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Measuring the effects of Compactness/Sprawl on COVID 19 spread patterns at the neighborhood level

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A R T I C L E I N F O

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A B S T R A C T

This study analyzes the compactness/sprawl index and its effects on the spread of COVID-19 in the neighborhoods of Ahvaz, Iran. Multiple Criteria Decision Making and GIS techniques were used to develop the index. Also, the effects of compactness/sprawl on COVID-19 were investigated using a regression model. It was found that when considering the number of COVID-19 cases per 1000 people, the compactness/sprawl index did not affect the spread of the disease. However, it had a low but significant effect if the raw number of cases was considered. Results also showed that the compactness index significantly affected the raw number of cases, with a coefficient of 0.291, indicating that more compact neighborhoods had more COVID-19 cases. This is unsurprising as more people live in compact areas and, therefore, the raw number of cases is also likely to be higher. In the absence of proper control measures, this could result in further contact between people, thereby, increasing the risk of virus spread. Overall, we found that compactness had a dual effect on the spread of COVID-19 in Ahvaz. We conclude that proper development and implementation of control measures in well-designed compact neighborhoods are essential for enhancing pandemic resilience.

1. Introduction

Since the detection of its first case in late December 2019, COVID-19 has remained a global public health crisis and the most significant human risk since World War II (Wang, Wu, et al., 2021). With the worldwide spread of the COVID-19 pandemic, there has been an increasing interest in understanding the factors influencing the difference in morbidity and mortality rates at various scales (Hananel et al., 2022; Sharifi, 2022). Among other things, there has been considerable attention to the relationship between urban form and COVID-19 dynamics, as well as the design and construction of resilient cities (Honey-Rosés et al., 2020; Pongutta et al., 2021; Sharifi & Khavarian-Garmsir, 2020; Shermin & Rahaman, 2021; Tricarico & De Vidovich, 2021). Examining the implications of different urban forms is critical for urban planning and design. Compactness and sprawl are two major urban forms that have significant impacts on public health, quality of life, and citizen well-being, particularly in developing countries (Frumkin et al., 2004; Habibi & Zebardast, 2021; Kamble & Bahadure, 2021; Mouratidis, 2018; Mouratidis, 2019; Stevenson et al., 2016; Yan et al., 2021).

Any deviation from a compact city, whether suburban, ribbon development, leapfrog, or scattered development, can be considered urban sprawl (Patacchini et al., 2009; Tsai, 2005). The differences between these opposing urban forms lie primarily in their building density, land-use mix, and transportation network structure. The two forms have substantially different effects, as urban sprawl is considered a highly unsustainable form of urban development (Pozoukidou & Ntriankos, 2017). The main concern associated with urban sprawl is its adverse environmental and socio-economic impacts (Burchell & Mukherji, 2003; Frumkin, 2016; Hasse & Lathrop, 2003), which could hinder progress toward sustainable development (He et al., 2018; Sharifi, 2019a). Urban sprawl is also argued to negatively impact public health (Ewing et al., 2014; Freudenberg et al., 2005; Frumkin et al., 2004; Zhou, Jiao, Yu, & Wang, 2019). Research shows that urban sprawl is correlated with more negligible physical inactivity, obesity, traffic fatalities, poor air quality, delayed emergency response, teenage driving, lack of social capital, and longer commuting distances and times (Ewing & Hamidi, 2014). On the other hand, well-designed compact urban development can bring various environmental and socio-economic advantages, including less

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car dependency, lower carbon emissions, constrained development of rural areas, encouragement of walking and cycling, and reuse of existing lands and facilities (Abdullahi, 2019).

For decades, compact urban development has been promoted to fight against non-communicable chronic diseases such as obesity, diabetes, asthma, and cardiovascular diseases (Wali & Frank, 2021). For instance, a study simulating the impacts of sprawl in six cities (Melbourne, São Paulo, Delhi, London, Boston, and Copenhagen) showed how compact city policies could minimize the risk of cardiovascular and respiratory disorders (Stevenson et al., 2016). Although the compact city benefits have been widely discussed, some potential trade-offs have also been mentioned in the literature. Several claimed benefits have not been experimentally validated (Tappert et al., 2018). For instance, in a 30-year analysis of metropolitan regions in the United Kingdom, Echenique et al. (2012) revealed that compact cities are not always more energy-efficient than their sprawled counterparts. Schindler and Caruso (2014) concluded that compactness could result in air pollution issues. Ihlebæk et al. (2021) stated that residents of compact urban neighborhoods, while enjoying more social space and more significant physical activity, also suffer from noise and air pollution. Rising mortality rates, declining mental health, anxiety, declining quality of life, and declining green space could also be other negative consequences of a compact city. Despite these, the literature favors compact cities, and it is argued that smart urban planning and design can minimize the potential trade-offs of compact cities (Sharifi, 2019b).

Issues related to compactness and sprawl have been studied at various levels, including the neighborhood scale (Bowyer, 2015; Eid et al., 2007; Lathey et al., 2009; Song & Knaap, 2004; Terzi & Bolen, 2009). Among other things, compactness and sprawl at the neighborhood level and their impacts on obesity, crime, and social capital have been examined (Ewing et al., 2014; Gálvez Ruiz et al., 2018; Mouratidis, 2018; Nedovic-Budic et al., 2016; Raman, 2010).

The emergence of the COVID-19 pandemic has increased the interest in examining different implications of urban compactness and sprawl. Mouratidis (2022) examined changes in health and well-being during the pandemic and explored the effects in the context of urban compactness. Focusing on Oslo and Viking, Norway, he concluded that residents of compact neighborhoods experienced worse welfare conditions than those in low-density neighborhoods. Furthermore, he argued that the benefits of a compact city, including public transportation, pedestrian activity, and the opportunity for social interaction, have diminished due to quarantine and social distancing measures. More housing space and better access to private gardens are two advantages of sprawl during the COVID-19.

While there have been concerns over the higher risk of transmission in denser urban areas, the evidence reported in the literature is mixed and does not always confirm such concerns (Alidadi & Sharifi, 2022). Khavarian-Garmsir et al. (2021) investigated the relationship between density and COVID-19 morbidity and mortality in Tehran using structural equation modeling. They used variables such as road density, population density, building density, the ratio of elderly, car ownership rate, distance from the bus station, literacy rate, employment rate, and average income. Their findings showed that density alone was not an influential factor. Similarly, Hamidi et al. (2020) examined the effect of density on the incidence and mortality rate of COVID-19 in U.S. metropolitan counties. They found that density alone is not a major risk factor. Indeed, they argued that compact cities could better deal with the pandemic due to better access to infrastructure and services. Other studies have also emphasized the importance of considering variables other than density in the analysis. Lak et al. (2021) examined the distribution pattern of COVID-19 cases in the neighborhoods of Tehran using variables such as density, the ratio of elderly, green space ratio, and the distribution pattern of services such as retail stores, chain stores, pharmacies, radiology centers, hospitals, bus stations, subway, and gas stations. They found that neighborhood demographic composition and physical characteristics are key determinants of morbidity and mortality in the city.

Hamidi and Zandiatashbar (2021) argued that through measures such as enhancing resident awareness, adherence to social distancing, promoting land use mix, and facilitating access to online shopping, compact cities could contribute to controlling the pandemic. Walkability is another feature of compact cities that could play an important role in this regard. Research shows that living in more walkable environments (that promote physical activity and lower the prevalence of chronic diseases) increases resilience to the pandemic (Frank & Wali, 2021).

Despite the wealth of knowledge on cities and the pandemic, the effect of compactness/sprawl on COVID-19 incidence at the neighborhood level has not been well explored, and the focus has mainly been on larger scales. Moreover, to the best of our knowledge, there has been no effort to develop an integrated index of compactness/sprawl to examine associations between urban form and the pandemic. Instead, individual indicators have been examined separately (Hamidi et al., 2020; Li et al., 2021; Wali & Frank, 2021). Furthermore, research on the association between urban form and the pandemic has mainly focused on cities from developed countries. More research on developing country cities is needed given their unique characteristics. To fill these gaps, the current study assessed the impacts of urban sprawl/compactness on COVID-19 in Ahvaz, one of Iran's largest cities. Iran has recorded 7,235,440 cases of COVID-19, resulting in 141,373 deaths as of June 27, 2022 (World Health Organization, 2022). Additionally, it has passed five COVID-19 waves. The city of Ahvaz, the capital of Khuzestan province in southwestern Iran, has not been an exception. More than 75,000 people have been diagnosed with COVID-19 in this city in 1 year.

This study examined compactness/sprawl at the neighborhood scale using the interactors developed by Ewing et al. (2014) and Ewing et al. (2018) and several new indicators. More precisely, this study sought to determine which neighborhoods in Ahvaz ranked highest in compactness/sprawl and how sprawl and compactness indicators affected coronavirus spread.

The results of this study can advance our knowledge of the association between urban form and the pandemic at the neighborhood level and provide urban planners with a clearer understanding of how compactness/sprawl could affect the spread of COVID-19. Also, its focus on Ahvaz is conducive to a better understanding of the patterns and dynamics of the pandemic in a developing country city. The approach adopted here can also be applied to other developing country cities, thereby facilitating the development and implementation of more context-specific pandemic control and response measures. Overall, the results of this study could contribute to the development of measures and strategies for enhancing the planning and design of compact cities, thereby contributing to the transition toward sustainable and resilient urban development.

2. Theoretical background

2.1. Urban sprawl and its indicators

Traditionally, human settlements have been characterized by their compactness. However, the invention of the automobile and other advances in mobility technologies have led to dispersed urban development in many parts of the world in the past century or so. Urban sprawl and its dynamics and consequences have been widely studied in the literature. Urban sprawl can affect health both directly and indirectly. Sprawl could affect physical and mental health through, among other things, reducing physical activity, excessive reliance on private cars, and increasing pedestrian risk (Burchell, Downs, McCann, & Mukherji, 2005). Some direct consequences are caused by high dependence on private cars. These include air pollution, car accidents, injuries, and pedestrian deaths. Indirect consequences include decreased physical activity, increased costs of infrastructure development and maintenance, and the intensification of the urban heat island effect (Iram et al., 2012). Griffin et al. (2013) suggested that sprawl can induce adverse health outcomes directly affecting obesity. In addition, urban sprawl may undermine social capital by increasing travel time and creating geographical boundaries between the workplace, shopping malls, and living spaces. This can, in turn, negatively impact human health and the capacity to cope with and adapt to adverse events (Sharifi, 2019a).

Due to the lack of a consensus on the definition of urban sprawl, it isn't easy to quantify it (Jaeger et al., 2010; Wilson et al., 2003). Several indicators have been developed to quantify different dimensions of urban sprawl. These are mainly concerned with population density (Schneider & Woodcock, 2008; Fulton, Pendall, Nguyen, & Harrison, 2021), land use change (Yu & Ng, 2007), and job accessibility (Weitz & Crawford, 2012). For example, researchers have examined land-use transformation trends and population change to calculate the relative sprawl intensity (Kasanko et al., 2006). Urban sprawl has also been measured using the relative entropy and Gini coefficient methods, assuming an equal distribution of built-up areas (Hu et al., 2015; Martellozzo & Clarke, 2011; Tsai, 2005). Indicators for land cover classification, such as Moran's index, are also widely applied to quantify sprawl (Altieri et al., 2014; Huang et al., 2007; Zhou, Jiao, Yu, & Wang, 2019). One-dimensional indices can be easily calculated using available data. But they rarely account for urban sprawl's negative social and environmental consequences (Ewing & Hamidi, 2015). Thus, there is no clear cut-off point (a definite value) for determining the presence of sprawl. However, some indicators are typically computed for a single city and then compared over time or across cities. Choosing the best indicators depends on the context and data accessibility. For example, some studies in the United States have focused on road networks and the density of single-family dwellings (Holcombe & DeEdgra, 2010). Ewing et al. (2002) used four factors: residential density; the neighborhood mix of homes, jobs, and services; the strength of activity centers and downtowns; and the accessibility of the street network to measure sprawl in 83 urban areas across the United States. They introduced 22 indicators to measure these four factors. The sprawl rate for each urban area was measured by summing the scores for each factor (Ewing et al., 2002). Song and Knaap (2004) measured neighborhood sprawl using five urban form indicators: street design, density, land use mix, accessibility, and pedestrian access. Similarly, Arribas-Bel et al. (2011) assessed urban sprawl based on connectivity, decentralization, density, scattering, open space availability, and land use mix. Pence (2008) measured sprawl in Omaha using housing unit density, job density, housing unit and job centrality, and housing unit and job proximity (Pence, 2008). Yue et al. (2016) assessed sprawl in large Chinese cities using a single growth ratio, reflecting the mismatch between land expansion and population growth and three key sprawl dimensions (low density, discontinuity of land use, and poor access).

The adverse outcomes of urban sprawl prompted the land management authorities to try to find sustainable solutions to the phenomenon. One of these solutions is to design and construct compact cities.

Given the multiple negative impacts of urban sprawl, many efforts have been made to promote compact urban development over the past few decades. However, the ideal of compact cities is still highly controversial, with many ongoing debates about its effectiveness and sustainability (Anabtawi et al., 2016). Despite this, there is a widely accepted political and scientific recognition that compact cities should be promoted (Artmann et al., 2017). As will be further discussed in the following section, compact urban development is the key to creating livable and sustainable cities (Tappert et al., 2018).

2.2. Compact city and its indicators

As discussed above, there have been many efforts worldwide to promote compact urban development as a remedy for the detrimental effects of urban sprawl. Compact cities are argued to provide multiple benefits, including positive physical and mental health outcomes. They can, for instance, reduce cardiovascular disease and diabetes by providing more opportunities for physical activity and walking, reduce the rate of respiratory diseases if designed properly to integrate green and open spaces, and contribute to the formation of local public spaces and places for formal and informal public interaction (that strengthens social capital) (Sharifi, 2019b). Compact cities could also provide positive mental health benefits by lower stress levels from long trips (Zhang et al., 2022). In contrast, a compact city may induce some adverse outcomes, such as increased urban air pollution and limited availability and accessibility to green spaces in high-density areas, leading to fewer outdoor physical and recreational opportunities.

There is still no consensus on how a compact city may affect residents' health. There are also controversies over the strength and interaction of factors related to the living place and their effects on public health in compact cities. To complicate the matter, the results of these factors may vary from one urban area to another, depending on each urban area's spatial and social characteristics (Ihlebæk et al., 2021). Reducing the negative impacts of the COVID-19 pandemic on cities requires addressing these challenges and assessing the sustainability of the compact city model more closely (Kwon et al., 2022). Despite some concerns about the safety of compact cities during the pandemic, researchers and urban planners have tried to seize this crisis as an opportunity to further promote compact urban development by increasing reclaiming urban streets, improving the pedestrian environment, increasing bike lanes, and further integration of open and green spaces (Wang, Yang, et al., 2021).

According to the literature, three primary indices of urban compactness are density, land use diversity (land use mix), and urban intensity (Abdullahi et al., 2015; Burton, 2002; Lin & Yang, 2006; Zhao et al., 2020). High urban density is the most frequently mentioned feature of a compact city and is a critical indicator of sustainable development (Burton, 2002; Elkin et al., 1991; Hall, 2001; Kamble & Bahadure, 2021). The main rationale for developing compact cities is facilitating the modal shift from private cars to active and public transport (Newman & Kenworthy, 1999). A higher density is a key characteristic of compact cities that promotes public transportation and ensures access to essential services and amenities more effectively and efficiently (UTF, 1999). Land use diversification is another key principle for developing compact cities. A mixed-use area integrates distinct land-use categories vertically within a single structure or horizontally throughout across neighborhoods (Tian et al., 2017). A mixed land-use environment can contain a variety of commercial, residential, light industrial, and community facilities (schools, hospitals, recreational facilities, libraries, etc.) (Abdullahi et al., 2017). This facilitates better access to daily needs using active and public transportation modes, offering multiple benefits for public health and the environment (Sharifi, 2019b). Finally, urban intensification is a process that focuses on increasing density through infill and brownfield redevelopment and mixed land use (Kamble & Bahadure, 2021; Lin & Yang, 2006). Urban intensity can be measured by examining the activity, accessibility, proximity, quantity, and quality of different types of community facilities (e.g., health care, education, and public transportation services, points of interest, open spaces, recreational facilities, and job opportunities) with a focus on the characteristics of nearby residences and neighborhoods (Abdullahi et al., 2017).

2.3. Compact city and COVID-19 transmission

With the COVID-19 outbreak, more attention has been paid to the impact of compact neighborhood and city design features on viral diseases. There have been some concerns that high population and housing densities in compact places can increase crowding and face-to-face interactions, leading to increased COVID-19 prevalence. Urban planners and health professionals have explored these concerns at various scales and in different parts of the world (e.g., the United States and China). Researchers have assessed the association between compact city indicators such as population density, building density, residential density, the density of commercial facilities, road density, school density, distance to the city center, mixed land use, green space ratio, and access to services with COVID-19 transmission risks and reported contradictory observations (Li et al., 2020; Mouratidis & Yiannakou, 2022; Sharifi & Khavarian-Garmsir, 2020; Wang, Wu, et al., 2021; Zhang et al., 2022).

Kwon et al. (2022) assessed the impacts of COVID-19 in two compact cities, Seoul in South Korea and New York in the USA. Both cities have compact urban features, such as high population density, diverse land use composition, and advanced transportation systems, but have displayed very different trends in COVID-19 transmission and response. The authors concluded that dense population and mixed land use are associated with disease transmission, arguing that the compact city model increases the vulnerability to disease transmission.

Aguilar et al. (2020) found that centralized and hierarchical cities are exposed to faster and more widespread outbreaks than sprawled ones. Enforcing mobility restrictions is a more challenging task in hierarchical cities. However, if enforced effectively, such restrictions and lockdowns in hierarchical cities are comparatively more effective. One factor that is likely to make it challenging to enforce mobility restrictions is the need to meet daily needs by visiting commercial facilities. Some studies have demonstrated the association between the density of commercial facilities and the risk of COVID-19 incidence (Li et al., 2020). This is explained by the fact that residents in areas with a higher number of commercial destinations and services are more likely to utilize these facilities (Kärmeniemi et al., 2018) and thus are exposed to a greater risk of infection (Li et al., 2020).

The association between various types of density (building, population, and residential) and COVID-19 prevalence has been examined in different studies. Although some studies have reported positive associations (Barak et al., 2021; Hu et al., 2020; Lak et al., 2021), others have reported negative or no associations (Hamidi et al., 2020; Khavarian-Garmsir et al., 2021). This indicates that transmission dynamics may differ depending on multiple factors such as contextual conditions.

Based on what was discussed in Section 2, different indicators for measuring the level of compactness and sprawl were selected for the purpose of this study. These are summarized in Table 1 and presented in Section 3.3. Our framework includes three recurring indicators of a compact city: density, mixed land use, and activity clustering. Also, as the literature has highlighted that different density measures may result in different outcomes, we have considered various density measures, including population density, neighborhood building density, net residential density, household density, and the ratio of population and building densities.

3. Materials and methods

3.1. The study area

Ahvaz is the capital city of the Khuzestan province, located between latitudes 31°13′ and 31°23′ N and longitudes 48°32′ and 48°47′ E with eight municipal districts (Fig. 1). According to the Iranian Statistical Center, the city had a population of 1,184,788 people in 2016 and was the seventh most populous metropolis in the country. Ahvaz is a commercial, service, and health care hub in southwestern Iran and the center of an oil-rich region. Additionally, it is home to steel, piping, and sugarcane industries and is located on a major transportation corridor to southern ports. The city's daily floating population is estimated to be around 1,600,000. Under the influence of Iran's urbanization trends, population growth, and immigration, Ahvaz's urban expansion has been steered toward an unsustainable decentralized development pattern that has resulted in a sprawling city. This unstructured growth, far exceeding the capacity of the city's population infrastructure, has resulted in the loss of farmlands, the construction of low-quality and short-lived structures, the expansion of poverty-stricken areas, the deterioration of roads and transportation services, the deterioration of public health, and a lack of appropriate service provision to all parts of the city.

3.2. Data and unit of analysis

Previous research has examined the relationship between urban density and coronavirus spread at various scales (Liu et al., 2021), including national, county, urban, intra-city, and neighborhood levels. According to the literature, the neighborhood is the most appropriate scale for examining the association between compactness and the spread of the virus (Barak et al., 2021; Kamble & Bahadure, 2021; Rahman, Islam, & Neema, 2022). Therefore, in this study, we chose the neighborhood as the geographical unit of analysis.

The data were collected from various organizations and centers in three categories: land use, population, and COVID-19. Like the land use data, the demographic data were collected by considering neighborhood boundaries. Land-use data for Ahvaz were collected in the form of GIS layers. The land-use layers were developed interactively for the whole city, and the ratio of each use per neighborhood was estimated based on the neighborhood area. The demographic data for all blocks of the city were obtained from the Statistics Center of Iran.

The COVID-19 data were collected from Ahvaz Health Center and Khuzestan Jundishapur University, the leading authorities responsible for preparing and integrating COVID-19 data in the province. These data were collected from September 2020 to September 2021, considering to the number of COVID-19 peaks and the available statistics. The land use, demographic, and COVID-19 data were then integrated and embedded in the neighborhood maps. The land-use and population data were used as the initial data in the VIKOR method (VlseKriterijumska Optimizcija I Kaompromisno Resenje in Serbian), and the COVID-19 data were used as the dependent variable in the regression analysis that will be further discussed later.

3.3. Indicators used in the analysis

In Table 1, we list the indicators used in the analysis and briefly described each. A multi-criteria approach was employed to analyze urban compactness/sprawl. While early efforts for analyzing sprawl have mainly used a single metric, such as density (population density or employment density), recent studies have employed multi-dimensional (multi-criteria) approaches to assess sprawl quantitatively (Liu et al., 2018). Based on the available data and whether and considering the study's objectives, we employed 17 indicators. These indicators were chosen based on the three elements of density, mixed land use, and activity clustering that were discussed in Section 2 (Ewing et al., 2018; Ewing & Hamidi, 2014; Hamidi et al., 2020). Population density, residential density (per unit neighborhood area), neighborhood building density, net residential density, household density, and the ratio of population and building densities to their corresponding highest densities were the indicators used for measuring density. The number and area of parcels with mixed land-use were used as indicators representing land-use mix. Other indicators were the ratio of employed individuals in the neighborhood to the total number of employed people in the city, distance from the city center (meters), the ratio of vacant land to the total neighborhood area, the ratio of single-story buildings to the total number of buildings in the neighborhood, the ratio of built-up land to the total neighborhood area, the average size of residential parcels, the ratio of service land-uses to the total neighborhood area, and the ratio of commercial land-uses within the neighborhood to the total commercial land-uses in the city. As the indicators grew in value, compactness and density were increased, while lower index values were observed in the more sprawled neighborhoods.

3.4. Procedures for ranking neighborhoods and estimating the effects of each indicator

The analysis was conducted in two stages. The MCDM was used in the first step to rank neighborhoods according to the compactness/sprawl indicators. MCDM is a practical multi-step approach that has

Table 1
Descriptive statistics of the Indicators.

Indicator	Brief description	Unit	Source	Mean	Std. deviation	Minimum	Maximum
Population density	$\frac{\text{Neighborhood population}}{\text{Neighborhood area}}$	N/ha	Galster et al., 2001; Rahman, Islam, & Neema, 2022; Neuman, 2005; Burton et al., 2003; Abdullahi et al., 2015; Koziatek & Dragićević, 2019 Zhao et al., 2020; Ewing & Hamidi, 2014 Ewing et al., 2018	112.88	60.20	4.848	253.08
Residential density (per unit neighborhood area)	$\frac{\text{Number of residential units in the neighborhood}}{\text{Neighborhood area}}$	Residential unit per hectare	Abdullahi et al., 2015; Noor et al., 2018; Ewing et al., 2002	17.19	13.87	0.1281	63.11
Household density	$\frac{\text{Number of households}}{\text{Neighborhood area}}$	Household per hectare	Pence, 2008;	31.35	17.57	1.27	72.69
Gross residential density	$\frac{\text{Neighborhood population}}{\text{Residential} - -\text{use land area}}$	N/ha	Frenkel & Ashkenazi, 2008;	312.23	136.970	0.0000	810.34
Number of mixed-use parcels in the neighborhood	Number of mixed-use parcels in the neighborhood	Number	Burton et al., 2003; Rahman, Islam, & Neema, 2022;	51.29	111.462	0	835
The ratio of mixed-use land within the neighborhood to the total neighborhood area	The ratio of mixed-use land within the neighborhood to the total neighborhood area	Percentage	Abdullahi et al., 2015; Zhao et al., 2020 Lee, 2020; Frenkel & Ashkenazi, 2008; Abdullahi et al., 2017 Ewing & Hamidi, 2014 Ewing et al., 2018	1.129	1.76	0.0000	12.03
Distance from city center	Distance from the city center in meters	Distance in meters	Bhatta et al., 2010; Tian et al., 2017; Al-sharif et al., 2017	4947.01	2372.36	657.38	11,336.68
The ratio of employed individuals	The ratio of employed individuals within the neighborhood to the total number of employed people in the city	Percentage	Lee, 2020; Liu et al., 2018; Ewing et al., 2018	1.04	0.9551	0.0000	5.264
The ratio of commercial-use land within the neighborhood	The ratio of commercial-use land area within the neighborhood to the total commercial-use land area in the city	Percentage	Abdullahi et al., 2017	1.88	2.53	0.0000	12.03
The ratio of vacant land within the neighborhood to the total neighborhood area	The ratio of vacant land within the neighborhood to the total neighborhood area	Percentage	Koziatek & Dragićević, 2019; López et al., 2021; Sperandelli et al., 2013	15.97	17.72	0.0000	73.76
The ratio of single-story buildings	The ratio of single-story buildings to the total number of neighborhood buildings	Percentage	Callen, 2014	80.99	14.48	35.97	100.00
The ratio of built-up land to the total neighborhood area	The ratio of built-up land to the total neighborhood area	Percentage	Koziatek & Dragićević, 2019; Frenkel & Ashkenazi, 2008	54.39	17.60	14.83	100.59
Building density	$\frac{\text{Floor area (on all floors)}}{\text{Neighborhood area}}$	Percentage	Abdullahi et al., 2015; Bhatta et al., 2010;	72.24	29.12	14.83	140.36
The ratio of service-use land to the total neighborhood area	The ratio of service-use land to the total neighborhood area	Percentage	Abdullahi et al., 2015; Koziatek & Dragićević, 2019; Kamble & Bahadure, 2021; Chen et al., 2008	16.80	15.20	0.9310	71.06
		Percentage	Authors	51.60	20.80	10.59	100.26

(continued on next page)

Table 1 (*continued*)

Indicator	Brief description	Unit	Source	Mean	Std. deviation	Minimum	Maximum
The ratio of building density to the highest density	The ratio of building density to the highest building density						
The ratio of population density to the highest density	The ratio of population density to the highest population density	Percentage	Authors	45.59	25.98	0.00000	107.69
The average size of residential parcels	Average size of residential parcels	Percentage	Hasse & Lathrop, 2003; Ewing et al., 2014	386.54	599.48	110.52	4515.26
COVID-19 cases	The number of COVID-19 patients per 1000 people	Number	–	1061.39	970.22	63	4904

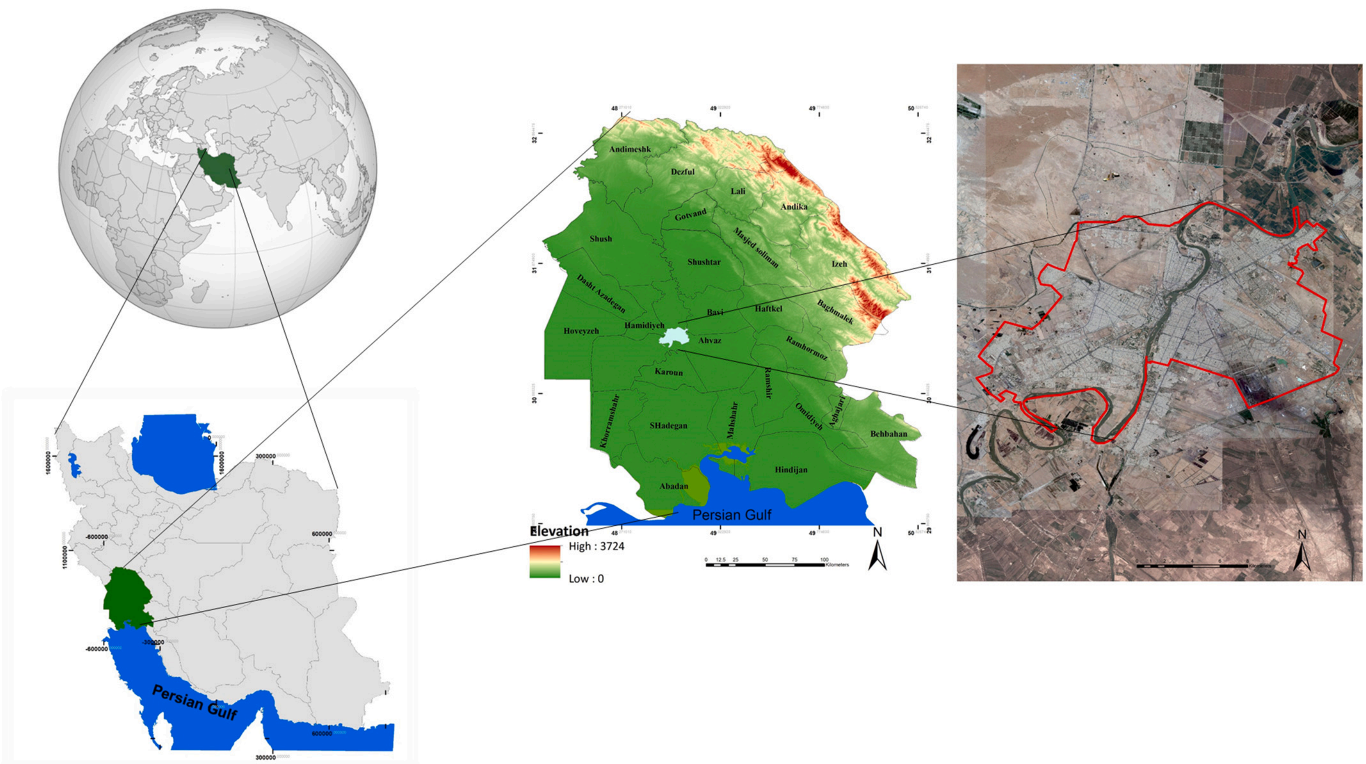

Fig. 1. Geographical location of Ahvaz in Southwestern Iran.

been frequently used in urban studies. The following are the steps in the process:

1) The statement of objectives;
2) Selection of criteria for measuring the objectives;
3) Determination of study items;
4) Weighting the criteria; and.
5) Implementing a suitable mathematical algorithm for ranking (da Cruz et al., 2021).

When combined with GIS-based local analysis, the MCDM approach can effectively measure compactness (Abdullahi et al., 2015; Rahman, Islam, & Neema, 2022). Indeed, many studies have used multi-criteria decision-making techniques to examine associations between the built environment and health and safety at the neighborhood scale (Zavadskas et al., 2017). MCDM techniques, especially VIKOR, have also been widely applied in COVID-19-related studies (Hezer et al., 2021). We refer readers to the cited articles for more information about these methods.

Using ArcGIS software, the values of the indicators were calculated for each neighborhood in Ahvaz. The neighborhoods were then ranked using the VIKOR technique, and the composite compactness/sprawl index was calculated. Given the varying effects of the indicators, their weights were calculated per neighborhood. The neighborhood with the lowest compactness/sprawl value had the highest sprawl rate, and the neighborhood with the highest compactness/sprawl value had the highest compactness.

VIKOR is a model for selecting the best item using an MCDM technique. This approach has been applied in various fields (e.g., tourism management, supply chain management, and water resource planning). It enables the selection of options in a complex environment with multiple weighting criteria. The VIKOR method has been successfully used to resolve MCDM issues involving contradictory or incomparable criteria (Mardani et al., 2016). Numerous studies (Baykasoğlu et al., 2013; Dalalah et al., 2011; Kobryń, 2017; Sharifi et al., 2021) have used this technique to determine the index weights. For details related to this method, we refer the readers to the cited articles. The indicators were weighted using the decision-making trial and evaluation laboratory (DEMATEL) technique. Various methods such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and entropy can be used for this purpose. However, DEMATEL is more effective due to its higher weight compatibility, lower computational complexity, and lower computational requirements. Another feature that makes DEMATEL a suitable method is that compared with AHP, it is better capable of dealing with situations when dominant criteria exist (for more details, see Kobryń, 2017). The questionnaire developed for this purpose was completed by ten Ahvaz-based urban planning researchers and managers.

The regression model was then used to investigate the effect of compactness/sprawl indicators on the coronavirus spread patterns (rate per 1000 patients and crude number of patients). SPSS24 software was used to perform the multiple linear regression analysis. The number of.

4. Results and discussion

4.1. Measuring compactness/sprawl in the neighborhoods of Ahvaz

To begin, distribution maps for the 17 indicators evaluated for Ahvaz neighborhoods were created, as illustrated in Fig. 2. The average size of residential parcels, distance from the city center, the ratio of residential land use within the neighborhood, the ratio of employed individuals, gross residential density, the ratio of population density to the highest population density, the ratio of service land use to the total neighborhood area, the ratio of building density to the total neighborhood area, the ratio of single-story buildings to the total neighborhood area, the ratio of vacant land to the total neighborhood area, the residential unit density, household density, net residential density, the ratio of built-up land to the total neighborhood area, and the neighborhood building density were the indicators in order of weight from lowest to highest (Table 2).

As stated previously, an MCDM technique (VIKOR) was used to rank neighborhoods according to their compactness/sprawl level. The negative indicators are those that increased sprawl as their values declined. These include the gross residential unit density, household density, net residential density, the number of mixed-use parcels within neighborhoods, the ratio of mixed-use land to the total neighborhood area, the ratio of employed individuals, the ratio of commercial land use to the total neighborhood area, the ratio of built-up land to the total neighborhood area, the building density of neighborhoods, the ratio of service land use to the total neighborhood area, the ratio of building density to the highest density, and the population density to the highest population density. By contrast, the positive indicators (those that increased sprawl as their values increased) were the distance from the city center, the ratio of vacant land to the total neighborhood area, the proportion of single-story buildings, and the average size of residential parcels. Indicator weights were calculated and multiplied by the corresponding indicator values. As shown in Table 3 and Fig. 3, the final results indicated that Kian Shahr (ranked first) and Zeitoon Karmandi (ranked 116th) were the most and least sprawled (most and least compact) neighborhoods in Ahvaz, respectively.

As displayed in Fig. 3, the neighborhoods on the outskirts of the city were more sprawled, whereas neighborhoods closer to the center and those with a higher socio-economic status (such as Zeitoon Karmandi (116th), Kianpars (106th), and Golestan (105th)) were less sprawled. These areas have the highest density of urban services and apartment dwellings.

4.2. Analysis of the effects of compactness/sprawl indicators on the rate of COVID-19 cases

The primary objective of this study was to determine the effects of compactness/sprawl on the spread of COVID-19. Regression analysis was used to study the effects of the coefficients obtained for each neighborhood in the compactness/sprawl index (the final results from the VIKOR model) and the 17 indicators separately on the spread of the disease in the neighborhoods of Ahvaz. Except for the average size of residential parcels, Table 4 indicates that no other indicators significantly affected the rate of COVID-19 cases. The significant effect of the average size of residential parcels could be attributed to the fact that there are large residential blocks in the compact districts that are characterized by high levels of density. As density could increase the chances of transmission, it could have led to higher levels of transmission in such parcels. Population density had a negative but limited effect on the rate of COVID-19 cases, implying that as population density increases, the rate of COVID-19 cases decreases. Additionally, the residential unit density index, which quantifies the number of residential units per unit neighborhood area, had a negligible effect. Household density also had a negligible impact. The effects of net residential density, the number of mixed-use parcels, the ratio of mixed land-uses to the total neighborhood area, the distance from the city center, the ratio of population density to the highest density, the ratio of employed individuals, and the ratio of vacant land to the total neighborhood area were all negative, indicating that the rate of COVID-19 cases was lower in neighborhoods with higher values for these indicators. The ratio of commercial land-uses to the total neighborhood area, the ratio of built-up land to the total neighborhood area, neighborhood building density, the ratio of service-use land to the total neighborhood area, and the ratio of building density to the highest density had a positive, but limited effect on the spread of the disease. Additionally, the effect of the VIKOR coefficient obtained in the previous analysis step was analyzed on the rate of COVID-19 cases, which was found to be nearly zero and statistically insignificant.

The number increases as the areas get denser and decreases as the areas become sprawled. While the raw numbers of COVID-19 cases in Kianpars, Golestan, and Padad Shahr were significant, these neighborhoods did not rank highly in terms of COVID-19 cases per 1000 residents. In other words, when the population (number of cases per 1000 people) was considered, they did not experience an infection peak. The effects of compactness/sprawl on the raw number of cases were also examined to conduct a more precise analysis. The population density, residential unit density, household density, building density to population density, and neighborhood building density had positive and significant effects on the raw number of cases; the raw numbers of COVID-19 cases were high in neighborhoods with higher values for these indicators. The overall compactness/sprawl index had positive and significant effects on the raw number of cases, with a coefficient of 0.291.

The study determined the compactness/sprawl of Ahvaz neighborhoods by first evaluating each index for each neighborhood. Kian Shahr and Zeitoon Karmandi were the city's most sprawling and compact neighborhoods, respectively. It is noted from Fig. 3 that compact neighborhoods/areas are not just located or constrained to the city's central business district or the immediate districts; several compact neighborhoods are located relatively far from the city center. The sprawling neighborhoods are distributed more or less uniformly along the city's periphery. In other words, neighborhoods that are further away from the city center and toward the suburbs are more sprawling.

The slums of Ahvaz with low socio-economic status ranked first in terms of sprawl. It is worth noting that the urban characteristics of Ahvaz's more sprawling neighborhoods differ from those of cities in western countries. Residents of sprawled cities in the United States and Australia are often wealthy and have a high socio-economic status. In Iran, specifically in Ahvaz, people with higher socio-economic status choose to live in more compact neighborhoods and adopt an apartment-lifestyle. While poverty, inexpensive land, and illegal land-ownership have given rise to suburban neighborhoods in Ahvaz, western sprawl is shaped by affluent households deciding to reside in the suburbs in search of a higher quality of life (Bagheri & Tousi, 2018; Ebrahimpour-Masoumi, 2012; Gouda et al., 2016). The compact neighborhoods identified in this study lack the essential characteristics of compact cities, which improve quality of life and promote urban sustainability. These neighborhoods lack sidewalks, cycling routes, green spaces, and public transportation. In Ahvaz's compact neighborhoods, building

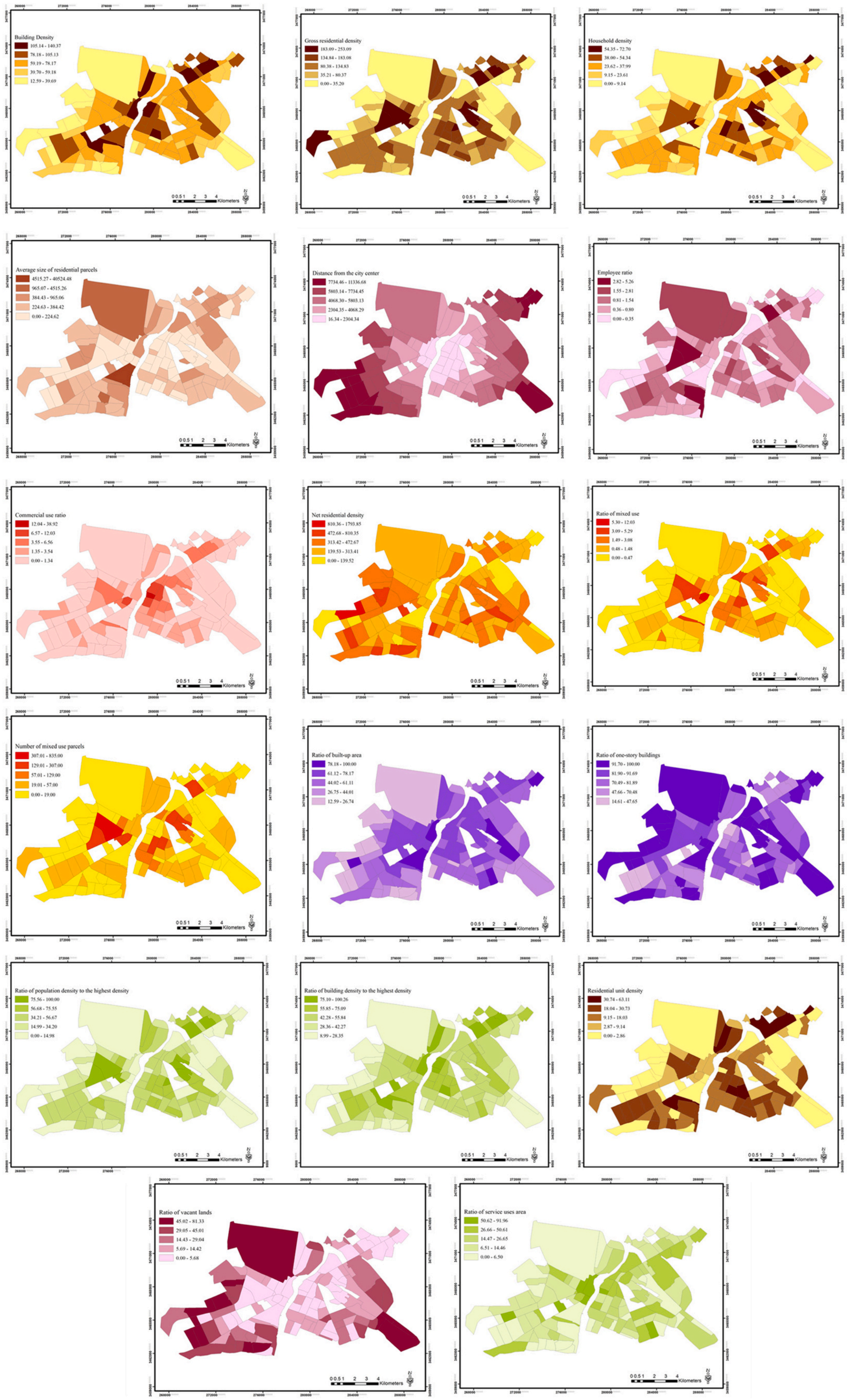

Fig. 2. Spatial representation of the indicators for different neighborhoods of Ahvaz.

Table 2
Final step for weight calculation in the DEMATEL technique.

W^-_j	w_j	R-J	R + J	R + J	J	R
0.05706359	12.41931972	1.893139389	12.27418126	12.27418126	7.083660322	5.19052093
0.062563011	13.61621369	−0.835858794	13.59053403	13.59053403	7.213196413	6.37733762
0.064782884	14.09934695	−0.08692386	14.099079	14.099079	7.093001428	7.00607757
0.067194912	14.62430054	−0.957171166	14.59294315	14.59294315	7.775057156	6.81788599
0.053173073	11.57258753	0.485947182	11.56238027	11.56238027	6.024163724	5.53821654
0.053714033	11.69032204	0.558622747	11.6769675	11.6769675	6.117795126	5.55917238
0.044553724	9.696672437	4.716383868	8.472394145	8.472394145	1.878020138	6.59437401
0.054273757	11.81214057	1.181397876	11.752913	11.752913	6.467155435	5.28575756
0.054171035	11.78978409	0.499000548	11.7792193	11.7792193	6.139109923	5.64010937
0.062517212	13.60624594	1.227301188	13.5507808	13.5507808	7.389040996	6.16173981
0.062082973	13.51173835	0.793678542	13.4884079	13.4884079	6.347364677	7.14104322
0.068538754	14.91677446	0.497982338	14.90845981	14.90845981	7.703221072	7.20523873
0.069996045	15.23393914	0.553380123	15.22388493	15.22388493	7.888632525	7.3352524
0.060861525	13.24590227	0.66973371	13.22896003	13.22896003	6.279613162	6.94934687
0.061352805	13.35282448	1.44805555	13.2740746	13.2740746	5.913009527	7.36106508
0.059157756	12.87509401	0.096206928	12.87473456	12.87473456	6.485470744	7.38106508
0.04420577	9.620943766	1.245110468	9.540034532	9.540034532	4.14762032	5.3925725
1	217.68415					

Table 3
Final results from the VIKOR method.

Rank	Neighborhood	Q	Rank	Neighborhood	Q	Rank	Neighborhood	Q
1	Kian-Shahr	0.00321296	41	West Resalat	0.368520191	81	Kooy-e Alavi	0.518656782
2	Municipality Houses	0.029148961	21	Padad-shahr – faz 5	0.372483585	82	Sepidar	0.519434661
3	Sayahi	0.043540585	43	Kooy-e Police	0.378941927	83	Bist-metri Shahrdari	0.526944333
4	Golbahar	0.044151071	44	Manazel Railway	0.391095891	84	Shahid Chamran University	0.551662121
5	Krishan	0.045023838	45	Golestan Mojtame Maskouni	0.391172172	85	Lashkar-abad	0.553904634
6	Elahiyeh	0.062639676	46	Golestan Jenoubi	0.409086208	86	Hasir-abad	0.557950873
7	Chanibeh Olya	0.074795342	47	Manzel Janbazan	0.419401895	87	Manzel15Khordad	0.564579678
8	Goldasht	0.090003165	48	Mohajerin	0.419551692	88	Pardis 1	0.566552854
9	Mandali	0.123929538	49	Newside	0.426553391	89	Zaferanieh	0.5688401
10	Al-e Taher	0.13488754	50	Farhang-shahr	0.426630729	90	Soltanmanesh	0.575777616
11	Zooye 2	0.137593259	51	Kooy-e Ramezan	0.430243161	91	Kamplo Jenoubi	0.585729587
12	Mnazel Foolad	0.143141198	52	Shahrvand	0.432351758	92	Shahr-e Salem (Lashkar)	0.586980979
13	Kooy-e Emam	0.148530467	53	Mojahed	0.436745552	93	University Town	0.590493274
14	Malashiyeh	0.152871032	54	Ameri	0.43779999	94	Melirah	0.605561007
15	Salim-abad	0.154330256	55	SHhrak Barq	0.438176417	95	Azad-shahr	0.615022592
16	Seyed Khalaf	0.169695915	56	Kooy-e Dolat	0.447230085	96	Javaheri	0.616041734
17	Moeinzadeh	0.169841767	57	Padad-shahr – Faz 1	0.447875081	97	Zabein Mendai	0.618519955
18	Sadat	0.170446367	58	Khoroosieh	0.449156378	98	Akhar-e Asfalt	0.619682661
19	Kooy-e Aboozar	0.180105842	59	SHhrak Naft	0.453024379	99	Ziba-shahr	0.643998142
20	Kooy-e Tolab	0.217910824	60	60Pareh	0.453683426	100	Baq-e Sheikh	0.680079625
21	Pardis 2	0.218446918	61	Kooy-e Silo	0.45666159	101	Koorosh – Faz 3	0.680191119
22	Janbazan	0.222131332	62	Nezam-Mohandesi	0.462580007	102	Simetri	0.704006355
23	Resalat GHarb	0.230348037	63	Pastorizeh	0.463894823	103	Bahonar	0.725462765
24	Boostan	0.244595996	64	Kooy-e Foolad	0.470381452	104	Yoosefi	0.730018238
25	Payam Town	0.247575355	65	Kooy-e Taleqani	0.475809673	105	Sa'di	0.777690456
26	Baharestan	0.259867669	66	Ahan-e Afshar	0.477249182	106	West Kianpars	0.78241819
27	Teraktorsazi	0.262102386	67	Jahad	0.485764024	107	Mokhaberat Houses	0.789333044
28	Rah-o Tarabari	0.262397979	68	Banafsheh	0.491771426	108	Padad-shahr	0.793112855
29	Pardis 3	0.28623284	69	Zeitoon Kargari	0.492812201	109	North Golestan	0.797841541
30	SHahrak Razmandegan	0.289825664	70	Padad-Shahr – Phase 2	0.492842028	110	Kooy-e Bistodo-e Bahman	0.810289492
31	Karoon	0.301140139	71	Charsad-Dastgah	0.493221908	111	Abdolhamid Bazaar	0.818824828
32	Nabovat	0.318777037	72	Manba-e Ab	0.493847456	112	Amanieh	0.881814411
33	Kooy-e Payam	0.328669452	73	Behzad-shahr	0.494979487	113	Baq-e Moein	0.883801444
34	Kooy-e Farhangian	0.340684974	74	Asi-abad	0.497158646	114	Manab'e Tabi'ie	0.936004343
35	Zooye 1	0.341328068	75	Kooy-e Mo'alemin	0.50030767	115	Koorosh – Faz 1&2	0.941941713
36	Aqajari	0.344711629	76	North Kamplo	0.501515349	116	Zeitoon Karmandi	0.944578454
37	Kooy-e Issar	0.35008412	77	Rafis-abad	0.506664185			
38	Kooy-e Taleqani	0.358256715	78	East Kianpars	0.508684725			
39	Khaz Olya	0.367106102	79	Kian-abad	0.511486984			
40	Zargan	0.36750414	80	Koorosh – Faz 4	0.51852309			

density, population density, and mixed land use were all significant indicators. According to Hamidi and Zandiatashbar, the distinction between these neighborhoods and sprawled ones is primarily due to improved access to social and commercial services (Hamidi & Zandiatashbar, 2019).

The second analysis examined the effect of compactness/sprawl indicators on the COVID prevalence. The findings indicated that the compactness/sprawl indicators had no statistically significant effect on COVID-19 case rates (infection rate per 1000 people) in Ahvaz neighborhoods. The average residential parcel size was the only index with a statistically significant positive effect on case rates. Parcel size is higher in areas that are more compact and with more chances of human interactions. People with a higher socio-economic status typically own larger houses. This may result in increased social contacts, such as

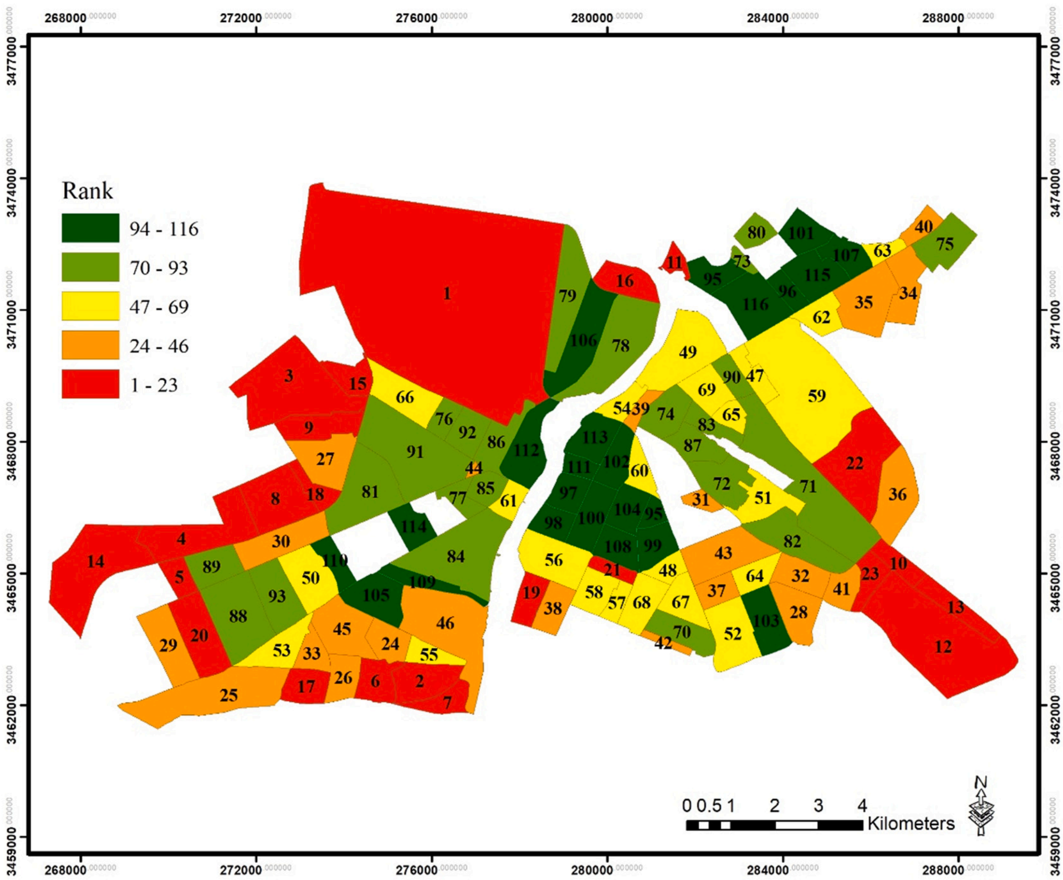

Fig. 3. Ranking map of the neighborhoods of Ahvaz in terms of sprawl.

Table 4
Regression model for the analysis of the effects of compactness/sprawl index on the spread of COVID-19.

Independent variables	Dependent variables					
	The raw number of COVID-19 cases			COVID-19 cases per 1000 people		
	Standardized coefficients	t	p-Value	Standardized coefficients	t	p-Value
Population density	0.353	3.115	0.003	−0.081	−0.669	0.506
Residential unit density	0.446	4.111	0.000	0.085	0.701	0.486
Household density	0.405	3.649	0.001	0.004	0.036	0.972
Net residential density	0.051	0.417	0.678	−0.150	−1.251	0.215
Number of mixed-use parcels	0.145	1.206	0.232	−0.166	−1.391	0.169
The ratio of mixed-use land to the total neighborhood area	0.073	0.603	0.549	−0.061	−0.505	0.615
Distance from city center	−0.092	−0.765	0.447	−0.178	−1.488	0.141
The ratio of employed individuals	0.484	4.555	0.000	−0.212	−1.792	0.078
The ratio of commercial-use land to the total neighborhood area	0.093	0.773	0.442	0.027	0.223	0.824
The ratio of vacant land to the total neighborhood area	−0.156	−1.301	0.198	−0.115	−0.953	0.344
The ratio of single-story buildings	−0.141	−1.177	0.243	−0.027	−0.220	0.827
The ratio of built-up land to the total neighborhood area	0.225	1.905	0.061	0.107	0.889	0.377
Neighborhood building ratio	0.244	2.076	0.042	0.057	0.471	0.639
The ratio of service-use land to the total neighborhood area	−0.040	−0.329	0.743	0.100	0.831	0.409
The ratio of building density to highest density	0.244	2.076	0.042	0.057	0.471	0.639
The ratio of population density to the highest density	0.394	3.531	0.001	−0.015	−0.120	0.905
Average size of residential parcels	−0.080	−0.663	0.509	0.266	2.275	0.026
Q (VIKOR coefficient)	0.291	2.508	0.015	0.050	0.415	0.680

gatherings, and interactions with others, ultimately resulting in a relatively small increase in the disease spread among them.

However, it should be mentioned that larger houses are associated with improved health status because they permit daily activities to be conducted inside the house during quarantine (Amerio et al., 2020). Furthermore, neighborhoods on the periphery benefited from superior air conditioning due to the high proportion of townhouses (rather than apartments) in these low-density neighborhoods. This may have resulted in a decrease in COVID-19 cases, as open spaces slow the spread of the disease. Ashcroft (2020) confirmed the same finding, citing the beneficial effects of housing design and building forms. One of the compactness indicators assessed in this study was building density for each neighborhood, but it differed from the block or residential density. Thus, a high building density per neighborhood does not suggest that housing units are necessarily small, and residents with better economic conditions in the neighborhoods have larger residential plots.

An analysis of the effects of the compactness/sprawl indicators and the overall compactness/sprawl index obtained from the VIKOR model on the raw number of COVID-19 cases (the number of infected in each neighborhood) indicated that the compactness/sprawl index had a significant but limited effect on the raw number of cases. According to Hamidi et al. (2020), the disease spreads more rapidly in densely populated areas with high external connectivity. At the neighborhood level, residents' socio-economic status dictates the extent to which they interact with other neighborhoods. Neighborhoods such as Malashiyeh (14th) and Sayahi (3rd) on the outskirts of the city had less interaction with other neighborhoods, resulting in a more limited spread of the virus; whereas neighborhoods such as Kianpars (106th), Zeitoon Karmandi (116th), and Golestan (105th) had more socio-economic interaction. Residents' economic and social circumstances, as well as the presence of attractive and mixed land uses foster social interaction in neighborhoods. Ashcroft (2020) has also emphasized the importance of socio-economic conditions over housing characteristics. However, the findings of this study took into account the physical characteristics affecting the neighborhoods' socio-economic conditions and the prevalence of COVID-19.

Mixed land use is viewed as a benefit of compact cities. It facilitates access to public and recreational services, increasing daily commute times and population density during certain hours. Credit (2020) found out that land use mix increases COVID-19 infections in the United States. However, in Hong Kong, a negative correlation was observed between mixed land-use and COVID-19 (Huang et al., 2020). Job opportunities and improved service access in Ahvaz's compact neighborhoods attract residents from sprawling neighborhoods. This causes the residents of compact neighborhoods to engage and interact with more people outside their neighborhoods, as Huang et al. (2020) reported. Li et al. (2021) and Yip et al. (2021) also concluded that built environment indicators, such as the housing size, the density of buildings, medical centers, and restaurants; and commercial land-use affect the COVID-19 rates. However, as our analysis of the number of cases per 1000 people showed, this does not mean that compact neighborhoods are necessarily more vulnerable.

Kwon et al. (2022) also reported that the presence of commercial and office activities in the city (mixed land use) could positively affect mobility and the number of trips. This could increase the risk of COVID-19 spread. Some studies have shown that despite government interventions and the perceived COVID-19 risk, citizens have continued to travel to the central parts of cities for various purposes, such as shopping (Abdullah, Dias, Muley, & Shahin, 2020; Shamshiripour et al., 2020). The absence of effective planning and management, such as mobility restrictions and social distancing protocols, higher service delivery, and mixed land use may, therefore, increase the risk of exposure to the coronavirus and create problems in controlling the pandemic. Accordingly, it is necessary to minimize crowding and reduce population absorption in such places during pandemics (Lak et al., 2021). As noted earlier, the compact neighborhoods in Ahvaz have higher concentration of services and mixed land use rates but limited green and open spaces. This may also affect compliance with health and social distancing protocols during health crises (Megahed & Ghoneim, 2020).

The current study was conducted at the neighborhood level. Prior studies conducted at larger scales, such as country, province, city, and county, discovered a more substantial effect of density indicators on COVID-19. Furthermore, it has been observed that the spread of COVID-19 was not always directly related to density: dense cities and countries such as Singapore, Taiwan, and Hong Kong had lower COVID-19 case rates than the United States (Kashem et al., 2021).

One finding of this study is that while the neighborhood compactness/sprawl index had no positive or significant effect on the COVID-19 case rate (number of cases per 1000 people), it had a significant but limited effect on the raw number of cases. The raw number of COVID-19 cases was significantly higher in more compact neighborhoods with higher building and residential unit densities and higher employment rates. This is unsurprising as more people live in compact areas and, therefore, the raw number of cases is also likely to be higher.

In some contexts, COVID-19 has encouraged people to move from dense neighborhoods to the suburbs, leading to a higher sprawl index (Peiser & Hugel, 2022). The findings of this study also indicated that the number of COVID-19 patients is higher in compact neighborhoods. However, as the less dense neighborhoods in Ahvaz and its suburbs do not have favorable conditions in terms of service accessibility, fewer people may move to these neighborhoods. While it is necessary to improve the living environment in the sprawled areas, actions should also be taken to ensure safety of the compact areas against health crises. These could, for instance, include better provision of open and green spaces and improved design of streets and public spaces to facilitate compliance with health protocols.

5. Conclusion

The current study was one of the first to examine the effect of a compactness/sprawl index on COVID-19 rates in urban neighborhoods, thereby contributing to the body of knowledge on the subject. MCDM and regression techniques were used to assess neighborhood compactness/sprawl indicators and their effect on COVID-19 rates. The VIKOR model was used to rank neighborhoods in order of compactness to sprawl.

The neighborhoods with the lowest and highest (close to unity) values were the most sprawled and compact, respectively. The proposed method can quantify compactness at various scales in both developing and developed countries, resulting in a better understanding of urban and neighborhood conditions. This could offer insights to strengthen urban compactness policies and facilitate the implementation of measures to enhance the sustainability and resilience of cities. As each city has its own unique conditions, we suggest that applying this method in other contexts will be useful for understanding how context-specific conditions may affect the spread patterns and dynamics of infectious diseases.

This study shows that different measures of density may result in different outcomes when analyzing the impacts of urban form on COVID-19 prevalence. When the number of cases per 1000 people was considered, neither the overall neighborhood ranking index nor any of the compactness/sprawl indicators, except for the average size of residential parcels, significantly affected COVID-19. This could be attributed to the fact that there are large residential blocks in compact districts that are characterized by high levels of population concentration. As high concentration could increase the chances of transmission, it could have led to higher levels of transmission in such parcels. When the raw number of COVID-19 cases was considered rather than the number of cases per 1000 people, the compactness/sprawl index had a positive and statistically significant but limited effect on COVID-19 in the Ahvaz neighborhoods. In other words, more compact neighborhoods had a higher incidence of COVID-19. As more people live in such areas, it is unsurprising that the raw number of cases is higher in compact areas. Compact neighborhoods such as Zeitoon Karmandi, Kianpars, Golestan, and Padad Shahr endured worse conditions during the COVID-19's peaks. Without effective control strategies, physical and built environment indicators such as mixed land use could increase the neighborhoods' permanent and floating population, resulting in more exposure and an increase in the number of COVID-19 cases. Yet, as no significant relationship between the number of cases per 1000 people and density indicators was found, it should be noted that for a given area (city, region, or neighborhood), increased population density alone does not lead to increases in COVID-19 rates; rather, the area's physical characteristics result in increased social interactions, which eventually leads to a rise in disease rates.

Numerous factors influence the spread of the coronavirus, including age, household type, travel behavior, and socio-economic status. Future research can provide a complete picture by analyzing individuals' characteristics, socio-economic status, and housing conditions. This study would suggest studying the income levels of households, their travel habits, their access to a vehicle, and their level of literacy and education. Additionally, future research should analyze the inter-neighborhood travel rate as a critical indicator of how frequently people travel to compact neighborhoods in conjunction with other indicators.

The present research had another limitation in that data were only available at the neighborhood level; if physical and COVID-19 data were available at the residential unit level, the effects of household and population densities within a residential unit, as well as the residential space of households, could be examined more precisely. However, it should be noted that gaining access to the COVID-19 data is very difficult in Iran, and even national and urban level data can be accessed only with special permissions. Additionally, the cost of COVID-19 tests, the limited number of free testing centers, and people's reluctance to visit COVID-19 testing centers may have contributed to a slight discrepancy between actual and available data.

Other studies have demonstrated the role of public transportation in the spread of COVID-19 and the stress and negative emotions accompanying it (Shamshiripour et al., 2020). Due to the lack of a comprehensive map of the bus system, roads, and stops, and the fact that the bus system was inactive during the COVID-19 pandemic, it was not considered a primary index in this work. This factor, however, had a negligible effect in the current study because Ahvaz lacks an underground metro system, bus services were suspended during the pandemic, and the city's outskirt neighborhoods lacked adequate public transportation. Additionally, the low rates of private car ownership reduced personal vehicle trips. This contrasts the suburban characteristics and sprawl patterns observed in American cities, where private car trips are prevalent (Hamidi & Zandiatashbar, 2021). Following the limitations of this study, future studies need to also consider the number of trips and their changes to understand how they may have affected the COVID-19 prevalence.

Our findings highlighted the need for assessing urban spatial characteristics and their role in achieving sustainable urban development, citizen health, and urban resilience, which is one of the U.N. Sustainable Development Goals (SDGs) and part of the new urban agenda.

The findings of this study have some implications for assessing compactness/sprawl indicators used for physical planning, optimization of urban forms, sprawl control, and urban growth management. The data from evaluating the impact of urban physical and spatial forms on COVID-19 prevalence can also contribute to the growing field of urban form assessment. Other contributions of this research are as follows: first, a compactness measurement was developed using multi-criteria decision-making and GIS techniques. Second, the effect of compactness/sprawl as a compound index on COVID-19 was assessed. Third, the study was conducted in one of the developing cities with a different social and cultural context and acute pandemic conditions (five COVID-19 waves). Fourth, this study examined the compactness/sprawl indicator and its impact on COVID-19 prevalence in each neighborhood. Thus, the findings can be used for developing neighborhood-centric measures.

A policy that could be adopted by urban managers is the decentralization and creation of service cores (following the compact polycentric city approach) in the urban fringe neighborhoods and provides more balanced access to services across all neighborhoods to reduce commutes in compact neighborhoods. This strategy can be optimized by considering employment, service, and population sub-centers. This multinuclear structure could strengthen urban resilience by distributing threats and reducing pressure on a center. Creating self-sufficient neighborhoods is a significant idea to decentralize and reduce crowding during the COVID-19 outbreak. Infill development approaches and urban growth management are suggested to control sprawl in city fringe neighborhoods. Besides, regulations limiting construction can be enforced more effectively in these areas. Realizing and implementing online shopping and teleworking strategies will be difficult due to the lack of proper infrastructure and the large number of labor and manual jobs in Ahvaz. We suggest that future research should elaborate on these different policies to better understand how they can contribute to building compact cities that are also pandemic resilient.

Urban officials worldwide are trying to increase compactness to achieve sustainability goals and control the unregulated growth of cities. If these control and planning measures consider ongoing issue such as the COVID-19 pandemic, they can benefit citizens and optimize urban and individual resilience. This study was conducted in the socio-cultural context of a developing country. While the findings cannot necessarily be generalized to other countries, the approach can be applied to other developing country cities by considering context-specific social, cultural, and climatic conditions. However, different thresholds should be adopted for each indicator according to the country-specific conditions.

Numerous studies have emphasized the importance of compactness and the positive effects it can have on the socio-economic, environmental, and transportation aspects of urban life. The current study and a small number of previous studies indicated that compactness affects coronavirus case rates during the COVID-19 pandemic by increasing social interactions and connections. Additionally, compactness improves the index of service accessibility (especially access to health services). Urban planners and managers can preserve the comprehensive benefits of compactness through effective management by enforcing relevant regulations and observing social distancing, particularly in compact areas. Finally, this study recommends the following policies be implemented:

- Improving compactness and service access in sprawled neighborhoods to reduce long-distance travel demand to access services; and.
- As higher rates of COVID-19 infection may increase concerns over living in compact areas, it is essential to develop strategies to enhance public health safety in high-density areas. This could be achieved by improving features such as cycling and pedestrian routes, and by the provision of more open and green spaces in compact neighborhoods.

We hope that the results of this study will inform actions toward enhancing pandemic resilience in Ahvaz and other developing country cities with similar conditions.

CRediT authorship contribution statement

Seyed Jafar Hejazi: Resources, Supervision, **Mahmoud Arvin**: Methodology, Data curation, Visualization, Writing- Original draft preparation, **Ayyoob Sharifi**: Writing- Original draft preparation, Writing- Review and editing, **Azadeh Lak**: Resources.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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