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Exploring urban housing disadvantages and economic struggles in Seoul, South Korea

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The present study investigates urban poverty in Seoul, South Korea, amid the COVID-19 pandemic, focusing on housing and economic challenges. Employing principal component analysis, clustering algorithms, and visualization techniques, it analyzes archived data to uncover disparities in housing conditions and economic well-being across Seoul. The research reveals significant socio-economic divisions, with over 75% of the city's areas marked by vulnerability, indicating widespread poverty or the concentration of economically disadvantaged populations. This highlights the pervasive nature of poverty and the precarious situation of the urban poor, who are at risk due to fragile living conditions. The findings advocate for inclusive urban development strategies that prioritize the needs of marginalized groups, suggesting a shift from focusing solely on economic growth to ensuring equitable welfare for all residents.

In recent times, the global population has grappled with formidable challenges, including the profound impacts of COVID-19, climate change, and others¹⁻⁹. These issues have exerted considerable pressure on societies worldwide. Among the various affected demographics, the urban poor have encountered substantial adversity, highlighting the critical need to address these multifaceted crises. South Korean society (hereafter referred to as Korea), akin to its global counterparts, has grappled with the multifaceted repercussions of these social issues. In Korea, the plight of the urban poor has risen to the forefront as a compelling concern, exacerbated by the concurrent challenges posed by the COVID-19 pandemic, natural disasters, economic hardship, and the alarming prevalence of suicide among older adults living in solitary conditions. In particular, the COVID-19 pandemic, a societal disruptor, has markedly heightened the vulnerability of the urban poor¹⁰. Consequently, it has become imperative to pinpoint the specific urban areas most susceptible to these challenges. The identification of these vulnerable zones is essential to formulate and implement targeted policies aimed at alleviating and mitigating the adverse social repercussions of these multifaceted crises.

While scholarly research has delved into the topic of urban poverty in Korea, the predominant focus has been on historical contexts and descriptive studies¹¹⁻¹⁴. While these studies contribute to an understanding of the broader social contextual framework of urban poverty, they have limitations when it comes to pinpointing the specific characteristics of urban poverty within discrete administrative units within the city. This limitation, in turn, hampers the formulation and execution of measures aimed at

alleviating systemic disparities. Despite recent literature addressing socio-economic disparities and inequalities across urban areas in Korea¹⁵⁻¹⁷, there has been a notable absence of targeted examinations of the urban poor, who confront multiple risks and vulnerabilities within disadvantaged urban environments. This study endeavors to bridge this gap by directing its attention toward the most socio-economically vulnerable urban areas, as opposed to the more privileged ones. The primary objective is to identify these highly vulnerable urban areas through the application of a data-driven approach that scrutinizes the attributes of housing and living poverty within urban spaces, an area that has received limited attention within the existing literature on urban poverty.

The selection of appropriate indicators that align with the research objective is crucial in conducting a data-driven study. This study delves into examining the attributes of poverty within the urban poor population of Seoul, the capital city of Korea, encompassing both housing and daily living conditions. Through an analysis of poverty encompassing both housing and daily living conditions in Seoul, this study seeks to pinpoint the areas within the city that are most exposed to vulnerabilities. To achieve this, the study employs principal component analysis (PCA) and clustering algorithms, utilizing extensive archived data. Through this data-driven approach, the present study identifies clusters within Seoul and assesses the disparities in housing and living poverty between different areas. Ultimately, this study sheds light on the areas that are most exposed to vulnerabilities. Seoul is an appropriate setting for this analysis due to its significant population size, accounting for ~17% of Korea's total population (In 2022, the population of

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Seoul is estimated to be ~9.5 million), and its diverse population composition, with individuals from various regions of the country residing in the city^{12,14,18}.

The findings of this research uncover a distinct division within Seoul, pinpointing one of two main areas where a significant portion of *dongs* (the smallest administrative units in Korea) exhibit vulnerabilities. This finding implies that the urban poor, who are particularly susceptible to various risks, are distributed throughout Seoul and live in close proximity to the residences of the majority of the population. The presence of instability among citizens living in poverty, resulting from their exposure to multiple risks, highlights the overall fragility and instability of the living environment for residents in Seoul. This underscores the interconnectedness of urban poverty and its impact on the broader social fabric of the city, emphasizing the urgent need to address these vulnerabilities and create a more equitable and inclusive urban environment for citizens.

The current study augments the prevailing literature by leveraging data-driven methodologies to pinpoint susceptible zones within an urban landscape. Initially, this study presents a methodology to examine the manifestation of urban impoverishment by considering attributes of housing and daily living conditions within specific urban areas. In tandem, this study introduces an algorithmic strategy to categorize areas based on a holistic data array, facilitating the exploration of expansive archived datasets. The probe into spatial aggregation tendencies and inter-cluster variations offers an understanding of the challenges encountered by the economically disadvantaged population in Seoul, a metropolis deeply intertwined with the global economic matrix. This observation resonates with the discourse on escalating spatial bifurcation in cosmopolitan cities as posited by Sassen¹⁹. In the context of an escalating impetus for data-informed urban governance²⁰, this study's methodology in evaluating urban indigence furnishes insights pertinent to Seoul's blueprint for evolving into a more inclusive metropolis.

Results

Poverty and vulnerability

The prevailing notion that poverty is solely a consequence of individual shortcomings, such as laziness or a weak will, fails to acknowledge the complex factors that contribute to poverty. Poverty is not a simple personal problem but a multifaceted social issue deeply rooted in systemic inequalities and structural constraints. While global efforts have resulted in a gradual decline in absolute poverty rates, inequality within countries has become more pronounced, exacerbating the challenges associated with poverty²¹.

The COVID-19 pandemic has laid bare the severity of poverty on a global scale, further underscoring the need to address its underlying causes and implement effective social policies^{22–25}. The pandemic has disproportionately impacted the poor, amplifying existing inequalities and vulnerabilities. It has highlighted the interplay between poverty and other social issues, such as inadequate healthcare, limited access to education, and precarious employment. Consequently, poverty has emerged as a pressing concern that requires comprehensive strategies to promote social inclusion and reduce inequality.

In the context of Korea, the issue of income and wealth disparities has garnered significant attention since the Asian financial crisis in 1997. Studies have identified various factors contributing to poverty in Korean society, including unequal opportunities, educational inequalities, and regional disparities^{15,26,27}. These factors restrict individuals' prospects for upward mobility, perpetuating a vicious cycle of poverty, particularly within low-income communities. The concentration of unemployment, specific labor market characteristics, and inadequate social safety nets further compound the challenges faced by the urban poor²⁸.

Moreover, research highlights the impact of housing inequality as a structural driver of poverty in Korea^{15,29,30}. Wealth disparities, particularly in the form of unequal access to housing, perpetuate socio-economic gaps and hinder upward mobility. This inequality can be transmitted across generations, leading to persistent poverty and limited opportunities for social

advancement²⁹. Consequently, individuals ensnared in housing and financial hardships face significant challenges in breaking free from the cycle of deprivation.

Comprehending the intricate interplay of poverty, its foundational drivers, and its persistent impacts is paramount for devising robust policies that target poverty's core origins and champion social fairness. Acknowledging poverty as a multifaceted societal challenge shaped by structural determinants enables policymakers and key stakeholders to aspire toward fostering egalitarian communities that proffer equitable prospects for individuals across all socio-economic strata.

Vulnerabilities of the urban poor

In recent years, scholars have increasingly recognized the importance of adopting a comprehensive and multidimensional approach when examining urban poverty. In the existing literature, a range of studies including those by^{31–39}, focus on exploring the living conditions and situations of impoverished areas and their inhabitants. These studies encompass various aspects of poverty, illuminating the intricate nature of social exclusion and isolation that the poor endure. They particularly emphasize the significance of spatial patterns in elucidating these social dynamics. Another line of research has focused on understanding the “area effects” or “neighborhood effects” within urban spaces. Scholars such as Atkinson and Kintrea⁴⁰ and Murie and Musted⁴¹ have examined how social exclusion affects individuals or groups residing in specific areas, encompassing dimensions such as health, education, employment, and safety, all of which are influenced by the characteristics of the locality. These studies commonly assume that residents of impoverished areas are more likely to encounter various challenges, including social isolation, limited social networks, poor health outcomes, and heightened vulnerability to natural disasters^{42–45}. Such research consistently emphasizes that the urban poor face a multitude of risks due to their disadvantaged spatial contexts.

Empirical evidence confirms the manifold risks that urban poverty poses to the urban poor, irrespective of whether they reside in the Global North or the Global South. For instance, individuals living in impoverished urban areas often encounter difficulties in accessing essential medical facilities, leading to limited healthcare services and an increased susceptibility to contagious diseases^{9,46–48}. Moreover, inadequate sanitation facilities, prevalent in these areas, further contribute to their vulnerability. The absence of basic amenities exposes the urban poor to higher levels of violence and perpetuates their overall deprivation, making them physically and psychologically susceptible to adverse outcomes^{9,46–48}.

A notable distinction arises when comparing affluent areas with their impoverished counterparts. In prosperous areas, economic resources, educational opportunities, and religious institutions foster the creation of social networks and enable access to social capital⁴⁹. However, individuals residing in impoverished areas are deprived of such benefits, exacerbating their social isolation and further hindering their integration into society⁴². This deprivation of social capital and networks intensifies the challenges faced by the urban poor, perpetuating their marginalization and reinforcing the cycle of poverty⁴².

Furthermore, the urban impoverished exhibit heightened vulnerability to natural calamities, encompassing heatwaves, floods, and hazards like building collapses and security concerns^{50,51}. Their peripheral living conditions, often marked by inadequate infrastructure and substandard housing, amplify their exposure to risks during such events, making the urban poor more vulnerable and unstable. Considering the nuanced dimensions of urban impoverishment and its associated perils, deciphering the spatial distributions of poverty within urban locales becomes imperative.

The context of urban poverty in Seoul

As urban centers undergo expansion, the socio-economic attributes of their residents become spatially manifested, reflecting the overarching social framework of society^{49,52,53}. In the year 2022, the population of Seoul stood at ~9.5 million individuals, constituting roughly 17% of the entire population of Korea. Seoul is characterized by its high population density, drawing

Table 1 | List of variables

	Category	Variable	Explanation	N
1	Housing poverty	Gosiwon	Number of Gosiwon	5582
2		Jiha/Banjijha	Number of habitable basements or semi-basements of detached and apartment houses	202,520
3	Living poverty	Basic living	Number of households receiving basic livelihood security	289,518
4		Old in poverty	Number of older adults living alone with basic livelihood security or low income	124,654

N for Housing poverty variables are estimated values based on raw data. There are as few as 20 people and as many as 100 people living in one Gosiwon. Source: See Supplementary Table 1.

diverse individuals from across the country in pursuit of employment opportunities^{15,18,54}. In the context of the Asian developmental state paradigm during the 1970s and 1980s, there was a marked concentration of wealth and employment opportunities within the Seoul metropolitan region¹⁸, thereby giving rise to a spatially defined socio-economic stratification^{15,16,55}. The intense confluence of economic and social activities within Seoul amplifies the repercussions of socio-economic disparities, effectively rendering the city a microcosm of the broader challenges tied to regional inequality. Historical factors, such as government policies centralized around *Gangnam* and oriented toward economic development^{55,56}, coupled with transformative events like the 1997 Asian financial crisis⁵⁷, have played pivotal roles in exacerbating these inequalities. In Seoul, phrases that represent specific spaces, such as affluent *Gangnam* versus less affluent *Gangbuk*, reflect individuals' identity, social status, and class^{55,58}. A region where an individual lives is one of the prime factors indicate an individual's socio-economic position^{17,58,59}.

According to the 2022 Global Power City Index, Seoul holds the 7th position⁶⁰, while the 2022 Global Cities Report situates Seoul at the 13th spot in the Global Cities Index⁶¹. These rankings underscore Seoul's global competitiveness and its significant standing on the international stage. However, in stark contrast to this global recognition, Seoul grapples with striking socio-economic disparities among its residents, which are prominently evident in its urban landscape¹⁵. For instance, the Global Power City Index evaluates the competitiveness of cities across various dimensions, including the economy, research and development, cultural interaction, livability, environment, and accessibility. Seoul performs admirably, ranking in the top 10 in most categories, except for livability, where its ranking falls beyond the 30th position (38th). This discrepancy indicates that Seoul lags behind other global cities concerning housing quality and the overall ease of living for its residents. In essence, Seoul presents a paradoxical landscape characterized by the coexistence of substantial affluence and profound vulnerability.

The academic discourse differentiates between "Housing poverty" and "Living poverty" as key factors that profoundly affect the urban disadvantaged in Seoul, as highlighted in previous research^{12,13,15,62}. For the purposes of our study, Housing poverty refers to poverty that is primarily associated with issues related to housing, whereas Living poverty encompasses poverty that impacts the everyday living conditions of individuals. To ensure clarity and coherence in our discussion, and to intuitively convey the distinct meanings of these terms, we will consistently use Housing poverty and Living poverty throughout this study. For a more detailed explanation and differentiation of these terms, please refer to Table 1 in the "Materials and methods" section. This distinction aims to provide a clearer understanding of the specific challenges faced by the urban underprivileged in Seoul. In light of the profound societal repercussions of the global COVID-19 pandemic, one of the most substantial societal disruptions in recent memory, it becomes imperative to discern how vulnerability manifests within this urban context. While the impact of the COVID-19 pandemic has been felt worldwide, it is conceivable that specific segments of the population may bear its repercussions disproportionately.

Impact of Covid-19 in Seoul

Before exploring the intricacies of housing and living poverty in Seoul, it is essential to examine survey data that illuminate the impact of COVID-19 on

the living conditions of the city's inhabitants. This preliminary analysis is crucial for contextualizing urban poverty within the specific environment of Seoul. These insights are derived from the 2022 *Koreans' Happiness Survey*, an initiative undertaken by the *National Assembly Futures Institute*. The primary objective of this survey is to collect data on happiness indicators, inequalities, and related variables in the Korean context. In adherence to the subjective well-being measurement guidelines provided by the OECD (Organisation for Economic Co-operation and Development), the survey also incorporates inquiries into attitudes, social values, and activities, aiming to elucidate the socio-psychological determinants of happiness.

Figure 1 presents the results of a survey on Seoul residents' perceptions of the impact of COVID-19 on their living environments. The survey participants were asked to evaluate the statement, "COVID-19 has negatively affected my housing environment," on a scale ranging from "Not at all" (coded as 1) to "Very much" (coded as 5). This question aimed to gauge changes in individuals' living conditions due to the pandemic, such as increased social isolation or concerns about safety. It should be noted that higher scores on this scale indicate a stronger perceived negative effect of the pandemic on housing conditions. The ensuing analysis considers demographic and socio-economic variables, such as income, education, and age. It also includes binary variables for sex, housing type and marriage. These are variables that generally influence Korean perceptions and behavior, reflecting socio-economic and demographic characteristics⁶³. Comprehensive information on data and variables is detailed in Supplementary Table 2.

Upon analyzing the differential impacts of COVID-19 across varied groups, discernible statistical distinctions were predominantly elusive for categories such as sex, marital status, and housing type. Contrastingly, age, education level, and income presented significant variances between their sub-groups. Notably, the elderly, those with lower education credentials, and individuals within the lower income brackets were more inclined to opine that COVID-19 has detrimentally affected their residential milieu compared to their counterparts.

Figure 2 offers a granular examination of how each variable influences the dependent variable, which is the perceived effect of COVID-19 on the housing environment. The analytical methodology employed is the Ordered Probit model. This model is particularly apt for probing ordered categorical dependent variables, facilitating the estimation of probabilities for each specific category. In our analysis, Model (1) represents a foundational construct integrating just the Age and Income variables. Subsequently, Model (2) incorporates solely socio-economic parameters, while Model (3) is exclusive to Demographic variables. Concluding the sequence, Model (4) amalgamates all the variables under scrutiny.

Figure 2 delves into the odds ratios of prominent variables, specifically age and income, under the scope of the Ordered Probit model. Distinctively, age exhibits a positive relationship with the dependent variable, while income, in contrast, exerts a negative influence on social trust. In the purview of Model (2) and Model (3), both education and marital status register as statistically significant, though their prominence diminishes in Model (4). However, age and income persistently shape the dependent variable throughout all the models. In the results, the odds ratio for age is 1.072. This implies that for each unit increase in age, the odds of an individual perceiving a more negative impact of COVID-19 on their housing environment increase by 7.2%. In other words, older individuals are more likely to feel that

Fig. 1 | Perceptions of COVID-19's impact on housing conditions by socio-economic and demographic variables in Seoul. Higher values indicate that COVID-19 has had a greater negative impact on the housing environment; $N = 2000$. Source: 2022 Koreans' Happiness Survey (see Supplementary Table 1 for details).

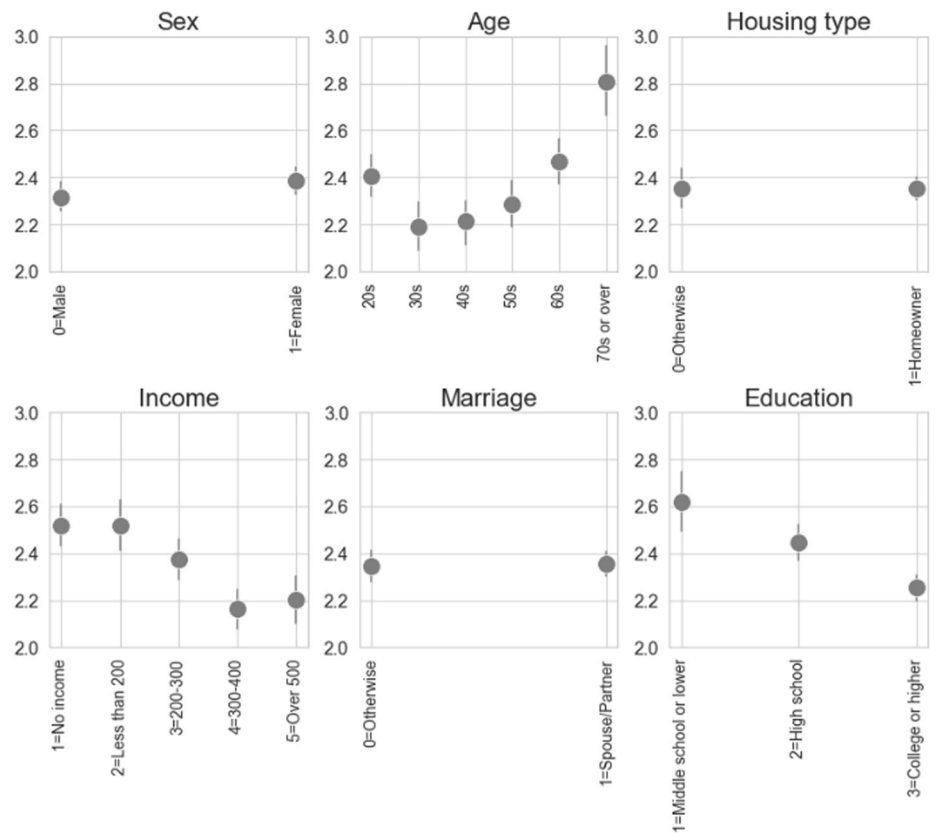
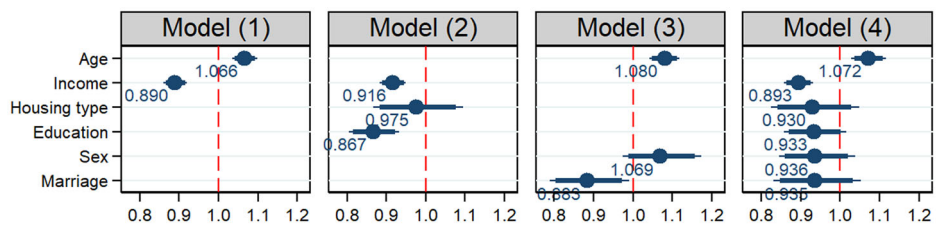


Fig. 2 | Effects of socio-economic and demographic variables (odds ratio). Coefficient plots with 90% (thick line) and 95% (thin line); see Supplementary Table 5 for full results.



the pandemic has adversely affected their housing environment compared to younger ones.

On the other hand, the odds ratio for income is 0.893. This suggests that for each unit increase in income, the odds of an individual feeling that COVID-19 has negatively impacted their housing environment are multiplied by 0.893, translating to a 10.7% decrease in odds. This means that individuals with lower incomes are more likely to perceive the pandemic as having a detrimental effect on their housing conditions compared to those with higher incomes. This analysis sheds light on the intricate dynamics intertwining housing conditions, age, and income in Seoul's urban landscape. Through this lens, a clearer understanding emerges regarding the challenges faced by the city's more susceptible populations. Consequently, this underscores the imperative for a comprehensive spatial examination of housing poverty and living poverty in Seoul's metropolitan framework.

Housing and living poverty

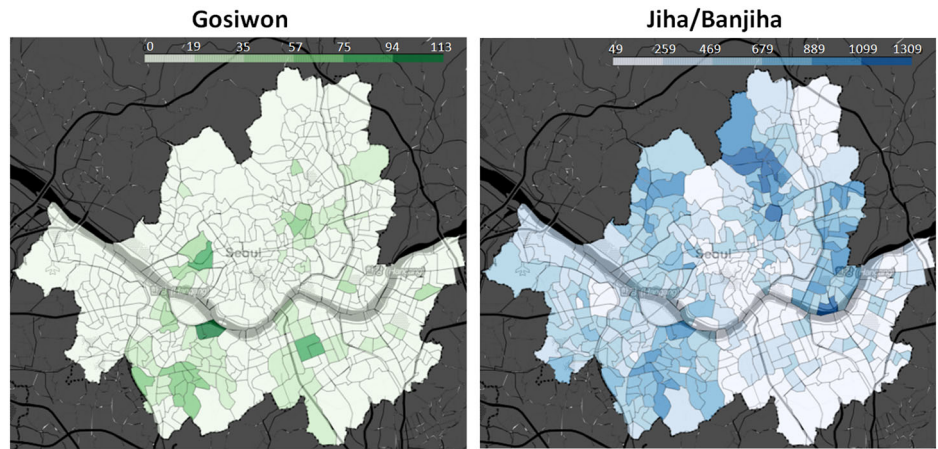
Our analysis now transitions to investigating housing and living poverty within Seoul. The city is organized into 25 *gus* (boroughs), further subdivided into 426 *dongs* (blocks). These 426 *dongs* serve as the spatial units for our study, providing a comprehensive framework for examining the

distribution and characteristics of poverty across the urban landscape. To begin with, for housing poverty, Seoul has *Gosiwon* or *Goshiwon* (Go-si-won) and *Jiha/Banjijha* (Ji-ha/Ban-ji-ha), which are types of housing reflecting the housing poverty of the poor in Seoul. In Korean society, there are various factors that determine housing type, and economic status determines the threshold for selecting the dwelling type⁶⁴. Therefore, the cheapest and most flexible type of housing is what the most vulnerable people in Seoul are looking for. *Gosiwon* is a low-cost dwelling place where larger rooms are usually divided by thin walls and makeshift doors. Thus, the lack of privacy in *Gosiwon* is an inevitable issue. *Gosiwon* residents tend to perceive *Gosiwon* as a temporary residence, so there is little interaction with neighbors and people are often socially isolated.

Rooms are rented on a monthly basis, and are the cheapest and most flexible form of housing in the country. Rooms are as tiny as 3.5 square meters and furnished with a desk, bookshelf, and bed. There are usually no windows, but if there are, sunlight does not filter in well. Unless an individual pays for the luxury of a private shower or toilet, the resident has to share one with many other tenants (ranging from 20 to 40). In a living space where contact with strangers is inevitable, individuals are exposed to many types of unpredictable risks every day.

Jiha/Banjijha refers to basement/semi-basement housing, made famous by the Oscar-awarded Korean film "*Parasite*" which vividly portrays

Fig. 3 | Map of Seoul Gosiwon and Jiha/Banjiha housing units in *dongs*. The legend indicates the count of observations per *dong* unit. See details in Table 1 and Supplementary Table 1.



this type of dwelling place⁶⁵. Jiha/Banjiha houses in Seoul were built intensively in the late 1980s and early 1990s. This rapid increase in the number of underground/semi-basement residences is attributable to the easing of construction standards for multi-unit dwellings in response to the sharp increase in housing prices due to Seoul’s rapid increase in population. These residential spaces are characterized by low income homes, and as more than half of the houses are located underground, they are exposed to various social risks and natural disasters such as fires, gas leaks, flooding, respiratory diseases, and pests. As recent floods resulted in many casualties in Seoul, Korean society has once again noted the vulnerability of those living in this space⁶⁶.

In Fig. 3, the spatial distribution of “Gosiwon” and “Jiha/Banjiha” in Seoul is depicted. Darker shades correspond to higher concentrations of these units, while lighter shades indicate lower concentrations. Based on the findings of this research, both Gosiwon and Jiha/Banjiha have a widespread presence across Seoul (a detailed description of these variables can be found in the subsequent section). Remarkably, the *dongs* exhibiting the highest concentration of Gosiwons are predominantly located in the southeastern and eastern sectors of the city. Concurrently, Jiha/Banjiha units are primarily concentrated in the *dongs* of the southeastern, northern, and western parts of Seoul. Transitioning to the subject of living poverty in Seoul, we turn our attention to basic livelihood security assistance recipients, those with incomes below 30–50% of Korea’s median income. Eligibility for these benefits depends on documented income, considering monthly income and assets or debts. For instance, in 2023, a single-person household with zero income and recognized income of 0 KRW (As of October 30, 2023, exchange rate of 1 USD = 1349 KRW) qualifies for livelihood, medical, housing, and education benefits because their recognized income falls below 623,368 KRW (~462 USD). They receive 623,368 KRW per month. On the other hand, in 2023, the Seoul Metropolitan Government introduced a “Seoul-style living wage” of 11,157 KRW (~8.27 USD) per hour. Working 209 h (the legal limit) yields a monthly income of 2,331,813 KRW (~1728.18 USD). If this living wage aims to ensure a decent standard of living with housing, education, and cultural opportunities in Seoul, recipients of basic livelihood security continue to experience living conditions significantly below the threshold for a decent standard of living.

Consequently, households housing individuals with the lowest income levels encounter formidable challenges in upholding fundamental living standards. It is imperative to recognize that income serves as a pivotal determinant not only impacting the economic facets but also the psychological dimensions of daily life for individuals facing poverty. As highlighted by research conducted by Jin and Hong⁶⁷, income exerts a significant influence on the subjective well-being of Seoul’s residents, implying that its effects extend beyond purely financial matters to encompass the psychological well-being of those grappling with poverty on a daily basis.

Poverty, pandemic, and psychological distress among the elderly

Korea bears the unfortunate distinction of having the highest suicide rates among all countries within the Organization for Economic Cooperation and Development (OECD)⁶⁸. This concerning trend is even more pronounced when examining the rates of suicide among older adults, a category where Korea also ranks at the top^{68–70}. In Korean society, the older adult population constitutes a significant proportion of those living in poverty, as illuminated by research by Jeon et al.⁶⁹ and Lee et al.⁷¹. It is crucial to note that poverty is tightly intertwined with the incidence of suicide in Korean society, as demonstrated by the work of Pak and Choung⁷². Moreover, poverty stands out as one of the most influential determinants of suicide among older adults in Korea, as emphasized by the studies of Cheong et al.⁶² and Jeong et al.⁷³. This risk is particularly pronounced for older adults residing in urban areas and living alone, who exhibit higher suicide rates compared to their counterparts in other regions of Korea⁶².

Consequently, impoverished older adults living alone in urban areas in Korea face an elevated vulnerability to extreme poverty and a heightened risk of suicide or dying alone. Their exposure to such perils encompasses isolation, as well as physical and mental health challenges, compounded by economic deprivation. The advent of the COVID-19 pandemic likely exacerbated these issues^{74,75}, with poor older adults possibly experiencing increased deprivation and heightened levels of physical and social isolation.

Figure 4 illustrates the distribution of 597 Seoul residents, out of a total of 3239, who indicated a decline in personal income attributable to the COVID-19 pandemic, as per the 2021 *Koreans’ Happiness Survey*. For an in-depth overview of the survey, readers are directed to Supplementary Table 2 and Supplementary Fig. 1. Remarkably, amongst these 597 respondents, a significant 38.69% were individuals aged 60 and above, the highest proportion among all age categories. Figure 5 delves into the suicide rates in Seoul in 2022, delineated by age brackets. There is a conspicuous surge in the suicide rate for age groups commencing at 70 years and above. This rising trend underscores the stark realities faced by Seoul’s elderly population. When juxtaposing the findings of Figs. 4 and 5, a somber narrative emerges: the elderly in Seoul are not only the demographic most financially impacted by the COVID-19 pandemic but also register the highest suicide rates in the city. This alignment of economic hardships with psychological distress signifies the heightened vulnerability faced by Seoul’s older population, particularly in the challenging pandemic era.

In Fig. 6’s map visualization, two distinct yet crucial demographics within Seoul’s vast landscape are highlighted: “Basic living” and “Old in poverty.” The term Basic living corresponds to households that are beneficiaries of basic livelihood security, ensuring their sustenance in economically challenging times. Meanwhile, Old in poverty pinpoints a more vulnerable subset—older adults who, in addition to residing alone, are grappling with curtailed basic livelihood security or are trapped in the clutches of low income. While these groups permeate various corners of

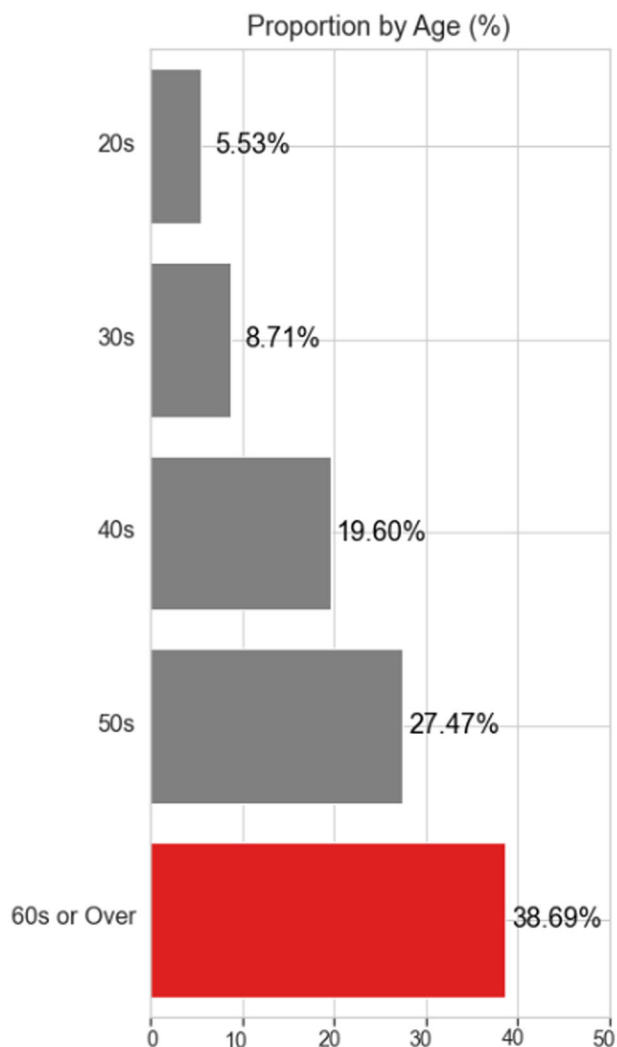


Fig. 4 | Income decrease due to COVID-19 by age. Source: 2021 Koreans' Happiness Survey (see Supplementary Table 1 for details).

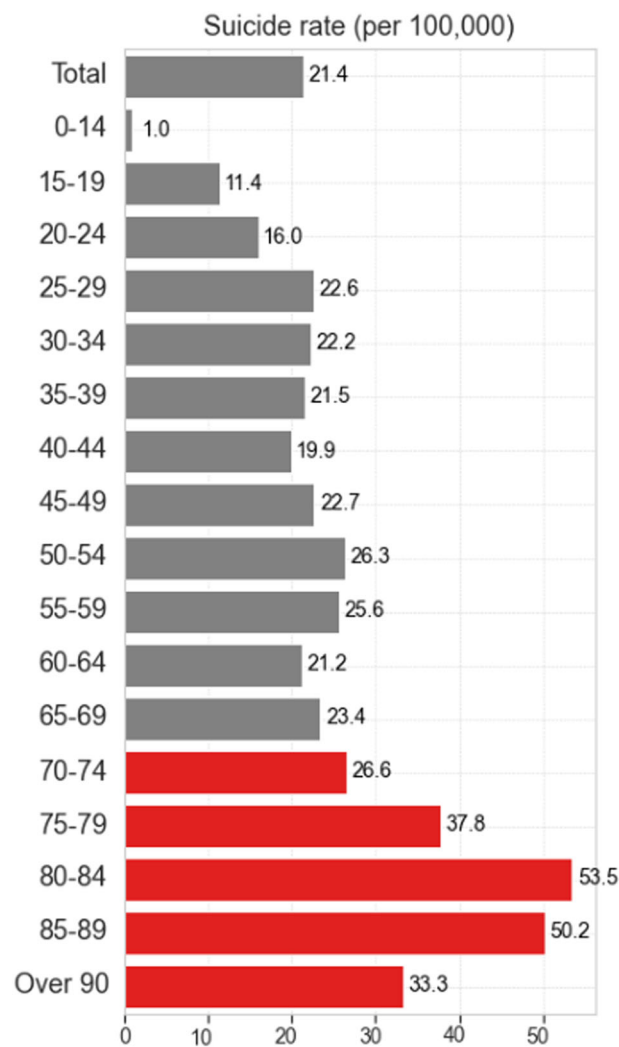


Fig. 5 | Suicide rate in Seoul (2022). Source: Seoul Open Data (<https://data.seoul.go.kr/dataList/10775/S/2/datasetView.do>).

Seoul, their spatial distribution reveals some telling patterns. Notably, there is a pronounced concentration of these demographics in specific quadrants of the city. The *dongs* located in the southwest, north, and northeast regions of Seoul form significant clusters, highlighting a narrative of spatial disparities across the city.

Analysis results

The analysis of PCA and clustering results is conducted through a sequential, four-step process. Initially, we evaluate the PCA outcomes, followed by a determination of the appropriate number of clusters. Subsequently, our focus shifts to identifying the most suitable clustering arrangement and spatial structure. Finally, we pinpoint the areas characterized as the most vulnerable. In Fig. 7, we present the PCA results for the housing and living poverty variables. As previously explained, the primary goal of employing PCA is to distill the numerous variables into two dimensions, specifically housing and living poverty, which encapsulate the essential characteristics of the dataset. The illustration in Fig. 7 reveals that PC1 in housing poverty emerges as a novel variable that independently elucidates 70.3% of the data distribution, while PC1 in living poverty expounds 99.1% of the data distribution. Notably, each PC1, as a newly derived variable achieved through dimensionality reduction, elucidates ~70% or more of the data distribution. This observation implies a substantial degree of correlation among the variables and a convergence in data distribution patterns.

From the maps in Figs. 3 and 6 in the previous section, we can see the spatial structure of housing and living poverty in Seoul. We can further understand them by analyzing the clustering results. The results of the silhouette analysis of Seoul are shown in Fig. 8. The *x*-axis refers to housing poverty and the *y*-axis refers to living poverty. In this figure, we can see how the silhouette score and its shape changes as the *K* increases. When divided into two clusters (*K* = 2), the silhouette score is the highest (0.426). Conversely, as *K* increases to three (0.334), four (0.356), five (0.345) and six (0.348), the silhouette score decreases. In other words, we can see that the silhouette score drops sharply when changing from *K* = 2 to *K* = 3 and maintains a similar level thereafter. Referring to Supplementary Fig. 2, we can confirm that the optimal number of clusters for Hierarchical Clustering is 2 as well and *dongs* belonging to each cluster are also the same.

Looking at the optimal clustering results when *K* = 2 in Fig. 5, 98 *dongs* belong to Cluster 0 and the remaining *dongs* belong to Cluster 1. In this figure, we can intuitively see that Cluster 0 outnumbers Cluster 1. That is, over 75% of *dongs* form one large cluster, and the rest form a smaller one. In Fig. 9, we can find a map visualization of the clustering result for Seoul (*K* = 2). Looking at the spatial shape of the clusters, we can find that Cluster 1 is mainly located in the center around the Han River and in the southeast. The rest belong to Cluster 0.

Figure 10 illustrates the observed mean differences between Clusters 0 and 1, focusing on four key metrics: Gosiwon, Jiha/Banjiha, Basic Living, and Old in Poverty. In comparative terms, Cluster 0 registers values that are

Fig. 6 | Map of Seoul basic livelihood security allowance recipients in *dongs*. The legend indicates the count of observations per *dong* unit. See details in Table 1 and Supplementary Table 1.

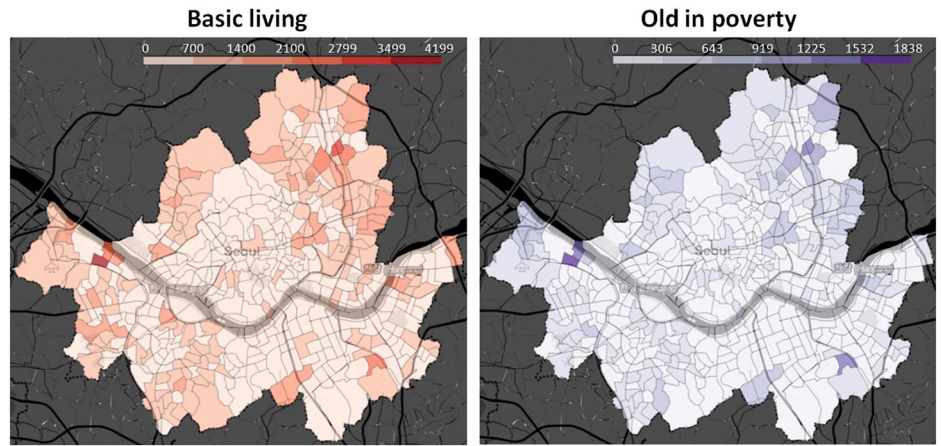


Fig. 7 | PCA of housing and living poverty. On the left is the results of PCA for the housing poverty variables, while on the right is PCA results for the living poverty variables.

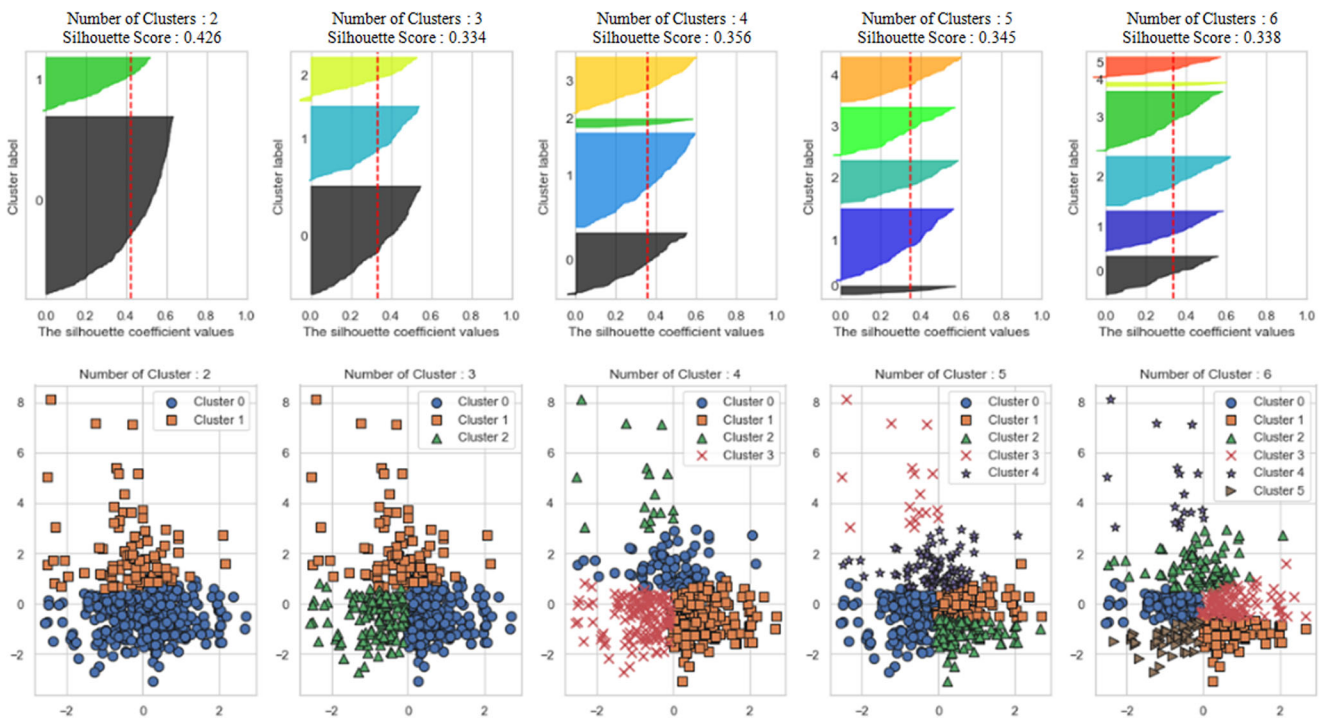
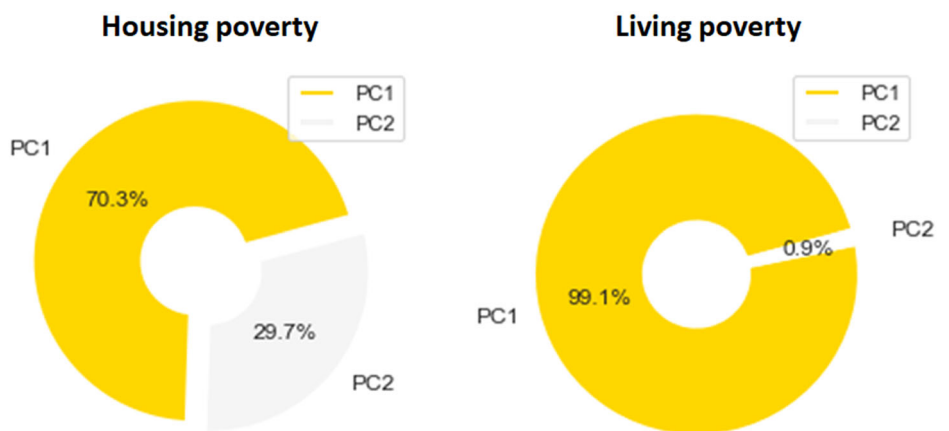


Fig. 8 | Clustering results. This figure illustrates the variation in the Silhouette Score with the number of clusters increasing from 2 to 6, indicating the optimal clustering solution for the dataset under analysis.

Fig. 9 | Optimal clustering and map of optimal clustering. On the left, the figure displays the optimal clustering result for a two-cluster solution, while on the right, a map of Seoul is presented with the clustering result applied.

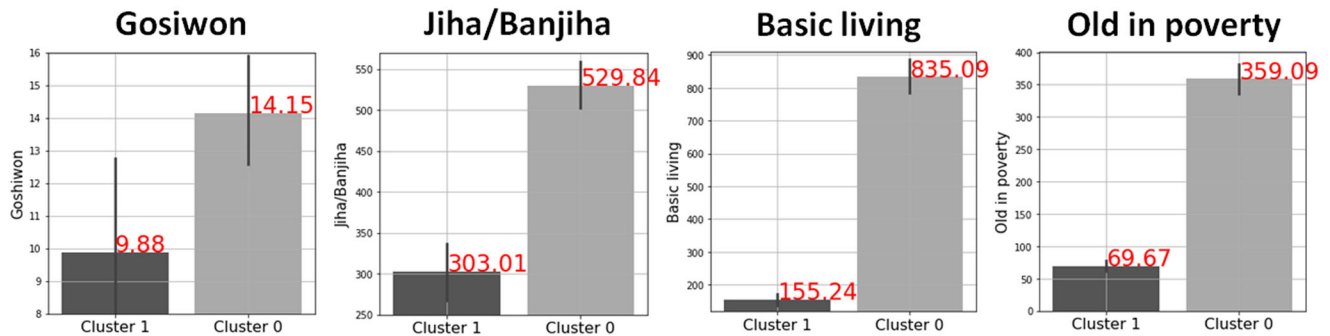
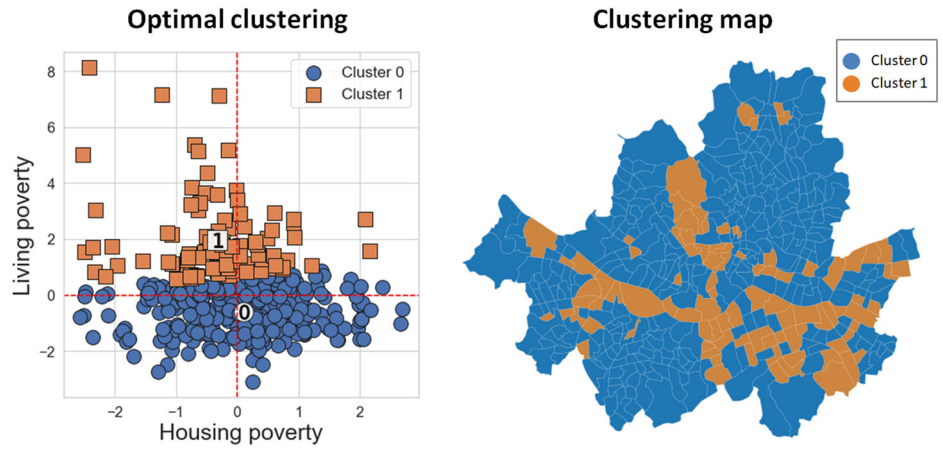


Fig. 10 | Poverty gap by cluster. The numbers in the plots above represent the actual averages, not the PCA values.

1.43 times greater for Gosiwon, 1.74 times greater for Jiha/Banjiha, 5.37 times greater for Basic living, and 5.15 times greater for Old in poverty than those of Cluster 1. This suggests that locales within Cluster 0 exhibit heightened vulnerability relative to those in Cluster 1 with respect to housing and living poverty, and these differences are substantial enough to warrant attention.

More specifically, Figs. 11 and 12 provide detailed insights derived from the PCA findings, clarifying the classification of 30 *dongs* with the highest PC values for housing poverty and living poverty, respectively, all within Cluster 0 (refer to Supplementary Fig. 3 for comprehensive PCA outcomes). These specified areas (*dongs*) are pinpointed as exhibiting acute vulnerability in relation to housing and living poverty. In the bar plots of Figs. 11 and 12, the counts—specifically, the number of Gosiwon, number of Jiha/Banjiha, number of households under Basic Living, and number of elderly in poverty—are presented for each neighborhood identified as vulnerable to housing and living impoverishment based on PCA analysis. Notably, these *dongs* display a significant density of residents facing the duress of housing or living poverty, underscoring their vulnerabilities in the urban landscape. A salient observation is the noticeable absence of *dongs* from Gangnam-3 *gu*, acclaimed as one of Seoul’s pinnacle affluent sectors^{35,38}, from both delineations. This observation emphasizes the profound nexus between housing and living vulnerabilities and the foundational socio-economic structures that give rise to disparities across Seoul’s multifarious districts^{15,16}.

The very limited representation of *dongs* from Gangnam-3 *gu* in the two groups indicates that these affluent areas generally exhibit lower levels of housing and living poverty compared to other locales in Seoul. This observation aligns with prior research that has highlighted the pronounced socio-economic contrasts and disparities prevalent within the city^{15,16}. The linkage between socio-economic foundations and housing and living vulnerabilities further stresses the urgency of addressing the spatial disparities in Seoul, pushing toward a more equitable and inclusive urban development.

In summary, the outcomes of the clustering analysis, utilizing housing and living poverty indicators derived through PCA, reveal that *dongs* in Seoul can be broadly classified into two distinct clusters. These clusters exhibit significant disparities in terms of housing and living conditions, underscoring the presence of substantial disparities in poverty levels. The primary aim of this study is to pinpoint specific areas in Seoul that bear heightened susceptibility to impoverishment. Contrary to the anticipation that select urban enclaves would emerge as the epicenters of acute poverty, the analytical results painted a divergent portrait. The findings indicate that more than 75% of Seoul’s urban areas are exposed to vulnerabilities associated with poverty. This implies that a substantial segment of Seoul’s population resides in proximity to areas characterized by elevated poverty rates. In essence, this means that even if these residents do not personally experience poverty, they coexist in neighborhoods with vulnerable populations, sharing living environment.

Recognizing the widespread vulnerabilities across much of Seoul’s urban landscape is crucial for the adept management of various socio-environmental challenges confronting its inhabitants. These challenges span health concerns, natural calamities, economic deprivation, and social estrangement. Through this analysis, pinpointing the areas most prone to these vulnerabilities—encompassing a significant portion of Seoul—becomes pivotal for formulating and executing policies designed to bolster the safety and welfare of the urban populace.

Discussion

Urban development of Seoul from the 1970s to the 1990s mirrors the rapid urbanization seen in many Asian cities, marking a path that aligns with both emerging and established urban centers in the region^{76,77}. This period of accelerated growth in Seoul was influenced by a combination of significant events and shifting paradigms. The adoption of neoliberal development ideologies in the 1980s, the impact of the Asian financial crisis in the 1990s, and the global economic downturn in the 2000s were instrumental in

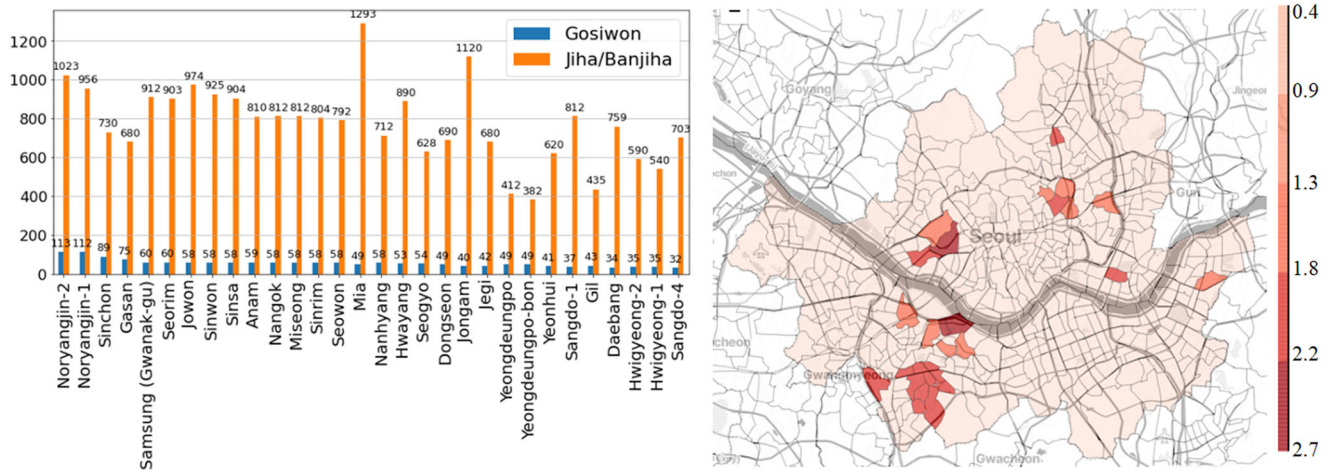


Fig. 11 | 30 dong in Cluster 0 with highest housing poverty based on PCA. The left plot represents the number of Gosiwon and Jiha/Banjiha in the top 30 dong with the highest housing poverty PCA values in Cluster 0, while the right map depicts the top 30 dong based on housing poverty PCA values in Cluster 0.

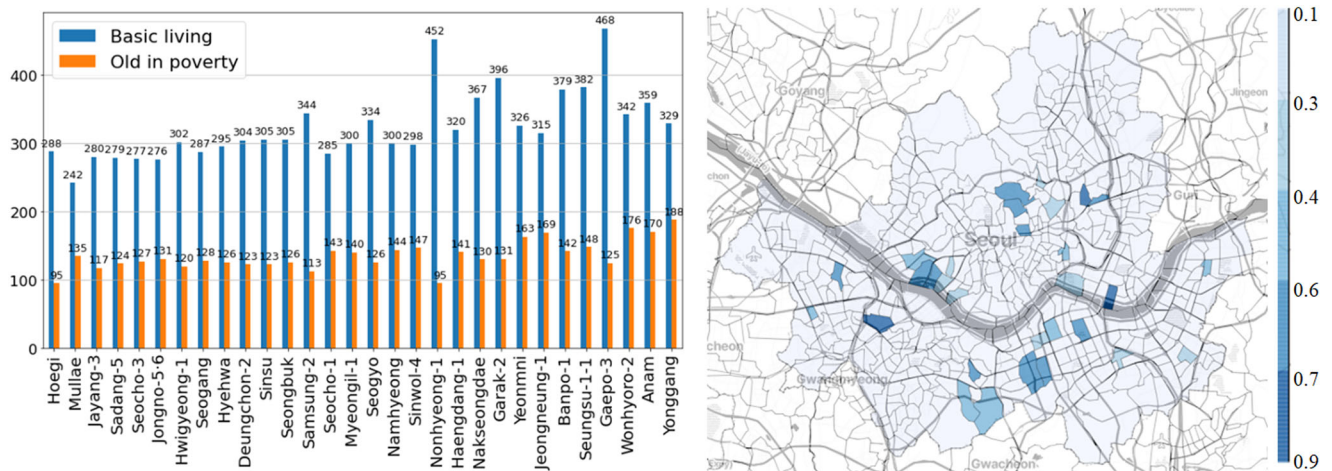


Fig. 12 | 30 dong in Cluster 0 with highest living poverty based on PCA. The left plot represents the number of Basic living and Jiha/Banjiha in the top 30 dong with the highest living poverty PCA values in Cluster 0, while the right map depicts the top 30 dong based on living poverty PCA values in Cluster 0.

defining the city’s developmental direction. This era was characterized by a strong focus on economic growth, striving for high positions in global city rankings, and enhancing urban competitiveness. However, these priorities inadvertently led to increased urban disparities. Technological advancements have contributed to urban convenience but have also widened the gaps between different neighborhoods and social groups⁷⁸. Consequently, these developments have impacted the quality of urban life, particularly affecting the experiences of Seoul’s residents, notably the urban poor. This group has faced compounded challenges, especially in light of the COVID-19 pandemic.

Essentially, the present study underscores the constraints associated with Seoul’s adherence to the Asian developmental state model and advocates for a transition away from an exclusive emphasis on economic advancement in favor of a more inclusive approach that addresses the needs of the city’s marginalized population segments. While maintaining economic competitiveness on the global stage remains crucial for Seoul, it is apparent that the city has, to some extent, lagged in terms of inclusiveness. This observation may reflect a recurring pattern among major cities in Asian countries that have prioritized economic development as latecomers, and this study sheds light on some of the shared limitations encountered in this context.

From the empirical results elucidated in the research, it is apparent that the spatial structures of living and housing poverty in Seoul are markedly

pronounced. Over 75% of Seoul’s neighborhoods exhibit heightened vulnerability to both housing and living poverty. Such statistics highlight the significant and widespread presence of urban poverty, underscoring the pressing need to address it. By 2023, in response to these burgeoning challenges, Seoul initiated the formulation of an inclusive city index, seeking holistic betterment across domains of livelihood, housing, educational access, cultural inclusivity, and broader social integration.

The discourse on urbanism has shifted from an initial emphasis on poverty mitigation to a more comprehensive exploration of systemic disparities. In this context, recently, Seoul has demonstrated a resolute commitment to cultivating an inclusive urban environment. The city’s housing policies are diverse, including the allocation of public rental properties, specialized support for disadvantaged groups, enhancement of living conditions for the at-risk populations, and addressing the distinct housing dilemmas faced by its younger residents. The Seoul Safe Income Project (SSIP) stands as a testament to Seoul’s endeavors to rectify income inequalities. Designed for households earning below the median income, SSIP seeks to narrow the economic chasm by compensating for income gaps.

Yet, for Seoul to actualize its ambition of a cohesive urban landscape, an extensive policy overhaul is imperative. Recognizing and confronting the complex interplay of economic, social, and geographical imbalances, as highlighted by the findings of this study, is pivotal. The empirical evidence

delineated here provides a strategic direction to identify Seoul's inherent areas of vulnerability and anticipate their potential trajectories. The methodology proposed in this study, which integrates transdisciplinary approaches including data-driven analytics, spatial observation, and disparity monitoring across different localities, coupled with policy formulation^{79,80}, is recommended for consistent application in assessing Seoul's progress toward its goal of becoming an inclusive city.

The current study elucidates the intricate relationship between urban vulnerabilities and socio-economic frameworks, particularly within the context of Seoul. It identifies a pronounced disparity in the representation of different *dongs*, or neighborhoods, across vulnerability clusters. Specifically, the sparse representation of *dongs* from affluent areas, such as Gangnam-3 *gu*, in high-vulnerability clusters highlights the disparities within the city. These findings illuminate the critical need for targeted policy interventions aimed at mitigating these imbalances and fostering a more equitable urban environment. As Seoul occupies a prominent place in the hierarchy of global urban competitiveness, the strategic direction it takes in addressing these issues is of paramount importance. The insights derived from this study, particularly regarding housing and living poverty, pinpoint specific vulnerabilities that must be addressed. This lays the groundwork for a truly inclusive urban future for Seoul, leveraging a nuanced, informed approach to urban planning and policy formulation.

In expanding the conversation around our research findings, we explore the consequences these insights have for policy-making and practical applications. Our analysis brings to the forefront the challenges faced by Seoul's elderly population, a demographic of special interest in our study. The distinct housing needs of this group, especially as observed in the context of *Jjokbangs*—subdivided flats that serve as a domicile for those grappling with both housing and living poverty—emerge as a critical aspect of our findings. These living conditions reflect the wider circumstances of Seoul's elderly and underscore the urgency of addressing their specific needs. While our study lays a foundational understanding of these issues, it also emphasizes the necessity for more comprehensive research focused on *Jjokbangs* and their occupants. Undertaking such studies is imperative for developing detailed, empathetic policy measures that are finely attuned to the needs of Seoul's elderly population. This research path not only contributes to a deeper understanding of urban vulnerabilities but also to the crafting of sophisticated, effective solutions aimed at enhancing the quality of life for all city residents, with a particular focus on its most vulnerable groups.

In discussing the limitations and implications of this study, it is crucial to emphasize that, from an empirical standpoint, the findings yielded by this study should be interpreted as provisional rather than conclusive. An illustrative example of this is Figs. 11 and 12, which represents an outcome derived through the application of an algorithmic approach utilizing the dataset presented in this study. This figure serves as a means to assess the spatial vulnerability framework introduced in this study. Besides, we estimated the number of *Jiha/Banjiha* using extrapolations from archived data, given the absence of direct data sources. As a result, the exact figures presented might carry a margin of error. However, it is essential to note that our data extraction procedure, executed through Python programming, followed a stringent and consistent methodology. This ensures a level of reliability in our results.

Furthermore, it is important to acknowledge that the data regarding housing poverty is confined to information pertaining to structures and commercial facilities registered with government agencies. Consequently, the dataset may not encompass the housing conditions of more marginalized populations residing in unregistered or informal settings. Additionally, it is imperative to recognize that the study does not encompass data concerning the spatial distribution of homeless individuals (as per Seoul's assessments, the city had ~9700 homeless individuals in 2019) who lack a registered residence and are not beneficiaries of basic livelihood support. A comprehensive exploration of these facets necessitates an approach that incorporates ethnographical observations and a broader spectrum of data sources. While the data has its limitations, the value of this study lies in its

pioneering approach to the subject, filling a gap in the existing research. These limitations could act as catalysts for future academic dialogues, potentially driving more specific data collection and research in these relatively unexplored domains. We anticipate that ensuing studies, anchored in more comprehensive datasets, will further elucidate and affirm the insights presented here.

This study, while primarily focused on Seoul, Korea, admittedly presents a limitation in its geographical specificity, potentially constraining the direct extrapolation of its findings to other contexts. However, this limitation is significantly counterbalanced when the study's outcomes are interpreted within the expansive lens of Asia's developmental state model. The meticulous examination of Seoul's urban development and its evolutionary path provides nuanced insights that hold value well beyond the Korean peninsula. These findings become particularly salient for other burgeoning economies within Asia, offering a rich repository of lessons and strategies that can inform their urban development initiatives.

The paradigms and urbanization patterns unearthed through this study of Seoul possess far-reaching implications, extending their applicability to urban centers in emerging economies across the globe. This universality is pivotal, as it enables the study's conclusions to act as a beacon for urban development and policy formulation across a diverse spectrum of economic and cultural settings. The insights derived from this research are instrumental in elucidating the dynamics of urban development and are integral to the broader discourse on sustainable development. Notably, the study sheds light on critical aspects relevant to poverty alleviation, aligning with the Sustainable Development Goal 1 (SDG1), and highlights the instrumental role cities play in achieving global sustainable development objectives. This facet amplifies the study's relevance, underscoring its contribution not only to regional but also to global conversations on sustainable urban development. Through this lens, the study transcends its initial geographical constraints, offering a valuable contribution to understanding and addressing the complexities of urban development in a global context.

To summarize, the present study embarks on a detailed exploration of urban housing and living poverty in Seoul, Korea's capital. The core of our analysis is the stratification of geographic areas, achieved through a comprehensive examination of vast datasets and the application of algorithmic techniques. A particular emphasis is placed on the spatial configurations that arise from this stratification, with a focus on identifying areas marked by heightened vulnerability. This study makes a significant contribution to the existing body of literature by employing data-driven methodologies to pinpoint vulnerable urban areas, methodologies that are sensitive to the distinct socio-economic attributes of the studied society.

By integrating these advanced analytical approaches, our research offers insights into the spatial manifestation of socio-economic disparities in Seoul. It illuminates the patterns of urban stratification, thereby enhancing our understanding of the complex interplay between socio-economic factors and urban geography. The methodologies adopted in this study not only facilitate a deeper understanding of the spatial dimensions of poverty and vulnerability but also highlight the potential of data-driven techniques to inform urban planning and policy development through the use of extensive data. Consequently, this study advances the discourse on urban socio-economic stratification, providing a foundation for further investigations into the spatial implications of socio-economic inequalities within urban contexts. The findings encompass the perpetuation of economic inequality and poverty, as discussed by Soja⁵³ and underscore the relevance and significance of this study within the broader scholarly discourse.

This study meticulously uncovers a marked socio-economic bifurcation within Seoul's urban fabric, delineating two sharply contrasted zones that mirror deep socio-economic divides. This binary landscape not only highlights the exclusionary dynamics of urban stratification but also evidences the perpetuation of economic inequalities and entrenched poverty. A striking finding from our investigation is that over three-quarters of Seoul's geographic expanses are mired in vulnerability, manifesting either through widespread poverty or the concentration of economically marginalized populations. Such widespread vulnerability accentuates the precarious

living conditions of the city's disenfranchised communities, necessitating urgent and holistic improvements to their quality of life.

Critical to understanding Seoul's extensive vulnerability is the concept of neighborhood effects, which significantly influence the formation and persistence of these conditions. These effects, stemming from the socio-economic characteristics of different areas, play a crucial role in shaping the lived experiences of residents, further entrenching disparities. Furthermore, the study highlights a crucial concern: in the face of a large-scale crisis similar to the COVID-19 pandemic, certain demographics could disproportionately suffer due to the complex interdependencies of housing, income, and age factors identified herein. Such insights underscore the urgency for Seoul to preemptively address these vulnerabilities, aiming to create a more equitable urban milieu.

Ultimately, the insights garnered from this investigation underscore the urgent necessity for systemic reforms aimed at narrowing the socio-economic divides permeating Seoul. This study shines a spotlight on the depth and repercussions of urban vulnerability, championing a unified push for greater inclusivity and resilience in the realm of urban development. As Seoul contends with impending challenges, the importance of addressing socio-economic inequalities cannot be overstated, serving as a critical pillar in the pursuit of a sustainable and equitable future for every inhabitant.

Methods

Data-driven methods and data

The present study adopts a spatial analysis technique anchored in data-driven methodologies to quantify housing and living poverty. Within this context, data mirror human behaviors, interactions, and societal nuances⁸¹. Humans exist in intricate matrices of relationships and endeavors that permeate and extend beyond individual spatial delineations. These entities embody myriad lifestyles and interconnections, reflecting the multifaceted tapestry of human life. Individuals, acting as dynamic participants, forge these spatial constructs through interpersonal engagements, while societal structures further mold these demarcations via institutional and associative networks. As such, spatial divisions materialize from the oscillation between cohesion and alliance and, conversely, discord and detachment, within these spatial entities. By analyzing data-driven approaches, this study aims to unveil the social relationships that underlie urban poverty and demonstrate how these relationships manifest as distinct spatial patterns.

This study's premise posits that multidimensional data, encapsulating the subtleties of societal ties, unveil discernable patterns instrumental in gauging housing and living poverty amid urban populations. By decoding these patterns, scholars can extract invaluable perspectives on the geographical expressions of impoverishment and its intertwined dynamics. Such an avenue facilitates a holistic scrutiny of the urban social tapestry, deepening comprehension of the predicaments confronting the urban impoverished and establishing a foundation for precise interventions and policy directives.

A critical question for the data-driven urban housing and living poverty approach is what indicators to choose to meet the aim of study. In this regard, when collecting data, it is necessary to have a sufficient understanding of the society from which data is being collected, as the socio-economic characteristics used to analyze poverty differs according to each society. For data set that is analyzed here, the focus is on housing and living poverty.

Table 1 shows the list of variables used in the analysis of this study (see Supplementary Table 1). The variable for housing poverty within this research incorporates both Gosiwon and Jiha/Banjiha types of housing. This demographic is projected to constitute ~5% of Seoul's total households, which number around 4,046,700. The number of Gosiwons was estimated by extracting the number of Gosiwons registered in Seoul from a commercial facility dataset. Information on all commercial facilities registered in Korea are provided through OpenAPI from the public data portal, provided by the government (data.go.kr). As the data on Jiha/Banjiha housing is not directly available, we used archived registered building data disclosed by government agencies (open.eais.go.kr). The data includes the structure of all

buildings registered in Korea. In this study, the number of Jiha/Banjiha was estimated by enumerating the number of habitable basements or semi-basements of detached and apartment houses located in Seoul.

The living poverty variable included Basic living and Old in poverty. Basic living refers to the number of households receiving basic livelihood security. Old in poverty refers to the number of older adults living alone with basic livelihood security or low income. Both data were extracted from government statistics (stat.eseoul.go.kr). The data on housing and living poverty were collected in units of *dong* (a block), the smallest administrative unit in Korea. There are 426 *dongs* (blocks) under 25 *gus* (boroughs) in Seoul. This study applies log transformation to social socio-economic clustering data, so that the interpretive difference between social groups depends on ratios rather than absolute values⁸².

Analysis strategy

This study employs a data-driven approach for the classification of "*dongs*" to assess urban vulnerability. This approach utilizes the Principal Component Analysis (PCA) algorithm, the K-means++ clustering algorithm, and various visualization techniques. Specifically, this study derives a new variable, referred to as the Principal Component (PC), from the two variables representing housing poverty and another new variable from the two variables denoting living poverty. The rationale behind employing PCA is not merely data compression but rather aimed at extracting latent factors that can offer a more effective explanation of the data through dimensionality reduction⁸³.

The strategy of extracting a single PC from either the housing or living poverty features serves the purpose of enhancing clustering efficiency by mitigating potential noise arising from high correlations between variables^{84,85}. The presence of extraneous noise in the dataset can impede the achievement of efficient clustering. For instance, while Basic living and Old in poverty are not entirely identical, they may exhibit substantial overlap. Consequently, extracting a novel key variable from them holds the potential to improve the efficiency of the clustering process. Therefore, it is necessary to create new variables by extracting potential factors that can best explain the data distribution. In addition, we can find visually and intuitively interpretable results by reducing multi-dimensional data through this approach.

K-means++ is a distance-based clustering algorithm that is developed from K-means; its core principles are identical, except for cluster centroid initialization⁸³. K-means is considered to be an unsupervised learning method; it selects a cluster centroid and then the data closest to the centroid based on the Euclidean distance⁸³. K-means++ (or K-means) is applied in clustering analysis based on the socio-economic characteristics of various groups^{15,82,86–88}. This study utilizes the silhouette score as a way to estimate *K* and optimize K-means++⁸⁹.

Efficient clustering is characterized by sufficiently large inter-cluster distances and closer proximity of data points within the same cluster. To visually assess clustering parameters, such as the number of clusters, a silhouette plot provides a concise and intuitive way to measure how close each data point within one cluster is to data points in neighboring clusters. The silhouette score, which falls within the range of -1 to 1 , serves as a benchmark for evaluating the quality of clustering. A score approaching 1 indicates that a data point is well-aligned with its cluster and exhibits distinctiveness from other clusters, thereby signifying a more suitable clustering arrangement. Conversely, an abundance of low or negative scores suggests an inadequate clustering configuration, potentially indicating an incorrect number of clusters. Besides, the approaches using map visualization enable the spatial analysis of urban poverty to visually identify spatial forms of housing and living poverty, and gain deeper insight into social structure^{90,91}.

To ensure its robustness, the current study shows the results from Hierarchical Clustering, which uses the Ward linkage method⁹². Hierarchical Clustering begins from each data point and combines similar points simultaneously to form hierarchical clusters. Compared with K-means++, a distance-based approach, the Ward linkage method is applied in Hierarchical Clustering⁹², merging clusters based on the

within-group sum of squares. Unlike K-means++, the Hierarchical Clustering algorithm performs without pre-determining the number of clusters, K , and can analyze clustering results by utilizing a dendrogram, a tree-shaped structure that indicates the order in which objects are combined.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its Supplementary Material.

Code availability

The Python code utilized for the analysis in this study is comprehensively provided in Supplementary Tables 6 and 7. Accompanying each segment of the code are detailed comments, facilitating an understanding of its functionality and application. The Python code encompassing all stages of data collection, preprocessing, and analysis is in the Supplementary Material.

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Author contributions

Yookyung Lee and Seungwoo Han designed the research, analyzed and interpreted the data, and wrote the paper. All authors contributed to the article and approved the submitted version.

Competing interests

The authors declare no competing interests.

Additional information

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