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Quantifying and mapping informal and formal building material stocks in Lima

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Abstract

Construction materials are essential for meeting societal needs in urban areas; however, they pose significant challenges for decarbonization, particularly in rapidly growing cities that struggle to meet the needs of all their citizens, such as those in the Global South (GS). This research develops and applies a GIS-based methodology to create an urban material stock map for Lima, Peru, encompassing both nonresidential and residential buildings, with the latter categorized into informal and formal housing. This study combines block-level spatial data with a refined definition of informality that better captures the nuances of reality while acknowledging its limitations, along with an extensive housing typology to calculate the material stocks present in the city. Material intensity (MI) factors were developed for each housing type, allowing for the estimation of material stocks across Lima's districts. The MI of informal housing is up to 70% less than that of formal housing. The results indicate that informal settlements comprise a substantial share of the housing (50%) and residential stock (31%) in the city. The research also highlights spatial disparities in material accumulation and their correlation with income inequality. This approach provides a replicable framework for other cities in the GS, addressing the urgent need for local data and tailored methodologies to inform sustainable urban planning and decarbonization strategies.

1. Introduction

Construction materials, often considered mundane, are vital for urban environments, supporting societal needs such as transportation, communication, education, healthcare, and housing [1]. While their environmental impacts per unit are moderate [2] (i.e. 0.27 kg CO_2-eq/kg brick [3]) and recovery rates are relatively high [4] (around 70% globally [5]), their substantial volume—accounting for 50% of global raw material usage—poses challenges for decarbonization [6]. Despite the extensive research done on urban material use, the overwhelming majority of studies have focused on the Global North (GN), where data availability and established development pathways have facilitated in-depth analyses. In contrast, research on the Global South (GS), where cities are experiencing rapid population growth and have yet to commit to specific development trajectories, remains limited [7, 8]. When GS areas are included in the literature, analyses frequently rely on GN studies as proxies to compensate for data gaps [9], which can lead to significant misrepresentations of local realities [10]. This is particularly problematic given the GS's distinct socioeconomic and climatic challenges [11], which underscore the necessity of localized, context-specific data. An urban material stock map can help assess material accumulation in cities, focusing on the composition, quantity, and spatial distribution of materials in the built environment [12–14]. However, the application of such tools in the GS remains rare, further reinforcing the need for empirical research grounded in local data and realities [12–14].

By creating a comprehensive urban map, we can explore new research avenues for the GS that promote equitable and sustainable development. Investigating the composition of in-use material stocks not only helps urban planners allocate resources more efficiently to meet community needs, but it also aids in identifying areas in need of intervention [12, 14]. Moreover, the urban map serves as a tool for identifying potential secondary resources in an area, which can be leveraged for future material recovery initiatives [12, 14]. Furthermore, analyzing in-use material stocks also reveals the volume of construction and demolition waste, informs waste management strategies, and ensures that recycling facilities are adequately prepared [12, 15, 16]. This knowledge is crucial for disaster response teams to mobilize resources during emergencies [15, 16] quickly. By quantifying material stocks, planners can estimate potential debris from disasters and develop resilience plans to strengthen infrastructure against climate vulnerabilities [17, 18].

From an environmental perspective, spatial data can guide strategies to reduce energy and material throughput, which is essential for meeting climate targets [1, 2, 19, 20]. Socioeconomic links to material stocks can provide insights into social well-being and income inequality, aiding long-term planning for sustainable development [17, 21]. Understanding stock usage trends ultimately allows urban planners to balance economic growth and environmental sustainability, fostering a more resilient and equitable urban future [1, 7].

The GS faces a unique challenge not encountered by the GN: informal settlements. These settlements arise in response to rapid urban growth, housing shortages, and a lack of urban growth strategies [11, 22]. With climate change driving urban migration, understanding informal housing dynamics is increasingly essential for future-proofing cities. By recognizing the role informal housing plays in providing societal services, we can develop effective urban planning strategies. Overlooking informal settlements skews housing stock assessments and urban demographics, misdirects policies, and hinders resource allocation. Conducting a comprehensive analysis of informal settlements ensures that decisions align with the city's socioeconomic realities. However, informal housing often lacks standardized measures to identify it. According to UN-Habitat, a building is classified as informal if it lacks any of the following: access to water, sanitation, sufficient living space, durability, or security of tenure [23]. Informal housing is constructed with materials different from formal structures and often lacks essential infrastructure and services [24]. Additionally, these homes are frequently situated in areas more vulnerable to the impacts of natural disasters, such as earthquakes and mudslides.

The topic of informality is delicate and controversial [25], making it difficult to define and identify in real-life scenarios. This is reflected in the varied reports [26–30] of informal housing prevalence in Lima, which range from 70% to 90% due to differing definitions. Lima's informal housing prevalence makes an interesting case study [31]. As Peru's capital and largest city with over 11 million residents [30]—one-third of the nation's population—Lima is a meaningful case study. The city contributes 37% to Peru's GDP [32] and faces ongoing housing shortages despite national initiatives [33]. Rapid urbanization since the 1980s has worsened the situation, leading to unequal access to essential services and increased vulnerability to environmental risks [34]. Located on the Pacific Rim, the city is highly vulnerable to earthquakes and has seen an increase in mudslides, further threatening informal settlements in the hillside [17, 35, 36].

Although Peru is not new to the material-stock research field [15, 17, 37, 38], previous studies have not distinguished between formal and informal housing, but instead assumed the same material usage between the two groups [37]. This approach was adequate for the previous study on Lima [37], where the presence of informal housing was minimal. However, for a comprehensive citywide study, the differentiation limits the accuracy of material stock assessment, especially in the context of residential buildings. To address this gap, our study develops a methodology for creating an urban material stock map in cities with limited available data and a high prevalence of informal housing. Using Lima as a case study, we quantify and spatially map the city's material stocks for both residential and nonresidential buildings, explicitly differentiating between formal and informal housing. Furthermore, we examine the relationship between material stocks and income inequality, a persistent challenge in the GS. Through this integrated approach, our research aims to provide valuable insights for more equitable urban planning strategies, ultimately enhancing the living conditions for all residents in Lima.

2. Methods

2.1. Definitions

2.1.1. Spatial boundaries

Metropolitan Lima is divided into two provinces (i.e. Lima and Callao) and 50 districts. Due to data limitations on Callao, this research covers the 43 districts of Lima province.

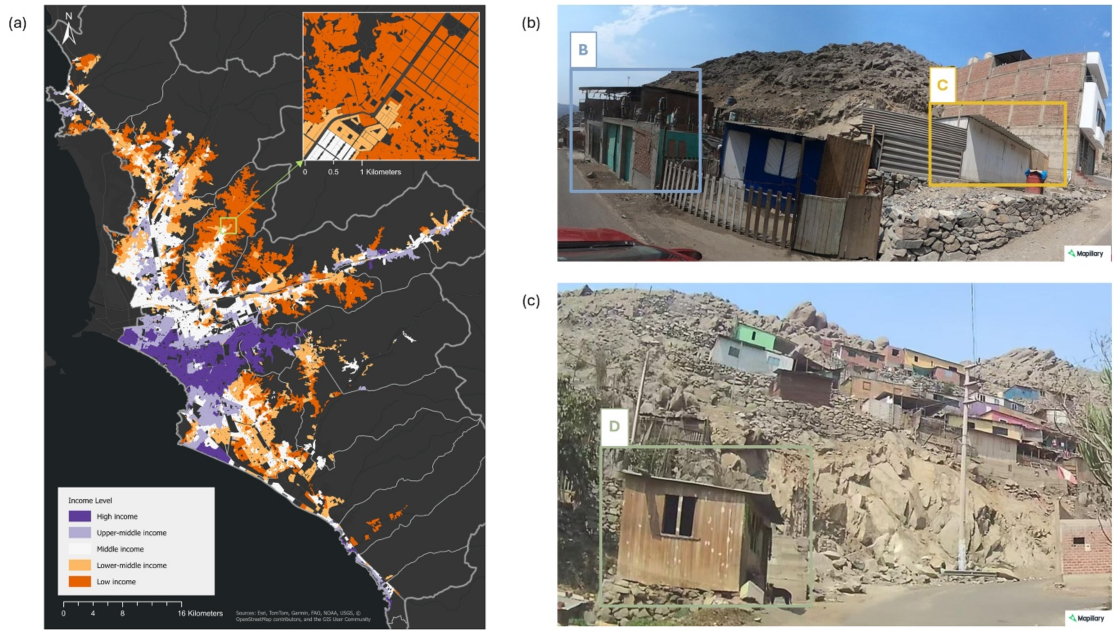

Figure 1. (a) Spatial distribution of the income levels per household in the city of Lima. (b) Informal housing Type B and Type C. (b) Photo credit: '540426084884607' <https://bit.ly/3HGAUVI> by 'kaart_2', licensed under CC-BY-SA). (c) Informal housing Type D. (c) Photo credit: '223590763475749' <https://bit.ly/418TPPF> by 'kaart_2', licensed under CC-BY-SA, licensed under CC-BY-SA). Type B refers to housing with permanent walls and roofing material that inhibits vertical growth. Type C refers to prefabricated sheds with mud or cement floors, plywood or steel roofs, and wooden walls. Type D refers to housing with mud or cement floors, plywood walls, and roofs made of either plywood or mud.

2.1.2. Informal housing in practice

Although UN-Habitat has established a definition of informality (see section 1), there are nuances of reality that are not encompassed by this definition. Therefore, we have extended the definition of an informal house to be one that lacks any of the following: access to water, electricity, or sanitation from the public network, durability, or security of tenure. The first three criteria, while similar to those in the UN-Habitat definition, have been expanded to focus on access that is dependent solely on connections to the public network. This means that houses that obtain their water, for example, from a cistern truck, or their sanitation services through septic tanks, are not considered formal [39]. Durability refers to both the choice of materials and the permanence of the building. Materials that cannot withstand natural disasters common in the area (such as mudslides and earthquakes) or do not meet regulations are regarded as lacking durability. Permanence stems from the fact that some houses are constructed to be temporary. This situation is due to economic constraints, as it is common for homes to be gradually improved over time; a foundation may be laid, but it could take years before permanent walls are constructed, as owners must wait for the next financial opportunity to arise. As a result, the house is built with the understanding that sections of it may be taken apart when financial opportunities arise for upgrades. Security of tenure can be defined either as a house located in an area not designated as residential and, therefore, could be relocated if ordered by local authorities, or one that does not possess property titles [40].

2.1.3. Residential building typology

We explicitly differentiate between formal and informal building typologies. Formal housing is subcategorized into three types. Informal housing is subcategorized into five types based on its wall and roof materials, as depicted in figures 1(b)–(d), based on the definitions of the Terwilliger Center for Innovation in Shelter report on temporary housing in Lima [41]. Definitions of all the housing types can be found in table 1.

2.1.4. Construction materials

The construction materials discussed herein include concrete, bricks, mortar, steel, glass, drywall, wood, adobe, and mud.

2.1.5. Income levels

To identify potential income-related disparities or material usage patterns, we integrate the income level for each household. This was based on the widely-used socioeconomic levels (NSE—*Niveles Socioeconomicos*),

Table 1. Classification of residential buildings and their defining characteristics.

Formality	Building	Description
Formal	Confined masonry	Masonry walls reinforced with concrete tie-beams and columns for seismic resistance [42, 43]
	Reinforced concrete	Apartment or residential buildings of more than three floors, with reinforced concrete walls and roofing [38, 42]
	Formal traditional	Houses utilizing traditional construction materials, mainly adobe (mudbrick)
Informal	Informal traditional	Identical material composition as traditional housing but is classified under our definition of 'informal housing.'
	Informal Type A	Cement or brick walls and a roofing material that allows for vertical growth under the 'informal housing' definition or in nonresidential zones
	Informal Type B	Cement, brick, or stone walls and a roofing material that does not allow for vertical growth (i.e. steel, plywood, or mud)
	Informal Type C	Prefabricated sheds with mud or cement floors, plywood or steel roofs, and wooden walls
	Informal Type D	Plywood walls, plywood or mud roofs, and mud or cement floors

categorizing society into five groups, numbered 1–5, representing high, upper-middle, middle, lower-middle, and lower-income levels [44]. The map is shown in figure 1(a) and can be accessed through a formal request to the *Instituto Catastral de Lima* (ICL) [45].

2.2. Urban material stock map

The urban map was created using street block-level spatial data provided by the ICL. This data was used as the basis for each block's unique ID, income level, and location [45]. Each block may contain multiple buildings, which cannot be differentiated in this data, and therefore, a building and a block refer to the same entity in our research. A flowchart illustrating the methodology can be found in SI 1.1.

2.2.1. Building function

The first step in building the map is to determine what function each block has, either residential or nonresidential. For this study, we refer to Lima's publicly available zoning map [46], which shows the official zoning designation for the city's blocks. The zoning map needs to be adapted, not only because it was in Spanish, but also because the level of detail exceeds the scope of this research. The zoning symbology is used as the guiding factor for creating the broader categories. For example, any zoning category starting with an H is grouped into healthcare, any starting with RD is grouped into residential, and E into education, with the differentiation between schools and universities, and so on. The complete table describing the translations and grouping per zoning symbology can be found in SI 1.2. For informal settlements, we can sometimes directly use the zoning symbology, such as preurban zones [46]. In other cases, we need to analyze satellite images [47] of the city and discover areas that, despite having specific zoning symbology, actually contain human settlements. In these cases, we select the relevant zoning symbology and categorize them as informal housing.

Moreover, the zoning map does not always align with the boundaries of the polygons representing each block. This discrepancy allows for a single block to have multiple zoning designations assigned to it. Since we only have one ID per block, assigning each block to a single primary function is necessary. This is done by calculating the total area of each block polygon and determining the space each function occupies within that polygon. The area of each function is then expressed as a percentage of the total area of the polygon. The function that occupies the largest portion of the block is designated as the block's primary function. However, educational and healthcare centers that share a block with other functions tend to be underrepresented by this simplification. A block partially designated for education or healthcare is assigned to that function to address this. By the end of this step, each block has a single function.

2.2.2. Residential building classification

The residential buildings are classified using data from the publicly accessible 2017 nationwide census [42]. The census provides information about the physical characteristics of each household, which can be summarized into broader categories such as house type, primary wall, roof and floor materials, water supply, sanitation services, electricity access, and ownership status. The details of these categories are outlined in SI 1.3. One block may contain multiple households, but we can only utilize one representative value per block, which means we must aggregate the data. The aggregation is performed by using census data to determine the most common category of house in each block and then assigning it to the block as a whole. This results in each block having one single value per category.

The census also provides data regarding the type of housing (house, apartment, or informal). Those labeled as informal are directly identified as such. However, we can further recognize any additional informal housing based on the absence of the key characteristics defined in our informal housing definition (section 2.1.2). Specifically, we determine if a house is considered informal if the water supply does not come from a public network, the sanitation services are not connected to public drainage, there is no electricity connection, and the land ownership lacks proper property titles.

Additionally, we can use the wall and roof materials to assess the durability of the dwelling. Adopting the housing classifications described in section 2.1.3, we can categorize each building into one of five types (A, B, C, D, or Traditional) based on the combination of wall and roof materials (SI 1.3.) These subcategories will aid in selecting the appropriate material intensity (MI) category for each block. Type A structures feature reinforced concrete roofs and masonry walls, while Type B structures have masonry walls without reinforced concrete roofs. Type C structures utilize wooden walls, and Type D structures are characterized by plywood walls. Dwellings with adobe walls are classified as traditional houses. Any structure that does not fall under Type A or the traditional house category is considered informal due to the use of non-durable materials. Based on the census data, Type A or traditional houses require further classification as informal.

The zoning map [46] serves as the final criterion to determine if a housing block is informal. Suppose a block is situated in a nonresidential zone but is identified as a residence in the census. In that case, it is classified as informal housing based on the security of tenure characteristics. Furthermore, satellite imagery [47] analysis reveals the presence of numerous informal settlements in areas designated for 'other uses' or 'restricted zones due to environmental risks,' and these blocks are also designated as informal housing. Blocks identified as informal by the zoning map but lacking census data are further categorized as classified in section 2.2.6.

2.2.3. Material intensities

MI coefficients indicate the estimated amount of material required to construct a building of a certain type in kilograms of a particular material per square meter constructed [48, 49]. For confined masonry and reinforced concrete residential buildings, education facilities like schools and universities, and commercial buildings, the MI values are used by Gutiérrez and Kahhat, who conducted a rigorous study in two districts in Lima [37]. For healthcare facilities, we adopt the same MI values used for schools. Since both are classified as essential structures in the Peruvian seismic code, similar building characteristics will lead to similar MIs [20]. In the case of traditional houses, the MI information was sourced from Mesta *et al* [15], a study performed in Chiclayo, another Peruvian coastal city.

Informal housing, however, has no MI values in the literature, as no study in Peru has differentiated them before. Informal Traditional uses the same MI values as traditional housing [15], and Informal Type A uses the same values as confined masonry [37], the same MIs as their formal housing equivalents. To create MIs for Types B, C, and D, we integrate information from previous research conducted in Lima [15, 37], the Terwilliger Center for Innovation in Shelter publication [41], and data from the 2017 national census [42]. The Terwilliger Center for Innovation in Shelter report provides the monetary requirements to build a house of 100 m^2. For example, a Type B house was described as a 5000 USD investment comprising 75 bags of cement, 100 half-inch planks, and 4000 bricks [41]. We used these details to estimate the intensity of materials per informal building, though without dimensions; we assume their quantities using industry standards based on online retailers specializing in construction materials [50].

For Informal Type B housing, we assume that all structural components, except for the roofing, are similar to those used in confined masonry. This is because Informal Type B homes feature masonry walls with roofing made from materials other than concrete, as they are mostly waiting for the financial capacity to build a permanent roof. Census statistics indicate that among houses featuring concrete or brick walls but lacking concrete roofs, 75% have steel roofs, 13% plywood roofs, and 12% mud roofs [42]. Therefore, we require the MI for all these materials to calculate the average MI of a Type B house, incorporating an overlap of 20% for both steel and plywood sheets. The standard dimensions and weights of corrugated galvanized steel and plywood sheets were used to calculate their material intensities. For mud roofing, the MI of traditional housing roofs is utilized.

We assume pine as the material of the Informal Type C walls, as it is the most economical alternative in the market [51]. The MI calculation for wooden walls is based on the number of panels necessary to cover the house's perimeter. To calculate this, we use the following formula (equation (1)), where the area is given in m^2, the plank dimensions are in meters, and the weight of the plank is in kg,

$$\mathrm{MI_{Wall}} = {4 * \text{Plank weight}} \Big/ {\text{Plank dimension} * \sqrt{\text{Area of house}}}. \tag{1}$$

According to the national census statistics, 83% of wooden-walled houses utilize steel roofs, while 17% use plywood [42]. The MI calculations for Type C roofing are the same as those of Informal Type B, with the roofing contribution now comprising 83% steel and 17% plywood. The materials of the floor are determined using the Terwilliger report, which states that 80% of Type C houses have concrete floors, and 20% have mud floors [41]. The MI for concrete flooring is derived from confined masonry houses, while the mud flooring MI corresponds with that of traditional housing.

Lastly, Informal Type D housing is defined by plywood walls. Using the same dimensions for plywood as those used for roofs, we find the MI for plywood walls using the same formula as the one used for walls in Type C (equation (1)). Census data reveals that 70% of roofs on plywood-walled houses are also made from plywood, while 30% utilize mud [42]. The MI for plywood and mud roofs remains consistent with values previously established for the other informal types. The Terwilliger report states that the distribution of flooring materials in Type D houses is evenly split, with 50% featuring concrete and the other 50% consisting of mud floors [41]. The respective MI values for these flooring types correspond to confined masonry and traditional housing. For the specific values used for calculating the MIs for all informal types, refer to SI 1.4.

2.2.4. Building dimensions

The World Settlement Footprint (WSF) 3D database [52] is the basis for determining the dimensions of buildings in this study. This data is organized into 90 m $\times$ 90 m grids, with each grid providing the total area occupied by buildings. For our analysis, we focus on the building's height and footprint area, which reflects its ground coverage in m^2. Given the nature of grid-based data, one block could overlap with multiple WSF grid cells, each possibly providing data on different building dimensions. Therefore, a summary of one representative value per block is necessary. To achieve this, we assess the area each grid occupies inside the polygon and the total size of the polygon. Similar to the process used for function per building, these values calculate the percentage of each grid's total polygon. This allows us to determine the weighted average of all the grids located within the polygon. Essentially, we multiply the percentage of each grid's area within the polygon by its corresponding value and then aggregate these results into a single total. We calculate the percentage of the original grid size instead of just within the polygon. This percentage is multiplied by the grid value and summed for a comprehensive total. An example is provided in SI 1.5.

Each block was assigned a building height and area in meters. The area represents the building's footprint, not the gross floor space (GFA); the total number of floors is required. To calculate the number of floors, the total building height was divided by the average height per floor of 3 m, a commonly used value for the floor-to-floor height [49] (for further information see SI 1.6). Then, the GFA was calculated by multiplying the building footprint area by the number of floors.

2.2.5. Material stock calculation

We calculate the total materials stocked within each block by multiplying the GFA (m^2) by the MI (kg m^{-2}) for each material and then aggregate these values to determine the total material stock (kg) (equation (2)), where m represents each material and b each block.

$$\text{Material Stock}_b = \sum_m \left(\text{GFA}_b * \text{MI}_{b,m}\right). \tag{2}$$

2.2.6. Building the map

During the integration process, we identified data gaps, as not all blocks had complete information. Specifically, less than 2% of the identified blocks lacked building dimension data, while under 15% were missing an MI category. To estimate building footprints accurately, we calculate the percentage of the original grid size instead of just within the polygon. This percentage is multiplied by the grid value and summed for a comprehensive total (SI 1.7). The resulting urban material stock map, detailed in SI 3, provides comprehensive information for each block, including the block's ID, district, GFA in m^2, height in meters, number of floors, total material stock in tons, function, MI category, and income level.

3. Results

3.1. Material intensities and stocks

Concrete is the primary material across all building types, followed by brick and mortar, while traditional houses are predominantly constructed from adobe and mud. Wood has a more limited application, mainly found in informal Types C and D and traditional houses, while drywall is exclusively used in commercial buildings. Healthcare facilities and schools are the most material-intensive categories, followed by confined masonry and Type A buildings, with traditional housing after these. The total amount of materials ranges

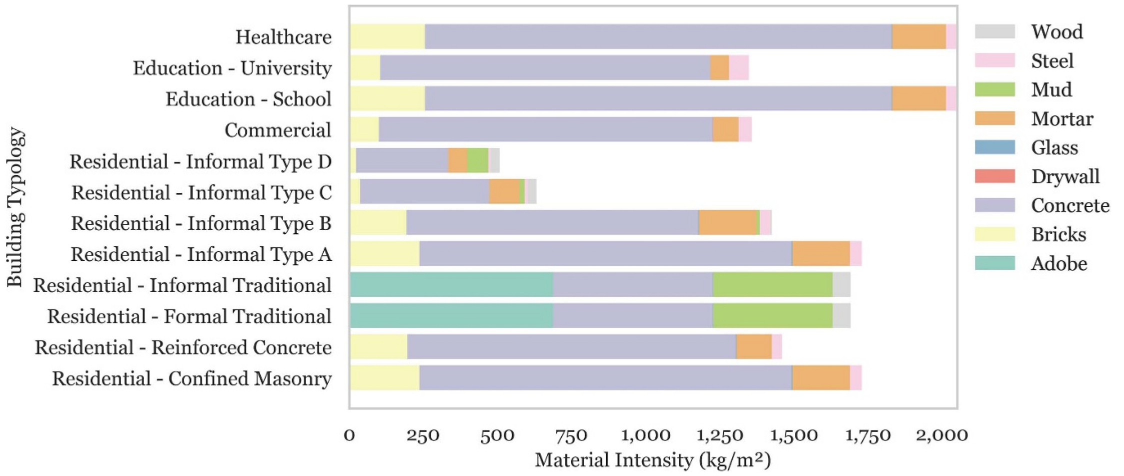

Figure 2. Material intensities (kg m^{-2}) of the studied materials for residential and nonresidential buildings. A table stating the values of each material can be found in SI 2.1, including the disaggregated and the weighted average material intensities.

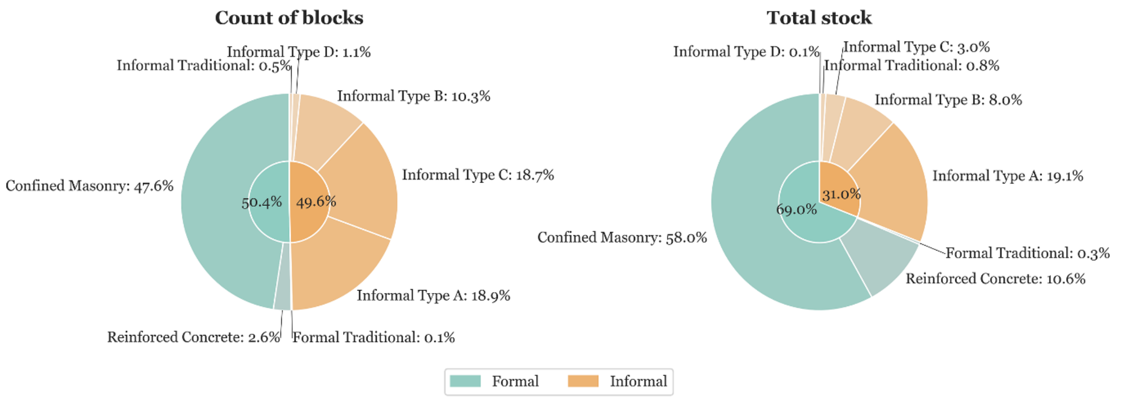

Figure 3. Contribution of each residential building category to the total number of blocks and the total stock of materials. A table stating the values of each material can be found in SI 2.2.

from 500 to 2050 kg m^{-2}, with concrete accounting for 74% of the total materials across all categories, except for traditional housing, where it only accounts for 32% (figure 2).

Of the total number of blocks, 89% are residential, while 11% are nonresidential. Figure 3 illustrates the distribution of residential blocks, distinguishing between formal and informal types. Informal blocks comprise 49.6% of the total count but only represent 31.4% of the material stock. Confined masonry and informal Type A are the most prevalent housing types, with nearly half of all houses in the city being confined masonry and just under a fifth being Type A. Type C is the third most common housing type, representing 18.7% of the total blocks while contributing only 3.1% to the city's material stock. Conversely, reinforced concrete constitutes 8.1% of the material stock despite making up just 1.6% of the blocks.

3.2. Spatial distribution of materials

3.2.1. Citywide distribution

The city has a central concentration of materials, as higher-density buildings can be found in the center (figure 4(a)). In this context, material density is defined as the total materials stored in the building divided by the building's footprint (the space it takes on the ground). Therefore, we can infer that either the city center has taller buildings, requiring more materials, or, if the buildings are of similar size, the materials used to build the houses in the city center are heavier than those in the outskirts, or that both are occurring.

Figure 4(b) examines the summed MI —total material stored divided by the GFA of the building—and its relation to household income. Buildings with greater MI are found in the center; however, the differentiation between high-rise and low-rise buildings is now clearer based on the MI. Moreover, we can observe the dynamics between the outskirts and income, corroborating what we already saw in figure 1(a). This analysis reveals the connection between two dimensions: households within the high, upper-middle, and middle income groups in the city have an average MI of 1650 kg m^{-2}, which is 7% greater than that of

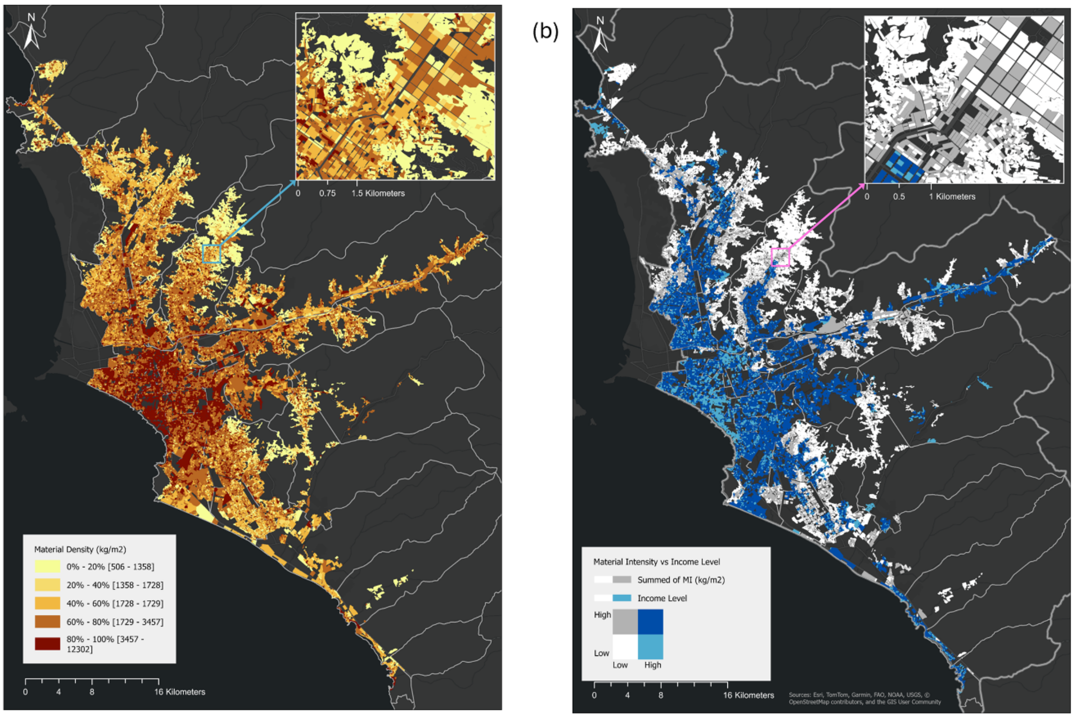

Figure 4. Spatial distribution of (a) material density of the stock per building footprint (kg m^{-2}) and (b) summarized material intensity values (kg m^{-2}) in a 2 × 2 bivariate scale against the income level of the household. The values for both maps can be found in SI 2.3. San Juan de Lurigancho, the most populous district in the city, is located in the corner as the zoomed-in area, primarily comprising middle- and low-income households.

lower income households (1540 kg m^{-2}) and 26% less than that of low income households in the outskirts (1224 kg m^{-2}) (SI 2.3).

3.2.2. Comparison between districts

Two of Lima's prominent districts, San Isidro and San Juan de Lurigancho (SJL), are compared in figure 5 across four different aspects. While San Isidro is one of the most developed districts of the Peruvian capital, mostly hosting families of high socioeconomic status, SJL is the most populated district representing middle and low-socioeconomic families. We selected an area characterized by informal settlements, which is also the area that is zoomed in on all the citywide maps (figure 4).

The building's functions are shown in figure 5(a). While the SJL area is predominantly residential, it also contains some educational facilities and several commercial establishments. On the other hand, San Isidro displays a greater diversity in its functions, with multiple commercial buildings, educational institutions, four healthcare centers, and a residential area.

The zoomed-in version of figure 4(b) can be found in figure 5(b), but with a 3 × 3 bivariate scale, which showcases the main difference between the two districts. With the exception of the central area, possibly around the main road, SJL predominantly has a low-income population (figure 1(a)), as well as a low MI consumption (figure 4(a)). However, there is a stark separation between the center and the outskirts, where higher-income, high-material-intensity residences are situated next to low-income, high-material-intensity homes. Moreover, regardless of the MI of the houses, all homes outside the main road center are low-income. In contrast, San Isidro, being a high-income district, is composed solely of high-income households, with varying MI.

Certain materials are only present in specific housing types, with wood being limited to Types C and D, while concrete is found across all types at varying intensities (figure 2). Therefore, these two materials can be useful in identifying spatial patterns. No wood is present in San Isidro (figure 5(c)), given the absence of informal houses in this district. On the other hand, the presence of wood in SJL increases with distance from the main road center, particularly in the outskirts where the informal settlements are situated in hilly terrains, as indicated by the transition from organized blocks to those conforming to the topography.

Although MI varies, there is an overall substantial prevalence of concrete in San Isidro, as seen in figure 5(d). In SJL, while the main road center has a substantial concentration of concrete, even at levels comparable to San Isidro, it is not the only location where this material is found. The neighborhood immediately to the north, which also displays wood, has a notable use of concrete as well, meaning that these

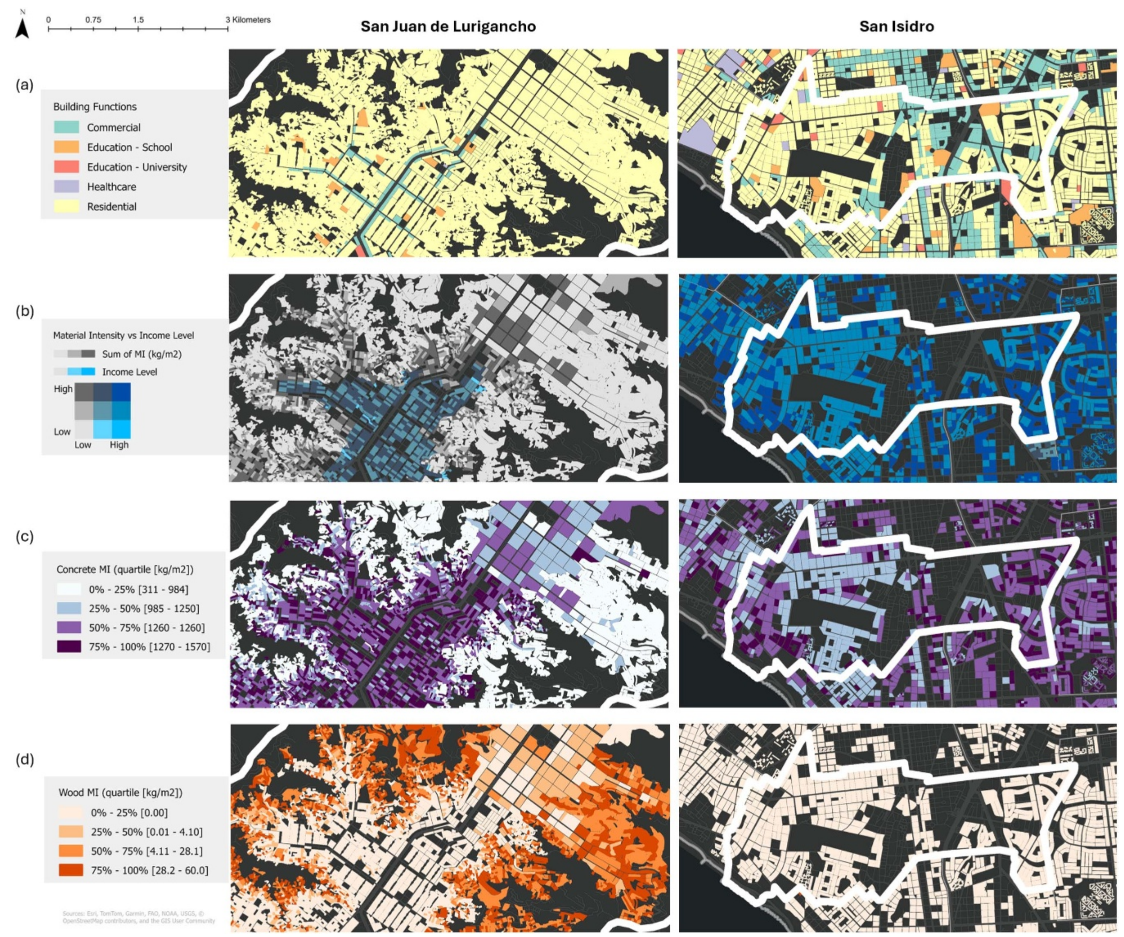

Figure 5. Spatial distribution of San Isidro and San Juan de Lurigancho under four characteristics. (a) Functions of each building, (b) summed material intensity values (kg m^{-2}) in a 3 × 3 bivariate scale against the income level of the household, (c) material intensity of wood (kg m^{-2}) in residential buildings, and (d) material intensity of concrete (kg m^{-2}) in residential buildings.

are masonry-walled, with those featuring wood categorized as Type B houses and those lacking it as Type A houses.

3.3. Population distribution

Figure 6 reveals that as population density increases, material density tends to decrease at a rate influenced by income. Higher population density does not automatically mean a higher material density. Furthermore, districts with higher incomes show different population density patterns compared to those with lower incomes, with wealthier areas generally displaying greater average material densities. In other words, lower-income districts tend to use fewer materials per capita than higher-income districts, as seen in San Isidro. High-income districts will most likely have a higher material density per capita than their lower-income counterparts within a given population density.

4. Discussion

4.1. The challenge of defining informal housing

Defining informality is not straightforward; it involves nuances and the risk of oversimplification when identifying it in practice. While this study found that 49.6% of houses in Lima are informally built, media estimates [26–30] suggest the figure is closer to 70%–90%. This raises questions about the definition of informality and whether more characteristics need to be added to our definition. For example, the Peruvian government considers a house informal if no professionals are involved in its construction [40]; however, this aspect is not included in the UN-Habitat definition [23] nor in our methodology because available data makes it impossible to determine if professionals were involved in the construction. The level of professional involvement necessary for a building to be deemed formal is also disputable. Many houses are labeled formal simply because an engineer signed the construction plans, even though the engineer may not have been

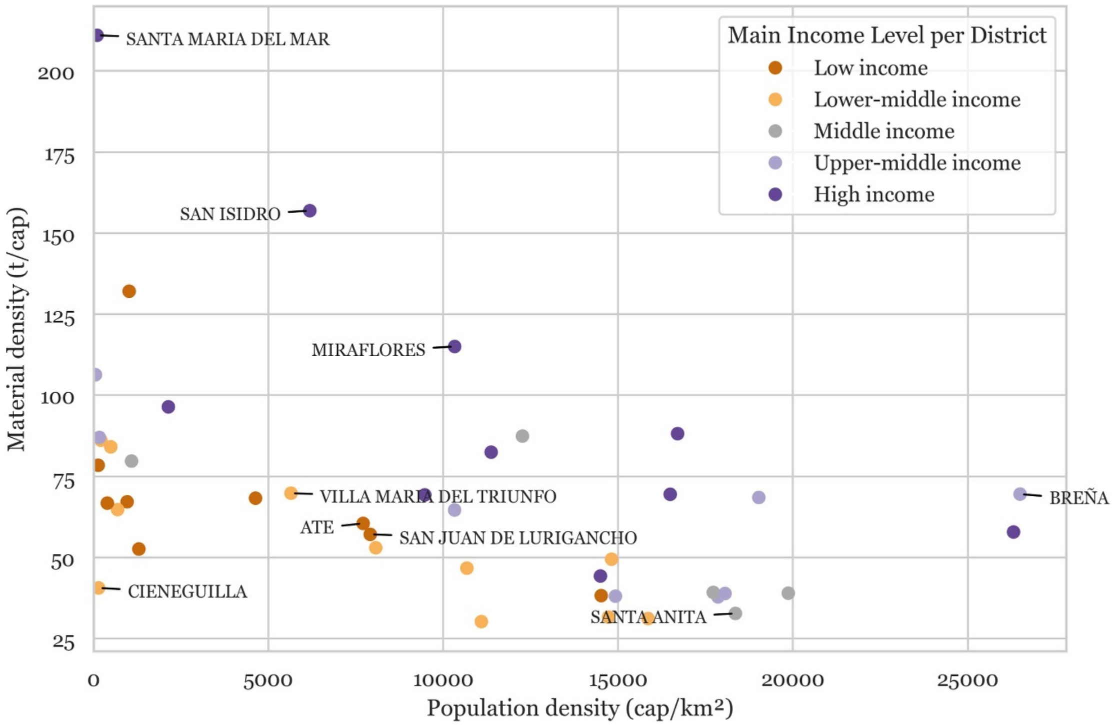

Figure 6. Material density (tons per capita) compared to population density per capita per district area, with a distinction between income levels. The data for this plot can be found in SI 2.4.

present during the actual construction, making it difficult to determine if the building adhered to those plans. Professionals may also be involved in building houses on land designated for uses other than housing. Thus, a house's production and materials are not sufficient to define it as formal or informal. Another prominent aspect of informality in Lima is self-construction, which is a common and more affordable way for families to build homes at their own pace based on their financial capacity. While self-constructed and informal housing are often perceived as synonymous in everyday life, between 3% and 6% of self-constructed homes involve professional assistance [30, 53]. Self-construction should not always be equated with informality; rather, the involvement of professionals alone may be sufficient to classify a home as formally constructed.

The study simplified the access to basic services, such as water and sanitation, in informal settlements. Before obtaining a network connection, informal houses often rely on water from cistern trucks, which are 5–8 times more expensive than public networks and carry a higher risk of contamination [54]. However, in terms of sanitation, houses with private systems, like septic tanks or treatment latrines, are not considered to be provided with sanitation in our current definition, even though the service could be satisfied. We can consider certain services satisfied if they are accessible through alternative means, raising the question of whether public accessibility is a necessary standard for equal service provisioning.

Throughout this study, the term 'informal' has been the only one used to refer to these houses and settlements, but there are two other terms that also play a role in the housing shortage and should be acknowledged: 'illegal' and 'irregular' housing. Illegal settlements refer to the unlawful occupation of land, land trafficking by unauthorized developers, or the use of land for purposes other than those legally allowed [55]. On the other hand, irregular settlements are those that do not fully comply with the legal or regulatory framework but do not involve outright criminality, meaning they usually occur in the gaps of official processes or regulations [55]. Ineffective urban governance allows illegality and informality to thrive, while irregularities are normalized in the absence of urban planning or enforcement. Typically, a settlement goes through a known cycle, starting with land occupation, self-construction of homes, self-organization of a community, and finally, or hopefully, leading to the consolidation of the settlement, meaning official acknowledgment by the government and inclusion into the 'formal city' [56]. Informal housing can be constructed irregularly, meaning legislation is still needed to fill the gap, or it can be built in illegal areas, bringing its own challenges.

4.2. Urban map data synthesis

When synthesizing these observations, a clear pattern emerges. Lower-income houses predominantly feature wood, which is not surprising, as this material is characteristic of informal housing, which is typically

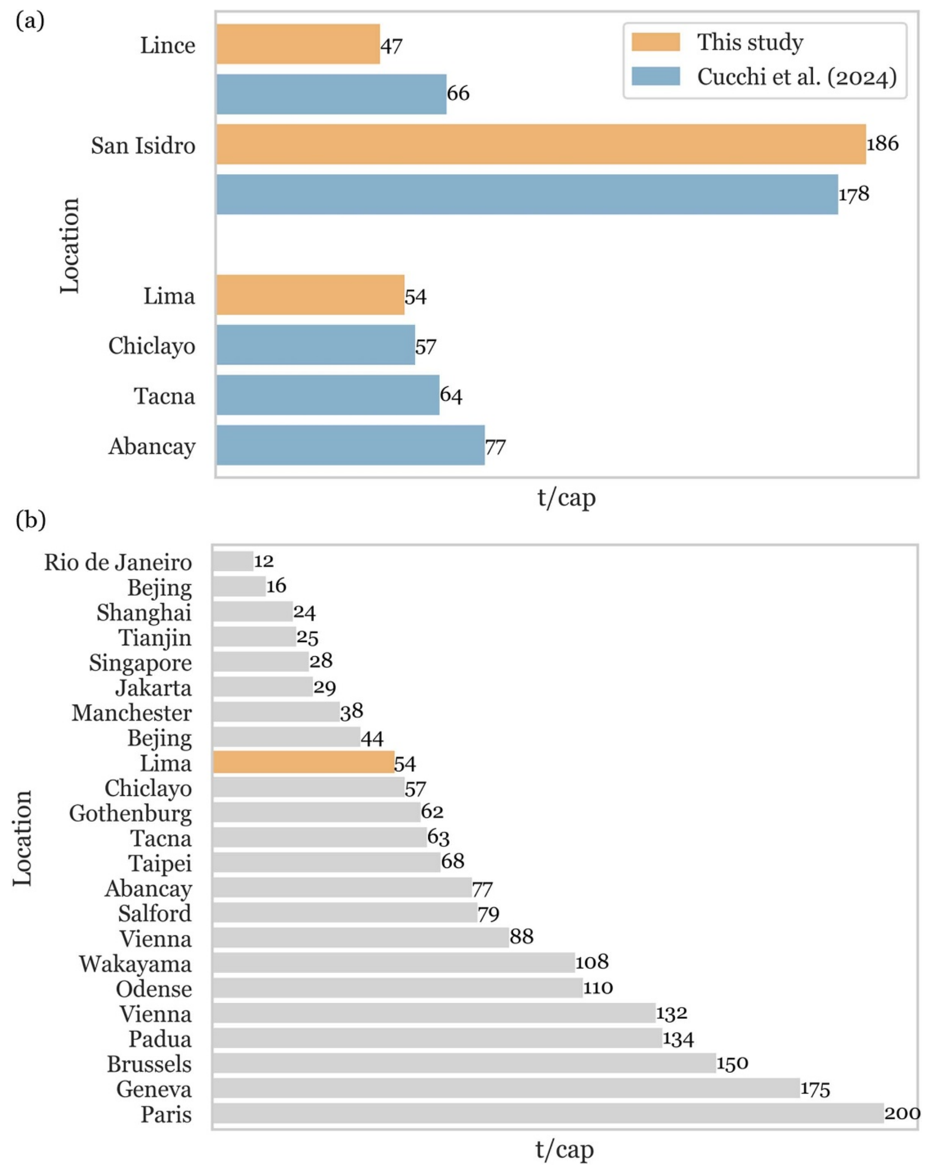

Figure 7. (a) Comparison of material consumption in tons per capita for previously studied locations and the current study (b) comparison of material consumption in tons per capita between different locations worldwide, where the year indicates not the publication year but the year of the data studied [12, 14–16, 37, 38, 60–72], for a detailed list, see SI 2.5.

inhabited by lower-income households. However, concrete does not serve as a reliable indicator for higher-income houses. While its presence is indeed predominant in formal buildings, it is not exclusive to these. Thus, it can be inferred that, in instances where income indicators are absent, wood could be used as a metric for identifying lower-income households within the context of Lima. In the GN, the integration of timber into construction is regarded as a promising alternative for decarbonizing housing [57, 58]. However, it is crucial to acknowledge that the wood utilized in these structures differs significantly from that examined in these scenarios. In this context, the wood comprises sheet panels that lack structural properties and exhibit high levels of deterioration in humid weather conditions [59].

4.3. Data validation

4.3.1. Comparison within Peru

Four studies have been conducted in Peru, all using consistent methodologies: one in Chiclayo (2016) [15], another in Tacna (2017) [17], one in Lima (2022) [37], and one in Abancay (2024) [38]. The stock per capita in this study, at both district and city levels, is lower than previous studies for all but San Isidro (figure 7(a)), most likely due to methodological differences. These differences include the source of the building dimension data; earlier studies used locally gathered data and on-site measurements [38], while we relied on satellite data. The 2022 study's data from San Isidro is compatible with our current methodology, allowing us to explore differences between the data sources and methodologies. Firstly, we can rule out any discrepancies coming from the presence of informal housing, as there are no such structures in the district. Secondly, when applying this study's methodology to the raw data from the Gutiérrez and Kahhat study, we find that the material stock per capita for the district would be 162.1 t/cap, a figure that is relatively close to the one identified in this study. The variation likely comes from the aggregation of buildings into single blocks, a result of data limitations, as the GFA per capita in the previous study was 22 m^2/cap smaller than in the current analysis. However, we can see that the previous findings and the current ones align closely enough for us to validate the use of global, top–down datasets such as the WSF [52] when local data is missing in a city like Lima.

4.3.2. Comparison with cities worldwide

A review of studies on material stocks in cities worldwide reveals variations in the per capita stocks (figure 7(b)). The accumulated stock can range from 12.3 t/cap in Rio de Janeiro [16] to 200 t/cap in Paris [71]. Lima, with an average value of 54 t/cap, appears to be on the lower end of this spectrum yet remains consistent with findings from previous studies [12, 14–16, 37, 38, 60–72]. A clear divide emerges between GN and GS cities, with the latter predominantly exhibiting stocks below 78 t/cap, whereas most GN cities report higher values. Interestingly, Lima's stock closely aligns with Beijing's, which stands at 44.1 t/cap [62]. This is intriguing, as the two cities differ visually and architecturally, suggesting a need for further research to understand how these differences result in similar material densities. The district of San Isidro (156.9 t/cap) occupies a position between Brussels (134 t/cap) and Geneva (175 t/cap) [69, 73]. It is crucial to emphasize that the methodological variations across these studies render direct comparisons of these values problematic; thus, figure 7(b) serves primarily as a reference point to corroborate that the material stock found in this study is within the expected range based on existing literature.

4.4. Uncertainties of the data

4.4.1. Material intensities

Among the necessary simplifications made in this study, we assumed that all houses with brick walls would have a confined masonry structure, regardless of whether the building is formal or informal. Confined masonry is standard in Lima since concrete tie beams and columns are legally mandated for seismic resistance [74]. However, many informally constructed homes may not comply with construction codes, resulting in uncertainties about their structural integrity. This raises questions about the suitability of applying the same MI to both formally constructed confined masonry homes and informal Type A houses. This discrepancy is exemplified in figure 8, where two informal Type B houses with distinctly different construction features are shown: one includes concrete beam reinforcement typical of confined masonry, while the other lacks such structural support. We can assess the sensitivity of this uncertainty by recalculating the city's stock under the alternative assumption that all informal houses with masonry walls lack any structural reinforcement, whether steel or concrete (the corresponding alternative MI values can be found in SI 2.6). This adjustment results in a 25% reduction in mass per building for Type A houses and a 30% reduction for Type B houses. Nonetheless, when scaled to a citywide level, the total material stock per capita reduction was relatively modest, decreasing from 54 t/cap to 50 t/cap. While the adjustment impacted the per-building scale, its comparatively limited aggregate level effect underscores the overall approach's robustness.

A challenge that is almost impossible to address in a systematic study of the magnitude of a city as a whole is illustrated in figure 8: the incorrect use of materials by the constructors. We can see the blue-framed house utilizes bricks that are not seismic-resistant, a common issue in Lima, as are those of lower cost. This complexity in material intensities within the informal sector is further increased by the possibility that this building may have been inspected and approved by an engineer. Yet, a different type of brick was ultimately used during construction. This situation suggests further exploration [75–77] in order to effectively distinguish between formal and informal housing, even when they appear nearly identical from the outside, a scenario that could occur if the exterior brick were covered with stucco.

Furthermore, it is important to address the source from which the material intensities were calculated. The qualitative study did not specify the total quantities of materials, only the types of materials required and their monetary values. Therefore, the weights and dimensions of the materials were sourced from industry standards. As previously mentioned, it is highly probable that informal housing does not adhere to these industry standards but instead utilizes more economical alternatives. Given that these cheaper options tend to be lighter or utilize fewer materials, one could argue that relying on industry standards may lead to overestimating material requirements. Furthermore, this classification limits informal housing into four distinct categories, though it is important to recognize the inherent variations within each class. For example, Type B houses may have steel, plywood, or mud roofs. Due to the data's limitations, we cannot determine the specific roofing material for each structure, meaning that we need to include all potential materials in a single

Figure 8. Two examples of informal Type B housing: with concrete reinforcement (blue) and without (orange). (Photo credit: '3375751716013054'<https://bit.ly/4fFNVvf> by 'kaart_2', licensed under CC-BY-SA).

category using a weighted average. This results in a MI estimation that does not accurately reflect individual buildings' reality but provides an overall average for the materials consumed within that category.

4.4.2. Spatial data

Two uncertainties regarding the spatial data warrant discussion in the context of our methodology, both arising from our data sources. First, we use the WSF, which provides valuable building size information globally [52]. However, it has only been validated in a few locations. In the GS, validation exists only in Cartagena, Colombia, along with three cities in Africa, two in the Middle East, and two in the Philippines. In contrast, validations in the GN included three cities in the United States, four cities in the European Union, China, Korea, and New Zealand [78]. Although this distribution reflects the considerable disparity in available data between the GN and the GS, uncertainties are inherent in a dataset with limited validation. While our findings correlate closely with prior studies using field data, as discussed in section 4.3.1, we cannot assume a similar level of accuracy for all GS cities. Moreover, the WSF data only covers aboveground features and excludes underground structures [52]. This limitation poses minimal implications for cities lacking subterranean infrastructure, such as Lima, where the underground structures are mainly parking lots. However, it is a factor to consider if this methodology is to be applied in other locations where such infrastructure is more common. Second, we use the ICL dataset, as it is available only at a block level [45]. As illustrated in the maps presented in the results, blocks can exhibit notable variability in size, meaning there is potential for error in estimating the dimensions of buildings or the quantity of specific service-providing facilities.

5. Conclusions

This study aimed to develop a methodology to create an urban material stock map for Lima, Peru, that would include nonresidential and residential buildings, the latter being subdivided into informal and formal housing. By doing so, this research filled two gaps in previous studies. First, it focused on a GS city, Lima, where research on the use of construction materials in urban environments is limited. Most studies have primarily focused on the GN, often leading to misrepresentations of the realities faced by cities in the GS. Second, this study explicitly distinguished between formal and informal housing types, a distinction that has often been overlooked in previous research. Classifying informal housing based on specific criteria and material compositions provided a nuanced understanding of material usage and its implications for urban planning.

The study opened avenues for further exploration into the dynamics of informal settlements, particularly their material composition and resilience to climate change. It encouraged the investigation of socioeconomic factors linked to material stocks, potentially leading to strategies that address income inequality and promote social well-being in urban planning. The methodology was developed using data sources that enable transferability across geographical locations, particularly in South America, due to the similar structure of census data. Future research should explore the applicability of this approach in other cities, as it has only been tested in one location to date. This would facilitate comparative studies that enhance our understanding of urban materials and inform global sustainable development practices. Ultimately, this study serves as a foundational step toward enhancing our understanding of urban material flows in the GS, paving the way for future research to refine methodologies further and tackle the pressing challenges of sustainable urban development in rapidly growing cities.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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CRediT authorship contribution statement

Alessia Linares-Capurro: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Visualization, Writing—Original Draft, Writing—Review & Editing. **Ramzy Kahhat**: Conceptualization, Data Curation, Formal analysis, Writing—Review & Editing. **Janneke van Oorschot**: Formal analysis, Writing—Review & Editing. **John L. Heintz**: Conceptualization, Validation, Formal analysis, Supervision, Writing—Review & Editing. **Tomer Fishman**: Conceptualization, Formal analysis, Writing—Review & Editing, Funding acquisition, Project administration.

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