



## Evaluation of Urban Environmental Carrying Capacity Using a Pressure–State–Response Framework and Shannon Entropy Weighting in a District of Tehran City, Iran

Zahra Dehghan Manshadi<sup>1</sup> | Shahrzad Faryadi<sup>1</sup>✉ | Ahmad Nohegar<sup>2</sup> | Nadia Abbaszadeh Tehrani<sup>3</sup>

1. Department of Environmental Planning, Management, and HSE, Graduate Faculty of Environment, University of Tehran, Tehran, Iran.

2. Department of Disaster Engineering, Education, and Environmental Systems, Graduate Faculty of Environment, University of Tehran, Tehran, Iran.

3. Khayyam Research Institute, Ministry of Science, Research and Technology, Tehran, Iran.

| Article Info                                                                                                                                                   | ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Article type:</b><br>Research Article                                                                                                                       | Increasing human pressures can limit ecosystems' ability to maintain natural functions and meet sustainable development needs. Therefore, environmental carrying capacity (ECC) evaluation, as a decision-making support tool, plays a key role in identifying limiting factors and formulating management policies. The present study aims to assess changes in environmental carrying capacity in District 6 of Tehran City from 2019 to 2025. For this purpose, Shannon entropy weighting was applied to 19 indicators selected across three components: pressure, state, and response, within the pressure-state-response (PSR) framework. In addition, the Mann-Kendall and Pettitt's tests were used to evaluate the trend and the Monte Carlo method was used to assess the uncertainty in ECC values from 2019 to 2025 in RStudio. Data import, preprocessing, and visualization were conducted using the readxl, dplyr, tidyr, ggplot2, tibble, and patchwork packages. The results revealed that the ECC value decreased from 0.72 in 2019 to 0.35 in 2025, representing a 51% reduction in environmental carrying capacity. Furthermore, the analysis demonstrated that the pressure component was the primary driver of variations in the ECC index, indicating a greater influence than the state and response components. Therefore, prioritizing the reduction of pressures at their source, strengthening preventative measures, implementing continuous monitoring of state indicators, and periodically assessing the effectiveness of management policies should be emphasized in environmental planning. |
| <b>Article history:</b><br>Received: 13 Jun 2026<br>Revised: 27 Jul 2026<br>Accepted: 27 Sep 2026                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| <b>Keywords:</b><br><i>Arid Regions</i><br><i>Change-Point Detection</i><br><i>Time Series Analysis</i><br><i>Monte Carlo</i><br><i>R Programming language</i> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |

**Cite this article:** Dehghan Manshadi, Z., Faryadi, Sh., Nohegar, A., & Abbaszadeh Tehrani, N. (2026). Evaluation of Urban Environmental Carrying Capacity Using a Pressure–State–Response Framework and Shannon Entropy Weighting in a District of Tehran City, Iran. *Pollution*, 12(4), 1185-1198.  
<https://doi.org/10.22059/poll.2026.416439.3380>



© The Author(s).

Publisher: The University of Tehran Press.

DOI: <https://doi.org/10.22059/poll.2026.416439.3380>

## INTRODUCTION

The rapid urbanization, high population density, and pressure from economic and service activities in metropolises have made the relationship between urban development and the environment's capacity to support it a central issue in sustainable urban planning (Tan et al., 2025). On the one hand, cities are considered centres of production, employment, services, innovation, and social interactions, and on the other hand, due to the high concentration of population and activity, increasing resource consumption, waste and wastewater generation, increased transportation demand, increased air pollution, and fragmentation of green spaces, they place significant pressure on the urban environment (Ren et al., 2023; Khalili & Nasrabadi,

\*Corresponding Author Email: [sfaryadi@ut.ac.ir](mailto:sfaryadi@ut.ac.ir)

2023). This issue is more important in metropolises, where daily travel, the concentration of services, and the presence of floating populations can also affect the functional and environmental capacity of urban areas (Parivar et al., 2023). The concept of carrying capacity has been defined as a fundamental benchmark for analyzing the relationship between human activity and the environment (Zhang et al., 2024; Ye et al., 2024), and refers to the maximum load that a habitat, or ecosystem, could withstand before causing irreversible damage or disruption (Li et al., 2022). Methods for evaluating carrying capacity include principal component analysis (Liu et al., 2018), fuzzy assessment (Wang et al., 2021), ecological footprint (Mu et al., 2021), system dynamics modeling (Fang et al., 2017), and Shannon entropy (Cui et al., 2018; Cheng et al., 2020). This study employed the Pressure-State-Response (PSR) framework, integrated with the Shannon entropy method, to evaluate the carrying capacity at the district level. The PSR framework has been used because it is one of the most widely applied frameworks for organizing indicators (Huang et al., 2011; Sun et al., 2019; Lu et al., 2022; Zhang et al., 2024). However, PSR does not provide a quantitative mechanism for weighting or aggregating indicators; therefore, the Shannon entropy method (Shannon, 1948) was incorporated. Shannon Entropy weighting was chosen because it derives weights objectively from the variability of the collected data during the study period, minimizing potential bias introduced by expert judgment and enhancing the reliability of the results (Sadeghitabar et al., 2025; Grausová & Hužvár, 2025). Furthermore, this study proposed a dual-level weighting mechanism, whereas most studies in this field have relied on Shannon entropy (Zhang et al., 2019; Sun et al., 2020; Shen et al., 2020; Liao et al., 2020). At the intra-component level, Shannon entropy was used to objectively assign weights to indicators within each of the Pressure, State, and Response components. At the inter-component level, the Analytic Hierarchy Process (AHP) was utilized to assign weights to the three PSR components. This integrated approach enhances the objectivity and data-driven nature of entropy weighting for indicator-level discrimination while incorporating expert judgment through AHP to reflect the relative strategic importance of each component within the district context. The applicability of the method will be analyzed through a case study in District 6 of Tehran City, a central district facing challenges such as air pollution, high population density, and water scarcity (Nazmfar et al., 2025). The main research question in this study is: What factors influence environmental carrying capacity in District 6 of Tehran City? The second question is: What efficient and effective responses have been given to improve the state of the urban environment?

### *Study area description*

District 6 of Tehran City is one of the central districts of the capital, encompassing a mix of residential, commercial, and cultural zones, covering approximately 21 km<sup>2</sup> and comprising 14 neighborhoods in an arid climate (Aghaei et al., 2019). According to statistics from the Tehran City Statistical Yearbooks for 2024, the district's population was estimated at approximately 268,368 inhabitants (Tehran Municipality, 2024). Green infrastructure encompasses several major public parks, such as Laleh Park (35 hectares) and Saei Park (12 hectares), and green space per capita is 13.24 m<sup>2</sup> (Tehran Municipality, 2024; Azimpour et al., 2026). Evaluating the carrying capacity in this area can provide a thorough understanding of its strengths and weaknesses, helping to identify strategies that improve service quality. Fig. 1 shows the location and land use classification of the study area.

## **MATERIALS AND METHODS**

### *Indicator system based on PSR framework*

The research period was considered to include the years 2019 to 2025. The data required for the selected indicators were available for this time period, with an acceptable level of continuity,

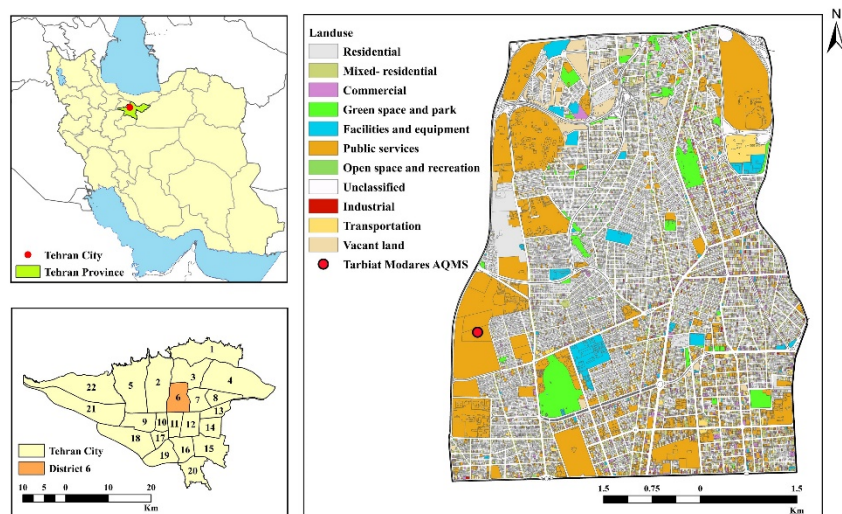


**Fig. 1.** Location and land use classification of District 6, Tehran City

**Table 1.** Indicator system of environmental carrying capacity based on the PSR framework

| Component | Indicator                                                | Code           | Unit                     | Type |
|-----------|----------------------------------------------------------|----------------|--------------------------|------|
| Pressure  | Population Density                                       | P <sub>1</sub> | persons/ km <sup>2</sup> | -    |
|           | CO                                                       | P <sub>2</sub> | ppm                      | -    |
|           | O <sub>3</sub>                                           | P <sub>3</sub> | ppb                      | -    |
|           | NO <sub>2</sub>                                          | P <sub>4</sub> | ppb                      | -    |
|           | SO <sub>2</sub>                                          | P <sub>5</sub> | ppb                      | -    |
|           | PM <sub>2.5</sub>                                        | P <sub>6</sub> | ug/m <sup>3</sup>        | -    |
|           | PM <sub>10</sub>                                         | P <sub>7</sub> | ug/m <sup>3</sup>        | -    |
|           | Per capita urban waste production                        | P <sub>8</sub> | kg/day                   | -    |
|           | Per capita domestic water consumption                    | P <sub>9</sub> | Liter/day                | -    |
| State     | Green space per capita                                   | S <sub>1</sub> | %                        | +    |
|           | Days with AQI > 100                                      | S <sub>2</sub> | %                        | -    |
|           | Trip Attraction rate                                     | S <sub>3</sub> | %                        | -    |
|           | Road links with traffic volumes exceeding capacity       | S <sub>4</sub> | %                        | -    |
|           | Proportion of delay in total travel time                 | S <sub>5</sub> | %                        | -    |
|           | Water distribution losses                                | S <sub>6</sub> | %                        | -    |
| Response  | Metro stations                                           | R <sub>1</sub> | Number                   | +    |
|           | Households with access to wastewater collection services | R <sub>2</sub> | %                        | +    |
|           | Treated wastewater                                       | R <sub>3</sub> | %                        | +    |
|           | Green space coverage ratio                               | R <sub>4</sub> | %                        | +    |

comparability, and accessibility. The selection of indicators was carried out in a multi-stage process involving 6 experts: three with PhDs in Environmental Planning, and three with PhDs in Urban Planning (Table 1). The data used in this study were derived from official available sources, including the Tehran City Statistical Yearbooks and the reports published by the Tehran Air Quality Control Company (TAQCC). Air quality data, including recorded pollutant values in the study, were collected from official reports and data published by the TAQCC. As shown in Fig. 1, to assess the air pollution situation in District 6 of Tehran Municipality, the Tarbiat Modares Air Quality Monitoring Station (AQMS) was selected because it provided a continuous and quality-controlled time series for the study period.

### Data normalization

Given that the indicators possess different units, they must be converted into dimensionless values prior to aggregation (Xu & Li, 2025). To this end, the minimum-maximum linear normalization method (Kim et al., 2025) is employed. For positive or benefit-type indicators,

equation (1) is utilized:

$$x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

For negative or cost-type indicators, equation (2) is used:

$$x'_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where  $x'_{ij}$  is the normalized value of  $j$ -th indicator, and  $x_{ij}$  indicates the original value of indicator  $j$ .  $\max(x_{ij})$  is the maximum value, and  $\min(x_{ij})$  is the minimum value of the index in the period 2019 to 2025. After normalization, all indicators fall between 0 and 1. A value closer to 1 indicates a more favorable situation, and a value closer to 0 indicates a less favorable situation (Dehghan Manshadi et al., 2023).

#### *Weighting the indicators*

After data normalization, the Shannon entropy weighting method was used to determine the relative importance of the indicators. Shannon entropy method was first introduced by Shannon (1948) to investigate the disorder and uncertainty of a system. In the first step,  $P_{ij}$  denotes the proportion of each indicator ( $j$ ) in each year ( $i$ ), and it can be calculated as follows:

$$P_{ij} = \frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \quad (3)$$

Where  $n$  refers to the number of years in the study. In the second step, the entropy value of each indicator is calculated using the following equation:

$$e_j = -K \times \sum_{i=1}^n (P_{ij} \times \ln P_{ij}) \quad (4)$$

Consequently, the weighting value for each indicator is represented as  $W_j$  and can be calculated as follows:

$$W_j = \frac{d_j}{\sum_{j=1}^m d_j} \quad (5)$$

#### *Spearman correlation and Trend Analyses*

Relationship between the ECC index and several pressure and state indicators, analyzed using Spearman's rank correlation test (Spearman, 1904). Statistical analyses were performed using the RStudio. For trend analysis, the Pettitt test (Pettitt, 1979) was applied in RStudio to detect whether the ECC time series encountered an abrupt change during the study period. In this study, the statistical significance of this test was evaluated at the 0.05 level. Additionally, the Mann–Kendall trend test (Mann, 1945; Kendall & Gibbons, 1962) was performed in RStudio to assess whether the ECC index exhibited a monotonic increasing or decreasing trend over time. This study also used another nonparametric test, the Sen-Slope test (Sen, 1968), in RStudio to estimate the trend magnitude and slope. Statistical significance was assessed using the p-value at the 5% significance level. For data import, preparation, processing, and visualization in RStudio, various packages were used, including readxl (Wickham & Bryan, 2019), dplyr

**Table 2.** Normalized values of the pressure, state, and response indicators

| Component | Indicator                                                | Code           | 2019  | 2020  | 2021  | 2022  | 2023  | 2024  | 2025 |
|-----------|----------------------------------------------------------|----------------|-------|-------|-------|-------|-------|-------|------|
| Pressure  | Population Density                                       | P <sub>1</sub> | 1     | 0.852 | 0.649 | 0.488 | 0.337 | 0.175 | 0    |
|           | CO                                                       | P <sub>2</sub> | 1     | 0.831 | 0.727 | 0.831 | 0.727 | 0.727 | 0    |
|           | O <sub>3</sub>                                           | P <sub>3</sub> | 0.951 | 1.000 | 0.725 | 0.946 | 0.835 | 0.753 | 0    |
|           | NO <sub>2</sub>                                          | P <sub>4</sub> | 0.665 | 0.457 | 0.630 | 0.954 | 1     | 0.125 | 0    |
|           | SO <sub>2</sub>                                          | P <sub>5</sub> | 0.947 | 0.807 | 1     | 0.518 | 0.237 | 0.123 | 0    |
|           | PM <sub>2.5</sub>                                        | P <sub>6</sub> | 1     | 0.899 | 0.840 | 0.407 | 0.231 | 0.088 | 0    |
|           | PM <sub>10</sub>                                         | P <sub>7</sub> | 1     | 0.898 | 0.731 | 0.655 | 0.442 | 0.381 | 0    |
|           | Per capita urban waste production                        | P <sub>8</sub> | 1     | 0.761 | 0.522 | 0.283 | 0.272 | 0.120 | 0    |
|           | Per capita domestic water consumption                    | P <sub>9</sub> | 0.755 | 0.673 | 0.367 | 0     | 0.490 | 0.673 | 1    |
| State     | Green space per capita                                   | S <sub>1</sub> | 0     | 0.081 | 0.147 | 0.728 | 0.787 | 0.831 | 1    |
|           | Days with AQI > 100                                      | S <sub>2</sub> | 1     | 0.928 | 0.619 | 0.542 | 0.381 | 0.285 | 0    |
|           | Trip Attraction rate                                     | S <sub>3</sub> | 1     | 0.975 | 0.934 | 0.934 | 0.877 | 0.025 | 0    |
|           | Road links with traffic volumes exceeding capacity       | S <sub>4</sub> | 1     | 0.955 | 0.909 | 0.818 | 0.818 | 0.5   | 0    |
|           | Proportion of delay in total travel time                 | S <sub>5</sub> | 1     | 0.931 | 0.862 | 0.726 | 0.724 | 0.686 | 0    |
|           | Water distribution losses                                | S <sub>6</sub> | 1     | 0.655 | 0.538 | 0.534 | 0.352 | 0.314 | 0    |
| Response  | Metro stations                                           | R <sub>1</sub> | 0     | 0     | 0.25  | 0.750 | 0.750 | 0.75  | 1    |
|           | Households with access to wastewater collection services | R <sub>2</sub> | 0     | 0.007 | 0.144 | 0.324 | 0.574 | 0.768 | 1    |
|           | Treated wastewater                                       | R <sub>3</sub> | 0     | 0.340 | 0.472 | 0.731 | 0.886 | 0.923 | 1    |
|           | Green space coverage ratio                               | R <sub>4</sub> | 0     | 0     | 0.009 | 0.702 | 0.716 | 0.720 | 1    |

(Wickham et al., 2023), tidyr (Wickham et al., 2020), ggplot2 (Wickham, 2016), tibble (Muller & Wickham, 2019), patchwork (Pedersen, 2021), and stats (Wickham et al., 2020).

## RESULT & DISCUSSION

### *Normalized and Entropy values of PSR indicators*

As shown in Table 2, the pressure indicators trended downward. Although the normalized values of most pressure indicators declined over time, this pattern reflects the cost-type (negative direction) normalization applied to these indicators. Therefore, the reduction in normalized values signifies an increase in the original pressure values, demonstrating elevated pressure on the ECC index from 2019 to 2025. As shown in Fig. 1, a main portion of the land use in District 6 is dedicated to public services (such as offices, universities, and hospitals) and residential uses. In addition, District 6 provides many employment opportunities; consequently, population density ( $P_1$ ), the travel absorption rate ( $S_3$ ), traffic exceeding the capacity of the district's roads ( $S_4$ ), and the proportion of delay to total travel time ( $S_5$ ) have increased over time (Fig. 2).

As shown in Fig. 2, although the number of metro stations ( $R_1$ ) has increased, this has not reduced the number of road links with traffic volumes exceeding capacity in the district ( $S_4$ ). Therefore, an upward trend in response indicators over time does not necessarily signify their effectiveness. As explained in the study area description, this district is located in an arid climate, and increasing water distribution losses ( $S_6$ ), while the population density ( $P_1$ ) is also increasing over time, have significant effects on the ECC index.

As shown in Table 3, the entropy values for the pressure component ranged from 0.72 to 0.92, resulting in indicator weights between 0.06 and 0.20. Per capita domestic water consumption received the highest pressure weight (0.20), followed by PM<sub>2.5</sub> (0.14) and per capita urban waste production (0.13). This pattern indicates a greater dispersion of normalized values for domestic water consumption, as evidenced by an entropy of 0.72 and a divergence coefficient of 0.28, compared to 0.81 and 0.19, respectively, for PM<sub>2.5</sub>.

As shown in Table 4, the result of the pressure component reveals that the value of the aggregate index  $P_i$  has decreased from 0.91 to 0.20 during the period from 2019 to 2025. Given that the indicators with a negative direction, including population density and other

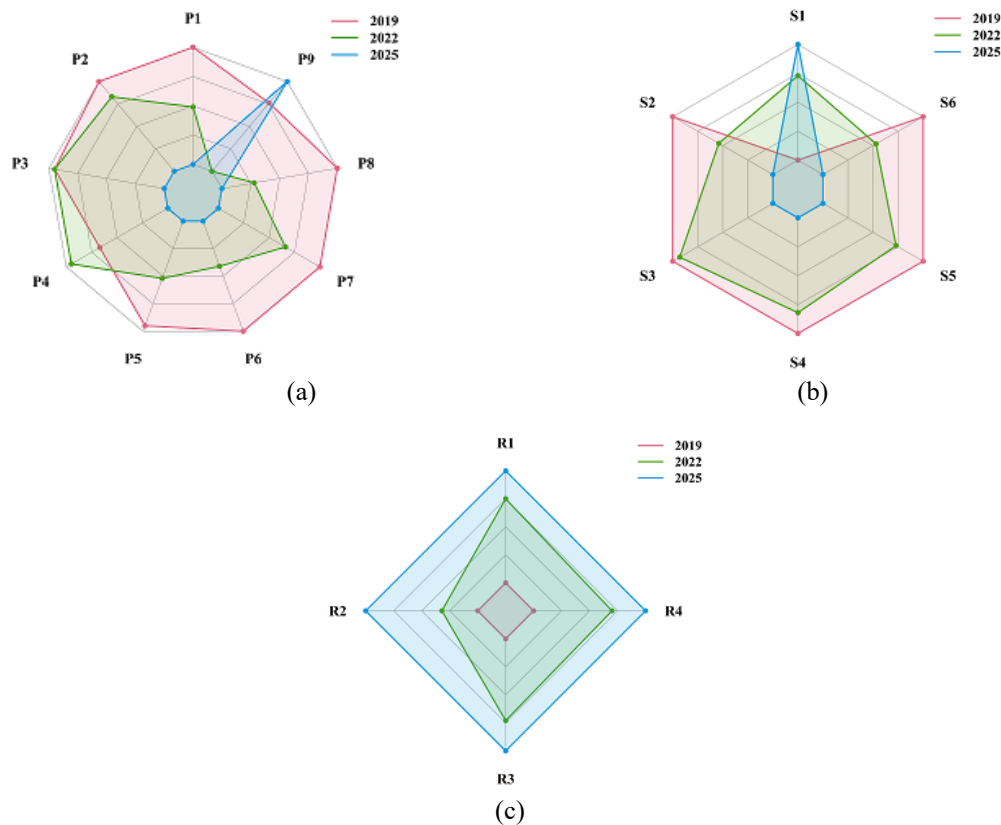


**Fig. 2.** Radar charts of normalized values: (a) Pressure indicators, (b) State indicators, and (c) Response indicators

**Table 3.** Entropy values ( $e_j$ ), dispersion degree ( $d_j$ ), and final intra-component weight ( $W_j$ ) of the pressure-state-response framework indicators

| Component | Indicator                                                | $e_j$ | $d_j$ | $W_j$ |
|-----------|----------------------------------------------------------|-------|-------|-------|
| Pressure  | Population Density                                       | 0.86  | 0.14  | 0.10  |
|           | CO                                                       | 0.92  | 0.08  | 0.06  |
|           | O <sub>3</sub>                                           | 0.92  | 0.08  | 0.06  |
|           | NO <sub>2</sub>                                          | 0.85  | 0.15  | 0.10  |
|           | SO <sub>2</sub>                                          | 0.83  | 0.17  | 0.12  |
|           | PM <sub>2.5</sub>                                        | 0.81  | 0.19  | 0.14  |
|           | PM <sub>10</sub>                                         | 0.89  | 0.11  | 0.08  |
|           | Per capita urban waste production                        | 0.82  | 0.18  | 0.13  |
|           | Per capita domestic water consumption                    | 0.72  | 0.28  | 0.20  |
| State     | Green space per capita                                   | 0.81  | 0.19  | 0.25  |
|           | Days with AQI > 100                                      | 0.87  | 0.13  | 0.16  |
|           | Trip Attraction rate                                     | 0.84  | 0.16  | 0.21  |
|           | Road links with traffic volumes exceeding capacity       | 0.91  | 0.09  | 0.12  |
|           | Proportion of delay in total travel time                 | 0.92  | 0.08  | 0.11  |
|           | Water distribution losses                                | 0.88  | 0.12  | 0.15  |
| Response  | Metro stations                                           | 0.79  | 0.21  | 0.25  |
|           | Households with access to wastewater collection services | 0.76  | 0.24  | 0.28  |
|           | Treated wastewater                                       | 0.89  | 0.11  | 0.13  |
|           | Green space coverage ratio                               | 0.71  | 0.29  | 0.34  |

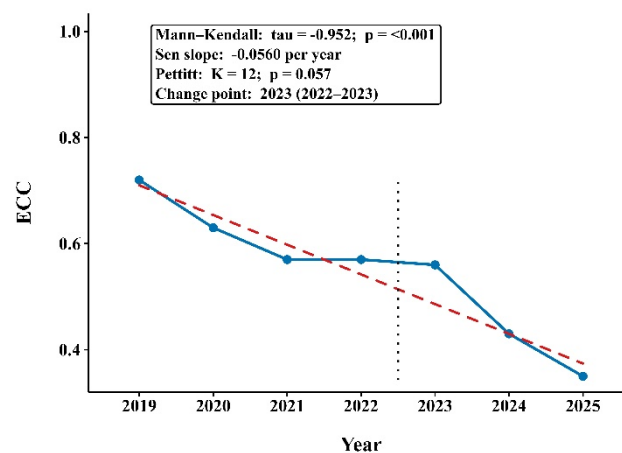
indicators of this component, are normalized using an inverse relationship, the decrease in the value of  $P_i$  should not be interpreted as a decrease in pressure. Therefore, the downward trend of  $P_i$  indicates that the conditions are becoming more unfavorable and the pressure on the environment is increasing (see 1-  $P_i$  column).

**Table 4.** Temporal variations in the normalized pressure, state, and response scores from 2019 to 2025

| Year | $P_i$ | $1 - P_i$ | $S_i$ | $1 - S_i$ | $R_i$ |
|------|-------|-----------|-------|-----------|-------|
| 2019 | 0.91  | 0.09      | 0.75  | 0.25      | 0     |
| 2020 | 0.77  | 0.23      | 0.69  | 0.31      | 0.05  |
| 2021 | 0.66  | 0.34      | 0.61  | 0.39      | 0.17  |
| 2022 | 0.46  | 0.54      | 0.72  | 0.28      | 0.61  |
| 2023 | 0.46  | 0.54      | 0.67  | 0.33      | 0.71  |
| 2024 | 0.33  | 0.67      | 0.44  | 0.56      | 0.77  |
| 2025 | 0.20  | 0.80      | 0.25  | 0.75      | 1     |

**Table 5.** AHP-derived weights and relative contributions of the pressure, state, and response components

| Component | AHP weight | Proportion (%) |
|-----------|------------|----------------|
| Pressure  | 0.54       | 53.96          |
| State     | 0.30       | 29.70          |
| Response  | 0.16       | 16.34          |

**Fig. 3.** Temporal trends and change point detection in ECC from 2019 to 2025

### AHP weights and trend analysis of the ECC index

The results of the Analytic Hierarchy Process (AHP) presented in Table 5 indicate that the pressure component was identified as the most significant component of the PSR framework, with a weight of 0.5396 (53.96%). The value of  $\lambda_{\max}$  was 3.0092, resulting in a CI of 0.0046 and a CR of 0.0079 (0.79%). Since the CR value was below the standard threshold of 0.10, the collective judgments were deemed highly consistent, and the derived weights were consequently retained for subsequent analysis.

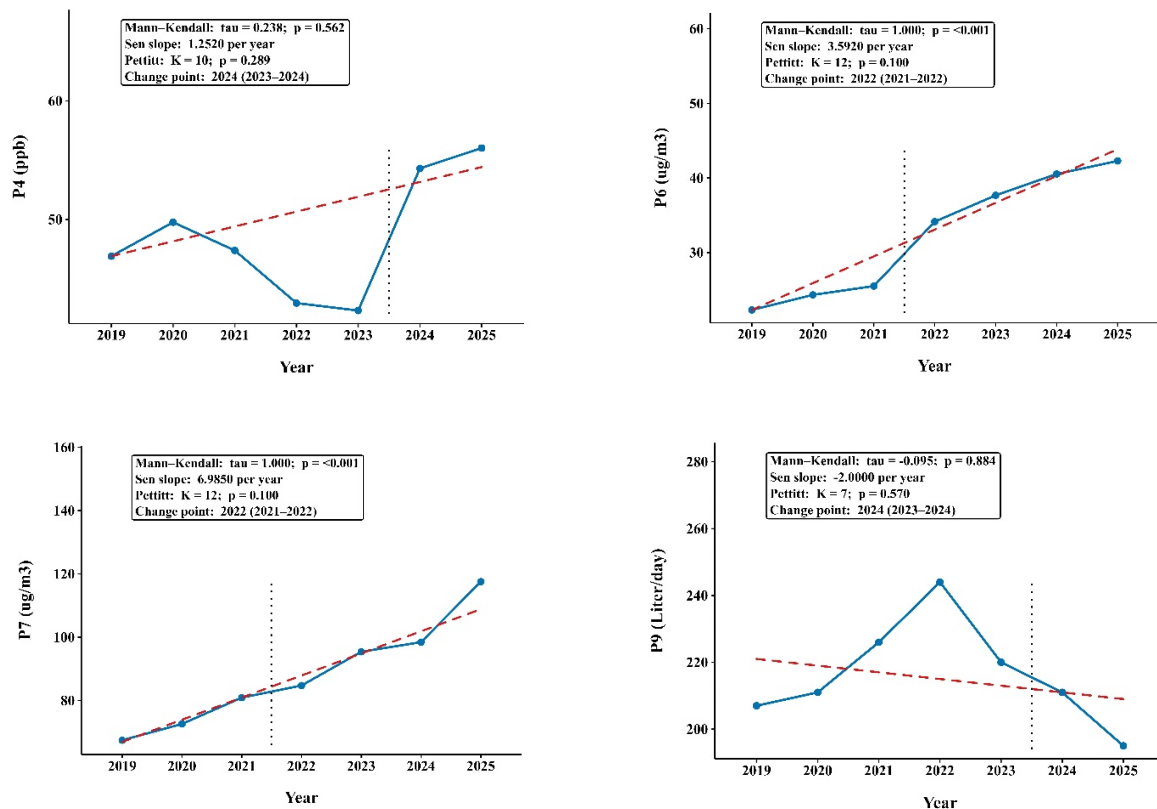
As shown in Fig. 3, Kendall's tau ( $\tau = -0.952$ ) indicates a downward trend, while the magnitude close to 1 signifies that nearly all data decrease consistently over time. The result was highly statistically significant ( $p < 0.001$ ); accordingly, the null hypothesis of no trend is rejected. The estimated Sen's slope was  $-0.056$ , indicating that the ECC index decreased by approximately 0.056 units per time step. In addition, the Pettitt test identifies 2023 as the most likely change point.

### Correlation Analysis

As shown in Table 6, Spearman's rank correlation showed a significant negative correlation between the eight selected indicators and the ECC index. Population density,  $PM_{2.5}$ ,  $PM_{10}$ ,  $CO_2$  per capita urban waste production, and days with AQI above 100 showed a very strong

**Table 6.** Results of Spearman's rank correlation analysis from 2019 to 2025

| Indicator                         | $r_s$ -Value | p -Value | Meaning                   |
|-----------------------------------|--------------|----------|---------------------------|
| Population density                | -0.99        | <0.001   | A very strong correlation |
| CO                                | -0.92        | 0.0038   | A very strong correlation |
| O <sub>3</sub>                    | -0.81        | 0.0269   | A strong correlation      |
| SO <sub>2</sub>                   | -0.85        | 0.0162   | A strong correlation      |
| PM <sub>2.5</sub>                 | -0.99        | <0.001   | A very strong correlation |
| PM <sub>10</sub>                  | -0.99        | <0.001   | A very strong correlation |
| Per capita urban waste production | -0.99        | <0.001   | A very strong correlation |
| Days with AQI > 100               | -0.99        | <0.001   | A very strong correlation |

**Fig. 4.** Temporal trends and change point detection in pressure indicators from 2019 to 2025

correlation with ECC. Additionally, O<sub>3</sub> and SO<sub>2</sub> showed a strong negative relationship, with  $r_s$  values of -0.81 and -0.85, respectively.

The findings of the current study demonstrate that an increase in the response component score does not necessarily indicate the effectiveness of policy actions. Furthermore, in this district, although management measures increased, the steady intensity of pressures from human activities continues to hinder a proportional improvement in the ECC index. The comparison of the original values of pressure indicators against an international benchmark emphasizes the significance of these trends. In 2025, the annual mean concentrations of PM<sub>2.5</sub> (P<sub>6</sub>) and PM<sub>10</sub> (P<sub>7</sub>) of this district were 42.8 and 117.53  $\mu\text{g}/\text{m}^3$ , respectively (Fig. 4). These values substantially exceeded the 2021 WHO global air quality guidelines values (World Health Organization, 2021) of 5  $\mu\text{g}/\text{m}^3$  for PM<sub>2.5</sub> and 15  $\mu\text{g}/\text{m}^3$  for PM<sub>10</sub>, indicating approximately 8.6 and 7.8 times higher, respectively, and the annual mean NO<sub>2</sub> (P<sub>4</sub>) concentration was 56.02 ppb, approximately 10.5 times the WHO annual guideline of 10  $\mu\text{g}/\text{m}^3$  (World Health Organization, 2021). Additionally, per capita domestic water consumption (P<sub>9</sub>) decreased from 244 litres per

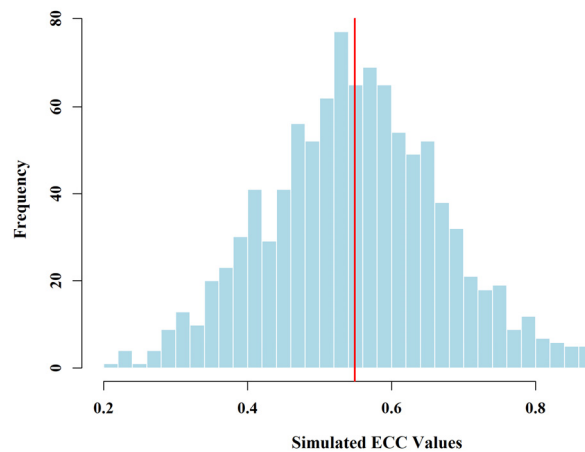


**Fig. 5.** Monte Carlo simulation of the ECC index

capita per day in 2022 to 195 litres per capita per day in 2025, a 20.1% reduction from its 2022 value. Nevertheless, the 2025 value in this district is approximately twice the upper limit of the 50-100 litres per capita per day range considered adequate for basic domestic needs (Howard et al., 2003; Howard et al., 2020).

The observed pattern in this study is consistent with the results of Hu et al. (2021). They also, using the PSR framework, confirmed that improvements in policy responses should be interpreted in relation to their ability to control pressures and improve the state of the environment. In other words, the number of projects or allocated budgets alone is not a sufficient criterion for assessing the policy actions and response. Moreover, the results of this study showed that per capita domestic water consumption is one of the most significant pressure indicators influencing environmental carrying capacity in District 6 of Tehran City. The findings of this study are consistent with studies conducted in Iran and Tehran City. Dehghan Manshadi et al. (2024), using a system dynamics model, showed that if the current trend in water resource consumption continues in Tehran City as an arid and semi-arid region, water sustainability index will decline sharply after 2026, and the urban carrying capacity to meet its water needs will be severely constrained. Dehghan Manshadi and Faryadi (2025), Parivar et al. (2023) and Parivar et al. (2021) demonstrated that in arid and semi-arid regions such as Yazd City with fragile ecosystem, water resources act as slow variables. These variable changes are gradual yet play a decisive role in maintaining the system's capacity and function. A significant feature of slow variables is that their shifts are often not apparent until they reach a critical threshold. Regarding the location of District 6 of Tehran City in an arid and semi-arid climate, limited renewable water resources, increasing demand driven by population growth and urban development, the gradual decline in surface and groundwater resources, and high per capita water consumption, water consumption management should be a main priority in urban policymaking (Tayebi et al., 2022; Barati et al., 2023; Zargari et al., 2025; Azimpour et al., 2026). In this regard, the implementation of demand management policies, the reform of the tariff system, the development of consumption-reducing equipment, the reuse of greywater, the minimization of water distribution losses, and the enhancement of public awareness regarding appropriate water consumption patterns can more effectively mitigate environmental pressures and enhance carrying capacity (Al Khoury et al., 2023; Bąk & Żaba, 2024).

On the other hand, the results of this study showed that air quality is also one of the most important factors affecting the reduction of environmental carrying capacity in District 6 of Tehran City. Air pollution has been one of the most serious environmental issues in Tehran City

for years, with widespread consequences for citizens' health, quality of life, and environmental sustainability (Naddafi et al., 2012; Bayat et al., 2019; Khoshakhlagh et al., 2023). Therefore, the results of this study are also consistent with findings from previous studies, such as Kazhal et al. (2020), Mousavi Fard et al. (2021), and Anbari et al. (2025), that have identified air pollution, especially PM<sub>2.5</sub> and PM<sub>10</sub>, as an important environmental challenge in Tehran City. This situation not only threatens public health but also signals a decline in the ECC's ability to absorb pollutants.

#### *Monte Carlo uncertainty analysis of the ECC values*

As shown in Fig. 5, the histogram of the ECC index shows an approximately normal, unimodal distribution, with simulated values clustering around the estimated mean. The lack of pronounced skewness indicates that the uncertainty in the ECC values is relatively balanced around the central value, rather than being influenced by extremely low or high results.

## CONCLUSIONS

This study aimed to assess trends in environmental carrying capacity using the pressure-state-response framework and a combination of entropy and the analytic hierarchy process. The results showed that environmental pressures increased from 2019 to 2025, and although the response component increased, the environmental carrying capacity index decreased from 0.72 to 0.35. This finding indicates that the measures taken, although significant, were still insufficient in intensity, timing, or scope to improve the environmental state. In other words, the response policies have moved more towards managing the consequences, while controlling the factors causing the pressure requires more attention. The 53.96% weight of the pressure component also confirms the importance of this issue. In a situation where pressures are rising, increasing response measures alone cannot ensure environmental sustainability. Therefore, the priority of policymaking should shift from purely compensatory responses to preventive measures that reduce pressures at the source and manage driving factors. The trend of the state component also showed that the environmental response to pressures is not necessarily immediate and linear. The system's resilience could influence the temporary improvement in the condition in 2022, positive changes in the condition index, management actions, or time lags in the emergence of consequences. However, the sharp decline in the index in 2024 and 2025 indicates that this temporary improvement has not become a sustainable trend. Overall, the research findings indicate that continuing the current trend could further limit the system's capacity to absorb new pressures. Therefore, the development of environmental management plans should focus on reducing the main pressures, strengthening the effectiveness of responses, continuously monitoring the condition indicators, and periodically assessing the ECC. According to the research results, controlling the main environmental pressures should be prioritized in management plans. Since the pressure component has the largest share in the calculation of ECC, it is necessary to identify pressure indicators with higher weights, especially per capita domestic water consumption, and design targeted interventions to reduce them. Several studies, such as Al Khoury et al. (2023) and Bąk and Żaba (2024), have shown that policy actions, including the installation of smart water meters, the implementation of increasing-block water tariffs, the promotion of water-efficient fixtures and appliances through financial incentives and building regulations, and public awareness, can help to control water consumption.

## LIMITATIONS

This study has several limitations. First, the ECC evaluation was conducted at the district scale because consistent, reliable neighborhood-scale data were not available for indicators over

time. Second, because data from other air quality monitoring stations were inconsistent during the study years, only one station, Tarbiat Modares, was selected. Therefore, it is suggested that future studies use data from multiple air quality monitoring stations. Moreover, future studies should consider smaller spatial scales, such as the neighborhood scale, to examine both spatial and temporal dynamics. Furthermore, in urban systems, ecological, social, and economic subsystems interact continuously and affect the ECC. Accordingly, especially in Iran, which faces economic damage from the war and economic sanctions, future studies should also examine economic pressures with the inflation rate, the consumer price index, GDP, and other relevant indicators to propose a comprehensive evaluation of ECC.

## ETHICAL APPROVAL

This article does not contain any studies with human or animal subjects performed by any of the authors.

## COMPETING INTEREST

The authors declare that they have no competing interest.

## AUTHOR CONTRIBUTIONS

Zahra Dehghan Manshadi conceived and designed the study, conducted the research, performed data analysis, and wrote the original draft of the manuscript, and was supervised by Shahrzad Faryadi, Ahmad Nohegar, and Nadia Abbaszadeh Tehrani. All Authors participated in the writing of the manuscript text and read and approved the final manuscript.

## FUNDING

This article is derived from the doctoral dissertation of the first author and was completed with the financial and institutional support of the Tehran Urban Research and Planning Center (TURPC).

## REFERENCES

- Aghaei, L., Varesi, H., & Zanganeh, S. (2019). Evaluating the Area-based Management Plan Based on the Criteria of Electronic Municipality: A Case Study of Districts 6 and 15 of Tehran Municipality. *WSEAS Transactions on Environment and Development*, 15, 153-163.
- Al Khoury, I., Ghanimeh, S., Jawad, D., & Atieh, M. (2023). Synergetic Water Demand and Sustainable Supply Strategies in GCC Countries: Data-driven Recommendations. *Water Resources Management*, 37(5), 1947-1963. 10.1007/s11269-023-03464-6
- Anbari, K., Sicard, P., Jamshidi, B., Naqvi, H. R., Rashidi, R., Sheikhrabat, M. V., & Khaniabadi, Y. O. (2025). Trends in PM10 and PM2.5 air pollution and related health risk in Tehran over the last two decades. *Urban Climate*, 61, 102450. 10.1016/j.uclim.2025.102450
- Azimpour, M., Faryadi, S., & Dehghan Manshadi, Z. (2026). The amount of urban impervious surface using remote sensing technologies and geographic information system: case study: District 6 of Tehran. *Environmant of Human Made Studies*, 2(2), 31-40. 10.30487/hmes.2025.2045355.1066
- Bak, J., & Žaba, T. (2024). Towards Reducing the Consumption of Drinking Water in Buildings as Part of the Circular Economy Model: Strengths–Weaknesses–Opportunities–Threats Analysis and Perspectives for Implementation. *Energies*, 17(6), 1444.
- Barati, A. A., Pour, M. D., & Sardooei, M. A. (2023). Water crisis in Iran: A system dynamics approach on water, energy, food, land and climate (WEFLC) nexus. *Science of The Total Environment*, 882, 163549. 10.1016/j.scitotenv.2023.163549

- Bayat, R., Ashrafi, K., Shafiepour Motlagh, M., Hassanvand, M. S., Daroudi, R., Fink, G., & Künzli, N. (2019). Health impact and related cost of ambient air pollution in Tehran. *Environmental research*, 176, 108547. 10.1016/j.envres.2019.108547
- Cheng, W., Xi, H., Sindikubwabo, C., Si, J., Zhao, C., Yu, T., . . . Wu, T. (2020). Ecosystem health assessment of desert nature reserve with entropy weight and fuzzy mathematics methods: a case study of Badain Jaran Desert. *Ecological Indicators*, 119, 106843. <https://doi.org/10.1016/j.ecolind.2020.106843>
- Cui, Y., Feng, P., Jin, J., & Liu, L. (2018). Water Resources Carrying Capacity Evaluation and Diagnosis Based on Set Pair Analysis and Improved the Entropy Weight Method. *Entropy (Basel)*, 20(5). 10.3390/e20050359
- Dehghan Manshadi, Z., & Faryadi, S. (2025). Storytelling in the planning process for sustainable development in local communities: a case study of Manshad village, Yazd, Iran. *Local Environment*, 1-25. 10.1080/13549839.2025.2575943
- Dehghan Manshadi, Z., Parivar, P., Sotoudeh, A., & Morovati Sharifabadi, A. (2023). Exploring the spatio-temporal dynamics of life support system capacity of urban regions based on ecosystem health assessment (the case of Tehran, Iran). *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-023-03148-6>
- Dehghan Manshadi, Z., Parivar, P., Sotoudeh, A., & Morovati Sharifabadi, A. (2024). Modeling urban growth effects on carrying capacity in arid and semi-arid regions using system dynamics. *Ecological Modelling*, 487, 110565. <https://doi.org/10.1016/j.ecolmodel.2023.110565>
- Fang, W., An, H., Li, H., Gao, X., Sun, X., & Zhong, W. (2017). Accessing on the sustainability of urban ecological-economic systems by means of a coupled emergy and system dynamics model: A case study of Beijing. *Energy Policy*, 100, 326-337. <https://doi.org/10.1016/j.enpol.2016.09.044>
- Grausová, M., & Hužvář, M. (2025). Entropy-weighted assurance region DEA: an application to healthcare system efficiency assessment. *Central European Journal of Operations Research*. 10.1007/s10100-025-01011-9
- Howard, G., Bartram, J., Water, S., & Organization, W. H. (2003). Domestic water quantity, service level and health.
- Howard, G., Bartram, J., Williams, A., Overbo, A., Geere, J.-A., & Organization, W. H. (2020). *Domestic water quantity, service level and health*. World Health Organization.
- Hu, X., Ma, C., Huang, P., & Guo, X. (2021). Ecological vulnerability assessment based on AHP-PSR method and analysis of its single parameter sensitivity and spatial autocorrelation for ecological protection – A case of Weifang City, China. *Ecological Indicators*, 125, 107464. 10.1016/j.ecolind.2021.107464
- Huang, H. F., Kuo, J., & Lo, S. L. (2011). Review of PSR framework and development of a DPSIR model to assess greenhouse effect in Taiwan. *Environ Monit Assess*, 177(1-4), 623-635. 10.1007/s10661-010-1661-7
- Kazhal, M., Farzad, F., Somayeh, Y., Mohammad, R., Hossein, A., Abbas, S., & Mostafa, H. (2020). Spatial modelling of PM2.5 concentrations in Tehran using Kriging and inverse distance weighting (IDW) methods. *Journal of Air Pollution and Health*, 5(2). 10.18502/japh.v5i2.4237
- Kendall, M. G., & Gibbons, J. D. (1962). Rank correlation methods.
- Khalili, M., & Nasrabadi, T. (2023). Assessment of occupational health risk due to inhalation of chemical compounds in an aircraft maintenance, repair, and overhaul company. *Environmental Science and Pollution Research*, 30(20), 57558-57570. 10.1007/s11356-023-26572-7
- Khoshakhlagh, A. H., Mohammadzadeh, M., & Morais, S. (2023). Air quality in Tehran, Iran: Spatio-temporal characteristics, human health effects, economic costs and recommendations for good practice. *Atmospheric Environment: X*, 19, 100222. <https://doi.org/10.1016/j.aeaoa.2023.100222>
- Kim, Y.-S., Kim, M. K., Fu, N., Liu, J., Wang, J., & Srebric, J. (2025). Investigating the impact of data normalization methods on predicting electricity consumption in a building using different artificial neural network models. *Sustainable Cities and Society*, 118, 105570. <https://doi.org/10.1016/j.scs.2024.105570>
- Li, X., Qin, X., Lu, Z., Gao, S., & Wang, G. (2022). Comparative analysis of ecological carrying capacity at different scales in Xilingol League, Inner Mongolia. *Ecological Indicators*, 141, 109127. <https://doi.org/10.1016/j.ecolind.2022.109127>
- Liao, X., Ren, Y., Shen, L., Shu, T., He, H., & Wang, J. (2020). A “carrier-load” perspective method for investigating regional water resource carrying capacity. *Journal of Cleaner Production*, 269, 122043. 10.1016/j.jclepro.2020.122043
- Liu, Y., Zhang, J., Wang, S., Wang, Y., & Zhao, A. (2018). Assessment of environmental carrying capacity using principal component analysis. *Journal of Geoscience and Environment Protection*, 6(3), 54-65.
- Lu, X., Lu, J., Yang, X., & Chen, X. (2022). Assessment of Urban Mobility via a Pressure-State-Response (PSR) Model with the IVIF-AHP and FCE Methods: A Case Study of Beijing, China. *Sustainability*, 14(5), 3112. <https://www.mdpi.com/2071-1050/14/5/3112>
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica: Journal of the econometric society*, 245-

- 259.
- Mousavi Fard, Z. S., Asilian Mahabadi, H., & Khajehnasiri, F. (2021). Investigation of suspended particle concentrations (PM<sub>10</sub>, PM<sub>2.5</sub>, TSP) in Tehran subway line one stations in the spring and autumn. *Pollution*, 7(3), 669-680.
- Mu, L., Fang, L., Dou, W., Wang, C., Qu, X., & Yu, Y. (2021). Urbanization-induced spatio-temporal variation of water resources utilization in northwestern China: A spatial panel model based approach. *Ecological Indicators*, 125, 107457. <https://doi.org/10.1016/j.ecolind.2021.107457>
- Muller, K., & Wickham, H. (2019). tibble: Simple data frames. R package version 2.1. 3. In.
- Naddafi, K., Hassanvand, M. S., Yunesian, M., Momeniha, F., Nabizadeh, R., Faridi, S., & Gholampour, A. (2012). Health impact assessment of air pollution in megacity of Tehran, Iran. *Iranian J Environ Health Sci Eng*, 9(1), 28. 10.1186/1735-2746-9-28
- Nazmfar, H., Afshon, Y., & Mahabadi pour, M. M. (2025). Evaluation and Ranking of Neighborhoods in Tehran's District 6 Based on the Development of Smart City Indicators and Factors Influencing Their Enhancement. *Journal of Sustainable Urban & Regional Development Studies (JSURDS)*, -.
- Parivar, P., Quanrud, D., Sotoudeh, A., & Abolhasani, M. (2021). Evaluation of urban ecological sustainability in arid lands (case study: Yazd-Iran). *Environment, Development and Sustainability*, 23, 2797-2826.
- Parivar, P., Saadatmand, M., Dehghan Manshadi, Z., Morovati Sharifabadi, A., & Malekinezhad, H. (2023). Evaluation of the effect of unsustainable urban development on water bankruptcy in arid regions using the system dynamics method: case of Yazd, Iran. *Sustain. Water Resour. Manag.*, 9(5), 166. <https://doi.org/10.1007/s40899-023-00937-9>
- Pedersen, T. L. (2021). patchwork: The composer of plots (2020). R package version, 1(1).
- Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 28(2), 126-135.
- Ren, W., Xue, B., Xie, X., Zhao, B., Li, J., & Han, B. (2023). Urban Comprehensive Carrying Capacity and Urbanization in Northeast China. *Sustainability*, 15(18), 13649. <https://www.mdpi.com/2071-1050/15/18/13649>
- Sadeghitabar, E., Ghasempour, R., Vaziri Rad, M. A., & Toopshekan, A. (2025). Optimization and Shannon entropy multi-criteria decision-making method for implementing modern renewable energies in stand-alone greenhouses. *Energy Conversion and Management: X*, 27, 101139. 10.1016/j.ecmx.2025.101139
- Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379-1389.
- Shannon, C. E. (1948). A mathematical theory of communication. *The Bell system technical journal*, 27(3), 379-423.
- Shen, L., Shu, T., Liao, X., Yang, N., Ren, Y., Zhu, M., . . . Wang, J. (2020). A new method to evaluate urban resources environment carrying capacity from the load-and-carrier perspective. *Resour. Conserv. Recycl.*, 154, 104616. 10.1016/j.resconrec.2019.104616
- Spearman, C. (1904). The Proof and Measurement of Association between Two Things. *The American Journal of Psychology*, 15(1), 72-101. 10.2307/1412159
- Sun, B., Tang, J., Yu, D., Song, Z., & Wang, P. (2019). Ecosystem health assessment: A PSR analysis combining AHP and FCE methods for Jiaozhou Bay, China. *Ocean & Coastal Management*, 168, 41-50. <https://doi.org/10.1016/j.ocecoaman.2018.10.026>
- Sun, F., Lai, X., Shen, J., Nie, L., & Gao, X. (2020). Initial allocation of flood drainage rights based on a PSR model and entropy-based matter-element theory in the Sunan Canal, China. *PLoS One*, 15(6), e0233570. 10.1371/journal.pone.0233570
- Tan, Y., Zhou, Y., Zhou, H., Gao, L., & Shi, L. (2025). Analysis of the coordinated development and influencing factors between urban population and environment: A case study of 35 metropolises in China. *Sustainable Cities and Society*, 121, 106160. <https://doi.org/10.1016/j.scs.2025.106160>
- Tayebi, S., Feizizadeh, B., Esfandi, S., Aliabbasi, B., Ali Alavi, S., & Shamsipour, A. (2022). A Neighborhood-Based Urban Water Carrying Capacity Assessment: Analysis of the Relationship between Spatial-Demographic Factors and Water Consumption Patterns in Tehran, Iran. *Land*, 11(12), 2203.
- Tehran Municipality. (2024). *Tehran Statistical YearBook*
- Wang, G., Xiao, C., Qi, Z., Meng, F., & Liang, X. (2021). Development tendency analysis for the water resource carrying capacity based on system dynamics model and the improved fuzzy comprehensive evaluation method in the Changchun city, China. *Ecological Indicators*, 122, 107232. <https://doi.org/10.1016/j.ecolind.2020.107232>
- Wickham, H. (2016). Elegant graphics for data analysis. In: Springer.
- Wickham, H., & Bryan, J. (2019). readxl: Read Excel Files. R package version 1.3. 1. In.
- Wickham, H., Bryan, J., Chang, W., McGowan, L., François, R., Grolemond, G., . . . Revelle, W. (2020). R: A

- language and environment for statistical computing. *J. Open Source Softw*, 8, 1-20.
- Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). dplyr: A grammar of data manipulation.
- Wickham, H., Vaughan, D., & Girlich, M. (2020). Tidy: Tidy messy data. *R package version*, 1(2), 397.
- World Health Organization. (2021). *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. World Health Organization.
- Xu, N., & Li, H. (2025). Towards management of sustainable tourism development in coastal destinations of the Bohai Rim: insights from a tourism carrying capacity analysis. *Discover Sustainability*, 6(1), 168. 10.1007/s43621-025-00951-1
- Ye, Y., Xiang, Y., Qiu, H., & Li, X. (2024). Revealing urban greenspace accessibility inequity using the carrying capacity-based 3SFCA method and location big data. *Sustainable Cities and Society*, 108, 105513. <https://doi.org/10.1016/j.scs.2024.105513>
- Zargari, M., Mofidi, A., Entezari, A., & Baaghideh, M. (2025). Climatology of Tehran surface heat Island: a satellite-based spatial analysis. *Sci Rep*, 15(1), 10567. 10.1038/s41598-025-95367-2
- Zhang, F., Wang, Y., Ma, X., Wang, Y., Yang, G., & Zhu, L. (2019). Evaluation of resources and environmental carrying capacity of 36 large cities in China based on a support-pressure coupling mechanism. *Science of The Total Environment*, 688, 838-854. 10.1016/j.scitotenv.2019.06.247
- Zhang, J., Guan, W., Wu, G., Wang, J., Rao, B., & Zhang, B. (2024). Study on water resources carrying capacity based on Pressure-State-Response modeling: An empirical study of the urban agglomeration in Central Yunnan, China. *PLoS One*, 19(9), e0308503. 10.1371/journal.pone.0308503