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Citation

Linares Capurro, A. D., Cardenas Mamani, U. C., Kahhat, R., & Fishman, T. (2026). Building inequality: how construction materials shape service provision and socio-economic divides in Lima. *Resources, Conservation And Recycling*, *228*. doi:10.1016/j.resconrec.2026.108815

Version:	Publisher's Version
License:	Creative Commons CC BY 4.0 license
Downloaded from:	https://hdl.handle.net/1887/4306998

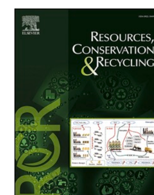
Note: To cite this publication please use the final published version (if applicable).

Resources, Conservation & Recycling 228 (2026) 108815

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling



Building inequality: How construction materials shape service provision and socio-economic divides in Lima

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ARTICLE INFO

Keywords:
Means and ends framework
Material stock analysis
Planetary boundaries
Informal housing
Urban inequality
Construction materials

ABSTRACT

Urban infrastructure is crucial for socio-economic development, yet the link between construction material stocks and societal needs in rapidly growing Global South cities remains insufficiently understood. This study conducts a spatially explicit analysis of Lima, Peru, mapping material stocks for buildings dedicated to shelter, education, healthcare, and collective amenities, and relates them to Decent Living Standard (DLS) thresholds and income levels. Results show that heavily populated, low-income, informal areas accumulate greater material stocks but suffer from poorer access to essential services, driven primarily by population demand. In higher-income zones, per-capita living space becomes more significant. This reveals socio-metabolic inequality, as material-intensive expansion in marginalized neighborhoods does not translate into improved well-being. Service privatization and informality exacerbate unequal access. The study concludes by recommending additional factors for future research to refine the understanding of material stocks and service provision relationships in urban contexts.

1. Introduction

Construction materials are crucial to the socio-economic dynamics of urban regions, forming the basis for the essential infrastructure needed to fulfill basic needs (Haberl et al., 2021). Urban infrastructure represents a durable, long-term investment, entailing substantial financial costs, resource consumption, and large waste generation (Han and Xiang, 2013; Liu et al., 2020). Their spatial distribution and function are shaped by local needs while simultaneously shaping how the area will be organized for decades to come (Fadda, 2024). In other words, construction materials are both a driver and a product of societal service provision.

Material consumption and societal services are interconnected: construction materials are needed to supply essential services such as housing, education, and healthcare, all of which are necessary to help eradicate poverty (Hickel et al., 2022; Vélez-Henao and Pauliuk, 2023). Yet the service access discipline typically measures either physical availability or user satisfaction in isolation, rarely linking these to underlying material stocks (Denpaiboon et al., 2019). This disconnect pervades mainstream policy frameworks, such as the Sustainable Development Goals (SDGs), which separate service provision (e.g., health and education in Goals 3 and 4) from material management (e.g., resource efficiency and waste reduction in Goal 12), with only Goal 11 (Sustainable cities and communities) partially integrating the two by emphasizing adequate housing and resilient infrastructure (UN, 2015). This separation echoes other disciplines, such as urban political ecology and critiques of the governance of resilience and infrastructure, which highlight unequal socio-ecological access conditions (March and Swyngedouw, 2022) but rarely quantify the material bases that enable or constrain service provision.

In rapidly growing Global South (GS) cities, limited urban planning and accelerated population growth have led to widespread informal housing and reliance on privatized service provision (Adharina and Rukmana, 2024; Fadda, 2024), both of which are the result of population growth outpacing both legislative and construction responses (UN-Habitat, 2018; Wegmann and Mawhorter, 2017). Society often depends on private institutions to supplement the delivery of public essential services, resulting in socio-metabolic inequalities: wealthier, long-established residents have easy access to services, while lower-income groups and recent migrants face persistent barriers (Schuster and Otto, 2023). To meet the needs of a growing population, more infrastructure is necessary. Given that material consumption

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https://doi.org/10.1016/j.resconrec.2026.108815
Received 27 August 2025; Received in revised form 21 January 2026; Accepted 23 January 2026
Available online 2 February 2026
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creates considerable environmental pressures, including greenhouse gas (GHG) emissions, loss of biodiversity, and water scarcity (Vélez-Henao and Pauliuk, 2023), we must consider construction materials not only in terms of their emissions but also in relation to human development.

A growing body of work has begun to explicitly connect material stocks, service provision, and well-being. Frameworks such as the energy service cascade (Kalt et al., 2019), the Decent Living Standards (DLS) (Vélez-Henao and Pauliuk, 2023), the stock-flow-service nexus (Haberl et al., 2021), RECC (Pauliuk et al., 2021), and Means and Ends (Tanikawa et al., 2021), address the gap between material use and societal outcomes by linking resource flows and material stocks to the services they enable and their environmental impacts. These frameworks emphasize that material and energy stocks mediate the relationship between resource consumption and human development, introducing concepts such as material stock productivity and minimum stock requirements for basic services (Pauliuk, 2024). Despite this, several gaps remain. First, many of these frameworks have been developed and applied mainly in high-income or rapidly industrializing contexts, with limited empirical work in GS cities facing inequality and partial informal growth. Second, existing assessments often rely on national or city-level aggregates, which can obscure intra-urban socio-spatial patterns of material stocks and service access. Third, few studies combine spatially explicit material stock data with service access and socioeconomic indicators, limiting our understanding of where material investments do and do not translate into services.

This gap matters because while material consumption and human development have a positive connection, this has its limits. Beyond a certain level, increased consumption fails to enhance well-being, particularly regarding qualitative needs such as healthcare and education (O'Neill et al., 2018). The concept of *prosperous consumption* captures the idea that social thresholds can be met without exceeding planetary boundaries (Pauliuk, 2024), which shifts attention from increasing stocks to understanding how stocks are distributed and converted into services. Quantifying the socio-metabolic relationships between material stocks and service provision, especially with spatially explicit data, is a critical first step (Singh et al., 2022). However, data scarcity is a primary limiting factor in research within these domains, particularly in urban areas experiencing population growth, where societal needs remain inadequately addressed (Brand-Correa et al., 2022; Kallis et al., 2025; Vélez-Henao and Pauliuk, 2023; Watari and Yokoi, 2021). Moreover, many of these studies still lack empirical validation in real-world contexts, particularly in the Global South.

To address these gaps, this study links construction materials and service provision using Lima, Peru, as a case study, employing an urban material stock map, or urban resource cadaster (Linares-Capurro et al., 2025), to identify material use by service type. We draw on the Means and Ends framework (Tanikawa et al., 2021) to conceptualize construction materials as a means to achieve societal ends, and on the DLS framework (Vélez-Henao and Pauliuk, 2023) to define minimum thresholds for essential services. This study maps stocks across shelter, education, healthcare, and collective services, relating them to DLS thresholds and income levels while considering building function, formality status, and income level. Lima exemplifies both challenges and opportunities of this approach: over a quarter of its population lives below the poverty line (INEI, 2023), >70 % of housing is informal (Pighui Bel, 2014), and the majority of educational and healthcare facilities are privately operated (Diario Médico Perú, 2024; Espiritu, 2024). By linking material stocks to service outcomes, this study provides empirical data to advance existing frameworks for social and environmental assessment, with a particular focus on underrepresented GS urban contexts. Our approach combines open-access data sources and a multidimensional perspective to link material stocks with essential service access, following the Decent Living Standards (DLS) framework, expanding the Means and Ends framework, and enriching methodological and theoretical views on the connection between urban infrastructure, service provision, and socio-metabolic inequalities in rapidly growing cities.

2. Methods

2.1. Theoretical framework

2.1.1. Means and Ends

This study uses the Means and Ends framework to assess how effectively construction material stocks serve as a means to achieve societal ends, such as shelter, education, and healthcare, that contribute to human well-being (Tanikawa et al., 2021). The framework provides indicators to link raw material use to societal outcomes, emphasizing material stock productivity as a measure of the relationship between built capital and service provision. Building on the conceptual discussion in the introduction, we apply this framework to examine how spatial patterns of construction materials in Lima relate to the distribution and quality of essential services. To operationalize the framework, we link spatially explicit material stock data from Linares-Capurro et al. (2025) to Decent Living Standards (DLS) thresholds (see Section 2.1.2). For each district, we calculate stock intensity (tons per capita, see Section 2.3.1) by service type based on the estimated quantities of construction materials embodied in buildings of each category. These intensities represent the material "means" available per person to support each service. We then relate these means to indicators of service "ends", which enables the identification of mismatches between material investment and actual service outcomes.

2.1.2. Decent living standards

Service provisioning can be understood through the framework of Decent Living Standards (DLS) and how construction materials support these services, building on the work of Vélez-Henao and Pauliuk (2023). DLS encompasses a range of sociocultural factors that can be viewed as the minimum requirements for human well-being (Rao and Min, 2018). Its dimensions include shelter, education, healthcare, collective services, communication, mobility, nutrition, hygiene, and clothing (Vélez-Henao and Pauliuk, 2023). Our focus is specifically on shelter (residential buildings), education (schools and universities), healthcare (hospitals and clinics), and collective services (offices, restaurants, governmental buildings, and retail spaces). This DLS classification allowed us to connect a function to each city block in the urban material stock map (SI 2.2). Vélez-Henao and Pauliuk (2023) provide baselines, or minimum values, to determine if a DLS dimension is being sufficiently fulfilled based on the amount of construction material present per capita in an area: 21 t/cap for shelter, 5 t/cap for collective services, 3 t/cap for education, and 2 t/cap for healthcare.

By combining DLS thresholds with the Means and Ends perspective, we evaluate not only whether districts meet the minimum material requirements for decent living, but also how effectively these material stocks are translated into actual service access.

2.2. Data sources

2.2.1. Material stock

We use the data from Linares-Capurro et al. (2025)'s urban material stock map of Lima, which provides block-level data on construction materials, building function, and housing typology across the city's 43 districts. It is the first dataset of Lima to explicitly differentiate between formal and informal housing using census and satellite data, employing GIS-based bottom-up material stock assessment. It includes gross floor area, material intensity coefficients, and total stocks for concrete, brick, steel, wood, mortar, adobe, glass, drywall, and mud, enabling a granular assessment of urban infrastructure distribution (Linares-Capurro et al., 2025). As this study is open-sourced and provides a detailed methodology, our study is able to conduct socio-spatial analyses without re-implementing the original methodology. Throughout the paper, district names are accompanied by their postal code in square brackets; a map of the districts and postcodes

is available in SI 2.1.

2.2.2. Informal housing

Following the previous study (Linares-Capurro et al., 2025), we define informal housing as that which lacks any of the following: access to water, electricity, or sanitation from the public network, durability, or security of tenure. We subcategorize informal housing into five types based on wall and roof material. 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 (Linares-Capurro et al., 2025).

2.2.3. Population

To calculate the amount of stock per capita, we assumed that the population within a district solely uses the services available there. We use population statistics at the district level from the National Statistics Institute (INEI) (INEI, 2023). This assumption has limitations, as some districts may have a high concentration of office buildings or many second homes, especially in beachfront areas (García, 2024). For hospitals and schools, it also implies that people only seek these services within their district, which is not always true, especially given the uneven distribution of schools and hospitals in Lima (Proexpansion, 2014). We determined population density by dividing the total population by the total area of each district.

2.2.4. Income levels

To determine each district's income level, we identified the most frequently occurring income level among residents in that district and used it to represent the entire area. Districts were categorized as high (>2412 PEN/cap), upper-middle (2 411 PEN/cap – 1 450 PEN/cap), middle (1 449 PEN/cap – 1 074 PEN/cap), lower-middle (1 073 PEN/cap – 863 PEN/cap), and low (<862 PEN/cap) income levels, based on income strata from INEI (INEI, 2020). For more details on each district's income distribution, see SI 1.1.

2.3. Analysis

2.3.1. Drivers of stock accumulation

To understand the drivers of stock accumulation, we integrated three existing indicators from the urban stock map, which allows us to explain the connection between the type of building materials, the amount of floor space per person, and the total demand for services in the area due to the total stock. Therefore, stock in a district can be described as shown in Eq. (1) .

$$Stock_{District} = Floor\ space\ per\ person \times Stock\ use\ intensity \times Population \quad (1)$$

The formula can be represented with our data as Eq. (2).

$$kg_{District} = m^2/cap \times kg/m^2 \times Population \quad (2)$$

The total stocks in each district were calculated by summing the stocks per block for each service within that area. A similar method was used to calculate the total floor space. The total floor space per person was calculated by dividing the district's total floor space by its total population, resulting in the average floor space per capita. We calculated stock use intensity by dividing the total stock by the total floor space, which gave the average intensity.

2.3.2. Statistical analysis

To assess the statistical significance of stock drivers across income levels, we conducted a two-step analysis. First, we calculated the mean for each driver in each district, categorized by income classification. Then, we applied the Kruskal-Wallis H test, a non-parametric method used for comparing more than two independent groups when normality cannot be assumed (SPSS, 2021). We set a threshold at $p < 0.05$ to determine the statistical significance of observed differences among income groups. A p-value below this threshold indicated that at least one group significantly differed from the others.

3. Results

3.1. Urban spatial structure: income vs informality

The spatial distribution in Lima exemplifies several dichotomies, notably formal versus informal housing, the distinction between the outskirts and the inner city, and the contrast between high-income and low-income households (Fig. 1). Informal housing predominantly occupies the peripheries of the city, while formal residences characterize the inner city. Higher-income households, represented by darker colors on the map, are situated in the central area, whereas lighter shades indicate the increasing presence of lower-income households at the city's margins. As one moves away from the center, there is a noticeable transition in map coloration from darker to lighter shades (lowering income levels) and from purple (formal) to orange (informal). However, some higher-income households can be found in the periphery; these are likely beach or country houses, commonly owned as secondary residences in regions farther south and east, making them outliers to the overall pattern.

Although not a definitive rule, formal housing generally correlates with higher income levels, whereas informal dwellings are typically associated with lower incomes and are located on the outskirts. However, it is crucial to recognize that informal housing can also exist within

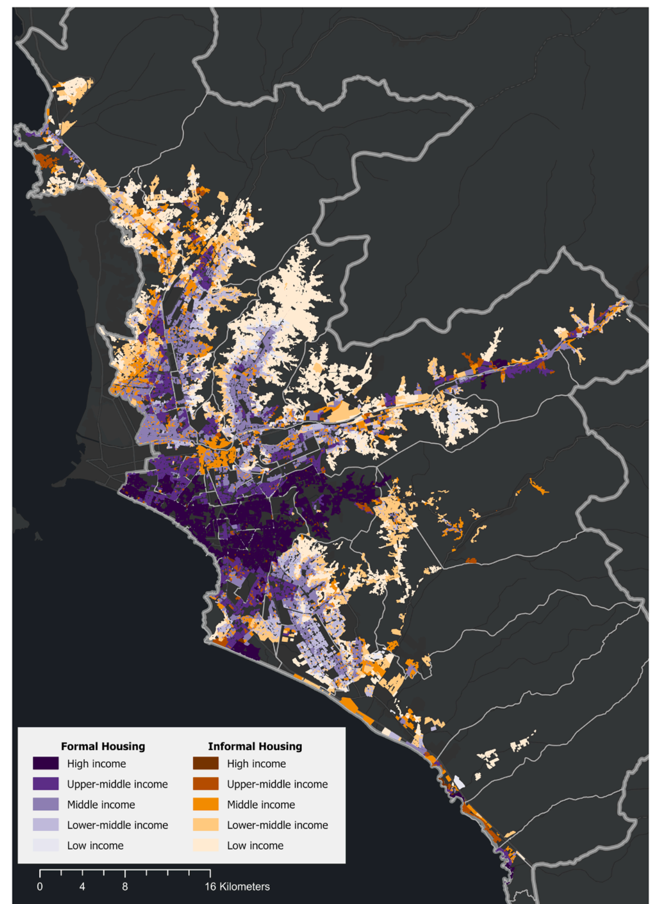

Fig. 1. Income level vs formality status of the household. The spatial distribution of formal and informal housing throughout the city and how they relate to the income levels of the households.

middle and upper-middle-income brackets, suggesting that informality does not necessarily indicate low income. Notably, informal houses located in proximity to formal residences tend to reflect higher income levels as well (Fig. 1). This observation reinforces the notion of a socio-economic divide, as wealthy individuals inhabit central, well-developed areas, while those of lesser means are relegated to the periphery, often situated on hilly terrain, far removed from the opportunities and security afforded by formal urban areas. Furthermore, there is a transformation in housing structure; the inner city exhibits a more organized grid-like layout with denser residential areas where vertical growth is the only option (Gutiérrez and Kahhat, 2022). This stands in stark contrast to the constraints of topographical conditions on the outskirts, which tend to enclose the city as much as possible but still permit more sprawling residential development.

3.2. Drivers of material stock accumulation

When analyzing the total stock accumulated in a district, we look at three drivers: stock use intensity (kg/m²), floor space per capita (m²/cap), and total population. Fig. 2 shows the total stock accumulated in each district, organized by income level and total amount accumulated, and the relative contribution of each driver to the total stock. Low-income districts have some of the highest total material stocks, with values in some cases (e.g., San Juan de Lurigancho [32]) reaching more than double those of any other income group. On the other hand, the lowest material accumulations are observed in upper-middle-income districts. While this could be explained by the sheer size of some districts, as is the case with San Juan de Lurigancho [32], it shows that most stock is accumulated in middle- to lower-income areas. The variation in total stock values decreases with increasing income, suggesting that material stock accumulation is more consistent among higher-income districts.

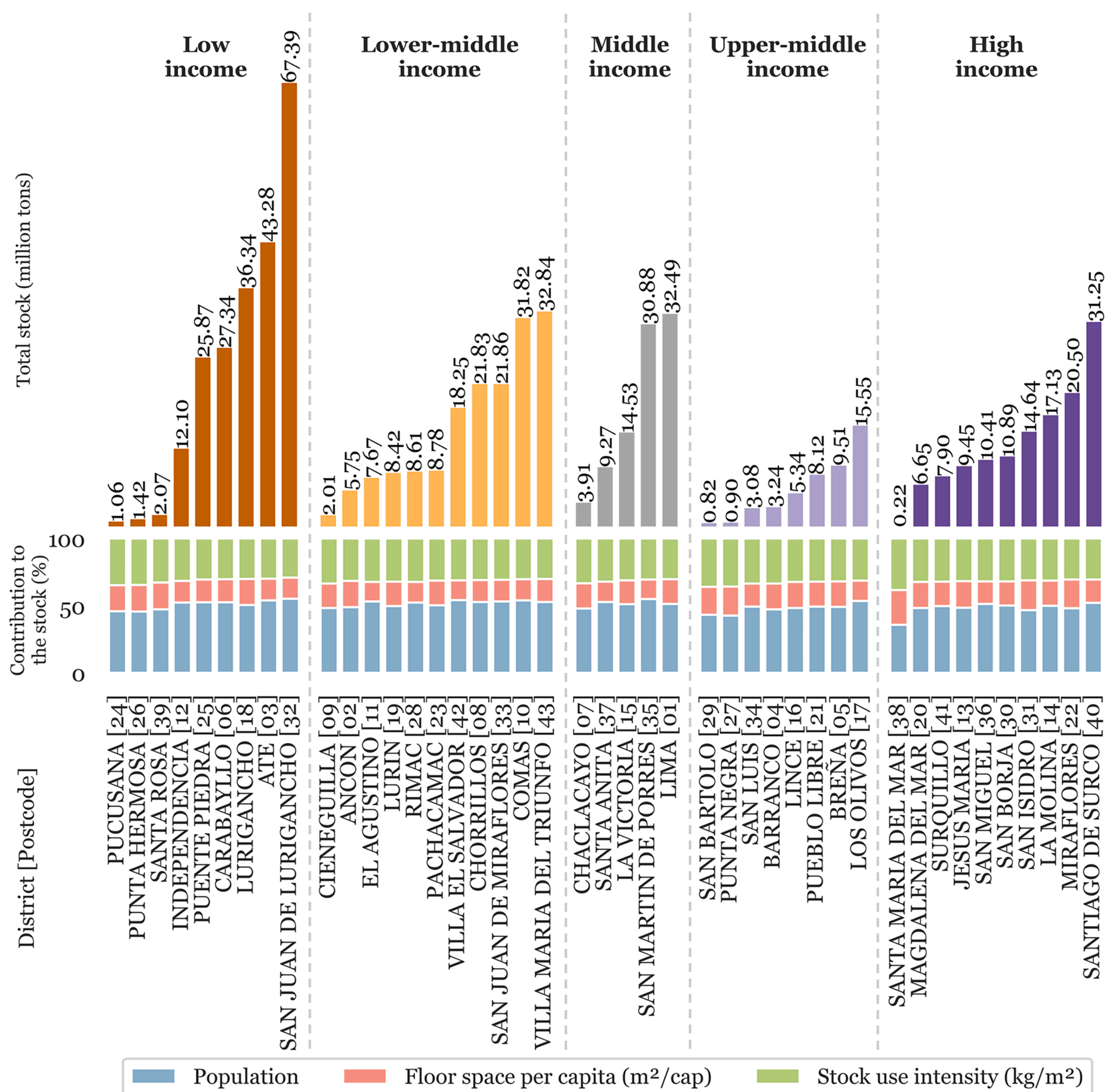

Fig. 2. Factor contribution to the material stock and the total value of the stock, organized by income level based on INEI (INEI, 2020). The total stock (in million tons) accumulated per district, alongside the percentage contribution of each factor—stock use intensity (kg/m²), floor space per capita (m²/capita), and total population—to the overall stock. Values are organized by income level, and the postcode of each district is found next to the district's name (see SI 1.2 for details on data, and SI 2.1 for a map of the districts and their postcode).

Analyzing the drivers of total stock distribution shows that, in every district except for the outlier Santa Maria del Mar [38], population size is the largest contributor to material stock. This pattern suggests that the demand generated by the population primarily drives material stock. Within each income group, as total stock increases, the proportional contribution of floor space per capita (m^2/cap) as a driver diminishes, indicating that the influence of larger housing decreases in districts with higher levels of total stock (Fig. 2). This is further exemplified when focusing on one district from each income group with a similar total material stock (approximately 15 million tons, see SI 1.2). The high-income representative district, San Isidro, has the smallest share of contribution from population, while floor space per capita becomes more prominent than in other districts. It is important to note that this occurs while having constraints in size, as is the case in San Isidro [31], where growth can only occur vertically (Gutiérrez and Kahhat, 2022). This pattern consistently demonstrates that as income declines, the influence of floor space per capita likewise lowers. It is important to note that this does not imply lower-income areas have less total floor space per capita; rather, in upper-income districts, the total accumulated stock is more strongly influenced by the space utilized per person than by population size.

Among the three drivers, stock use intensity (kg/m^2) is the most stable variable across districts. Stock use intensity does not differ significantly across income groups, likely due to the relatively small number of material intensity categories and their relative homogeneity. In contrast, both floor space per capita and population contributions differ significantly by income group (see SI 1.2. for statistical analysis).

3.3. Material stock and service provisioning

To further explore the role of population as the primary driver of material stock accumulation, we investigate the strength of the correlation between stock per capita and population density across the various service sectors of shelter, collective services, education, and healthcare (Fig. 3) across district income levels.

The scatterplot reveals two distinct distribution patterns among the services. In the shelter and education sectors, the relationship displays a more "triangular" distribution, indicating an accumulation of lower-income districts in the low-density, low-stock section of the graph, while higher-income districts are more dispersed across both axes, positioned above the lower-income areas. For shelter, a steep dividing slope (from 1600 cap/km^2 to 100 tons/cap) can be drawn to separate the lower-income districts, which consistently fall below the slope, from the higher-income districts, which are predominantly located above it. These trends highlight how sensitive shelter stock accumulation is to shifts in urban density, especially in more affluent districts. While education shows a similar pattern, it is less distinct, with some higher-income districts appearing in the lower range of the axes and some lower-income districts located in the higher range. On the other hand, collective services and healthcare exhibit "pillar-like" distributions with an upper limit cap on stock per capita (at 25 t/cap and 3 t/cap, respectively) and demonstrate a weaker correlation between factors.

The figure also presents thresholds of values that can be leveraged to identify districts we could consider materially sufficient in their service provision. Such districts (i) achieve at least the Decent Living Standards (DLS) threshold, (ii) do not exceed the average per-capita stock, (iii) exhibit higher-than-average population density, and (iv) provide high-quality services. This last assumption is based on the assumption that high-income districts offer a higher quality of services. By selecting these materially sufficient districts, we find that no districts are meeting all the criteria in healthcare, as the city average does not meet or surpass the DLS threshold. In education, no high-income district can be classified as materially sufficient. Finally, we observe that no single district meets all the sufficiency criteria across all services, with only one district, Los Olivos, fulfilling the criteria for both shelter and collective services.

4. Discussion

4.1. The weight of shelter provisioning inequalities

Lima exhibits significant disparities in shelter-provisioning material stock per capita, largely due to the prevalence of informality within its housing sector, a pattern representative of many South American cities. In extreme cases, the city is physically divided by a wall, with one side featuring million-dollar houses while the other hosts homes lacking basic infrastructure, such as roads, electricity, and running water

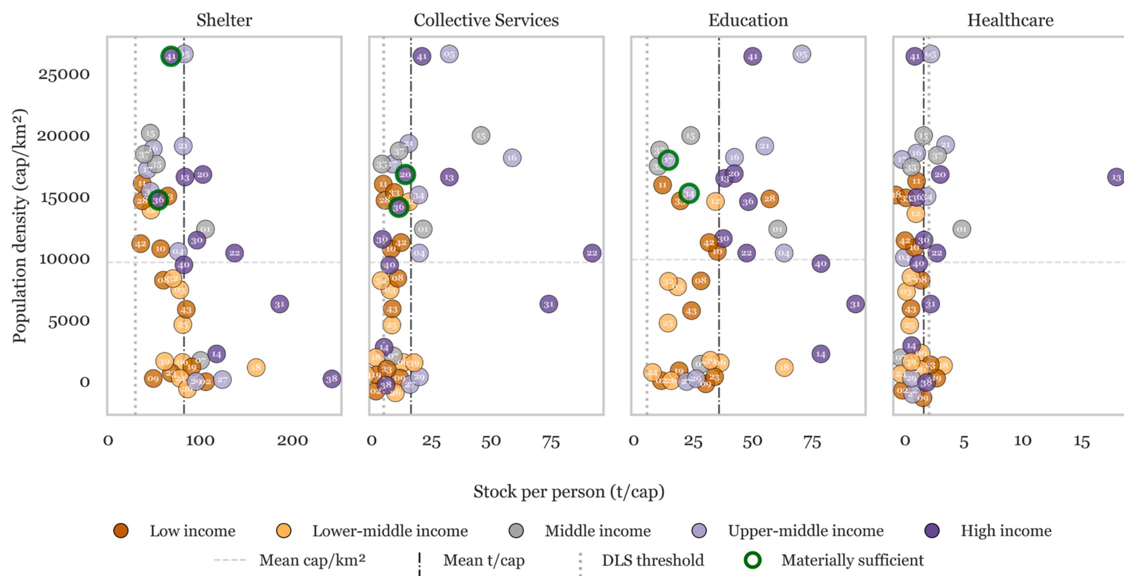

Fig. 3. Total material stock per capita in relation to the population district. Each dot represents a district, with colors indicating the income level and numbers indicating the postcode (see SI 2.1 for a map of the districts and their postcode). The graph displays two vertical lines: the minimum Decent Living Standard (DLS) threshold and the city average (both in t/cap). Additionally, it includes a horizontal line depicting the city's average population density (inhabitants per km^2). The districts with green edges are the higher-income districts with a value above the minimum DLS and the city's average population density, while those below the city average are those with a stock per capita. See SI 1.3 for details on the data.

(Desmaison and Boano, 2016). The distinct spatial pattern of lower-income households on the outskirts and higher-income households in the center has multiple links with Lima's material stocks and their service provisioning capacities.

Informal settlements, typically located on the city's periphery, are initially constructed with lighter, less durable materials and are disproportionately found in areas vulnerable to natural hazards. The informal homes, built with materials such as mud or straw, lack the durability and seismic resilience required by law. While brick and concrete are widespread building materials in the city (Linares-Capurro et al., 2025), formal housing, and by extension, seismic-resistant housing, constitutes only a minority of Lima's overall building stock (Pighui Bel, 2014; RedacciónRPP, 2021). Lower-income districts, such as San Juan de Lurigancho [32], have the highest accumulation of total shelter stock, double that of any other income group, primarily due to large population sizes rather than increased floor space per capita (Fig. 2). The statistical analysis confirms significant differences in population and floor space per capita across income groups, while stock use intensity does not differ significantly (Section 3.2). In lower-income areas, the demand for shelter materials is more influenced by population density than by the size of living spaces, resulting in greater vulnerability due to the material choices of informal housing.

It is critical to clarify that higher material accumulation does not equate to environmental inefficiency. Mud or reed mats are materials commonly found in informal housing, may involve high volumetric material intensity but carry low embodied energy and carbon, reflecting a lower environmental burden at the expense of structural integrity. In contrast, masonry buildings may appear more material-efficient, but entail a much higher carbon footprint due to industrial manufacturing and transportation of the materials (Oh et al., 2023). Thus, our analysis does not equate high stock with inefficiency; rather, it reveals that material intensity alone is an incomplete metric for assessing sustainability or equity. The environmental implications of construction types must be evaluated in tandem with their social function, particularly in contexts where informal housing provides essential shelter despite its fragility.

While current literature focuses on reducing the impacts of material consumption by focusing on more lightweight materials (Lehmann, 2012; Vélez-Henao and Pauliuk, 2023), it is important to recognize that houses designed to withstand natural disasters are heavier and thus have a higher environmental footprint. Moreover, informal housing, especially Types C and D, which represent 19.8 % of the total housing in Lima and are mainly present in low-income districts, is frequently considered temporary, with homeowners likely to upgrade as economic opportunities arise. This phased construction increases waste generation over time (Terwilliger Center for Innovation in Shelter, 2018). Lima's high humidity accelerates material deterioration, requiring frequent replacements, which generates significant waste and imposes a financial burden. A study done in Lima suggests that informal housing could emit 450 % more greenhouse gases (GHG) per person than a formal apartment building, partly because informal houses are more sprawling and less efficiently built, and partially due to longer construction stages and lack of professional planning, both of which can lead to increased material use (Sarmiento-Pastor et al., 2025). Financial constraints often prevent timely replacement for lower-income households, which can reduce the quality of life in the long term. Therefore, we should not just look at the local stock but also at the quality and structural capabilities of these materials.

Location further exacerbates vulnerability. Many informal settlements are established in high-risk zones, such as hillsides prone to mudslides or near rivers susceptible to flooding, where even robust structures may not withstand severe natural disasters (Republica, 2023). Climate change has intensified the frequency and severity of such events (Santos et al., 2025), leaving thousands of low-income families repeatedly homeless. Media narratives often blame residents for refusing to relocate since these areas represent their homes and livelihoods (Andina, 2018; Redacción Latina, 2024). However, no district in Lima has developed a proactive plan to relocate at-risk populations, as it is viewed as too costly (Redacción Latina, 2024). Relocation typically occurs only after disasters, and even willing families may wait years for government support (Panamericana Televisión, 2024). A brief comparison with mapping from the Ministry of Housing, Construction, and Sanitation (Ministerio de Vivienda, Construcción y Saneamiento, 2019) indicates that roughly 60 million tons of residential stock are at risk either due to flooding or seismic activity; therefore, we must consider the local context when discussing material consumption in cities.

4.2. Local context matters in understanding the distribution of stocks

As the capital city of Peru, most government buildings and company headquarters are concentrated in Lima. This is particularly evident in three districts: Lima [01], San Isidro [31], and Miraflores [22]. The district of Lima hosts most national government offices, while San Isidro and Miraflores concentrate business and tourist-focused establishments. These districts exhibit higher levels of stock consumption per capita, especially in comparison to the minimum DLS threshold (Fig. 3). This reflects not only greater investment in infrastructure but also higher service quality and accessibility, factors not captured by stock intensity alone.

4.3. Quality education for those who can afford it

In Lima, education is characterized by high privatization and unequal resource allocation. All districts exceed the minimum DLS for education, with the district with the lowest stock per capita, San Martin de Porres [35], having a material stock three times greater than the threshold (Fig. 3). Nevertheless, these patterns are not fully explained by population density or income. Instead, other factors, such as privatization and household investment, likely play a significant role.

Although 74 % of schools in Lima are private, only 46 % of registered students attend them (INEI, 2024). This percentage varies by level: 38 % of students in early education, 46 % in primary, and 50 % in secondary education (INEI, 2024). This indicates that access is defined not only by the number of schools or their material stocks, but also by access and affordability. Public schools often serve more students with fewer resources, while private schools, as they are viewed as a pathway to better life prospects, come at a substantial cost. Households spend an average of 19 % of their monthly income on private schools, reaching up to 27.7 % for high-quality institutions (Proexpansion, 2014).

Inequities are deepened by mobility, as families frequently commute long distances to send their children to preferred schools. In 2013, just 13 % of students lived in districts containing 32 % of high-quality schools (Proexpansion, 2014). Our data shows that a few high-income districts, such as San Isidro [31], La Molina [14], and Santiago de Surco [40], have high per capita resources despite low population density, suggesting that the schools serve students from surrounding areas (Fig. 3). Conversely, lower-income districts tend to have fewer per capita resources, supporting the notion that public schools, more likely located in lower-income areas, are under-resourced, despite having to serve more students. This spatial mismatch reveals a privatized logic of service provision, where infrastructure investment follows market demand rather than equitable need.

4.4. Material stocks reflect systemic failures of healthcare

Lima's healthcare system stands out as the urban service where the city, on average, fails to meet the minimum DLS material stocks threshold (Fig. 3). One outlier is the district of Jesús María [13], which, despite its relatively small population, is home to the city's largest hospital, the National Hospital *Edgardo Rebagliati Martins,* and the highly specialized National Cardiovascular Institute (INCOR), both under nationwide social health insurance coverage (EsSalud, 2023a, 2023b). The National Hospital alone accounts for half of the district's per capita

stock, significantly skewing the data. Lima's healthcare infrastructure is highly centralized, with a heavy reliance on a few large hospitals, while smaller centers throughout the city remain underfunded and under-resourced. The prevalence of privatization, with 60 % of healthcare in Lima being private, further fragments access (Diario Médico Perú, 2024).

This shortfall is both quantitative and qualitative and is deeply intertwined with persistent systemic deficiencies in the city's healthcare provisioning. Governmental healthcare expenditure stands at 6 % of GDP, below the Latin American and Caribbean average of 7.11 % (OECD, 2017). Values that also reflect how 60 % of all health centers in the city are private (Diario Médico Perú, 2024). Public health spending in Peru is nearly eight times lower than the OECD per capita average (Gestión, 2024), with total investment constituting only 13 % of that average, and 45 % of this investment directed toward Lima (Cetrángolo et al., 2013). This chronic underfunding has led to persistent understaffing, outdated infrastructure, and a deep lack of public trust in the system.

Affordability and accessibility are major barriers. Out-of-pocket healthcare costs have risen by 29 % since 2019 (Gestión, 2024). In 2019, 45 % of the population with health issues did not seek medical care due to cost, distance, or waiting times; this number climbed to 55 % by 2021 (World Bank, 2023). As a result, 46 % of the population visit pharmacies, instead of going to a healthcare provider (COMEXPERU, 2024; World Bank, 2023). This systemic failure was exposed during the COVID-19 pandemic, when Peru reported the highest mortality rate globally (Horton, 2020), affecting all income levels (Dorregaray-Farge et al., 2021). The material stock data reflect this failure: most districts, regardless of population density, do not have sufficient stock to achieve a DLS (Fig. 3). This demonstrates that it's not only about infrastructure but also about investment, governance, and service delivery.

4.5. Limitations and data gaps

Data availability, reliability, coverage, and resolution remain issues in socioeconomic metabolism studies. We used the Linares-Capurro et al. (2025) urban material stock map, which relies solely on open-sourced data sources that were sometimes incomplete or outdated. While we consider it the best available representation of reality thus far, it restricts examination of specific topics. For example, population figures are based on the address listed in the citizen's ID, which may exclude internal (lacking a legal address) or international migrants lacking legal documentation (e.g., Venezuelans unable to obtain passports (Olmo, 2018)), particularly in lower-income, informal areas, introducing uncertainty and potentially underestimating stock per capita in these districts. Furthermore, the assumption that residents seek services only within their district does not account for commuting, especially for schooling and work, nor does it reflect the centralized nature of healthcare access. Given that population is the primary driver of stock accumulation (Section 3.2), improving this data is crucial for further assessments.

5. Conclusion

Our research advances the Means and Ends framework, building on the mathematical formulation by Tanikawa et al. (2021), as well as the Decent Living Standards framework, by applying it to Lima, a rapidly urbanizing megacity in the Global South. This perspective allows us to examine the relationship between material stocks and human well-being in the context of informality, privatization, and socio-spatial fragmentation. While materials provide insight into levels of service provisioning, they fall short in quantifying societal benefits. Our findings indicate that high stock intensity does not necessarily result in equitable service provision, particularly in low-income, informal districts. Instead, the material service productivity is influenced by institutional, spatial, cultural, and economic conditions that disrupt the assumed linkage between means (material stocks) and ends (decent living).

We show that material intensity alone is an insufficient metric for material stock productivity, as it is currently used in the Means and Ends framework (Tanikawa et al., 2021). Our studies show that informal housing, although "inefficiently" built and producing more waste, often uses low-embodied-carbon materials like mud and reed. In contrast, formal buildings may seem more material-efficient but tend to have higher carbon footprints. By distinguishing between these aspects, we challenge narrow views of "efficiency" and advocate for integrated assessments that consider both environmental and social factors.

The relationship between privatization and service provisioning is highlighted in our study, particularly in the education and healthcare sectors, where infrastructure investment follows market demand rather than equitable need. Our findings from Lima underscore the following: despite exceeding DLS thresholds, access to and the quality of services still depend on income and geography, further confirming that while materials and service provisioning are connected, more factors play a role.

To address these limitations, we encourage future research to pursue a multidimensional approach for developing service-adjusted stock productivity indicators. This could include factors such as accessibility (physical and financial), per capita resource availability (e.g., beds, books, teachers, nurses), service effectiveness (e.g., literacy or mortality rates), infrastructure per individual (e.g., floor space per capita), population density, material quality (e.g., durability), and material resilience (e.g., against natural disasters, especially for shelter). Although the diversity of these factors presents methodological challenges, including them is crucial for creating a more accurate and policy-relevant measure of service provision within planetary limits.

We also suggest that future research considers scientific perspectives drawn from urban political ecology, service access studies, and environmental impact assessments, including critical work that exposes how urban socio-ecological transformations generate uneven vulnerabilities. Furthermore, the DLS framework should be considered to reflect intra-urban inequalities better, since our results show that even within a single city, new approaches are needed to understand disparities. Finally, we suggest exploring potential trade-offs between different services in a single geographical area, as no district was found to be materially sufficient for all services. Lima's case illustrates that while in-use materials are central to operationalizing the Means and Ends Framework, material stocks alone are not enough. It is the interplay of informality, privatization, and climate vulnerability that compels the adoption of context-sensitive frameworks, especially for the Global South.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly purely for text editing post-writing. After using this tool/ service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Alessia Linares-Capurro: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Úrsula Cárdenas-Mamani:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Ramzy Kahhat:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Tomer Fishman:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This research was funded by the European Union ERC-2023-STG project 101116116, Materials-GRoWL: Gauging the Rest-of-the-World's Lifecycles of construction materials. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. Parts of this study developed from a master's thesis by A.L.C. in the Industrial Ecology MSc Programme of Leiden University.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108815.

Data availability

The journal article on the urban resource cadaster can be found in Linares-Capurro et al. (2025).

Declaration of competing interest

The authors declare that no conflict of interest exists regarding this work.

Supplementary information

The SI 1 contains the data behind the figures and calculations, and SI 2 contains a map of the districts and their postcode, as well as further methodological explanations.

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