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Biophilic architecture as a strategy to enhance urban energy efficiency: an empirical modeling study in Urmia

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Abstract

Rapid urbanization and rising energy consumption have intensified the need for innovative urban planning approaches that integrate nature and sustainability. This study examines the role of biophilic urban design in enhancing energy efficiency in the Urmia metropolis. A quantitative analytical approach was employed, and data were collected using a specialized questionnaire administered to 360 experts in urban design, energy, and environmental fields. Structural equation modeling was used to evaluate causal relationships between biophilic design components and urban energy efficiency. The results indicate that all proposed pathways are statistically significant. Physical and environmental design features show the strongest direct effect on energy efficiency, followed by green spaces, accessibility, and human–nature interaction. Psychological–social dimensions and biophilic management and innovation act as important mediators. Model fit indices confirm strong validity. The findings demonstrate that biophilic urban design improves energy performance by improving microclimate, promoting environmental quality, and strengthening institutional mechanisms, highlighting its potential as an integrated strategy for low-carbon urban development in cold and semi-arid cities.

Keywords

Biophilic urban design
energy efficiency
green infrastructure
structural equation modeling
urban sustainability

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1. Introduction

Rapid urbanization and physical development in recent decades, coupled with increased energy consumption and exacerbated climate change, have transformed cities into major epicenters of global environmental and energy challenges (Zhu et al., 2022; Zhang, 2015). The building and urban development sector accounts for a substantial share of energy consumption and greenhouse gas emissions, and projections indicate that without a shift in development patterns, urban energy demand will increase dramatically by mid-century (IEA, 2023; Movahed et al., 2021; Stamenković et al., 2018). These circumstances underscore the necessity to re-evaluate conventional urban design and planning approaches and transition towards paradigms capable of simultaneously enhancing energy efficiency, mitigating environmental impacts, and improving urban quality of life.

The term "biophilic" is derived from the root "biophilia," which signifies humans' innate affinity for life and nature. Biophilic urban planning and design, as a human-centric approach based on this innate affinity for nature, has increasingly gained attention as an effective strategy for enhancing human well-being and the environmental performance of urban environments (Beatley & Newman, 2013; Kellert et al., 2011; Browning & Ryan, 2020). Evidence suggests that biophilic elements such as green cover, green roofs and walls, natural lighting and ventilation, and nature-inspired materials can reduce energy consumption, improve thermal comfort, and mitigate the urban heat island effect (Bevilacqua, 2021; Latini et al., 2024; Mihalakakou et al., 2023). However, international studies are predominantly descriptive or based on building simulations, and the analysis of causal relationships between biophilic components and energy efficiency indicators at the urban scale has received less attention. Furthermore, global standard frameworks, such as LEED, BREEAM, and WELL, have not yet provided integrated, evidence-based models for metropolitan areas (Algarni et al., 2022; Balvedi & Giglio, 2023; Santamouris et al., 2017; Li et al., 2024; Wijesooriya et al., 2021; Mihalakakou et al., 2023). In Iran, attention to biophilic concepts has also increased, with studies focusing on identifying indicators and developing indigenous models (Asadi & Khatibi, 2021; Mahdavian & Parhiz, 2024; Sarboland & Abedini, 2025). Nonetheless, most of these investigations are limited to descriptive analyses or ranking of criteria, and a structural, model-driven examination of the causal relationships between biophilic components and energy efficiency at the metropolitan scale remains neglected.

This research gap becomes particularly significant in the city of Urmia, which is grappling with scattered physical development, increased energy consumption, pressure on natural resources, and vulnerability to climate change. Despite the potential of urban green spaces and surrounding natural areas, no systematic study has yet investigated the role of biophilic urban design in enhancing the energy efficiency of this city using a causal approach and structural equation modeling (SEM) (Sarboland & Abedini, 2025). This clearly underscores the necessity of the current research.

The present research evaluates the role of biophilic urban design in enhancing energy efficiency in the Urmia metropolis. By employing SEM, it seeks to elucidate the relationships among key components – including green cover, microclimate, natural lighting, and natural ventilation – and urban energy efficiency indicators. The main research question addresses how and to what extent biophilic urban design components influence the energy consumption optimization. It seems that these components have a positive and significant impact on urban energy efficiency by improving microclimatic conditions and enhancing environmental quality.

2. Literature review

In recent years, biophilic urban design has attracted the attention of researchers as a novel approach to enhancing environmental resilience, improving the quality of urban life, and increasing energy efficiency. Research in this field has primarily focused on three main axes:

(1) Biophilic design components and their impact on environmental-climatic conditions;

(2) The role of biophilia in promoting human health and well-being;

(3) The interaction of biophilia with urban policy-making and planning.

This conceptual categorization enables a precise analysis of the relationship between biophilic design components and energy efficiency indicators, providing a suitable framework for the conceptual model of the present study.

Regarding the first axis, studies on environmental-climatic components show that urban natural elements, including vegetation, water, natural lighting, and ventilation, play an effective role in moderating the microclimate and reducing energy consumption. For instance, Naderi et al. (2023) measured temperature and humidity in spaces featuring biophilic components. They demonstrated the positive impact of these elements on thermal comfort and on reducing building energy loads. Similarly, through climate simulation and expert interviews, Raisi et al. (2025) reported up to a 30% reduction in energy consumption and a 20% improvement in energy performance across various urban samples. Furthermore, the findings of Maleki et al. (2021) underscored the importance of preserving green spaces and implementing greening programs to mitigate urban heating and flooding. These studies identify the independent variables (green cover, water, natural lighting, and ventilation) and the dependent variable (urban energy efficiency), thereby establishing a solid empirical foundation for the conceptual model of the current research. However, the present study distinguishes itself by employing a structural equation modeling (SEM) approach to investigate the causal relationships among these components in the Urmia metropolis—an aspect that has received less attention in previous literature.

Regarding the second axis, research related to human health and well-being indicates that biophilic design not only improves environmental conditions but also has significant psychological and behavioral effects. Yassein & Ebrahiem (2018) and Agboola et al. (2024) demonstrated that natural lighting, views, and the experience of nature promote mental health, enhance well-being, and strengthen the human-nature connection. Similarly, Bitaraf et al. (2018) reported improvements in residential quality and the fulfillment of residents' psychological needs at the residential complex level as a direct result of implementing biophilic principles. The commonality between these studies and the current research lies in the emphasis on the role of natural components in improving the quality of life and reducing energy consumption; however, the primary difference is that the present study examines the impact of these components at the metropolitan scale using structural modeling.

Regarding the third axis, urban policy and planning studies indicate that implementing biophilic design requires convergence with urban policies and energy planning. Littke (2016) and Sadick et al. (2023) identified institutional and budgetary constraints as the most significant barriers to implementing biophilic strategies. In contrast, Sarboland and Abedini (2025) and Aniekan et al. (2024) demonstrated that integrating biophilia with green transportation and renewable energies can improve urban energy efficiency. These findings share an important commonality with the model of the current research, as the study's conceptual model addresses the interaction between spatial-environmental components and urban policy-making in enhancing energy efficiency. However, by focusing on the Urmia metropolis and utilizing SEM analysis, the present research fills previous empirical and practical gaps.

Overall, the literature analysis reveals that while previous studies have separately addressed environmental components, human impacts, and policy-making, the integration among these components and their causal effects on urban energy efficiency remain under-researched. This research gap highlights the need for the current study. Structural modeling enables the measurement of the direct and indirect effects of biophilic design components on energy indicators at the metropolitan scale, thereby contributing to nature-based and energy-efficient urban decision-making.

3. Theoretical model

A theoretical analysis of the relationship between biophilic urban design and energy efficiency necessitates the interdisciplinary approaches formed at the intersection of theories on sustainable urbanism, environmental psychology, urban climatology, and energy performance. In contemporary literature, no single theory can comprehensively explain the complex relationships among humans, nature, urban form, and energy consumption. Therefore, this study adopts an integrative and critical approach to re-examine and select key elements from relevant theories to establish a coherent and operational framework for empirical analysis.

The theoretical point of departure for this research is the biophilia hypothesis, first proposed by Wilson (2017), which emphasizes the innate human tendency to affiliate with nature. This theory forms the cognitive and biological basis for biophilic design, explaining that the presence of natural elements in built environments can yield positive outcomes for human health, environmental perception, and behavior. Despite its fundamental importance, the primary criticism leveled against this theory is its relatively abstract and anthropocentric nature; in its original form, it does not establish a direct link to objective variables, such as energy consumption or the climatic performance of urban spaces. Thus, in the present research, the biophilia hypothesis is not treated as a definitive explanatory model but rather as the conceptual underpinning for understanding the significance of human-nature interaction within the city.

Building on this framework, the theory of biophilic design developed by Kellert et al. attempts to translate this innate tendency into principles and patterns for architecture and urban planning (Kellert et al., 2011; Browning & Ryan, 2020). By introducing patterns such as the direct presence of nature, the indirect experience of nature, and spatial conditions inspired by natural systems, this theory takes a significant step toward operationalizing the biophilic concept. However, a fundamental critique of this approach is that it predominantly focuses on psychological and qualitative environmental outcomes, while its energy-related impacts are often addressed implicitly or secondarily. By reinterpreting these patterns, the present study redefines them as measurable latent variables in relation to urban energy efficiency.

From an urban planning and macro-scale perspective, theories about sustainable cities and low-carbon development offer a framework that positions the reduction of energy consumption and the optimization of cities' environmental performance as primary objectives (Beatley & Newman, 2013; Zhu et al., 2022). These theories emphasize the role of urban form, density, land use, and green infrastructure in reducing energy demand. Nevertheless, classical approaches to urban sustainability have predominantly focused on physical and functional indicators, less frequently incorporating the experiential-perceptual dimension of human-space interaction into their analytical models. From this perspective, biophilic urban design can act as a mediating link between physical sustainability and the quality of human experience, a link that remains overlooked in many urban sustainability models.

At the functional level, theories of urban climatology and climate-responsive design establish a direct connection between natural elements, physical form, and energy consumption. These theories demonstrate that components such as vegetation cover, shading, natural ventilation, and daylight access can reduce the need for fossil energies by moderating the urban microclimate and improving thermal comfort (Santamouris et al., 2017; Bevilacqua, 2021). The strength of these approaches lies in their measurability and direct correlation with energy indicators; however, their limitation is rooted in a one-dimensional perspective and a focus on isolated design elements. By integrating this viewpoint with the biophilic approach, the current research attempts to analyze the simultaneous and network-based effects of these components within a causal structure.

The synthesis and critique of the aforementioned theories indicate that explaining the relationship between biophilic urban design and energy efficiency requires a theoretical model that integrally encompasses three complementary levels: first, the perceptual-human-centric level rooted in the biophilia hypothesis; second, the physical-spatial level derived from the principles of biophilic design and sustainable urbanism; and third, the functional-energy level based on theories of urban climatology and energy performance. Within this framework, biophilic urban design is considered a multidimensional construct that directly and indirectly affects urban energy efficiency by improving environmental quality and thermal comfort.

Accordingly, the theoretical model of the current research posits that biophilic urban design components can explain variations in urban energy efficiency not only directly but also through mediating variables such as microclimate improvement and enhanced thermal comfort. This theoretical model provides the necessary foundation for developing the conceptual model and empirically testing the causal relationships among latent variables through structural equation modeling (SEM), and is directly operationalized to achieve the research objectives.

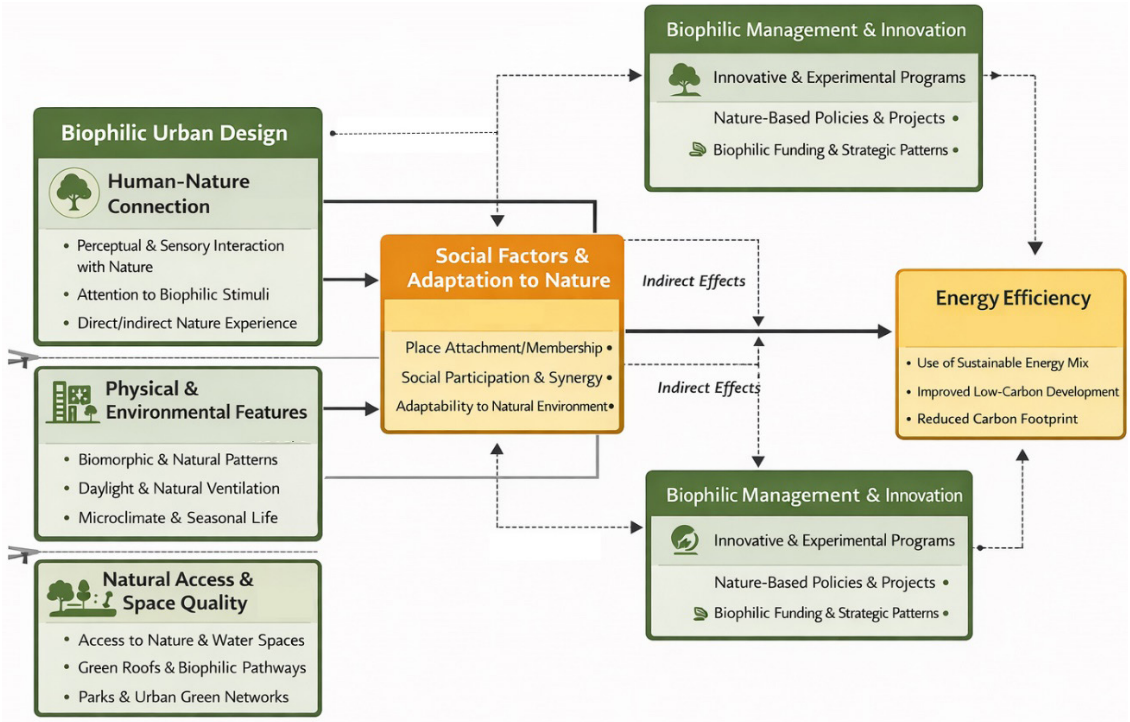

Figure 1. Theoretical model of research

4. Research methodology

From the perspective of the philosophy of science, the current research is based on critical realism, which posits that social and environmental reality exists independently of the observer, but its comprehension is only possible through the interaction between the observer and the environment. This philosophical approach enables the analysis of causal relationships between biophilic urban design and energy efficiency, while simultaneously considering the impact of mediating variables such as human psychological and social dimensions, as well as biophilic management and innovation.

In terms of the research approach, the study is quantitative and analytical, focusing on numerical data and structural equation modeling (SEM) to test the causal relationships among the variables. At the strategy level, it employs a descriptive-analytical design, combined with correlational and causal methods, to identify the components and indicators of biophilic urban design and evaluate the magnitude of their impact on urban energy efficiency.

Regarding the method, the study is a quantitative mono-method research, with the primary data collected through a specialized questionnaire. The timeframe of the research spans from spring 2024 to early 2025.

Table 1. Research layers based on Saunders' Research Onion

Onion layer	Content/details	Explanation related to the current research
Research philosophy	Critical realism	The existence of an objective social and environmental reality, and the possibility of understanding it through human interaction with the environment, was taken as the assumption; causal relationships and the role of mediating variables could be analyzed.
Research approach	Deductive, quantitative	Hypotheses were formulated based on a conceptual model derived from the literature and tested with numerical data; correlation analysis and SEM were used to measure causal relationships.
Research strategy	Descriptive-analytical, correlational, and causal	The biophilic urban design components and indicators were identified, and the magnitude of their impact on energy efficiency was evaluated.

Onion layer	Content/details	Explanation related to the current research
Method choice	Quantitative mono-method	Primary data were collected via a specialized questionnaire; the statistical population included urban experts and professionals related to biophilic design and energy in Urmia; Snowball sampling (N=360) was used.
Time horizon	Cross-sectional	Field and statistical data were collected from May 2024 to early 2025 (corresponding to the Iranian year 1403).
Techniques and procedures	Likert-scale questionnaire, confirmatory factor analysis (CFA), SEM	A specialized questionnaire including independent, mediating, and dependent indicators was used; reliability was confirmed with Cronbach's alpha >0.7; data were analyzed using SPSS and AMOS; data normality was checked before SEM.

The statistical population of the study comprises academic experts, researchers on biophilic cities and energy, and specialists from the Department of Roads and Urban Development, Urmia Municipality, the Department of Environment, and the Urmia Energy Department. The sample size for the questionnaire was determined to be 360 participants using the robust G-Power software. A snowball sampling method was employed because the number of specialists in biophilic urban design was limited, and direct access to the entire target population was not feasible. This method also increases the likelihood of reaching qualified individuals who are knowledgeable about the specialized aspects of biophilic design and energy efficiency, ensuring that the sample consists of participants with sufficient experience and practical knowledge. The sample population was characterized with educational backgrounds in architecture, urban design, environment, energy, and urban planning, as well as practical experience in urban projects and a history of participation in relevant research endeavors. The data collection tool was a specialized, custom-designed questionnaire, structured using closed-ended questions based on a five-point Likert scale, with its indicators directly extracted from the research framework's table of variables, criteria, and indicators. The questionnaire was designed to comprehensively cover all components of biophilic urban design (human connection with nature, physical characteristics and environmental design, green spaces, and accessibility), mediating variables (human psychological and social dimensions, biophilic management and innovation), and the dependent variable (energy efficiency). The questionnaire data were collected in person and distributed in coordination with the relevant organizations and specialists.

Table 2. Introduction of research variables and indicators

Variable type	Variable	Criterion/ component	Cronbach's Alpha	Operational definition of the criterion	Indicators
Independent	Biophilic urban design	Human connection with nature	0.859	The degree of human attention and perception of natural elements, and the sensory and psychological interaction with nature in the designed environment	Attention to biophilic elements; attention to biophilic elements that encourage performance and health; attention to biophilic elements in preventing adverse environmental effects; attention to natural sensory stimuli; attention to contexts influencing direct experience of nature; attention to contexts influencing indirect experience of nature; "authentic" experience of nature; attention to the experience of space and place; attention to visual and non-visual connection with nature.
Independent		Physical characteristics and environmental design	0.816	The extent to which patterns, microclimate, texture, color, light, and natural elements are considered in the design to enhance the human-nature experience	Attention to airflow and thermal changes; attention to biomorphic forms and patterns; attention to unknown elements in nature; attention to the element of fire; attention to natural texture/images/color; attention to connected and integrated environments; attention to enhancing a wide range of nature's values; attention to light; degree of attention to refuge/shelter; degree of attention to the presence of animals.

Variable type	Variable	Criterion/ component	Cronbach's Alpha	Operational definition of the criterion	Indicators
Independent	Biophilic urban design	Accessibility and quality of natural spaces	0.843	The degree of accessibility and quality of green spaces (indoor and outdoor), green roofs, and pathways in urban design	Attention to the accessibility of biophilic spaces; attention to roof gardens/green roofs/hanging gardens/green atriums; attention to the collection of indoor, outdoor, and transitional spaces and views; attention to ecological networks/native species; attention to parks and green spaces; attention to pristine and semi-pristine nature; attention to vegetation/forest cover; attention to urban green facades; attention to pedestrian/dynamic pathways; attention to the presence of water; attention to natural materials; attention to vistas and landscapes; attention to biophilic-oriented transitional spaces; attention to public gardens and parks.
Mediating		Attachment, social interaction, and adaptation to nature	0.769	The degree of psychological dependence, sense of belonging, social participation, and human ability to adapt to the natural environment	Emotional attachment to structures, landscapes, and places; sense of community membership; willingness to participate in bringing nature into the city; attention to strengthening the human relationship with natural systems; attention to gardening and nature restoration activities; environmental education and information; attention to sense of belonging/place attachment; attention to social synergy; degree of human adaptation to nature.
Mediating	Biophilic management and innovation	Planning, policies, and creative projects	0.837	The extent of strategic plans, budget, innovative projects, and the use of nature-based design patterns	Attention to experimental and creative biophilic projects; attention to the existence of strategic biophilic plans; biophilic or nature-supporting organizations; budget for biophilic activities; number of experimental and innovative biophilic projects; attention to projects using biomimicry patterns; attention to design patterns with complexity and order criteria; attention to design patterns with mystery criteria.
Dependent	Energy efficiency	Energy, consumption, and sustainable development	0.799	The degree of attention to using sustainable methods in environmental design and to reducing negative environmental impacts	Attention to and use of hybrid energies; attention to improving consumption/recycling; attention to the development of a sustainable economy; carbon footprint reduction projects (low-carbon footprint).

To ensure the validity and reliability of the instruments, the questionnaire was pre-tested, and confirmatory factor analysis (CFA) was used to assess the factor structure of the indicators, ensuring that the questions for each criterion genuinely measure its relevant dimensions. Based on the CFA results, all statistics are at an optimal level, indicating a good fit.

Table 3. Model fit indices

	P	CMIN/DF	GFI	CFI	RMSEA	NFI	TLI	SRMRR
Statistic	0.439	1.27	0.968	0.994	0.017	0.978	0.967	0.009

Furthermore, Cronbach's alpha coefficient was calculated to assess the internal reliability of each scale. All scales had a coefficient higher than 0.7, indicating sufficient homogeneity of the questions and the reproducibility of the results. Face and content validity were also confirmed by experts in urban design and the environment to ensure that all theoretical components of the conceptual model were covered.

The data analysis method consists of two main parts: first, descriptive statistical analysis to examine the distribution, mean, and variance of the indicators; and second, correlation analysis and structural equation modeling (SEM) to test the causal relationships between the independent, mediating, and dependent variables. Data normality tests (Kolmogorov-Smirnov and Shapiro-Wilk) were conducted prior to analysis, and according to the results in Table 4, the research samples had a normal distribution. The SEM model allowed for an accurate evaluation of the direct and indirect impacts of biophilic urban design variables on energy efficiency, as well as the mediating role of psychosocial variables and biophilic management and innovation. In addition, the impact intensity of each indicator within the framework of the conceptual model and the discriminative power of the variables in determining the executive priorities of biophilic urban design were identified.

Table 4. Evaluation of research data distribution

Test	Statistic	Degrees of freedom (df)	Significance level (Sig)	Interpretation
Kolmogor-ov-Smirnov	0.098	355	0.428	Since Sig.>0.05, the assumption of data normality is not rejected.
Shapiro-Wilk	0.764	355	0.644	Since Sig.>0.05, the assumption of data normality is not rejected.

SPSS and AMOS software were used for data analysis. SPSS was used for descriptive analysis, correlation tests, checking data normality, and calculating Cronbach's alpha coefficients. AMOS was used to analyze SEM and perform CFA. These software programs were selected for their capability in modeling complex multivariate relationships, providing model fit indices, and enabling the evaluation of direct and indirect variable paths.

4.1. Study area

Urmia, formerly known as Rezaieh, is the capital of West Azerbaijan Province and Urmia County in northwestern Iran. According to the 2016 census, it includes a population of over 736,224, making it the tenth most populous city in Iran and the second most populous in the northwest region of the country. Located at an elevation of 1,332 meters above sea level, west of Lake Urmia, on the slopes of Mount Sir and within the Urmia Plain, this geographical position has led to a semi-humid climate with significant solar radiation and seasonal temperature variations. Urmia's summers are generally cool and pleasant, although temperatures occasionally exceed 40°C, while winters feature severe cold with temperatures dropping to -15°C to -20°C. The long-term average precipitation in this city is approximately 238 mm, and the average wind speed is 10.5 m/s (Tarh-o-Kavosh, 2019).

Historically and culturally, Urmia has a history spanning several millennia and was located on the regional trade routes of the Caucasus and Mesopotamia. This historical and commercial position has endowed the city with a diverse urban fabric, varied land uses, and scattered public and green spaces. Furthermore, possessing nationally registered monuments and historical-cultural activities, Urmia has significant cultural and social capacities that facilitate the study of the interaction between urban design and environmental quality (Tarh-o-Kavosh, 2019).

However, Urmia faces dilemmas that underscore the importance of studying biophilic urban design. These include air pollution caused by traffic and temperature inversion, high vehicle density, marginalization challenges (informal settlements), the drying of Lake Urmia, and salt storms. Additionally, the city experiences structural differences in its urban fabric, comprising a historical core, a middle fabric, and newly developed areas resulting from recent migrations, each possessing distinct microclimatic conditions that impact urban energy consumption.

Based on the aforementioned characteristics, Urmia was selected as the study area because:

- Its climatic and microclimatic diversity allows for the analysis of the effects of biophilic components on environmental conditions and energy consumption.
- The structural diversity and urban land uses enable the investigation of the interaction between urban design and energy efficiency indicators.
- Access to accurate demographic, climatic, and urban energy data facilitates structural equation modeling and scientific analysis.
- The presence of green spaces, rivers, and urban natural elements provides favorable conditions for examining biophilic urban design strategies.

- Urban and environmental challenges, such as air pollution, traffic congestion, and marginalization, create an incentive to find sustainable solutions and improve energy efficiency.

Due to its specific geographical, climatic, historical, structural, and environmental characteristics, Urmia is considered an appropriate case study to investigate the impact of biophilic urban design on enhancing urban energy efficiency. The results obtained can serve as an applicable model for other Iranian metropolises with similar conditions.

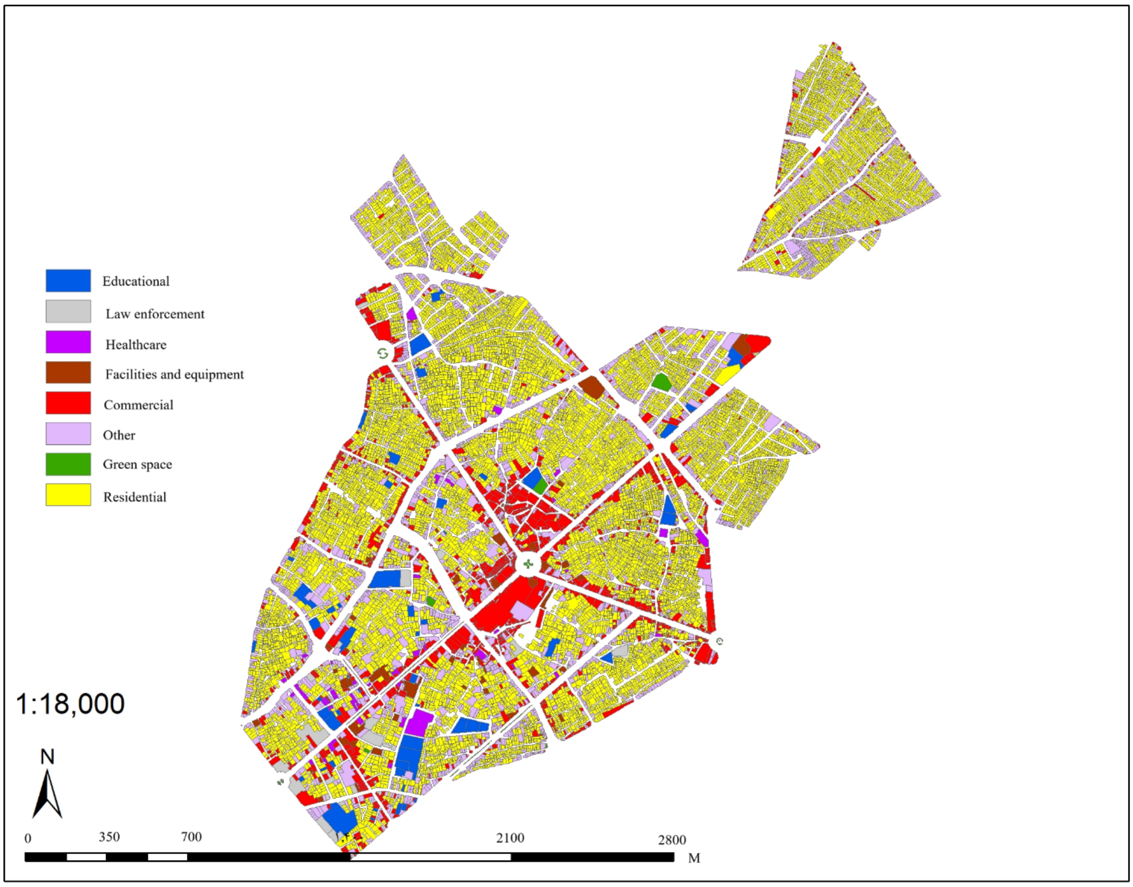

Figure 2. Land use map of Urmia city (Urmia Master Plan, 2019)

5. Findings

Descriptive analysis of the data showed that the means of the independent and mediating variables are at a positive level, and the dispersion of the data is relatively reasonable, indicating that the distribution of responses is suitable for subsequent analyses. "Human connection with nature", with a mean of 3.20, and "Green spaces and accessibility", with a mean of 3.30, show the most attention, highlighting the importance of human experience and access to natural elements in biophilic urban design. "Physical characteristics and environmental design" (mean 3.17) and "Human psychological and social dimensions" (mean 3.03) also exhibit a positive tendency; however, the greater dispersion of responses indicates a divergence in perspectives on the evaluation of physical design details and psycho-social impacts.

In contrast, "Biophilic management and innovation", with a mean of 2.90, and "Energy efficiency", with a mean of 2.93, are lower than the other variables, indicating a need to strengthen planning, policymaking, and operational measures to improve energy performance and innovative projects in the city. The skewness and kurtosis values for all variables are close to zero; therefore, the data distribution is approximately normal, enabling the application of SEM and correlation analyses.

These results demonstrate that biophilic urban design in Urmia has a high capacity to enhance human interaction with nature and the quality of green spaces; however, it requires strengthening management and policy dimensions to realize a positive impact on energy efficiency. The descriptive analysis clearly identifies existing gaps in the planning and implementation of biophilic design and provides a foundation for causal analysis in the SEM model.

Table 5. Descriptive statistics of research criteria

Variable	Criterion	N	Mean	Standard deviation	Range	Skewness	Kurtosis
Human connection with nature	Direct and indirect experience of nature	360	3.2021	0.51603	3.17	0.015	0.309
Physical characteristics and environmental design	Physical and environmental design	360	3.1698	0.44246	2.75	0.600	0.731
Green spaces and accessibility	Access and quality of natural spaces	360	3.3029	0.54393	2.83	0.413	0.046
Human psychological and social dimensions	Attachment, social interaction, and adaptation to nature	360	3.025	0.76139	4.00	0.091	−0.127
Biophilic management and innovation	Planning, policies, and creative projects	360	2.8963	0.57095	2.75	−0.104	−0.507
Energy efficiency	Energy, consumption, and sustainable development	360	2.9300	0.46073	2.63	−0.013	−0.245

5.1. Structural equation modeling (SEM)

The results of the structural equation modeling indicate that all hypothesized paths between the independent and mediating variables and the dependent variable of energy efficiency in the Urmia metropolis are statistically significant and confirmed. According to the standardized regression coefficients, the highest direct impact on energy efficiency is attributed to Physical characteristics and environmental design, with a standardized coefficient of 0.784 and a regression coefficient of 1.636. This highlights the importance of physical design, biomorphic patterns, airflow, light, and texture in enhancing urban energy performance. The next in rank is Green spaces and accessibility with $\beta std=0.712$ and $\beta=1.815$, demonstrating that access to parks, pedestrian pathways, ecological networks, and biophilic-oriented transitional spaces plays a significant role in improving energy efficiency. The variable “Human connection with nature”, with a standardized coefficient of 0.659 and a regression coefficient of 1.710, also has a significant effect on energy efficiency, emphasizing the importance of direct and indirect experiences of nature and human-nature interaction.

The role of the mediating variables is also well-represented in the model. “Human psychological and social dimensions” ($\beta std=0.708$, $\beta=1.779$) and “Biophilic management and innovation” ($\beta std=0.687$, $\beta=1.864$) create significant mediating pathways to energy efficiency. These findings demonstrate that, in addition to the direct impact of biophilic urban design, psychosocial factors such as attachment, social interaction, sense of belonging, and human adaptability to nature, as well as project management, creative programs, and nature-based innovations, play a crucial role in reinforcing the effects of urban design on energy efficiency.

All model paths have a critical ratio (C.R.) higher than 3 and a significance level less than 0.001, indicating high statistical significance and reliability of the results. The Standard error (S.E.) of the paths is also within an appropriate range, which suggests precision in the coefficient estimates and the absence of significant measurement error. All paths have a “Confirmed” status, which strengthens the validity of the conceptual model.

In summary, the modeling results show that enhancing urban energy efficiency in Urmia requires a combination of three main factors: Human connection with nature, physical characteristics and environmental design, and green spaces and accessibility, along with support and planning through the mediating variables of human psychological and social dimensions and biophilic management and innovation. These findings underscore the importance of an integrated approach to biophilic urban design, indicating that the direct and indirect effects operate simultaneously to promote urban energy efficiency.

Table 6. Results of structural equation modeling in AMOS software

Dimension	Component	Path	Dependent variable	Rank	Regression coefficient	Standardized regression coefficient	(C.R.)	S.E.	Significance level (Sig.)	Status
Independent variable	Human connection with nature	→\ rightarrow→	Energy efficiency	5	1.710	0.659	3.461	0.494	0.000	Confirmed
	Physical characteristics and environmental design	→\ rightarrow→		1	1.636	0.784	3.597	0.455	0.000	Confirmed
	Green spaces and accessibility	→\ rightarrow→		2	1.815	0.712	3.524	0.515	0.000	Confirmed
Mediating variable	Human psychological and social dimensions	→\ rightarrow→		3	1.779	0.708	3.321	0.492	0.000	Confirmed
	Biophilic management and innovation	→\ rightarrow→		4	1.864	0.687	3.508	0.311	0.000	Confirmed

5.2. Correlation relationship

The results of the Pearson correlation analysis indicate positive, significant relationships among all research variables at the 95% confidence level (Sig<0.05), demonstrating the internal consistency of the constructs and their alignment with the theoretical framework of the research. The highest correlation with the dependent variable, energy efficiency, belongs to "Physical characteristics and environmental design" (r=0.784), indicating the determining role of the quality of physical design, biomorphic patterns, microclimate control, and environmental elements in improving urban energy performance. This finding confirms that physical interventions, compared to other dimensions of biophilic design, have a more direct and stronger impact on energy indicators.

Ranking next, "Green spaces and accessibility" (correlation coefficient of 0.712) and "Human psychological and social dimensions" (coefficient of 0.708) exhibit a strong and significant relationship with energy efficiency. These results suggest that access to green spaces, ecological networks, and natural landscapes, alongside the enhancement of place attachment, social interaction, and human adaptation to nature, can indirectly yet effectively influence energy consumption and related behaviors.

Furthermore, "Biophilic management and innovation" has a significant correlation with energy efficiency (r=0.687), reflecting the role of policymaking, pilot projects, nature-based innovations, and biomimicry patterns in strengthening urban energy performance. This emphasizes the importance of the institutional and managerial dimension in achieving the goals of biophilic urban design, a dimension that has been less empirically examined in many previous studies.

Among the relationships between independent and mediating variables, significant and, in some cases, relatively strong correlations are also observed. For instance, "Green spaces and accessibility" highly correlates with "Human psychological and social dimensions" (r=0.647), indicating that the quality of and access to urban nature play a crucial role in fostering place attachment and social interactions. Additionally, the notable correlation between "Human connection with nature" and "Biophilic management and innovation" (r=0.602) suggests that human experience and perception of nature provide the basis for supporting biophilic policies and innovations at the urban scale.

Overall, the correlation pattern demonstrates that the research variables do not act independently, but rather as an interconnected system, in which physical design, human experience, green spaces, psychosocial dimensions, and urban management simultaneously impact energy efficiency. These significant correlations provide the necessary statistical foundation for entering the structural equation modeling phase and support the conceptual fit of the theoretical model with the actual conditions of the Urmia metropolis.

Table 7. Correlation results among components in SPSS software

Variable	Energy efficiency	Human connection with nature	Physical characteristics and environmental design	Green spaces and accessibility	Human psychological and social dimensions	Biophilic management and innovation
Human connection with nature	0.659	1				
Physical characteristics and environmental design	0.784	0.493	1			
Green spaces and accessibility	0.712	0.517	0.592	1		
Human psychological and social dimensions	0.708	0.344	0.538	0.647	1	
Biophilic management and innovation	0.687	0.602	0.425	0.566	0.519	1
Note: All relationships are at a significance level of (Sig<0.001).						

6. Discussion and conclusion

The findings of this study indicate that biophilic urban design in the Urmia metropolis affects energy efficiency not as a set of isolated interventions, but rather as a multi-layered physical-social-institutional system. The significance of all SEM paths and the relatively high coefficients of the direct and indirect effects of the variables demonstrate that the relationships between biophilic design components and urban energy performance possess a networked and interactive nature. This finding directly addresses the gap highlighted in the broader literature, in which most studies, despite their theoretical emphasis on the importance of nature-based design, lacked empirical evidence on the causal mechanisms concerning these impacts (Wijesooriya et al., 2021; Zhu et al., 2022; Li et al., 2024).

Based on the SEM results, physical characteristics and environmental design exhibit the highest direct effect on energy efficiency (βstd=0.784), emphasizing the determining role of urban form, biomorphic patterns, natural ventilation, urban fabric permeability, and the use of natural light in reducing cooling and heating loads. This result is consistent with the findings of Mihalakakou et al. (2023), Bevilacqua (2021), and Santamouris et al. (2017), which demonstrated that the quality of physical design and microclimate control are among the most effective factors in improving energy performance at the urban scale and within building complexes. However, the higher contribution of this component in Urmia can be interpreted in the context of the city's cold semi-arid climate and its extreme temperature fluctuations, where physical interventions such as building orientation, shading, fabric porosity, and airflow optimization play a far more prominent role than in cities with temperate climates. From this perspective, the present finding goes beyond merely confirming previous studies, underscoring the necessity to localize biophilic strategies to align with specific climatic characteristics. Green spaces and accessibility (βstd=0.712) and human connection with nature (βstd=0.659) also demonstrate significant effects on energy efficiency. These results indicate that the function of green spaces is not limited to enhancing visual or recreational quality; rather, it can reduce energy consumption by moderating ambient temperature, increasing relative humidity, mitigating urban heat islands, and altering citizens' behavioral patterns. This finding aligns with the studies of Balvedi and Giglio (2023) and Algarni et al. (2022), which emphasize the role of ecological networks and pedestrian-oriented access to nature in improving thermal comfort and reducing energy demand. Concurrently, the results of this research demonstrate that the human experience of nature and the subjective perception of the environment are also directly linked to energy indicators. This issue has received less attention in many intermediate studies and is often limited to physical variables.

One of the most important theoretical achievements of this study is revealing the mediating role of human psychological and social dimensions, as well as biophilic management and innovation. The relatively high coefficients of these two variables (βstd=0.708 and βstd=0.687) indicate that the impact of biophilic design on energy efficiency is not transmitted solely through the physical pathway, but is reinforced through increased place attachment, social interactions, behavioral adaptation to nature, and the institutional capacity to plan and implement nature-based projects. This finding is consistent with the results of Latini et al. (2024), which emphasized the role of perceived environmental quality in moderating energy-intensive behaviors; however, it simultaneously goes beyond that by empirically incorporating the managerial dimension into the model, a dimension that has been less quantitatively investigated in the international literature, and particularly in domestic studies.

Compared to domestic research, which has mainly focused on extracting indicators or conducting qualitative feasibility studies of biophilic design (Asadi and Khatibi, 2021; Maleki et al., 2021; Mahdavian and Parhiz, 2024; Sarboland and Abedini, 2025), this research, by utilizing structural equation modeling, has been able to explain, for the first time in the Iranian urban context, the direct and indirect causal relationships between biophilic components and energy efficiency. From this perspective, the present research has not only achieved its overall objective of explaining the role of biophilic urban design in enhancing energy performance, but it has also taken a methodological step beyond descriptive approaches or simple rankings, providing an analytical framework for the simultaneous measurement of latent variables.

Contextual interpretation of the findings reveals that in Urmia, the relatively weak biophilic management and innovation, and lower average energy efficiency compared to other components, reflect institutional challenges, limited financial resources, and the lack of coherent energy-oriented policies at the urban level. This explains why, despite the city's high physical and natural capacity, the full realization of biophilic design benefits requires strengthening governance mechanisms, economic incentives, and nature-based pilot projects. Therefore, the main practical implication of this research is that urban policymakers should consider biophilic design as part of a comprehensive urban energy strategy and integrate it into development documents, building codes, and urban fabric regeneration plans. Prioritizing low-cost but high-yield physical interventions, developing continuous green networks, raising public awareness, and creating an institutional foundation for biomimetic innovations can be proposed as key levers to enhance energy efficiency.

Despite these achievements, the current research also faces certain limitations, including reliance on perceptual data rather than actual energy consumption data, focus on a single city, and the inability to examine seasonal variations. These limitations necessitate that future research strengthen the external validity of the model and investigate the temporal dynamics of biophilic design impacts by combining field energy data, climate simulations, and inter-city comparative studies.

Overall, the results of this research indicate that biophilic urban design, when combined with targeted physical interventions, enhancement of psychological-social dimensions, and institutional support, can serve as an effective framework for improving energy efficiency in cold and semi-arid cities. By providing empirical and model-based evidence, this study demonstrates that the transition to low-carbon cities does not require new technologies alone but necessitates rethinking the relationship between humans, nature, and urban structure. This conclusion can serve as a basis for informed decision-making towards sustainable urban design in Iran.

Authors' Contributions

The corresponding author was solely responsible for all stages of the research process, including study design, data collection, data analysis and interpretation, and preparation of the final manuscript. The author approved the final version of the manuscript.

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Conflict of Interest

The author declares that there are no actual or potential conflicts of interest regarding the publication of this article.

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