countries' wealth (Figure 7(b)) suggest a 'valley of neglect' for earthen dwellings in the medium and high HDI stages of development. These stages typically coincide with the period of highest demand for housing due to increasing wealth, a growing population and rural-urban migration (Figure 12). Advocates of earth construction identify this as the window of opportunity where earthen dwellings can have the largest positive impact. Comparing the adoption trajectories with a business-as-usual approach (Figure 13), successful adoption of high-quality earthen dwellings at the

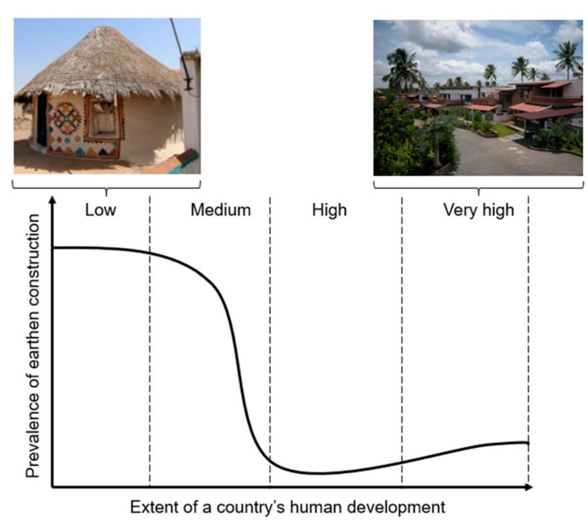

Figure 12. Schematic plot showing the changes in prevalence and type of earth dwellings at various stages in the development trajectory. Low development photo courtesy of Y. Kulshreshtha, very high development photo courtesy of A.T.M. Marsh.

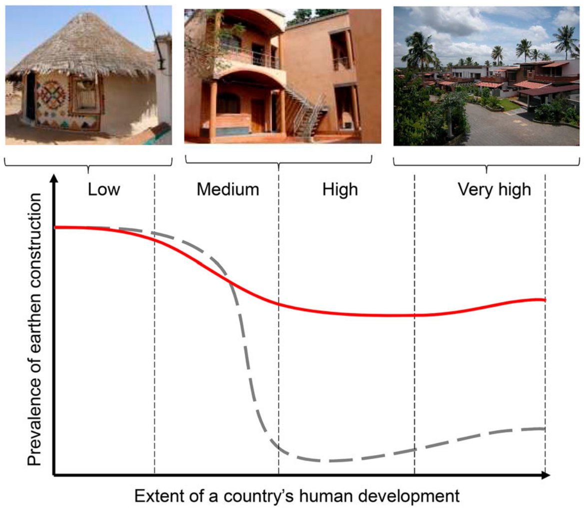

Figure 13. Schematic plot showing the changes in prevalence and type of earth dwellings at various stages in the development trajectory. The dashed grey line shows the 'business-as-usual' trajectory; the solid red line shows a trajectory with large-scale adoption of high quality earthen dwellings in the medium and high development stages. Low and medium/high development photos courtesy of Y. Kulshreshtha; very high development photo courtesy of A.T.M. Marsh.

medium and high development stages offers the potential to displace large amounts of non-earthen construction. This could potentially have large net benefits for housing affordability and embodied impacts of construction, as has been modelled for India (Mastrucci & Rao, 2019). Such a strategy would also be in line with another target of SDG 11, to encourage 'building sustainable and resilient buildings utilizing local materials'. Whilst the most suitable typologies would depend largely on the specific contexts in a given location, this supports the arguments of previous sections: policymakers should focus in replacing poor quality earth housing (rather than earth housing universally), and acknowledge the potential environmental and health benefits that high-quality earth housing can provide.

Research and policy recommendations

From the findings of this study, three key recommendations for research and policy are made:

1. Design improvements for earthen dwellings. Despite trends of decreasing adoption of earthen construction, in many less developed countries poor quality earthen dwellings will continue to be lived in, and built in large numbers, for many years to come. In acknowledgement of this reality, there is an argument for research into low-cost design interventions which can improve the health and quality of life for occupants of low-quality earthen dwellings who cannot yet afford to substantially upgrade their dwellings. An example of this is the approach taken by ARCHIVE Global (https://archiveglobal.org/), although this is arguably still a neglected research area.
2. Housing for health and environment. Whilst health and development research advocates the upgrading of poor quality earthen housing to concrete or brick for health outcomes (SDG 3), civil engineering research often advocates the retention of earthen housing for reducing the embodied carbon emissions of construction (SDG 13). Positive outcomes for both health and environment can be obtained by investment in high-quality earthen dwellings which are suitable regardless of development stage.
3. Development of comprehensive earthen construction standards. This article has highlighted the lack of national standards for earthen construction in several countries, which is arguably a barrier to modern earthen construction and needs to be addressed. Furthermore, standards should include a diverse range of earthen construction techniques, covering both stabilized and unstabilized techniques. Most of the standards available are for material performance – these should be extended to encompass comprehensive standards on earthen masonry and structural design, including the design of different earthen roofing systems.

Conclusions

For the world as a whole, the trends for earthen housing are clear. Whilst the stocks of earthen dwellings in some countries have been relatively stable, the proportion of households living in earthen dwellings worldwide have been consistently decreasing, driven by the growing wealth and other demographic changes of developing countries. As a result, the most widely used estimate of 33% of the global population living in earthen housing is now out of date. A more accurate range is suggested to be 8–10%, and 20–25% in developing (low and medium HDI group) countries. Within this global trend, attitudes towards (and use adoption of) earthen housing are not homogenous. In developing countries, national demographic data clearly show a consistent move away from earthen housing over several decades. In contrast, in some highly developed countries, earth construction is arguably enjoying a renaissance, indicated by development of standards and commercial interest.

High-quality earthen housing can be a cross-cutting contribution across different SDG categories, and an effective means to ensuring adequate housing, improving health outcomes and mitigating climate change. Research and policy should focus on three areas:

1. Development and implementation of affordable improvements to poor quality earthen dwellings already in existence in developing countries, in order to improve health outcomes and quality of life of occupants.
2. Acceleration in the adoption of high-quality earthen housing that can be desirable and appropriate for both developing and highly developed countries.
3. Development of national standards in more countries, which cover a range of earth construction techniques and architectural forms.

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