



An Analysis of the Impacts of the Carbon Footprint on the Sustainability of the Tehran Metropolis

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Article Info	ABSTRACT
Article type: Research Article	The metropolis of Tehran has developed based on modern urban planning. Over the past decade, it has experienced significant transformations, including a decline in the region's biocapacity, uncontrollable socio-economic impacts, and exorbitant costs associated with healthcare and medical treatment. This study aims to analyze the impacts of the carbon footprint on the sustainability of the Tehran metropolis. The research is applied in terms of objective and descriptive-analytical in terms of methodology. Data collection was conducted using library research and field methods (questionnaires). The statistical population of this study consists of the Tehran metropolis with a population of 8,693,706. To select the sample size, Cochran's formula was applied, determining a sample of 384 participants, which was completed using a simple random sampling method. Data processing was conducted using SPSS software, and the analysis of the questionnaire results was performed using Structural Equation Modeling (SEM) via SmartPLS software. The research findings indicated that the carbon index in the city of Tehran is in an unfavorable condition. The highest factor loading or standardized regression coefficient was recorded for the low-carbon planning index, while the lowest was for the low-carbon society index at 0.218. Furthermore, it was revealed that low-carbon planning has the greatest impact on carbon reduction in the Tehran metropolis. Following that, low-carbon urban development, low-carbon environment, low-carbon economy, low-carbon transportation, low-carbon construction, and low-carbon society indices had varying effects on carbon reduction in Tehran, respectively.
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Introduction

Rapid population growth, urban development, urban sprawl, increased consumption of natural resources, rising waste generation, and damage to climatic conditions have imposed limitations on the Earth's carrying capacity (Radaei et al., 2020: 194). On the other hand, the rapid growth of population and the consequent pressure on natural resources have confronted humanity with unprecedented environmental challenges (Naghibi et al., 2021: 1074). Living in urban environments has made many of us easily forget that nature operates in a closed loop, leading to a neglect of resource and capacity constraints (Sasanpour et al., 2011: 243). Over the past century, cities have attracted a large percentage of the global population. Although cities occupy only about 3% of the Earth's land surface, they account for more than half of the world's population and the highest share of resource consumption (Dhanju, 2008: 10). The crisis of urban spaces lacking quality of life, which suffer from environmental challenges such as air pollution, water scarcity, water pollution, climate change, the deep rift between humans and nature, and the alteration of indigenous and natural conditions, is a dilemma that has plagued human society for decades (Radaei et al., 2021: 2). Cities are considered the primary drivers of global instability (Sasanpour and Aghajani, 2015: 62). One of the most critical prerequisites for improving the quality of life, both now and in the future, is achieving sustainable development at the societal level. Sustainable development is a complex and ambiguous concept that has consistently been assessed using various methodologies. Today, the most effective method to determine the sustainability of societies is to evaluate the impacts of human activities on nature (Rahnama and Hosseini, 2021: 267). One quantitative approach that can reflect the environmental status of a region is the ecological footprint method, which is capable of determining the impacts of environmental loads by calculating the consumption rate of materials and resources (Zhiying and Cuiyan, 2011: 2387). All human activities leave an ecological footprint; therefore, the ecological footprint can be calculated for activities such as construction, transportation, food consumption, and energy consumption. The ecological footprint (EF) reflects the impacts that societies exert on nature through their lifestyles (Mansouri and Zarghami, 2021: 283). Meanwhile, the Tehran metropolis, as the country's capital, has been continuously growing and expanding, a trend that still persists. The ever-increasing population of Tehran, coupled with the rise in per capita private car ownership, the circulation of outdated vehicles in the urban transit fleet, low fuel quality, and, overall, the lack of an environmentally compatible consumption pattern in industrial, residential, and commercial-administrative sectors, has resulted in high fuel consumption in the Tehran metropolis. The residential, commercial, and public sectors constitute the largest consumers of fossil fuels, accounting for more than 70 percent of fossil fuel consumption in the city (Lotfi and Mohammadnejad, 2020: 136). Human health is directly threatened, and societies face the consequences of inappropriate energy resource utilization. Climate change and global warming are also among the critical issues directly impacting cities and communities. One of the proposed solutions to address these challenges is reducing the carbon footprint, which can facilitate and enhance the sustainability of metropolises. Accordingly, this study analyzes the impacts of the carbon footprint on the sustainability of the Tehran metropolis.

Reducing the carbon footprint and implementing sustainable measures in cities are of paramount importance and urgency, as outlined below:

Climate Change and Global Warming: One of the greatest challenges of the contemporary world is climate change. The rise in greenhouse gases leads to global warming and increasing temperatures. By reducing the carbon footprint, global warming can be mitigated, and climate change can be managed.

Air Quality Improvement: Cities face severe air pollution issues that adversely affect human health and the environment. Reducing the carbon footprint and utilizing clean and renewable energy resources lead to a reduction in air pollutants and the improvement of air quality.

Protection of Natural Resources: Sustainable use of natural resources such as water, soil, and forests ensures their conservation for future generations. Reducing the carbon footprint and optimizing energy use not only limit resource depletion but also contribute to their preservation.

Public Health Enhancement: Air pollution and pollutant emissions severely threaten human health. Minimizing the carbon footprint through clean energy adoption reduces air pollution, thereby positively impacting public health.

Sustainable Development: Carbon footprint reduction and the implementation of sustainable initiatives support the sustainable development of cities. Relying on renewable and green energy sources, creating green jobs, and fostering a sustainable economy are key drivers of urban growth and progress.

Competitiveness and Innovation: Reducing the carbon footprint and adopting sustainable approaches allow cities to achieve higher competitiveness. As major economic, social, and cultural hubs, cities can promote green innovations and secure more sustainable access to limited resources by choosing sustainable strategies.

Therefore, reducing the carbon footprint and implementing sustainable practices in cities are highly significant. These measures not only preserve the environment and mitigate the negative impacts of climate change but also enhance public health, conserve natural resources, promote sustainable development, and foster innovation. Ultimately, these actions are vital for improving the quality of life for future generations and creating sustainable, resilient communities capable of facing future challenges.

Given the aforementioned points, the objective of the present study is to analyze the impacts of the carbon footprint on the sustainability of the Tehran metropolis. Due to its strategic position as the capital of Iran, a population exceeding 10 million, acute water and energy resource scarcity, and severe environmental crises, the city of Tehran demands deeper attention from urban management—specifically the municipality—to control, guide, and supervise the preparation of urban plans and programs aligned with achieving sustainable urban development.

Broadly, this study attempts to analyze the impacts of carbon footprint reduction on the sustainability of the Tehran metropolis. To this end, a mixed-methods approach incorporating both quantitative and qualitative data analysis will be employed. Ultimately, this research helps provide a better understanding of the impacts of carbon footprint reduction on Tehran's sustainability. The findings of this study can serve as a guideline for

future policy-making and decision-making aimed at reducing the carbon footprint and improving the environmental and economic conditions of Tehran.

Theoretical Foundations and Literature Review

The concept of urban sustainability is closely linked to sustainable urban development. Maclaren distinguishes the two by defining sustainability as a desirable state or condition that persists over time, whereas “development” in sustainable urban development denotes the process through which sustainability is achieved. Some key characteristics of a sustainable city include intergenerational equity, intragenerational equity (encompassing social, geographical, and governance equity), conservation of the natural environment and living within its carrying capacity, minimal use of non-renewable resources, economic viability and diversity, community self-reliance, individual well-being, and fulfillment of basic social needs (Sasanpour, 2010: 96). In this regard, environmental and nature-oriented concerns have become a global benchmark, expanding progressively since the late 1960s with the emergence of environmentalism. The 1971 United Nations Conference on the Human Environment in Stockholm marked the beginning of governmental efforts to address this global demand (Razzaghian, 2022: 102). Due to their population density and concentration of socio-economic activities, cities are the primary hubs of resource consumption and waste/pollution generation; global cities consume approximately three-quarters of the natural resources required worldwide (Xing et al., 2009: 209).

Following the Industrial Revolution, cities expanded rapidly, bringing numerous consequences that have primarily impacted the environment and human quality of life. The escalation of these impacts prompted the United Nations to introduce the sustainable development approach, which was subsequently integrated into the agendas of governments and planners. A fundamental tenet of sustainable development is that human societies must live within nature’s biocapacity. Since then, various methods have been devised to measure societal sustainability, among which the ecological footprint is prominent. Today, this method is globally utilized as a key sustainability indicator. According to this approach, a region’s development is deemed “unsustainable” when its ecological footprint exceeds its local biocapacity. The ecological footprint method has been applied to evaluate the sustainability of major global cities such as London, Santiago, and Liverpool (Jomehpour et al., 2013: 191). The ecological footprint method was first introduced by Wackernagel and Rees in the early 1990s at Columbia University (Sasanpour et al., 2017: 19). This approach is based on the premise that the consumption of goods or energy requires a specific amount of land across one or more environmental sectors to sustain resource flows and absorb the resulting waste (Hataminejad et al., 2020: 187).

Richard Register’s perspective on the eco-city proposes urban construction that, like a living system, supports the physical health of the entire city through land-use patterns, enhances biodiversity, and diversifies urban roles by employing evolutionary and sustainability frameworks. Strategies implemented to manage this equilibrium include high-rise construction instead of outward urban sprawl, strong incentives to reduce private automobile usage, and the utilization of renewable energy and green tools to create a self-sufficient city.

An eco-city typically features a compact fabric, prioritizes pedestrians, and relies on mixed-use neighborhoods that emphasize land reuse and public transit. Notable examples of eco-cities include Sino-Singapore Tianjin Eco-city and Shenzhen in China (Razzaghian and Rahnama, 2020: 92).

Scientific consensus suggests that until the mid-20th century, environmental capacity exceeded the footprint of human activities on nature; whenever environmental damage occurred, various natural factors coordinated to repair it and maintain ecological balance. However, since 1961, the impact of human activities has outpaced the Earth's biocapacity. Currently, the global per capita consumption footprint is 2.7 hectares, while the global biocapacity is 1.8 hectares per capita. This indicates that humanity consumes approximately 50 percent more than its available ecological reserve. Under current consumption patterns, humans require 1.5 planets to regenerate their consumption, meaning the Earth needs approximately one year and six months to regenerate the resources consumed by humans in a single year. Consequently, the impacts of human activities on nature have recently gained significant attention from NGOs and global environmental organizations (Rahnama and Hosseini, 2021: 269).

In 2010, the National Development and Reform Commission (NDRC) announced the pilot implementation of low-carbon cities, initiating pilot programs in low-carbon provinces, regions, and cities (Yang et al., 2023: 2). Within economic mechanisms, cities produce goods, but these goods lack the capacity to regenerate the ecosystem using the imported raw resources. This dynamic drives unsustainability in many cities. There are three critical perspectives on this function: urban consumption patterns, urban production patterns, and the ecological footprint of cities. Cities consume three-quarters of the world's generated energy and account for roughly three-quarters of global pollution. They are also the primary sites for the production and consumption of most industrial goods. The impacts of this production and consumption are not confined to immediate surrounding areas. Due to urban expansion, cities increasingly draw resources from other regions. The resources consumed by cities can be measured through the ecological footprint, which spans globally and often extends far beyond the physical boundaries of the city itself (Rogers, 1997: 30).

- Deductive or composite perspective: This perspective was developed by the founders of the ecological footprint model, namely Rees and Wackernagel. It adopts a centralized, top-down approach and uses national data to calculate the ecological footprint. This method is mostly applied at the global and national levels, generally at a small scale. The resources under study are classified into five main groups: productive land (cropland, pasture, and forest), marine bioproductive areas (water bodies), land required for energy production, and built-up land (buildings, roads, and so on).
- Inductive or component-based perspective: This perspective follows a decentralized, bottom-up approach. In this view, ecological impacts are calculated for specific places by considering the ecological effects of particular activities, such as transportation, energy use, and others (Saraii and Zarei Farshad, 2011: 101).

Some of the studies conducted on the research topic are as follows: Lan et al. (2023), in an article, addressed the “significant impacts of urban form and function on low-carbon urban

development.” The results of the study indicated that adjusting the urban functional form holds important theoretical and practical significance for low-carbon urban development.

Zeng et al. (2013) examined an article titled “Can low-carbon city construction reduce carbon intensity? Empirical evidence from the low-carbon city pilot policy in China.” The research findings offer useful policy insights for constructing low-carbon cities under China’s “dual carbon goals” and contribute to achieving a win-win path of green development and carbon mitigation transition. Zhiying and Cuiyan (2016), in an empirical article on the ecological footprint of household consumption in China, sought to answer whether China should pursue an environmentally friendly consumption pattern given that it is a developing country with a per capita income ranking beyond 100th in the world. They concluded that the per capita ecological footprint is rising, while the per capita change in ecological carrying capacity remains constant.

Yijian Song (2011), in an article titled “Eco-city and Sustainable Urban Development,” argues that to achieve the goal of sustainable urban development, it is necessary to transform not only the concept of economic development but also that of social development. This study identifies the primary challenge of eco-city construction as the conceptualization of the city and its functional ecological zoning. Ghaemi Rad et al. (2022) evaluated the environmental status of urban tourism using the ecological footprint method (case study: Rasht city). Based on the results, considering the 13,600-hectare area of Rasht, the pressure exerted on the city’s environmental space is evident. Therefore, planning for environmental conservation alongside tourism development is deemed vital. Shiripour et al. (2022) assessed the role of the spatial structure of metropolises in the environmental resilience of the Tabriz metropolis using the fuzzy MABAC method. The research findings indicate that regarding the criteria determining spatial structure, the city of Tabriz has a monocentric structure dominated by the central district compared to other sectors.

Yargholi and Kanaani (2022) examined the optimization of agricultural water consumption in the Lake Urmia watershed through modifying the impact of agricultural operations on greenhouse gas emissions. The carbon footprint of tomato production also showed that it was equivalent to 0.04 in the treatment group and 0.06 (kg CO₂/kg) in the control group, indicating a reduction of approximately 33 percent. For sugar beet in West Azerbaijan Province, the amount of CO₂ emissions and carbon footprint in the treatment group showed reductions of 11.7 percent and 28.5 percent, respectively, compared with the control group. Mansouri and Zarghami (2021) evaluated the ecological footprint of fossil fuel consumption in the city of Ahvaz.

Based on the obtained results (2011 to 2014), the impacts and ecological footprint of fossil fuels in the years 2011, 2012, 2013, and 2014 for the city of Ahvaz were 6.71, 11.36, 7.17, and 8.83 global hectares per capita, respectively. Comparing these with the city’s per capita ecological carrying capacity during the mentioned years, which stood at 0.0173, 0.0164, 0.015, and 0.031 global hectares per capita, respectively, the significant discrepancy between these two values indicates that the city of Ahvaz does not possess a rational ecological footprint in terms of fossil fuel consumption. Lotfi and Mohammadnejad (2020) conducted an analysis of greenhouse gas emission assessment approaches in urban areas (case study:

Tehran metropolis). The results show that Tehran's per capita carbon dioxide emission is higher than that of major and highly populated metropolises such as Rio de Janeiro, Seoul, Bangkok, Buenos Aires, Hong Kong, and London. Taghizadeh Diva and Roshanas (2019) applied the ecological footprint method to evaluate environmental sustainability, using Gorgan county as a case study. The findings of this study show that the ecological footprint of Gorgan county in the consumption categories of food, waste, transportation, electricity, natural gas heating, water, and housing was 1.24 global hectares. The lowest ecological footprint was associated with the land required for waste disposal, while the highest was related to electricity.

Hajinejad et al. (2018) examined the carbon footprint in urban drinking water supply in the city of Sepidan. The results showed that supplying water from a spring located at a higher elevation than all parts of the city requires much less energy due to the specific topography of Sepidan, which is characterized by steep undulating terrain; consequently, it emits less pollution and carbon dioxide.

Kouzegar Kalaji et al. (2018) proposed an ecological footprint-based assessment of urban sustainability, with Tabriz as the case study. The results showed that the ecological footprint of Tabriz in the consumption categories of food, transportation, natural gas heating, water, electricity, and land required for waste disposal was 3.30 global hectares. Comparison of this footprint with its supporting areas, such as the county and province, indicates that Tabriz depends on an area beyond East Azerbaijan Province to meet its biological needs and ensure its sustainability.

Sasanpour et al. (2017) examined the sustainable development of Isfahan County using the ecological footprint method. According to the findings, the ecological footprint of an average individual in Isfahan County was calculated at 4.2 hectares per capita. In addition, the biocapacity was estimated at 0.427 hectares per capita.

Haghparast et al. (2017) assessed the environmental impacts of buildings using the ecological footprint system. The results indicate that indigenous and traditional methods should be applied with caution, taking into account the context in which a building is developed; otherwise, traditional approaches may not be particularly efficient. The findings also provide some support for increasing the density of residential settlements.

Sasanpour and Norouzi (2016) addressed the sustainability of urban areas using the eco-city approach, focusing on the 22 districts of Tehran metropolis. The results show that District 4, with a coefficient of 1, ranks first and is in a favorable condition, while District 11, with a coefficient of 0.278, is in an unfavorable state.

Shahinifar and Habibi (2016) applied the ecological footprint method to evaluate the sustainability of regional geography, using Kermanshah County as a case study. The results of this study confirm that Kermanshah County relies on an area beyond the county and Kermanshah Province to meet its biological needs and sustain itself. Given that Iran's biocapacity is 0.8 hectares per capita, the ecological footprint of 2.445 hectares per capita for Kermanshah County means that it consumes three times its share of the country's sustainable biological capacity.

Jomehpour et al. (2013) examined the status of sustainable development in Rasht County using the ecological footprint method. Analysis of the obtained results indicates that Rasht County is ecologically unsustainable. Finally, the ecological footprint index calculated for Rasht is compared with the value of this index at national (Iran), regional (Asia), and global levels.

Firoozi et al. (2013) assessed the ecological capacity of the Shahid Abbaspour Dam exemplary tourism zone, emphasizing sustainable tourism development. The findings of the ecological capacity evaluation of this area, using Geographic Information Systems (GIS) and established models, show that the Shahid Abbaspour Dam exemplary tourism zone comprises both intensive and extensive tourism areas. Furthermore, the results indicate that economic investment in intensive tourism is not cost-effective due to the region's steep slopes. Considering the high gradients, as well as the unfavorable soil and rock conditions, it is concluded that extensive recreation is the most suitable type of tourism land use for this region.

Shokoor et al. (2011) evaluated and measured the sustainability of tourism in Behesht-e Gomshodeh of Bovan Mamasani using the ecological footprint model. The findings indicate that tourism in the study area is sustainable.

Hosseinzadeh Delir and Sasanpour (2006) examined the ecological footprint method in relation to the sustainability of metropolises, with a focus on Tehran metropolis. According to the results, Tehran metropolis imports a flow of goods and resources from its supporting hinterland in order to sustain itself, while exporting a flow of waste and refuse from within the city. Consequently, under the current pattern of production and consumption, this ecological space has become unsustainable and is no longer capable of meeting the basic needs of its population.

Material and Methods

This study employed a descriptive-analytical research method. This approach was used to describe and analyze the existing conditions and to examine the relationships among the variables. Data were collected through two methods: documentary research (library-based sources) and survey research (questionnaire). Accordingly, library resources and relevant documents were used to gather the required information. In addition, a questionnaire was employed to obtain further data and to assess respondents' opinions and perspectives.

The statistical population of the study consisted of Tehran metropolis. Cochran's formula was used to determine an appropriate sample size, and ultimately 384 respondents were selected as the study sample. This sampling was conducted with the aim of evaluating and examining the indicators identified in the research. The questionnaire items were designed based on the indicators under investigation, including zero carbon, energy, buildings, transportation, air, environmental monitoring, and sustainability, the latter comprising carbon emissions, greenhouse gas emissions, and reductions in resource and energy consumption. The items were structured using a five-point Likert scale.

Finally, data processing was carried out using SPSS software, and the questionnaire data were analyzed through structural equation modeling (SEM) using Partial Least Squares (PLS) software.

Table 1. Research Indicators

No.	Component	Explanatory Indicators
1	Low-Carbon Environment	Degree of coexistence with nature; level of ecosystem protection; expansion of green space and tree planting; level of renewable energy consumption; level of consumption of polluting and warming resources; extent of environmental degradation resulting from physical development
2	Low-Carbon Transportation	Extent of the use of smart and modern transportation methods; degree of reliance on various transportation and mobility options; level of fossil fuel use in urban transportation; quality of urban traffic management and control; extent of implementation of and inclination toward public transportation use; tendency toward green transportation (walking and cycling)
3	Low-Carbon Society	Citizens' sense of belonging to the city in relation to improving quality, cleanliness, and environmental protection; extent to which lifestyles and preferences compatible and harmonious with nature are realized; level of social cohesion and participation in the use of non-polluting tools and forms of consumption in the city; degree of social participation in education and promotion of clean and organic lifestyles in the city
4	Low-Carbon Economy	Level of consumption of natural and non-renewable resources; extent of investment in renewable and clean energy; degree of investment in institutional and educational structures for the protection of the urban environment; extent of utilization of and investment in modern and organic technologies in urban services and consumption; level of investment in transportation systems and production sites (factories) based on renewable and clean methods
5	Low-Carbon Construction	Suitability of infrastructure; adequacy of building quality and age; compliance with building height and number of floors; extent of implementation and construction of green buildings; degree of selection of materials with lower carbon production indices (such as recycled materials)
6	Low-Carbon Urban Development	Extent to which compact urban development with limited physical and developmental sprawl is achieved; degree of use of mixed and multiple urban land uses in urban development; extent of balance between nature and the urban fabric in urban development design; degree of pedestrian-oriented environmental design in centers and crowded areas within the urban development planning process; extent of use of vacant and barren inner-city lands for infill development instead of expansion into natural and pristine areas
7	Low-Carbon Planning	Extent of efforts toward achieving integrated management in decision-making for the creation of livable cities; quality and realization of planning for establishing supervisory institutions aimed at clean and non-polluting urban production and consumption; planning for the realization of green and livable urban design; level of institutional-private sector participation in achieving a city with an environmental sustainability approach; extent of attention to and implementation of plans supporting innovative and renewable structural methods in the production and creation of urban physical and non-physical structures

Source: Compiled by the authors based on the theoretical foundations, 2023.

Introduction to the Study Area

Tehran is located between 34° and 36.5° north latitude and 50° and 53° east longitude. The area of this province is 12,981 square kilometers. It is bounded by Mazandaran Province to the north, Qom Province to the south, Markazi Province to the southwest, Alborz Province to the west, and Semnan Province to the east (Figure 1). According to the 2016 national

census, the population of this province was 13,267,637, of whom 12,452,230 lived in urban areas and 814,698 in rural areas. In terms of administrative divisions, Tehran Province consists of 23 counties, with Tehran as its capital (Tehran Municipality, 2021).

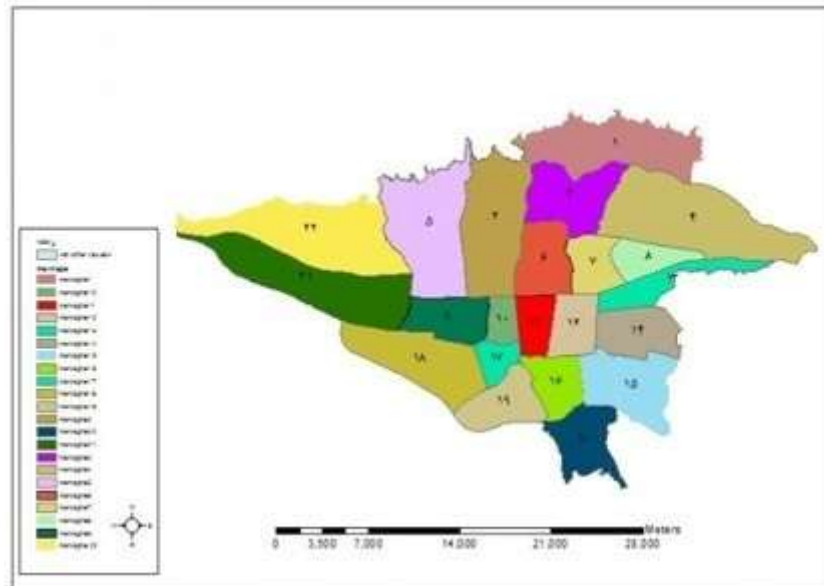


Figure 1. The Spatial Extent of Tehran City

Results and Discussion

Assessment of Carbon Status in Tehran

In this section, given that the indicators were measured on a five-point scale, a one-sample t-test was applied using the mean level, or “sustainable” condition, as the test value. The test was performed at the 95% confidence level.

Carbon Index Status: The results for the carbon index in the study sample are presented in Tables 2 and 3. The findings at the mean, or sustainable, level indicate that the carbon index in Tehran is in an unfavorable or unsustainable condition. In this regard, the calculated t-value for the carbon index was 26.43, with a significance level of $p < 0.01$. Therefore, it can be inferred that the status of the carbon index in Tehran is unfavorable and significantly higher than the normal average level.

Table 2. Descriptive Statistics of the One-Sample t-Test for the Status of the Carbon Index

No.	Dimension	Mean	Standard Deviation	Standard Error of the Mean
1	Carbon	3.76	0.49	0.03

Source: Research findings, 2023.

Table 3. . Assessment of the Carbon Index Status in the Study Area Based on the t-Test

Table 5.7: Assessment of the Carbon Index Status in the Study Area Based on the t-Test							
No	Dimension	Test Value = 3				Status	
		Mean Difference	t-value	Significance Level (p)	95% Confidence Interval		
					Lower Bound	Upper Bound	
1	Carbon	0.76	26.43	0.000	0.28	0.97	Unsustainable

Source: Research findings, 2023.

The discussion then proceeded to examine the status of carbon monoxide (CO) levels in Tehran in 2021. The results obtained for carbon monoxide concentrations, based on the air quality monitoring stations in Tehran, as presented in Table 4, indicate that the mean carbon monoxide level in 2021 was 2.08 micrograms per year. The highest level was recorded at 3.84 micrograms on 23 Azar, while the lowest level, 1.23 micrograms, was observed on 12 Ordibehesht.

Table 4. Mean Carbon Monoxide Status in Tehran

Mean	Standard Deviation	Minimum	Maximum
2.08	0.44	1.23	3.84

Source: Research findings, 2023.

Figure 2 also examines the status of carbon monoxide across the months of the year in Tehran. The results show that the highest concentrations were recorded in Azar and Dey, at 2.51 and 2.46 micrograms, respectively, while the lowest concentration was observed in Ordibehesht, at 1.52 micrograms. The higher concentration of this pollutant during the colder months, compared with other months, may be attributed to increased consumption of fossil fuels as well as the inefficient performance of vehicle engines under cold weather conditions. In addition, the occurrence of stable atmospheric conditions and temperature inversion phenomena during the cold seasons, especially at night, can be considered another reason for the increased concentration of carbon monoxide in these months.

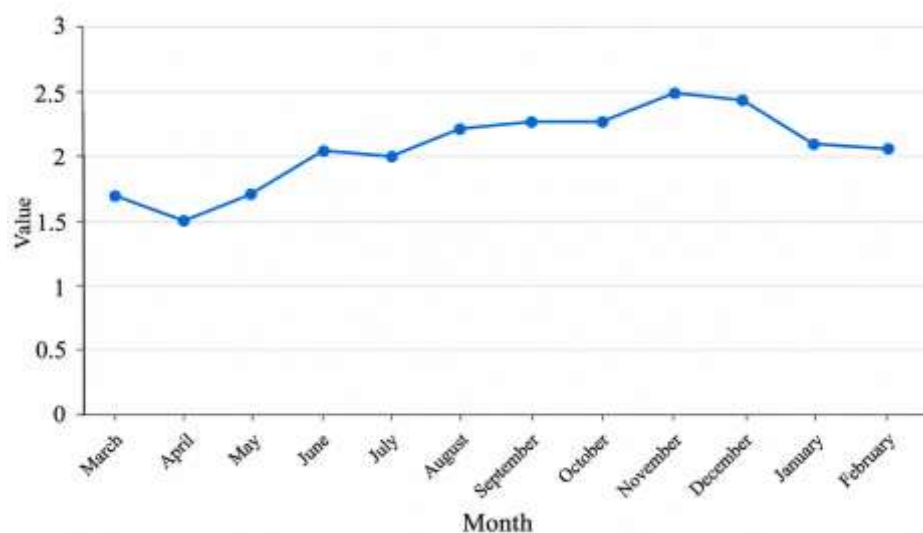


Figure 2. Carbon monoxide (CO) concentration levels in Tehran (2021, µg/m³)

Identifying the Low-Carbon Influencing Indicators in Tehran Using Structural Equation Modeling

In this section, structural equation modeling (SEM) using PLS software was employed to identify the indicators influencing the low-carbon status of Tehran. To assess the goodness of fit of the measurement models, the following criteria were used:

1. Reliability test (Cronbach's alpha and composite reliability coefficient)

2. Convergent validity (significance of factor loadings, internal consistency, average variance extracted [AVE], and comparison of CR with AVE)
3. Discriminant validity (Fornell and Larcker test, 1987).

The First Criterion of the Measurement Model: Factor Loadings Between the Items and Their Corresponding Latent Variables

According to Tables 5 and 6, the factor loadings obtained for all research components were significant at the 0.000 level and were therefore confirmed. The results for each indicator are presented separately; overall, the model demonstrated an acceptable level of fit.

Low-Carbon Environment Indicator: Table 4 examines the factor loadings between the items related to the low-carbon environment indicator. Based on the results presented in this table, the factor loadings for the items of the low-carbon environment indicator ranged from 0.668 to 0.818. These results indicate that the factor loadings of the items for this indicator are at an acceptable level.

Table 5. Factor loadings of the items associated with the latent construct of the low-carbon environment indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
1	0.682	14.67	0.00	Acceptable and significant
2	0.818	38.03	0.00	Acceptable and significant
3	0.797	30.35	0.00	Acceptable and significant
4	0.649	15.16	0.00	Acceptable and significant
5	0.668	17.65	0.00	Acceptable and significant
6	0.762	22.97	0.00	Acceptable and significant

Source: Research findings, 2023

Low-Carbon Transportation Indicator: Table 6 examines the factor loadings between the items related to the low-carbon transportation indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon transportation indicator ranged from 0.746 to 0.857. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 6. Factor loadings between the items and the latent variable related to the low-carbon transportation indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
7	0.811	36.84	0.00	Acceptable and significant
8	0.781	25.63	0.00	Acceptable and significant
9	0.834	38.40	0.00	Acceptable and significant
10	0.857	45.33	0.00	Acceptable and significant
11	0.851	41.10	0.00	Acceptable and significant
12	0.810	37.84	0.00	Acceptable and significant
13	0.746	20.83	0.00	Acceptable and significant
14	0.827	33.26	0.00	Acceptable and significant
15	0.841	38.34	0.00	Acceptable and significant

16	0.823	21.11	0.00	Acceptable and significant
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Source: Research findings, 2023

Low-Carbon Society Indicator: Table 7 examines the factor loadings between the items related to the low-carbon society indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon society indicator ranged from 0.614 to 0.840. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 7. Factor loadings between the items and the latent variable related to the low-carbon society indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
17	0.840	35.29	0.00	Acceptable and significant
18	0.705	9.86	0.00	Acceptable and significant
19	0.614	8.04	0.00	Acceptable and significant
20	0.617	7.69	0.00	Acceptable and significant
21	0.720	17.26	0.00	Acceptable and significant

Source: Research findings, 2023

Low-Carbon Economy Indicator: Table 8 examines the factor loadings between the items related to the low-carbon economy indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon economy indicator ranged from 0.676 to 0.765. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 8. Factor loadings between the items and the latent variable related to the low-carbon economy indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
22	0.716	16.09	0.00	Acceptable and significant
23	0.703	15.65	0.00	Acceptable and significant
24	0.724	19.49	0.00	Acceptable and significant
25	0.728	21.45	0.00	Acceptable and significant
26	0.676	16.52	0.00	Acceptable and significant
27	0.765	25.53	0.00	Acceptable and significant

Source: Research findings, 2023

Low-Carbon Construction Indicator: Table 9 examines the factor loadings between the items related to the low-carbon construction indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon construction indicator ranged from 0.796 to 0.869. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 9 . Factor loadings between the items and the latent variable related to the low-carbon construction indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
28	0.802	28.37	0.00	Acceptable and significant

29	0.801	32.85	0.00	Acceptable and significant
30	0.811	27.75	0.00	Acceptable and significant
31	0.869	46.85	0.00	Acceptable and significant
32	0.796	22.49	0.00	Acceptable and significant

Source: Research findings, 2023

Low-Carbon Urban Development Indicator: Table 10 examines the factor loadings between the items related to the low-carbon urban development indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon urban development indicator ranged from 0.674 to 0.824. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 10 . Factor loadings between the items and the latent variable related to the low-carbon urban development indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
33	0.726	17.18	0.00	Acceptable and significant
34	0.824	30.63	0.00	Acceptable and significant
35	0.674	13.14	0.00	Acceptable and significant
36	0.822	35.68	0.00	Acceptable and significant
37	0.683	11.95	0.00	

Source: Research findings, 2023

Low-Carbon Planning Indicator: Table 11 examines the factor loadings between the items related to the low-carbon planning indicator. Based on the results presented in this table, the factor loadings obtained for the items of the low-carbon planning indicator ranged from 0.732 to 0.845. These findings indicate that the factor loadings of the items associated with this indicator are at an acceptable level.

Table 11 . Factor loadings between the items and the latent variable related to the low-carbon planning indicator

Item No.	Factor Loading	t-Statistic	Significance Level	Result
38	0.756	23.40	0.00	Acceptable and significant
39	0.845	47.36	0.00	Acceptable and significant
40	0.808	28.46	0.00	Acceptable and significant
41	0.732	19.06	0.00	Acceptable and significant
42	0.826	29.50	0.00	Acceptable and significant
43	0.818	29.15	0.00	Acceptable and significant
44	0.786	25.29	0.00	Acceptable and significant
45	0.817	30.46	0.00	Acceptable and significant
46	0.832	31.97	0.00	Acceptable and significant
47	0.805	26.20	0.00	Acceptable and significant

Source: Research findings, 2023

Second and Third Criteria of the Measurement Model: Reliability (Cronbach's Alpha and Composite Reliability)

Cronbach's alpha is considered a traditional criterion for assessing internal consistency among the observed variables in a measurement model. Based on the results presented in Table 12, the reliability coefficient of the research variables was found to be at an acceptable level. In this regard, the highest Cronbach's alpha value was obtained for the low-carbon transportation variable, at 0.948, while the lowest Cronbach's alpha coefficient was related to the low-carbon construction indicator, at 0.834.

Table 12. Evaluation of the reliability of research variables in structural equations

Variables	Cronbach's Alpha	Variables	Cronbach's Alpha	Variables
Low-Carbon Environment	0.931	0.939	0.615	Acceptable
Low-Carbon Transportation	0.948	0.952	0.530	Acceptable
Low-Carbon Society	0.898	0.915	0.680	Acceptable
Low-Carbon Economy	0.854	0.915	0.689	Acceptable
Low-Carbon Construction	0.834	0.846	0.625	Acceptable
Low-Carbon Urban Development	0.867	0.803	0.689	Acceptable

Source: Research findings, 2023

Fourth Criterion of the Measurement Model: Convergent Validity (AVE)

Convergent validity exists when the scores obtained from two measures of the same construct are highly correlated. Table 13 examines convergent validity for the research indicators, and its values ranged from 0.530 to 0.689.

Table 13. Convergent validity of the research variables

Variables	AVE > 0.5	Result
Low-Carbon Environment	0.615	Acceptable
Low-Carbon Transportation	0.530	Acceptable
Low-Carbon Society	0.680	Acceptable
Low-Carbon Economy	0.689	Acceptable
Low-Carbon Construction	0.625	Acceptable
Low-Carbon Urban Development	0.689	Acceptable

Source: Research findings, 2023

Fifth Criterion of the Measurement Model: Divergent Validity (Fornell–Larcker Criterion)

Another important criterion assessed through Divergent validity is the extent of the relationship between a construct and its own indicators in comparison with the relationship of that construct with other constructs. The results of this method are presented in Table 14.

Table 14. Divergent validity results based on the Fornell–Larcker criterion

Research Variables	Environment	Transportation	Society	Economy	Construction	Urban Development	Planning
Low-Carbon Environment	0.73						

Low-Carbon Transportation	0.52	0.81					
Low-Carbon Society	0.31	0.55	0.76				
Low-Carbon Economy	0.56	0.59	0.39	0.74			
Low-Carbon Construction	0.32	0.31	0.32	0.31	0.80		
Low-Carbon Urban Development	0.28	0.40	0.36	0.37	0.41	0.80	
Low-Carbon Planning	0.34	0.44	0.43	0.45	0.34	0.51	0.75

Source: Research findings, 2023

Based on the results obtained in Figure 3, it can be inferred that the low-carbon planning indicator, with a beta coefficient of 0.558, low-carbon urban development with a beta coefficient of 0.497, low-carbon environment with a beta coefficient of 0.485, low-carbon economy with a beta coefficient of 0.422, and low-carbon transportation with a beta coefficient of 0.398, have a strong effect on the low-carbon city context in Tehran. In this regard, low-carbon construction with a beta coefficient of 0.293 and the low-carbon society indicator with a beta coefficient of 0.218 have a weak effect in Tehran. In light of the foregoing, the highest factor loading or standardized regression coefficient was obtained for the low-carbon planning indicator, while the lowest value was observed for the low-carbon society indicator, at 0.218.

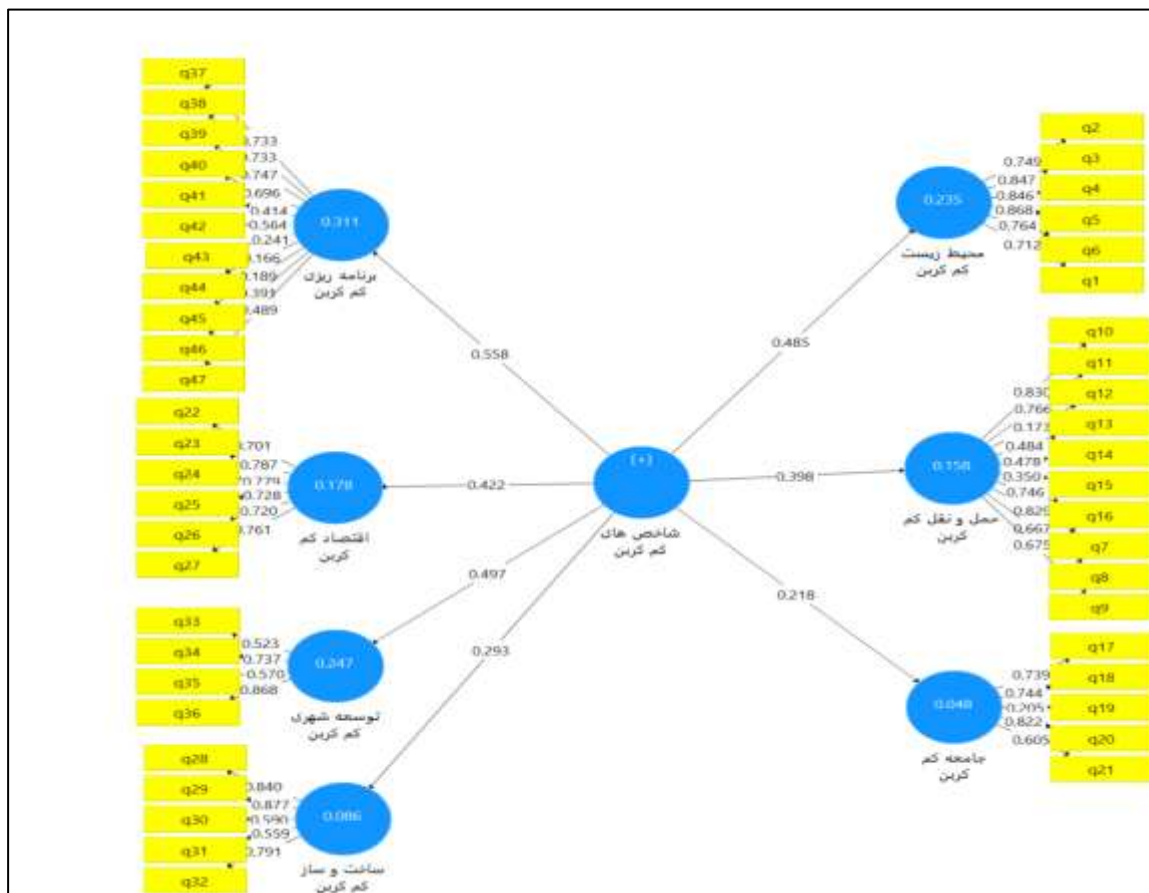


Figure 3. Research model with standardized factor loading coefficients and path coefficients (Evaluation of measurement models).

Conclusion

Today, humanity faces unprecedented environmental challenges. In this regard, there is a broad and shared understanding among environmental scholars that the Earth's ecosystem can no longer sustain current levels of economic activity and material consumption. Accordingly, scholars in environmental economics have sought to identify meaningful units of measurement and, by adopting a biophysical approach, to examine the principle of sustainability and align the internal needs of the economy with the environmental carrying capacity.

The present study examined the effects of the carbon footprint on the sustainability of Tehran metropolis. The findings showed that the carbon index in Tehran exceeds the sustainable threshold and is therefore in an unfavorable or unsustainable condition. In other words, the status of the carbon index in Tehran is undesirable and considerably higher than the normal average level. The highest factor loading, or standardized regression coefficient, was related to the low-carbon planning indicator, whereas the lowest value was observed for the low-carbon society indicator, at 0.218. The results also indicated that low-carbon planning had the greatest effect on carbon reduction in Tehran metropolis. This was followed, respectively, by the indicators of low-carbon urban development, low-carbon environment, low-carbon economy, low-carbon transportation, low-carbon construction, and low-carbon society, each of which exerted a different level of influence on carbon reduction in Tehran.

In this respect, the findings of the present study are consistent with those reported by Jing and Quyan (2016), Zhao et al. (2016), Fan et al. (2006), Ghaemi Rad et al. (1401), Deh Cheshmeh (1400), Hazar Khani (1398), Abolghasemi (1398), and Habibi (1395). Given these considerations, the expansion and development of green spaces in human settlements play a substantial role in the process of photosynthesis, the mitigation of carbon monoxide in the atmosphere, and the promotion of sustainability, particularly in Tehran metropolis. Therefore, planning and urban development are among the most important factors affecting the carbon footprint and the sustainability of Tehran metropolis.

Conducting research on carbon footprint reduction and the implementation of sustainable measures in cities can lead to substantial knowledge enhancement and numerous innovations. Some of the most important contributions are outlined below:

Emerging technologies

Research in this field can contribute to the development and optimization of innovative technologies related to carbon footprint reduction and clean energy. For example, studies on renewable energy sources such as solar, wind, and hydrogen energy, as well as energy storage systems, can promote advanced technologies and improve methods of energy production and use.

Data analysis

Collecting and analyzing data related to energy consumption, air pollution, transportation, and urban patterns can facilitate a better understanding of urban environmental conditions and support the formulation of sustainable policies and strategies. The use of advanced analytical approaches, such as artificial intelligence and machine learning, can also improve the efficiency of extracting meaningful information and useful patterns from data.

Smart city design

Research on smart cities, together with the use of communication technologies, sensors, and Internet of Things networks, can contribute to the design and implementation of intelligent systems for energy management, smart transportation, waste management, and the improvement of citizens' quality of life.

Policy and legal strategies

Research on reducing the carbon footprint and implementing sustainable measures can assist in formulating appropriate policy and legal strategies. Examining existing policies and regulations, assessing their impacts, and proposing improvements for their implementation can generate valuable outcomes.

Resource management

Research in this area can also improve the management of resources such as energy, water, soil, and other natural assets. Investigating optimal methods of resource use, reducing waste, and increasing recycling can contribute to resource conservation and environmental protection.

Education and public awareness

Research in this domain can help raise public awareness and improve environmental education regarding carbon footprint reduction. Developing effective communication and educational methods, providing accurate and understandable information to society, and encouraging behavioral change can all contribute to the achievement of sustainability goals.

Collaboration and networking

Research on carbon footprint reduction and sustainable implementation can foster international cooperation, networking, and the transfer of knowledge and experience among countries. Sharing expertise, exchanging information, and collaborating on joint projects can produce positive and far-reaching outcomes.

In summary, research on carbon footprint reduction and the implementation of sustainable measures can contribute to the development of innovative technologies, improved resource management, smart city design, advanced data analysis, the formulation of effective policies and strategies, increased public awareness, and international cooperation. Ultimately, such research seeks to enhance the resilience and sustainability of environmental systems and improve human quality of life.

Recommendations**1 .Prioritizing Low-Carbon Planning through Micro-Scale Geospatial Monitoring**

Given that low-carbon planning was found to exert the most substantial influence on the carbon index, it is recommended that urban planners identify high-risk, carbon-intensive zones. This can be achieved by integrating ground-level pollutant data from air quality monitoring stations with satellite imagery analysis. Implementing these spatial assessments will enable targeted micro-level interventions to systematically eliminate or reduce emissions at the neighborhood scale.

2 .Expanding Urban Green Infrastructure and Buffer Zones

Considering the vital role of green spaces in sequestering and mitigating atmospheric carbon dioxide, it is recommended to design, develop, and expand protective green belts and urban forestry networks across the Tehran metropolitan area. Promoting urban green infrastructure acts as a natural carbon sink, significantly lowering environmental pollutants and advancing ecological sustainability.

3 .Transitioning to Renewable Energy Sources in Key Sectors

As another practical recommendation, it is proposed that fossil fuels be replaced with renewable energy sources in industrial facilities, power plants, and manufacturing sectors. Such a transition is essential for mitigating the emission of environmental pollutants and improving air quality within the Tehran metropolitan area.

4 .Decarbonizing and Expanding Public Transportation Networks

To reduce private (non-public) vehicle usage, it is recommended that the Municipality of Tehran expand and develop the public transportation fleet using renewable energy sources, while establishing suitable infrastructure for rapid access to minimize travel time and financial costs for citizens.

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