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Computational Intelligence for Sustainable Urban Planning and Smart Cities

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Abstract

Urbanization is increasing at an accelerated rate, specifically in developing countries such as Pakistan, which leads to urban planning and sustainability challenges. Conventional urban planning approaches have the inadequacy of flexibility, potential for growth, and sophistication to handle the dynamic urban needs, resulting in issues like wastage of energy usage, contamination, traffic congestion, and inferior infrastructure governance. Computational intelligence (CI), incorporating approaches such as machine learning, artificial intelligence, and fuzzy logic, provides innovative solutions to improve urban systems and strengthen sustainability. This study utilizes a quantitative statistical approach based on primary original data obtained from the urban planning professionals in Pakistan to analyze the impact of CI on sustainable urban development. 180 inputs were received from respondents, and used the Partial Least Squares Structural Equation Modeling (PLS-SEM). This study explores the influence of CI tools on the different sustainability indicators. The results support that the adoption of CI significantly promotes the environmental, social, and economic sustainability. The outcomes not only fill the gap of the methodology in the prior literature but also offer actionable suggestions for policymakers and urban planners in terms of Pakistan. This study highlights the transformative potential of CI in enhancing smart urban cities and supports the climate efforts.

Keywords: Computational Intelligence, Smart Cities, Urban Planning, Sustainability, PLS-SEM, Pakistan

1. Introduction

Pakistan is encountering fast urban growth, resulting in uncontrolled expansions, environmental damage, and poor utilization of resources in major cities such as Karachi, Lahore, and Islamabad (Azhar *et al*., 2024) [6]. These issues are mainly because of the reliance on traditional urban planning methodologies that are inflexible and information-deficient (Liu *et al*., 2022) [22]. CI presents an encouraging alternative by incorporating AI and machine learning into the urban design process, empowering cities to become more dynamic, proactive, and efficient (Alahi *et al*., 2023 [2]; Shah *et al*., 2023). By employing the CI, urban planners can model the city's dynamics, streamline the transportation systems, regulate the energy consumption, and reduce the environmental impacts in real-time (Son *et al*., 2025 [34]; Naeem *et al*., 2025a, b). Therefore, the CI possesses the opportunities to resolve multiple urban issues in Pakistan via evidence-driven and smart decision-making processes that strengthen the green sustainability and robustness of the cities (Ahmad *et al*., 2024 [1]; Naeem *et al*., 2024a, b).

Regardless of the expanding global literature on smart cities and CI applications, a major research gap is present specifically in the framework of the developing economies (Das *et al*. 2025) [13]. Firstly, some evidence-based studies have investigated the utilization and impact of the CI in South Asian urban planning (Gupta *et al*. 2024) [18]. Secondly, the research limitations exist in many studies, depending on the secondary data and non-qualitative investigations without statistically verified approaches (Cheong *et al*., 2023) [12]. Thirdly, the conceptual integration of the green sustainability frameworks with the digital models is limited (Yadav *et al*., 2024 [10]; Naeem, 2023 [25]; Naeem *et al*., 2024c). These gaps require a comprehensive and data-driven investigation to examine the impact of CI on sustainable urban planning, specifically in Pakistan, where smart cities are still emerging. Addressing these deficiencies will increase the theoretical discourse and guidance in the practical implementations.

This research is specifically important in terms of Pakistan as the country encounters complex urban challenges, which include environmental vulnerability, shelter shortages, and inefficient waste management. The implementation of the CI in the urban planning can significantly support to achieve the Sustainable Development Goals (SDGs) of the United Nations like eco-friendly cities and communities (SDG 11) and environmental action (SDG 13) (Blasi *et al*. 2022; Ali et l., 2022; Anser *et al*., 2024) [9, 3, 5]. Additionally, the study supports the strategy planning and asset allocation by delivering research-based insights. As Pakistan initiates its investments in the intelligent city projects, appreciating the impact of CI is crucial for ensuring that these initiatives give genuine improvements in the city's sustainability and administration (Khan *et al*., 2020) [19].

To investigate these research objectives, this study uses a quantitative methodology utilizing the primary data collected via standardized survey questionnaires. The sampling method used is non-probability based, focusing on the city planners, engineers, and local government involved in municipal development projects. The research method is positivist, focusing on hypothesis testing and extrapolations of the results. The data analysis is implemented with the PLS-SEM through the Smart PLS software, selected because of its efficacy in handling the intricate frameworks and limited to moderate sample sizes. This analytical approach assures the reliability and accuracy of results and supports conceptual development in this emerging field of research.

The findings of this study demonstrate the significant impact of the CI tools on the sustainability of the urban systems in Pakistan. The measurement and structural model evaluations verify the internal reliability and validity of the research framework. Hypothesis testing indicated that the adoption of the CI was associated with the ecological, economic, and societal dimensions of cities' sustainability. These results provide both the conceptual and applied impacts by confirming the suitability of the CI models in the context of South Asia. This study summarizes by presenting the policy suggestions and pointing out the possible fields for future study, particularly focusing on the expansion of the CI applications throughout the various city zones and population densities.

This study was formatted as provided: Section 1 comprises an introduction, Section 2 displays the literature review, Section 3 was composed of the methodology, Section 4 offers the results, and the last section encompasses the conclusion and implications of the study.

2. Literature Review

2.1 Computational Intelligence

CI encompasses the set of nature-motivated computational methodologies and methods that are used to address complex practical problems (Goel *et al*., 2020) [17]. Within urban planning, the CI involves machine learning, artificial intelligence, neural networks, and fuzzy logic, which facilitate the evidence-based decision-making (Lazaroiu *et al*., 2022) [21]. These computational technologies permit the planners to model and frame the urban environments, estimate the future expansion, regulate the energy systems, and enhance the traffic flows (Chalal *et al*., 2016; Naeem *et al*., 2023) [11, 30]. Conversely, sustainable urban planning strives to balance the environmental, economic, and social objectives in the city development strategies (Bibri *et al*., 2020) [7]. Its objective is to develop the habitable, resilient, and energy-efficient urban spaces. The integration of the CI with sustainability is emerging as a critical area of research because of the increasing need for smart urban management solutions (Bibri *et al*., 2024) [8].

2.2 Theoretical Background

The conceptual foundation of this research was anchored in the Triple Bottom Line (TBL) paradigm, which implements the integration of fiscal, ecological, and social sustainability in the process of decision-making (Singh *et al*., 2022 [33]; Shah *et al*., 2024a, b). Pioneered by Elkington (1994) [14], the TBL approach transcends the conventional financial metrics and implements a comprehensive view of the institutional and societal performance. About the sustainable urban development and the smart cities, the TBL provides an integrated lens through which the efficacy of the CI techniques can be determined (Mehmood *et al*., 2024) [23]. These computational tools, involving Machine Learning, Artificial Intelligence, and other related intelligent systems, equip the urban infrastructures with the capability to model, predict, and refine the urban systems in ways that directly influence the triple pillars of sustainability (Al-Raeei *et al*., 2025) [4]. For instance, CI can strengthen the fiscal sustainability via optimizing asset allocation, environmental sustainability via mitigating emissions through intelligent energy systems, and social sustainability via enhancing the quality of life via streamlined delivery service (Mishra *et al*., 2023; Farooq & Ahmad, 2023; Farooq *et al*., 2023) [24, 15, 16].

The conceptual alignment was directly linked with the objectives of the study, which sought to investigate the influence of the CI on sustainable urban development using the TBL framework as an analytical framework. Prior literature often evaluates in the isolation of digital interventions without embedding them into a sustainability context; this study bridges this gap by assessing how CI suggests a multidimensional approach to urban sustainability. Moreover, this study assists the evidence-driven urban governance, catalyzing the shift from responsive to proactive planning. In Pakistan, where cities face rapid pressures from demographic surges, infrastructure stress, and climate risks, applying the TBL via the lens of CI offers a long-term framework to guide urban transformation. This integration not only increases the academic debate but also provides implementable pathways for urban cities aiming to achieve long-term adaptation and intelligent growth.

2.3 Hypotheses Development

Anchored with the TBL model, this research formulates its hypotheses by investigating the capacity of the CI to assist the triple pillars of sustainability: Environmental, societal, and economic vitality. The CI technologies like Artificial Intelligence, Machine Learning, neural networks, and evidence-based decision making, which are progressively integrated into intelligent city frameworks, globally. These computational methods enable urban planners to model the development scenarios, forecast demographic shifts, optimize energy efficiency, and refine asset management. Like, the CI is not just a technological innovation but a strategic catalyst for sustainable development. The capability of the CI to diagnose real-time problems and generate intelligent solutions establishes it as a critical contributor to sustainable urban planning, particularly in asset-constrained and rapid-growth environments like Pakistan.

Ecological sustainability is an important dimension for urban centers in Pakistan, where cities face acute challenges like contamination, unplanned development, and inefficient waste disposal. The CI tools, like the IOT sensors and AI machine monitoring systems, can facilitate to detect the environmental deterioration, estimate climate-related risks, and automate mitigation strategies. So, this study hypothesized that the greater adoption of CI technologies would lead to enhanced environmental sustainability results.

Similarly, social sustainability in cities revolves around aspects like equitable access to services, citizen safety, health, and participatory governance. CI-powered platforms can facilitate e-governance, enhance urban mobility, and improve public services through automation and feedback loops. These capabilities can improve the quality of life for urban populations, especially in underdeveloped areas where governance and service delivery are weak. Thus, CI is expected to positively influence social sustainability in urban planning.

Lastly, economic sustainability is integral to smart cities, where efficient infrastructure, energy savings, traffic decongestion, and digital services can lower costs and increase productivity. CI applications help in cost-effective urban resource management, predictive maintenance of infrastructure, and the creation of smart public utilities. Such advancements have the potential to generate economic value and reduce operational inefficiencies. Based on this understanding, the study proposes the following hypotheses:

H1: Computational intelligence adoption has a positive impact on environmental sustainability in urban planning.

H2: Computational intelligence adoption has a positive impact on social sustainability in urban planning.

H3: Computational intelligence adoption has a positive impact on economic sustainability in urban planning.

2.4 Conceptual Framework

The conceptual framework of this study is given below in Figure 1.

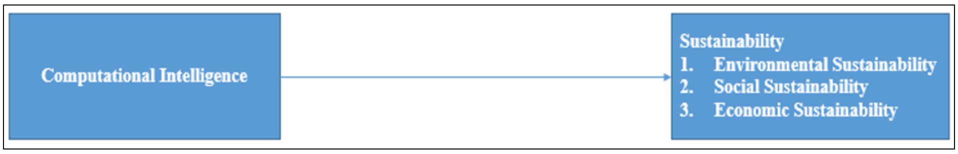

Fig 1

3. Methodology

This study adopts a quantitative research methodology under the positivist paradigm, which emphasizes objectivity, measurement, and hypothesis testing. The research focuses on understanding the causal relationship between the adoption of computational intelligence and the sustainability outcomes in urban planning. A structured questionnaire was developed based on validated scales from existing literature and adapted to the local context. The instrument includes items measuring CI tools usage and three sustainability dimensions: Environmental, social, and economic. The questionnaire used a five-point Likert scale to capture respondents' perceptions and experiences.

The target population includes urban planners, engineers, municipal officials, and technology experts involved in smart city projects across major Pakistani cities. A convenience sampling technique was used due to access limitations and time constraints. A total of 200 responses were collected, of which 180 were valid and used for analysis. The study used Smart PLS 4.0 software to perform PLS-SEM. PLS-SEM was selected for its capability in exploring the intricate relationships among the latent variables, accommodating the reflective and formative frameworks, and working well with non-parametric data and limited to medium sample datasets.

The data analysis methodology involves the two main stages. First, the measurement framework was evaluated for reliability and validity by using Cronbach's Alpha, Composite Reliability (CR), Average Variance Extracted (AVE), and the Heterotrait-Monotrait (HTMT) ratio. Second, the structural model was analyzed through the path coefficients, R-squared values, and hypothesis testing utilizing bootstrapping. The results achieved from the Smart PLS provided statistical support for the framework and the support for the proposed hypotheses. This rigorous model assists in the comprehensive assessment of the impact of the CI on sustainable urban development in Pakistan.

4. Results

4.1 Demographic Result

Table 1: Demographic Profile of Respondents

Demographic Variable	Frequency	Percentage
Gender		
Male	128	71.1%
Female	52	28.9%
Age		
20–30 years	74	41.1%
31–40 years	64	35.6%
41–50 years	32	17.8%
51+ years	10	5.5%
Designation		
Planner	65	36.1%
Engineer	48	26.7%
Government Official	42	23.3%
IT Expert	25	13.9%

The demographic profile of the respondents provided that the major portion was male (71.1%), while females represented 28.9%, indicating a gender imbalance prevailing in the urban planning and technical professions in Pakistan. Concerning the age distribution, the predominant group fell within the range of 20–30 years (41.1%), followed by 31–40 years (35.6%), and denoted a relatively young and active professional population. The respondents aged between 41–50 years accounted for 17.8%, and only 5.5% were exceeding 50 years. Regarding the professional roles, the urban planners represented the largest proportion of 36.1%, followed by the engineers (26.7%), civil officials (23.3%), and IT experts (13.9%). This heterogeneous mix tells that the study captured perspectives from a multi-spectrum of the stakeholders engaged in the intelligent city and urban ecological initiatives.

4.2 Measurement Model

Table 2: Reliability and Validity

Construct	Abbreviation	Factor Loading	Cronbach's Alpha	CR	AVE
Computational Intelligence	CI1	0.782	0.872	0.901	0.654
	CI2	0.915			
	CI3	0.731			
	CI4	0.827			
	CI5	0.864			
	CI6	0.839			
	CI7	0.795			
Environmental Sustainability	Env_S1	0.932	0.889	0.917	0.688
	Env_S2	0.982			
	Env_S3	0.871			
	Env_S4	0.823			
	Env_S5	0.825			
Social Sustainability	Soc_S1	0.845	0.860	0.895	0.672
	Soc_S2	0.797			
	Soc_S3	0.734			
	Soc_S4	0.839			
	Soc_S5	0.824			
	Soc_S6	0.819			
Economic Sustainability	Eco_S1	0.719	0.878	0.902	0.661
	Eco_S2	0.823			
	Eco_S3	0.853			
	Eco_S4	0.871			
	Eco_S5	0.820			

The measurement model results show strong reliability and validity for all constructs used in the study. For CI, factor loadings for all seven items (CI1 to CI7) exceed the threshold of 0.70, ranging from 0.731 to 0.915, indicating that each item significantly contributes to the construct. The Cronbach's Alpha (0.872) and Composite Reliability (CR = 0.901) values are above the acceptable threshold of 0.70, confirming internal consistency reliability. Additionally, the Average Variance Extracted (AVE) of 0.654 surpasses the 0.50 benchmark, reflecting satisfactory convergent validity and confirming that the items collectively explain a significant portion of variance in CI.

For environmental sustainability, all factor loadings (ranging from 0.823 to 0.982) were surpassing the satisfactory thresholds, with particularly strong loading for Env_S2 (0.982), suggesting exceptional variable contributions to the latent construct. The Cronbach's Alpha of 0.889 and CR of 0.917 exhibit high reliability. Additionally, an AVE of 0.688 further validated the convergent validity of this construct, indicating that the indicators effectively exhibited the environmental sustainability as predicted by the respondents. These findings assist the robustness of this dimension in calculating the influence of the CI on the ecological results within the intelligent urban settings.

The constructs of Social Sustainability and Economic Sustainability also displayed better psychometric properties. Social Sustainability exhibited the loadings between 0.734 and 0.845, with the Cronbach's Alpha = 0.860, CR = 0.895, and AVE = 0.672, which exceeded the recommended levels. Economic Sustainability showed the loadings from 0.719 to 0.871, with Cronbach's Alpha = 0.878, CR = 0.902, and AVE = 0.661, confirming that the results of the items were both consistent and valid. These values validated the structural soundness of the model and affirm that the items reliably capture the dimensions of sustainability influenced by the computational intelligence.

Table 3: Heterotrait-Monotrait (HTMT) Ratios

Constructs	CI	Env_S	Soc_S	Eco_S
CI				
Env_S	0.721			
Soc_S	0.738	0.745		
Eco_S	0.682	0.621	0.701	

The HTMT (Heterotrait-Monotrait) proportion values presented in the table demonstrated that all the constructs used in the model exhibited strong discriminant validity, as all values were well below the valid threshold of 0.90. The highest HTMT value was between the Social Sustainability and Environmental Sustainability (0.745), indicating a moderate but distinct relationship. The HTMT value between CI and Social Sustainability (0.738) also reflected a meaningful but separate connection. Consequently, the CI and Environmental Sustainability (0.721) and CI and Economic Sustainability (0.682) indicated valid construct differences. The lowest HTMT value was found between the Economic and Environmental Sustainability (0.621), confirming that these constructs measured various aspects of sustainability. Overall, the HTMT analysis confirmed that each of the constructs uniquely contributed to the framework without significant multicollinearity issues.

4.3 Hypothesis Testing

Table 4: Hypothesis Testing

Hypothesis	Path Coefficient	T-Value	P-Value	Result
H1	0.488	6.72	0.000	Supported
H2	0.423	5.89	0.000	Supported
H3	0.407	5.66	0.000	Supported

The structural model results presented in the hypothesis testing table demonstrated that statistically significant relationships exist between the CI and the triple dimensions of sustainability, as conceptualized by the TBL theory. Hypothesis H1, which posits that CI positively impacts environmental sustainability, is strongly supported with a path coefficient of 0.488, a T-value of 6.72, and a p-value of 0.000. This indicated a robust influence of CI technologies, like the AI-powered monitoring systems, smart energy grids, and predictive analytics, on decreasing environmental degradation and enhancing resource utilization in urban contexts. These outcomes validated the environmental component of TBL, emphasizing that the technological integration in smart cities is important for ecological protection and climate resilience.

Hypothesis H2, related to social sustainability, also finds strong support with a path coefficient of 0.423, T-value of 5.89, and p-value of 0.000. This shows that CI tools play a significant role in enhancing the social dimension of urban life by improving public services, citizen engagement, digital governance, and overall quality of life. The implication here is that smart applications such as automated public transport systems, AI-driven health monitoring, and digital inclusion initiatives contribute toward socially sustainable urban environments. This affirms the social pillar of TBL, wherein technological advancement must also serve human well-being, equity, and community development in urban planning.

The economic dimension of the TBL framework is validated through the support of Hypothesis H3, which demonstrates a positive and significant relationship (path coefficient = 0.407, T-value = 5.66, p-value = 0.000) between CI and economic sustainability. This underscores the potential of CI in enhancing cost efficiency, infrastructure maintenance, traffic management, and data-driven policymaking. From a practical standpoint, the implication is that investments in CI not only offer technological upgrades but also create long-term economic value by optimizing city operations. For policymakers and urban planners in Pakistan, these results provide clear evidence that computational intelligence is a strategic tool for balancing environmental protection, social equity, and economic growth, core principles of the TBL model in sustainable urban development.

5. Conclusion, Implications, and Limitations

This study provided convincing evidence of the substantial impact of the CI, which in turn functions in fostering ecological urban development in Pakistan, conforming to the TBL model. The results demonstrated that the CI effectively influenced the ecological, social, and fiscal sustainability, validating its potential as a revolutionary tool in the situation of the smart city projects. By examining the primary data and applying a thorough quantitative method, the study emphasized how CI can improve asset management, increase public service delivery, and stimulate economic efficiency in city environments. As cities in Pakistan struggle with rapid urbanization and environmental issues, the results emphasize the importance of incorporating CI technologies into city planning processes to generate sustainable, resilient cities that present both the current and future generations.

5.1 Implications

From a functional standpoint, the study provided actionable understandings for the policymakers and city planners in Pakistan. It highlights the importance of incorporating the CI into the framework and management of smart cities, recommending funding in AI, Machine Learning, and data analytics to improve the urban systems for sustainability. The conceptual significance of this study contributes to the TBL framework by confirming the connection between technological advancements and sustainability aspects in urban planning. Furthermore, this study enhances the literature by showing how CI can concurrently enhance the environmental, social, and economic sustainability, promoting the TBL theory in the situation of smart cities.

5.2 Limitations and Future Directions

While the study provides useful understandings, it has several constraints that require further exploration. One limitation is the emphasis on the individual country, Pakistan, which may not completely represent the broader global context of smart city expansion and CI integration. Future research could extend the geographical extent to include many countries with various urban problems to validate the generalizability of the results. Additionally, this study depended on the quantitative data from a convenience sample, which may restrict the variety of the responses. Future studies should consider using the longitudinal research designs and bigger, more diverse samples to examine the long-term effects of the CI on urban sustainability. Lastly, examining the specific CI uses in sectors like transportation and healthcare could offer more profound insights into their role in obtaining sustainable urban results.

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