

Improving Housing and Infrastructure to Mitigate COVID-19 Transmission in Slums of Bhopal, India

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Abstract

Slum communities are structurally ill-equipped to absorb the public health demands of airborne infectious disease outbreaks such as COVID-19. Overcrowding, absent cross ventilation, shared sanitation facilities, and deficient community infrastructure collectively create conditions that amplify SARS-CoV-2 transmission and obstruct pandemic mitigation measures. This study assessed the housing conditions and community infrastructure of a selected slum in Bhopal, India, to quantify household-level resilience to COVID-19 transmission and identify key modifiable risk factors. Using a structured questionnaire survey of 36 households—selected through proportionate stratified sampling using Slovin's formula from a total city slum population of 568,433—data were collected on 48 indicators spanning housing design, housing infrastructure, community design, and community infrastructure. A composite Resilience Score (0–1) was calculated per household and aggregated into a Combined Index for the settlement. Multiple linear regression was used to identify the most significant structural predictors of resilience. Ward-level ecological analysis confirmed a 763% disparity in COVID-19 case burden between the highest- and lowest-density wards. The Combined Index for the settlement was 0.56 (average), with household scores ranging from 0.36 to 0.66; approximately half of households fell below the average threshold. Community infrastructure was the strongest independent predictor of resilience ($\beta = 0.552$, $p < 0.001$), followed by housing design ($\beta = 0.482$, $p < 0.001$). The model accounted for 98.8% of variance in household resilience ($R^2 = 0.988$). Critical deficiencies included near-universal absence of cross ventilation, substandard window areas, intermittent water supply, narrow lanes preventing physical distancing, and restricted emergency access.

Introduction

Urban slums are a defining challenge of 21st-century public health. The United Nations defines slums as settlements characterised by insecure housing tenure, poor structural quality, high population density, and insufficient access to safe water, sanitation, and basic infrastructure [1]. These settlements represent an informal and market-driven response to the prohibitive cost of legally compliant urban housing—one that entraps impoverished households in a cycle of physical vulnerability and social marginalization [2, 3]. Globally, approximately one billion people live in slum conditions, a figure the United Nations projects will double by 2030 in the absence of targeted policy intervention [1].

The COVID-19 pandemic, caused by the SARS-CoV-2 virus first identified in Wuhan, China in December 2019, has tested the resilience of every urban health system in the world [4]. However, its consequences have been profoundly unequal. Early pandemic narratives that framed COVID-19 as a great equaliser cutting across social classes were rapidly contradicted by accumulating epidemiological evidence demonstrating steep socioeconomic gradients in infection, hospitalisation, and mortality [5, 6]. Slum populations have emerged as among the most disproportionately affected, not because of biological predisposition, but because the physical conditions of informal settlements are structurally incompatible with the behavioural interventions prescribed to control an airborne respiratory pandemic [7].

SARS-CoV-2 is primarily transmitted through respiratory droplets and aerosols generated during breathing, speaking, coughing, and sneezing [8]. The probability of transmission is strongly modulated by three environmental parameters: ventilation quality, population density, and contact duration [9]. In well-ventilated environments, infectious aerosols are rapidly diluted and dispersed; in enclosed, poorly ventilated spaces, they accumulate and remain suspended for extended periods, dramatically increasing the probability of inhalation by susceptible individuals [10]. These dynamics are particularly consequential in slum dwellings, where rooms are small, households are large, windows are few and undersized, and cross ventilation is structurally absent. Research from Bangladesh has demonstrated that average household sizes of 4.7 persons sharing 1.7 rooms in Khulna slums rendered home quarantine guidelines not merely impractical but physically impossible [11].

India's slum population is among the largest in the world, with approximately 65 million slum dwellers across its urban centres as of the 2011 Census [12]. Urban vulnerability mapping studies conducted across Indian cities during the pandemic consistently identified housing density, ventilation deficits, and infrastructure access as the dominant predictors of localised COVID-19 spread, reinforcing the case for built-environment-focused intervention rather than behavioural messaging alone [13]. Bhopal, the capital city of Madhya Pradesh, is home to approximately 568,433 slum residents—nearly a quarter of its total population—distributed across 19 administrative zones [14]. The city gained tragic global recognition for the 1984 Union Carbide gas disaster, the world's worst industrial accident, and its slum settlements have historically received limited planning attention relative to the scale of need. Despite being known as India's 'City of Lakes' for its natural landscape, Bhopal harbours profound spatial inequalities in housing quality and service provision that became acutely visible during the COVID-19 pandemic [14].

Airborne biological disasters, including the 1918 influenza pandemic, the 2002–2003 SARS outbreak, the 2009 H1N1 pandemic, the Middle East Respiratory Syndrome (MERS) outbreak, and COVID-19, share a common epidemiological logic: transmission is mediated by environmental conditions that modulate aerosol generation, suspension, and inhalation [15, 16]. Multiple studies have established that temperature, humidity, ultraviolet radiation intensity, wind patterns, and built environment characteristics—particularly ventilation, room volume, and occupancy density—are significant determinants of airborne transmission risk [10, 17]. Indoor environments with inadequate natural ventilation and limited sunlight penetration are particularly high-risk because UV radiation is a documented virucidal agent capable of inactivating SARS-CoV-2 on surfaces and in aerosols [18].

The urban planning and public health literature increasingly recognises that pandemic resilience in informal settlements cannot be achieved through behavioural interventions alone [7, 19]. Structural determinants—the physical design of dwellings, the layout of settlement lanes, the location and design of shared facilities, and access to emergency services—shape the boundaries of what is behaviourally possible for residents [9]. This understanding calls for a rigorous, evidence-based assessment methodology that quantifies structural vulnerability at the household level, identifies the most influential risk factors, and translates findings into actionable architectural and planning recommendations [20].

Several slum upgrading programmes have been attempted in India, including the National Slum Development Programme (NSDP), Valmiki Ambedkar Malin Basti Awas Yojana (VAMBAY), Jawaharlal Nehru National Urban Renewal Mission (JNNURM), and Rajiv Awas Yojana [21]. While these programmes have improved living conditions in some areas, they have often been criticised for inadequate attention to ventilation, natural lighting, and community infrastructure design—precisely the factors shown to be critical for pandemic resilience [21]. Weak institutional governance frameworks for slum management, characterised by fragmented jurisdiction between municipal, state, and housing-board authorities, have been identified as a structural barrier to the consistent implementation of building and infrastructure standards in informal settlements across developing countries [22]. The standard community medicine field-survey methodology for assessing housing and sanitation adequacy in Indian settlements, which informed the design of the present household questionnaire, similarly emphasises room ventilation, occupancy density, and water and sanitation access as core indicators of habitability [23]. The informal and insecure nature of slum land tenure further complicates service delivery and deters resident investment in housing improvements [3].

This study aimed to (1) establish the ecological relationship between population density and COVID-19 burden at the ward level in Bhopal; (2) characterise the housing design and community infrastructure of an urban slum in Bhopal with respect to SARS-CoV-2 transmission risk; and (3) develop and apply a composite Resilience Index to assess household- and settlement-level capacity to mitigate COVID-19 transmission. Findings are intended to inform targeted architectural, infrastructural, and policy interventions for slum communities facing airborne pandemic risks, and to contribute to the growing evidence base on urban health equity in low- and middle-income country cities.

Methods

Ecological Analysis: Population Density and COVID-19 Burden

To contextualise the selection of the study area, a ward-level ecological analysis was conducted using official COVID-19 case data for Bhopal's 85 wards. The ten wards with the lowest reported case counts and the ten with the highest were compared with respect to absolute case burden, cases per lakh population, and population density. This analysis served to establish density as a valid contextual risk proxy and to situate the selected slum zone within the broader epidemiological landscape of the city.

Study Site Selection

Zone 6 was selected as the study area because it has the second-highest proportion of slum dwellers among Bhopal's 19 administrative zones (51,643 slum residents, accounting for 9.09% of the city's total slum population), and because it contains 19 distinct slum pockets offering internal heterogeneity. Within Zone 6, the 'Sai Baba Slum' (also designated '12 No. Slum') in Arera Colony was chosen for its

unique combination of features: a heterogeneous topography spanning a hillock and flat terrain, proximity to a higher-income residential colony (creating a relevant COVID-19 importation interface), and an active government housing relocation programme that underscored the urgency of evidence-based housing assessment.

Sample Size Determination and Sampling Procedure

A proportionate stratified sampling approach was adopted. The total sample size for Bhopal's slum population ($N = 568,433$) was calculated using Slovin's formula ($n = N / [1 + Ne^2]$) with an acceptable margin of error of 5%, yielding a sample size of 400 households. Zone 6's proportionate allocation of 9.09% produced a zone-level target of 36 households. All 36 households in the Sai Baba Slum were surveyed, representing a complete enumeration of the designated study site. Data were collected on both weekdays and weekends to ensure representation of both male and female household respondents.

Resilience Index: Indicator Selection and Weight Assignment

A composite Resilience Score (RS) was developed based on 48 indicators identified through a systematic review of peer-reviewed literature on COVID-19 vulnerability in informal settlements [9, 11, 19, 20, 24–26] and corroborated against the National Building Code of India (NBC) 2016 standards for habitable rooms, ventilation, and sanitation [27]. Indicators were organised under four thematic domains:

1. Housing Design (room dimensions, occupancy, ventilation, natural lighting);
2. Housing Infrastructure (attached toilets, toilet and kitchen ventilation, water connection);
3. Community Infrastructure (public toilets, communal water access points, waste management, cleanliness); and
4. Community Design (lane width, open/green spaces, ambulance access, proximity to essential services).

Each indicator was assigned ordinal weights between 0 and 1, calibrated to reflect the strength of association between the indicator characteristic and COVID-19 transmission risk. Binary indicators received weights of 1 (protective) or 0 (risk factor). Indicators with three response classes received weights of 1, 0.5, and 0; those with four classes received 1, 0.66, 0.33, and 0; and those with five classes received 1, 0.75, 0.5, 0.25, and 0. For indicators with multiple household members as units (e.g., age composition), weighted averages were calculated proportionate to the number of members in each class. A representative selection of 18 of the 48 indicators, with associated weights and rationale, is presented in Table 3.

The household Resilience Score (RS) was the arithmetic mean of all 48 indicator weights:

$$R. S = (W_1 + W_2 + W_3 + \dots + W_{48}) / 48 = \sum_{i=1}^{48} \frac{W_i}{48}$$

The Combined Index (CI) for the settlement was the mean of all household RS values:

$$C. I = (R. S_1 + R. S_2 + R. S_3 \dots + R. S_{36}) / 36 = \sum_{i=1}^{36} \frac{R. S_i}{36}$$

Scores were interpreted using the following scale: Good (0.75–1.0), Average (0.50–0.75), Below Average (0.25–0.50), and Poor (0.0–0.25).

Statistical Analysis

Descriptive statistics were used to characterise housing and infrastructure conditions across the 36 surveyed households. Pearson correlation coefficients were calculated to assess bivariate associations between each of the four domain scores and the household RS. Multiple linear regression was performed using all four domain scores as independent predictors of the RS, with standardised beta coefficients (β) and the coefficient of determination (R^2) reported. All statistical analyses were conducted using IBM SPSS Statistics (version 26).

Results

Ward-Level Density and COVID-19 Case Burden

The ten wards with the lowest COVID-19 burden recorded a mean population density of 28,558 per km² and a combined total of 547 confirmed cases (Table 1). In contrast, the ten highest-burden wards had a mean density of 35,371 per km² and 4,721 total confirmed cases (Table 2), representing a 763% increase in case burden. A single-day spike of 52 cases was reported from densely settled slum pockets including Banganga, Bhim Nagar, and Piplani localities [28]. These data established population density as a significant contextual predictor of COVID-19 burden at the ward level in Bhopal, supporting the rationale for focusing the study within a high-density slum zone.

Table 1

Ten wards with the lowest COVID-19 case burden and corresponding population density, Bhopal

S. No.	Ward No.	COVID Cases /lakh population	Ward Population	Absolute COVID Cases	Ward Density (person/km ²)
1	9	88.5	26,000	23	32,779
2	65	189	23,322	44	4,455
3	41	197	25,430	50	67,267
4	50	213	19,719	42	13,060
5	67	239	25,994	62	17,647
6	47	250	24,018	60	23,700
7	69	258	19,363	50	31,957
8	60	287	24,757	71	2,621
9	63	298	25,180	75	6,112
10	40	301	23,230	70	85,978
Total	—	2,319	—	547	28,558 (mean)

Table 2

Ten wards with the highest COVID-19 case burden and corresponding population density, Bhopal

S. No.	Ward No.	COVID Cases /lakh population	Ward Population	Absolute COVID Cases	Ward Density (person/km ²)
1	22	2,670	19,442	519	50,893
2	13	2,445	25,322	619	8,331
3	23	2,223	21,005	467	74,546
4	2	2,197	23,173	509	3,188
5	1	2,140	25,889	554	2,220
6	56	1,950	24,770	483	4,039
7	21	1,825	19,288	352	57,068
8	24	1,784	25,001	446	4,915
9	19	1,723	19,733	340	47,428
10	14	1,669	25,884	432	101,083
Total	—	20,625	—	4,721	35,371 (mean)

Socio-Demographic Profile

The settlement exhibited a strongly patriarchal demographic structure; surveys conducted on weekdays found only female household members available, with male members present only on weekends, almost all of whom reported being the sole earning member of the household. The mean household size was 5.02 persons, exceeding the national average of 4.44. Of children below 18 years, only 39.5% were female, reflecting the broader gender composition of the settlement. Limited ethnic segregation was noted—a small Bengali community occupied two lanes near Mira Nagar—but no religious or faith-based spatial division was observed.

Housing Design and Physical Infrastructure

All 36 surveyed households had semi-pucca construction with asbestos sheet roofing without exception, and none were structurally reinforced. Semi-pucca structures with asbestos roofing are known to significantly elevate indoor temperature and humidity, conditions documented to prolong the airborne suspension of SARS-CoV-2 relative to well-ventilated environments [9]. A total of 61% of households had at most two bedrooms, and 30.6% had only one. With a mean occupancy of approximately three persons per room, the settlement substantially exceeded the UN-recommended maximum of 2.5 persons per habitable room [29].

Ventilation was critically deficient across almost all households. Approximately 14% had no exterior windows, and 36% had only one. In no household did the aggregate window area meet the NBC 2016 minimum of one-sixth of floor area for warm-humid climates [27]. Orientation was largely suboptimal, with 47% of external windows facing south—a direction that, while capturing prevailing wind, limits cross-ventilation when paired with a single-facade opening pattern. Cross ventilation was functionally absent in 34 of 36 households. A total of 85.7% of residents rated their ventilation quality as 2 or below on a 1–5 Likert scale. Toilet ventilation was equally deficient; only 8.3% of attached toilets had properly sized ventilation openings ($\geq 0.3 \text{ m}^2$), and 44.4% had no ventilation at all. Kitchen ventilation was similarly poor, with 36.1% of kitchens having no openings and the remainder relying on undersized mesh openings or brick jali rather than functional windows or exhaust fans. Natural lighting penetration was severely restricted; over a quarter of households relied on artificial lighting for more than six hours per day, and 69.4% rated their natural lighting quality as 2 or below. This matters for infection control because UV radiation in sunlight is a documented virucidal agent capable of inactivating airborne SARS-CoV-2 [18].

Water, Sanitation, and Community Infrastructure

Despite 94.4% of households having piped water connections, the supply was available for less than one hour on alternate days only. This intermittency compelled most households to store water in drums and tanks and, for 22.2% of residents, to rely periodically on communal water access points where ten to twenty or more individuals gathered simultaneously. The average waiting time at communal points was

approximately 10–20 minutes, and the volume-filling process took most households under 20 minutes—meaning each visit involved 30+ minutes of proximity to multiple other households. Over three-quarters of respondents (77.8%) rated their satisfaction with neighbourhood cleanliness as 3 or below, and garbage accumulation was observed at multiple locations within the slum, consistent with the known role of organic waste accumulation in generating pathogen-laden aerosol environments [26].

A total of 27.8% of households used communal public toilets, with the majority visiting two to five times per day and spending more than 15 minutes per visit; 70% waited less than two minutes at the toilet but typically found 1–5 people already waiting—meaning every toilet visit involved sustained close contact with multiple persons. Only 25% of households had access to any open or green space, limiting residents' capacity to use outdoor environments to relieve household crowding—a strategy documented to be protective during lockdowns, with evidence from multiple countries showing that access to green and blue (water-adjacent) spaces during COVID-19 confinement was associated with improved mental wellbeing and reduced household stress, independent of its physical distancing benefit [30,31]. More than two-thirds of households (69.4%) could not be reached by ambulance at their doorstep due to lane width constraints, representing a critical limitation for emergency medical access in severe or deteriorating COVID-19 cases.

Lane widths were less than 2 metres for 16.6% of households and 2–3 metres for 30.6%, meaning that for nearly half the settlement, physical distancing in communal circulation spaces was physically impossible. In 69.4% of lanes, only 2–3 persons could pass simultaneously without contact.

Resilience Index and Regression Analysis

Household Resilience Scores ranged from 0.36 to 0.66. The Combined Index for the settlement was 0.56, placing it in the 'average' category. However, a significant proportion of individual households fell into the 'below average' category ($RS < 0.50$). A representative selection of resilience indicators and associated weights is presented in Table 3.

Table 3. Selected resilience indicators, weights, and rationale (18 of 48 indicators shown)

No.	Indicator	Classes	Weights	Explanation / Rationale
1	Age of household members	<10	1	Children in shared rooms increase crowding risk
		10–18	0.5	
		≥18	0	
2	Building typology	Kuccha	0	Semi-pucca increases indoor heat and humidity, prolonging viral suspension
		Semi-Pucca	0.5	
		Pucca	1	
3	Room size	≥9.5 m ²	1	Larger rooms improve quarantine capacity per NBC 2016
		<9.5 m ²	0	
4	Number of bedrooms	1	0	More bedrooms facilitate self-isolation of symptomatic members
		2	0.25	
		3	0.5	
		4	0.75	
		5	1	
5	Occupants per room	≤2.5	1	Higher occupancy raises intra-household transmission probability
		2.5–5	0.5	
		≥5	0	
6	Household size	≤4	1	Larger households have more potentially susceptible members
		5–8	0.5	
		≥8	0	
7	No. of exterior windows	<2	0	More windows improve natural ventilation and aerosol dilution
		2–4	0.5	
		≥4	1	
8	Opening area vs floor area	<1/6 FA	0	Minimum 1/6th floor area required by NBC 2016 for warm-humid climate
		≥1/6 FA	1	
9	Cross ventilation	Yes	1	Cross ventilation reduces suspension time of airborne particles
		No	0	
10	Ventilation rating (Likert 1–5)	1	0	Subjective rating validates objective ventilation indicators
		2	0.25	

No.	Indicator	Classes	Weights	Explanation / Rationale
		3	0.5	
		4	0.75	
		5	1	
11	Attached toilet	Yes	1	Reduces exposure at shared sanitation facilities
		No	0	
12	Toilet ventilation	Proper	1	Poor toilet ventilation recirculates pathogens indoors
		Improper	0.5	
		None	0	
13	Kitchen ventilation	Proper	1	Reduces indoor air pollution from cooking; reduces respiratory risk
		Improper	0.5	
		None	0	
14	Natural lighting (Likert 1–5)	1	0	UV in sunlight inactivates SARS-CoV-2; absence prolongs survival
		2	0.25	
		3	0.5	
		4	0.75	
		5	1	
15	Piped water connection	Yes	1	Decentralized access reduces gatherings at communal water points
		No	0	
16	Hours of water supply	<6	0	Longer supply reduces reliance on community tankers or points
		6–12	0.33	
		12–18	0.66	
		≥18	1	
17	Use of public toilet	Yes	0	Shared facilities are documented SARS-CoV-2 transmission foci
		Sometimes	0.5	
		No	1	
18	Lane width (metres)	<2	0	Wider lanes enable physical distancing and emergency access
		2–4	0.33	
		4–6	0.66	
		≥6	1	

Pearson correlation analysis revealed that Housing Design ($r = 0.698$, $p < 0.001$) and Community Design ($r = 0.661$, $p < 0.001$) had the strongest bivariate associations with household RS. Community Infrastructure ($r = 0.601$, $p < 0.001$) and Housing Infrastructure ($r = 0.419$, $p < 0.05$) also showed significant positive correlations. In the multiple linear regression model (Table 4), all four domain predictors were statistically significant independent predictors of household RS ($p < 0.001$). Community Infrastructure had the highest standardised beta coefficient ($\beta = 0.552$), followed by Housing Design ($\beta = 0.482$), Community Design ($\beta = 0.304$), and Housing Infrastructure ($\beta = 0.248$). The model accounted for 98.8% of variance in household RS ($R^2 = 0.988$; $r = 0.994$, $p < 0.001$).

Table 4. Multiple linear regression coefficients for predictors of household Resilience Score

Variable	B	Std. Error	Beta (β)	t	p-value
(Constant)	.016	.013	—	1.272	.213
Housing Design	.351	.016	.482	21.912	<.001
Housing Infrastructure	.216	.019	.248	11.240	<.001
Community Design	.171	.012	.304	14.258	<.001
Community Infrastructure	.231	.009	.552	26.062	<.001

Dependent variable: Resilience Score. All coefficients significant at $p < 0.001$ unless otherwise stated.

Discussion

This study provides a systematic, household-level empirical assessment of the structural determinants of COVID-19 transmission risk in an urban Indian slum, using a novel composite Resilience Index framework grounded in both peer-reviewed evidence and NBC 2016 building standards. The combined settlement score of 0.56, with approximately half of households falling below the average threshold, confirms that the existing housing and infrastructure conditions of the Sai Baba slum are insufficient to support effective pandemic mitigation. These findings are consistent with, and extend, a growing body of international evidence on the structural dimensions of COVID-19 vulnerability in informal urban settlements [7, 11, 19, 24–26, 32]. They also echo a broader pattern observed across other airborne pandemic-potential pathogens, where built-environment characteristics—rather than pathogen biology alone—have repeatedly been shown to determine the scale of transmission in densely populated, resource-constrained settings [33].

The ward-level ecological finding—a 763% disparity in COVID-19 case burden between the highest- and lowest-density wards—provides a compelling contextual foundation for the study's premise. While ecological associations cannot establish causation, the magnitude of this density gradient is consistent with international evidence from Brazil, Spain, and Belgium documenting strong positive correlations between area-level deprivation, overcrowding, and SARS-CoV-2 incidence [5, 34].

The near-universal absence of cross ventilation—present in only 2 of 36 households—is perhaps the single most critical structural vulnerability identified. Ventilation is the primary environmental mechanism for diluting and removing infectious aerosols from enclosed spaces [9, 10]. The World Health Organization and multiple national building codes specify that rooms should have openings on at least two opposing walls to enable cross ventilation, and that opening areas should constitute a minimum of one-sixth of floor area in warm-humid climates—a threshold met by none of the surveyed households [27]. Rooms with asbestos roofing, high occupancy, and no cross ventilation represent near-ideal conditions for aerosol accumulation, as heat-driven air stratification impedes vertical mixing and concentrates infectious particles at breathing height.

The severe restriction of natural light penetration documented in this study—with 69.4% of respondents rating natural lighting at 2 or below on a 1–5 scale—has implications beyond occupant comfort. Solar ultraviolet radiation, particularly the UV-B and UV-C components of direct sunlight, is a well-established virucidal agent. Studies have demonstrated measurable photoinactivation of SARS-CoV-2 in aerosols under natural sunlight conditions [18], suggesting that environments with minimal sunlight exposure may sustain higher aerosol viral loads for longer periods. The small, misoriented, and frequently obstructed windows documented in this study not only impair ventilation but eliminate this natural photoinactivation mechanism, compounding transmission risk.

The identification of community infrastructure as the strongest independent predictor of resilience ($\beta = 0.552$) in the regression model is a finding of substantial policy significance, and one that diverges from the intuitive assumption that household-level design factors would dominate. This result reflects the reality that pandemic mitigation in dense informal settlements is not determined solely by what happens within individual dwellings, but is fundamentally shaped by the shared physical infrastructure through which all residents must pass in the course of daily life—communal water points, public toilets, narrow lanes, waste collection systems, and community facilities. This is consistent with Bamba et al.'s conceptual framing of the COVID-19 pandemic as an inherently social and environmental phenomenon rooted in the physical conditions of inequality [6], and with findings from socioeconomic inequality studies in urban Italy showing that shared infrastructure conditions mediated household-level COVID-19 outcomes [34].

The intermittent piped water supply—less than one hour on alternate days—is a structural driver of congregational behaviour that directly undermines pandemic control. When households cannot rely on individual connections, they are compelled to gather at communal access points, where ten to twenty individuals may be present simultaneously. Akter et al. documented the same pattern in Khulna, Bangladesh, noting that communal water collection points became effective transmission amplifiers during COVID-19 due to the prolonged and repeated close-range contact they necessitated [11]. Patel and Shah argue that the absence of reliable individual water connections in Indian slums represents a systems-level failure of municipal service delivery that structural public health interventions must address, rather than relying solely on behaviour change campaigns [35].

The shared toilet infrastructure findings mirror patterns documented in Nairobi, Bangkok, and Jakarta. Nyadera and Onditi observed that shared sanitation facilities in Nairobi's informal settlements were identified by residents themselves as among the highest-risk communal spaces during the pandemic [24], a perception corroborated by environmental sampling studies detecting SARS-CoV-2 RNA in toilet aerosols [19]. In the Sai Baba slum, the combination of multiple daily visits, extended visit durations, and queuing in close proximity created conditions structurally analogous to those identified as transmission-amplifying in these international studies. The absence of adequate ventilation in 44.4% of attached toilets further concentrated infectious aerosols within the dwelling itself, undermining the protective function of having a private toilet at all.

The lane-width data reveal a dimension of COVID-19 vulnerability that has received less attention in the literature than ventilation or water access, but which has equally direct implications for transmission. When 47% of settlement lanes are narrower than three metres, the WHO's recommended one-metre physical distancing guideline cannot be observed during normal pedestrian movement. This is not a matter of behavioural non-compliance; it is a physical impossibility imposed by the built environment. Pongutta et al. documented the same structural barrier in Bangkok slums [25], and the present findings confirm its applicability in the Indian context. The lane-width constraint also explains the inaccessibility of ambulance services to 69.4% of households—a finding with potentially fatal consequences for severe COVID-19 cases requiring emergency hospitalisation, particularly given the higher comorbidity burden in socioeconomically deprived populations.

The regression model's extraordinary explanatory power ($R^2 = 0.988$) indicates that the four structural domains collectively capture almost all of the variance in household resilience, suggesting that the indicator framework is comprehensive and internally consistent. The fact that community infrastructure ($\beta = 0.552$) outpaces housing design ($\beta = 0.482$) as an independent predictor—despite housing design having a stronger bivariate correlation—reflects a pattern of partial mediation whereby the effects of household design are attenuated when shared infrastructure deficiencies are held constant. This underscores the interdependence of household- and community-level variables in determining actual pandemic resilience, and supports arguments for a systemic rather than piecemeal approach to slum upgrading.

The disclosure rate for COVID-19 infection was effectively zero, with clear indicators of social desirability bias: children were visibly instructed to remain silent when their responses might indicate household infection. This pattern is a recognised limitation of community health surveys in low-income settings where COVID-19 carried stigma and fear of punitive isolation measures [36]. National home isolation guidelines for mild and asymptomatic COVID-19 cases explicitly presuppose the availability of a separate, well-ventilated room for the isolating individual [37] — a precondition that, per the present findings, was structurally unmet in the substantial majority of surveyed households, rendering official guidance largely inapplicable in this settlement context. It likely results in underestimation of actual transmission within the settlement and means that the resilience assessment represents an analysis of structural exposure risk rather than confirmed infection outcomes.

Our findings regarding the resilience index further underscore that vulnerability is driven by systemic structural factors. This aligns with recent mathematical modeling, which demonstrates that the density and connectivity patterns inherent to informal settlements are primary determinants of epidemic spread, operating independently of individual household behaviors [38]. Finally, the emergence of community infrastructure as a critical predictor of resilience suggests that collective physical conditions are more decisive in managing transmission risk than individual dwelling characteristics. This is consistent with broader research identifying shared infrastructure and urban transport networks as primary vectors for the transmission of airborne biological hazards in densely populated urban settings [39].

Several limitations should be noted. The sample of 36 households, while representing a complete enumeration of the study site and a statistically proportionate zone-level allocation under Slovin's formula, constrains generalisability to other zones and slum typologies. The use of 2011 census data for population denominators may introduce error given demographic changes over a decade. The cross-sectional design precludes causal inference, and the absence of objective environmental measurements (e.g., CO₂ concentrations as a proxy for ventilation adequacy, or meteorological data) limits the precision of ventilation risk characterisation. Future research should extend the resilience framework across all 19 Bhopal zones, validate the instrument's test-retest reliability, and supplement survey data with objective environmental measurements and geocoded COVID-19 case data.

Conclusions

Housing design and community infrastructure in the Sai Baba slum of Bhopal are structurally insufficient to prevent SARS-CoV-2 transmission or enable effective pandemic mitigation. Semi-pucca construction with asbestos roofing, near-universal absence of cross ventilation, substandard window areas, severely limited natural light, shared sanitation and water facilities, narrow lane networks, absence of ambulance access, and lack of community shelter collectively constitute a built environment highly conducive to airborne viral transmission and fundamentally incompatible with home isolation protocols. The composite Resilience Index—with a settlement Combined Index of 0.56 and approximately half of households in the below-average category—quantifies this vulnerability in a reproducible, indicator-based framework that can be applied and compared across settlements. Community infrastructure emerged as the most influential structural predictor of pandemic resilience, indicating that collective physical conditions, rather than individual dwelling characteristics alone, are decisive in determining transmission risk in informal settlements. These findings have direct implications for slum upgrading policy, building standards, and pandemic preparedness planning in Indian cities.

Declarations

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Statement

This study relied on anonymous household survey data collected for academic purposes. All participants provided verbal informed consent prior to participation. No personally identifiable data were collected or retained.

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