The Moderating Effect of Urbanization on the Link Between Digitalization and Carbon Emissions

Mohd Ashari Bakri[1,*], Masnun Al Mahi[2], and Abdul Rahim Ridzuan[3]

[1]Labuan Faculty of International Finance, Universiti Malaysia Sabah, Labuan, Malaysia
[2]BRAC Business School, BRAC University Dhaka, Bangladesh
[3]Institute for Big Data Analytics & Artificial Intelligence (IBDAAI), Universiti Teknologi Mara, Malaysia

Abstract. Over the past two decades, Asia's economic transformation has driven by digitalization and urbanization, and yet its environmental impact remains insufficiently understood. Using panel data from 22 Asian countries between 2000 and 2021, this study investigates whether internet usage influences carbon emissions and whether urbanization (urban population) amplifies this effect. The results reveal that urbanization intensifies the environmental impact of internet usage (digitalization). Testing for endogeneity concerns using a quasi-natural experiment, the results confirm that the moderating effect persists under stable economic conditions; however, the impact is not prominent during crises such as COVID-19. The discoveries emphasize the growing challenge of integrating digital expansion, rapid urban development, and environmental sustainability. More importantly, the study highlights the need for synchronization between environmental engineering strategies and urban planning methods that align with digital infrastructure. This evidence contributes to the debate on sustainable urban transitions in emerging economies and offers insights into how environmental engineering and urban planning can reduce the environmental pressure of digitalization.

1 INTRODUCTION

The Internet is recognized as a driver of not only productivity but also innovation. However, its environmental effects remain debated among scholars. Internet usage can improve energy efficiency and mitigate emissions through smart technologies. But it relies on energy-heavy infrastructure such as data centers and ICT devices. These can increase carbon emissions (Chen et al., 2023; Wang & Xu, 2021). These contradictory findings demonstrate the need to study the internet–environment nexus.

Urbanization is known as a cause of environmental change. Studies demonstrate that urban population growth changes energy demand, industry structures, and spending habits. This influences carbon emissions in complex ways (Chikaraishi et al., 2015; Kusiyah et al., 2024). Data suggest that urbanization can increase the environmental footprint of human activities, including digital connectivity. This happens due to the concentration of humans and the increasing use of resources. (Zhong et al., 2021; Anochiwa et al., 2022). On the contrary, urbanization can enable economies of scale in infrastructure and support innovation that mitigates environmental harm (Sheng et al., 2019).

Recent empirical findings have used moderation frameworks to illustrate these patterns. For instance, energy services companies (ESCOs) moderate the association between industrialization, urbanization, and emissions in China (Zheng et al., 2021). Additionally, foreign direct investment (FDI) also shown to mitigate lower energy use in BRICS economies. These discoveries show that structural changes can shape environmental results (Balsalobre-Lorente et al., 2022). Another study highlighting a moderating effect shows that renewable energy adoption acts as a moderator by balancing the environmental costs of urban growth (Kusiyah et al., 2024). These studies show that context and structure change the association between economic activities and ecological harm.

Current empirical findings may not have fully explored the environmental effects of internet usage, especially in relation with urbanization. Global data demonstrates that internet use might follow an inverted U-shaped relationship with emissions based on human capital (Wang & Xu, 2021). However, regional empirical studies demonstrate different findings. Internet development in China led to more emissions due to spending changes (Chen et al., 2023). Analysis across varieties of provinces demonstrates that the influence of internet access vary depends on city size (Zhong et al., 2021). On the other hand, mobile phone adoption changed the association between urbanization and emissions in Africa, specifically, it shown to lower carbon intensity in high-emission economies. (Anochiwa et al., 2022). These discoveries imply that the environmental effect of digitalization depends on demographics, spatial, and institutional settings.

* Corresponding author: mohd.ashari@ums.edu.my

This study examined whether urbanization moderates the environmental impact of internet usage across 22 Asian countries from 2000 to 2021. The analysis places internet usage within the wider process of urbanization. This study expands prior research regarding contextual moderators like innovation, FDI, and renewable energy (Sheng et al., 2019; Balsalobre-Lorente et al., 2022; Kusiyah et al., 2024). The findings offer policy guidance for Asian economies in balancing the digital shifts with environmental sustainability. This balance demonstrates the value of a unified plan that ensures a match of technological advancement, urban growth, and environmental sustainability.

2 Literature Review

Urbanization and internet usage effects on environmental sustainability remain widely debated among scholars and practitioners. For instance, Parikh & Shukla (1995) and York et al. (2003) discovered a positive association between urbanization and CO_2 emissions. The study posited that people's migration into cities increases energy demand and pollution, which is also supported by Cole & Neumayer (2004). On the contrary, Martínez-Zarzoso & Maruotti (2011) demonstrated an inverted U-shaped relationship in developing countries, in which emissions are shown to increase at low levels of urbanization and then fall after a threshold. A study by Sadorsky (2014) in emerging economies highlights that the result depends on estimation techniques. The coefficients sometimes demonstrate significant and insignificant relationships, and country-specific evidence shows this variety. Shahbaz et al. (2016) and Ahmed et al. (2019) illustrate a U-shaped relationship in Malaysia and Indonesia, respectively. Whereby Ali et al. (2019) discovered a consistent positive influence in Pakistan. These findings demonstrate that the link between urbanization and emissions highly depends on the context, i.e., income levels, infrastructure, and governance.

Wang & Xu (2021) provide global empirical evidence of a non-linear inverted U-shaped association between internet usage and CO_2 emissions. Specifically, their findings show that internet usage increases emissions when human capital is low. Regional studies by Chen et al. (2023) found different results; the study shows that internet development in China increased emissions due to the increase in consumption. Zhong et al. (2021) demonstrate that urbanization and internet penetration affect sustainability simultaneously, but the effect varies across provinces. A study by Anochiawa et al. (2022) showed that mobile phone use affects the association between urbanization and emissions. Wang et al. (2022) show that the internet lowers emissions directly and indirectly by mitigating traffic demand, in which technological innovation amplifies these effects.

Several studies emphasize that moderators shape the connection between urbanization, the internet, and emissions. Sheng et al. (2019) demonstrate that innovation affects the relationship between urbanization emissions in Chinese city groups. Vinh Le Hoang et al. (2023), through a Southeast Asia perspective, showed that innovative efforts mitigate the positive influence of internet usage on emissions. Balsalobre-Lorente et al. (2022) discovered that FDI mitigate negative effects of energy use in BRICS economies. Whereby, renewable energy is shown to balance the cost of urbanization by Kusiyah et al. (2024). Zheng et al. (2021) demonstrate that urbanization and internet usage effects are not fixed and depend on factors like innovation, FDI, renewable energy, and institutions. Motivated by these various discoveries, this study provides the foundation for examining Asia-wide comparative evidence. Additionally, the minimum number of studies examines urbanization's role in the internet-environment nexus further enhances the contribution to the body of knowledge.

3 Methodology

The analysis covers the years 2000 to 2021 and uses an unbalanced panel of 22 Asian countries. The sample includes major emitters like China, India, Japan, and South Korea. The data also covers fossil fuel–dependent economies such as Saudi Arabia, Qatar, Iran, Iraq, Kazakhstan, Turkmenistan, and Azerbaijan. Rapidly urbanizing nations like Malaysia, Thailand, Vietnam, Indonesia, Bangladesh, the Philippines, and Pakistan are also included. The list also features global hubs like Singapore, Israel, and Turkiye, alongside Central Asian players such as Uzbekistan and Turkmenistan. Together, they represent varied development stages, population densities, and trade integration. The selected sample is crucial in understanding the link between internet adoption, urban growth, and environmental outcomes. Data used in this study were collected from the World Bank and the Our World database. Although the datasets ended in 2021 (due to data availability of the number of people using the internet), the study captures the important stages of internet adoption that reached mass scale across Asia. The structural dynamics in Asia during this period continue to shape current trajectories and ensure the findings remain relevant to ongoing policy and research debates. We measure carbon emissions (dependent variable) in metric tons per capita in natural logarithms. Digitalization proxied by Internet usage is the main independent variable and interacts with urbanization (urban population) to capture moderation effects. Control variables include gross domestic product (GDP), population size, FDI, and trade openness. We log-transformed all continuous variables following Yu et al. (2022) and Bakri et al. (2025). This reduces heteroscedasticity and mitigates outliers. The econometric specification is designed to test whether the level of urbanization conditions affects the internet usage on carbon emissions. The specification in this study is static and emphasizes contemporaneous link rather than cross-year dynamics. This is crucial and appropriate to isolate the moderating effect of urbanization in the digitalization-emission nexus. The baseline model is expressed as:

$$LnCO^{i,t} = \alpha^{i,t} + \beta LnIT^{i,t} + \beta Urban^{i,t} + \beta LnIT^{i,t} \times \beta Urban^{i,t} + \beta LnGDP^{i,t} + \beta LnPop^{i,t} + \beta LnFDI^{i,t} + \beta LnTrade^{i,t} + \mu^{i,t} + \varepsilon^{i,t} \quad (1)$$

Here, terms i, t denote the country and the year. An interaction term shows whether urbanization increases or decreases the internet's impact on emissions. The study considers fixed-effects and random-effects estimators. The Hausman test helps us to determine the best option. We also use robust standard errors to account for heteroskedasticity and serial correlation. The method also reduces bias from missing variables and hidden factors.

4 Results

Table 1 presents the descriptive statistics for the variables in the present research. The mean value of LnCo2 is noted as 1.5597, with observed values between -1.6069 and 11.6168. This suggests that the sample has a diverse range of carbon emissions. As for LnIT, the record is on average 16.0286, and for Urban, the mean is 61.8414, which demonstrate the differences in the levels of urbanization across the surveyed countries. The mean for LnGDP is 9.7017, which indicates the disparity in the income levels of the economies. LnPop, which represents Population, is averaged at 17.6714, and for financial development (LnFDI), the mean is documented as 0.7030. Lastly, for Lntrade, the mean is 4.2276, which indicates a more even balance in trade openness within the sample. Overall, the descriptive statistics demonstrate that the data can provide a range of values for further analysis.

Table 1: Descriptive Statistics

Variable	Observation	Mean	Standard Deviation	Min	Max
LnCo2	550	1.5597	1.1826	-1.6069	11.6168
LnIT	476	16.0286	2.1150	8.7173	20.7645
Urban	549	61.8414	22.1921	23.3145	100
LnGDP	549	9.7017	1.0510	7.6009	14.8656
LnPop	550	17.6714	1.8432	-1.5608	21.0955
LnFDI	516	0.7030	1.2915	-4.7421	4.0087
Lntrade	548	4.2276	0.6067	2.9735	6.0807

Table 2: Correlation Analysis

Variables	$lnCO_2$	LnIT	Urban	LnIT_Urban	LnGDP	LnPop	LnFDI	Lntrade
$lnCO_2$	1							
LnIT	-0.1437***	1						
Urban	0.7805***	-0.0562	1					
LnIT_Urban	-0.1425***	-0.1447***	-0.1042**	1				
LnGDP	0.8343***	-0.0049	0.8865***	-0.1912***	1			
LnPop	-0.6617***	0.6849***	-0.5502***	0.0570	-0.6000***	1		
LnFDI	0.1215***	-0.2870***	-0.0137	-0.1686***	0.067	-0.3881***	1	
LnTrade	0.3178***	-0.2946* **	0.3094***	-0.2100***	0.4527***	-0.5254***	0.5440***	1
VIF	-	4.21	5.64	1.14	7.94	7.01	1.72	2.18

The correlation results show that $LnCO_2$ emissions are strongly and positively associated with urbanization (r = 0.7805) and economic activity (LnGDP; r = 0.8343), indicating that more urbanized and economically larger economies tend to exhibit higher emission levels. Trade openness also displays a moderate positive correlation with emissions (r = 0.3178), while population size is negatively related to CO_2 emissions (r = −0.6617). In contrast, information technology (LnIT) intensity and its interaction with urbanization are negatively correlated with emissions. The correlation structure and VIF values (less than 10) further indicate that multicollinearity is not severe, supporting the suitability of the variables for multivariate regression analysis.

Table 3: Panel Analysis

Variables	Panel A: Pooled OLS	Panel B: Random Effect	Panel C: Fixed Effect
LnIT	-0.0722** (0.0289)	-0.0202 (0.0407)	-0.0296 (0.0453)
Urban	0.0080*** (0.0029)	0.0199*** (0.0074)	0.0201** (0.0074)
LnIT_Urban	-0.0003 (0.0007)	-0.0028*** (0.0010)	-0.0031** (0.0011)
LnGDP	0.8111*** (0.0667)	0.2461 (0.1602)	0.2279 (0.1705)
LnPop	-0.0151 (0.0468)	0.0359 (0.1525)	0.1657 (0.2270)
LnFDI	0.1234*** (0.0297)	-0.0024 (0.0109)	-0.0018 (0.0104)
LnTrade	-0.3507*** (0.0603)	0.1339** (0.0675)	0.1315* (0.0663)
Constant	-4.6463*** (1.2348)	-2.0523 (3.4913)	-4.1804 (4.2762)
Observations	449		
Breusch-Pagan LM test	3621.96 (0)		
Hausman test	2.81 (0.9201)		

Under the random-effects model (validated by the Breusch–Pagan LM and Hausman tests), urbanization significantly increases CO_2 emissions, while internet usage alone shows a weak, non-significant negative effect. More importantly, the interaction term is negative and highly significant, indicating that digitalization within urban settings mitigates the otherwise harmful impact of urbanization. Trade openness also raises emissions, whereas GDP, population, and FDI are not robust drivers. Overall, urbanization amplifies emissions, but internet adoption in urban contexts provides a significant moderating effect.

Table 4: Robustness Check

Variables	Panel A: Pre-COVID-19 (2000-2019)	Panel B: COVID-19 (2020-2021
LnIT	-0.011 (0.0362)	0.2998** (0.1264)
Urban	0.0200*** (0.0073)	0.0060 (0.0092)
LnIT_Urban	-0.0025*** (0.0009)	0.0003 (0.0022)
LnGDP	0.2316 (0.1544)	0.6210*** (0.1870)
LnPop	0.0218 (0.1422)	-0.2711* (0.1507)
LnFDI	0.0013 (0.0095)	-0.0088 (0.0059)
LnTrade	0.1323** (0.0659)	-0.0824 (0.0866)
Constant	-1.6747 (3.1278)	0.5765 (3.7806)
Observation	413	36

Table 4 functions as an endogeneity test. It tests whether the observed relationships are robust to external shocks. If the internet, urbanization, and emissions link were purely causal and stable, it should persist across both periods. Instead, the breakdown during COVID-19 suggests that unobserved crisis-related factors influence the relationship. Thus, the results partially support the hypothesis that under normal conditions, urbanization amplifies emissions, but digitalization moderates this effect. However, under crisis conditions, endogeneity emerges, and the relationship collapses.

5 Discussion

This study provides new evidence on how urbanization increases the environmental impact of internet usage in Asian economies. It places these results within debates on digitalization, emissions, and urban development. Our findings reveal that urbanization worsens the emissions effect of digitalization before COVID-19. But this effect fades during crises. Specifically, structural shocks can break the link between digital, urban, and environmental factors. This matches recent cross-country evidence that digitalization follows an Environmental Kuznets Curve pattern. High-income developing nations use ICT to reduce emissions, whereas low-income economies face infrastructural and institutional barriers that limit such gains (Nasser & Abdelkaoui, 2025). Both spatial context and income level determine the environmental results of digitalization.

Research shows that digitalization and urban growth drive the environment and the economy. Urbanization has mixed effects depending on the timeframe and structural conditions (Li et al., 2024). This dual role complicates policy design. Digital expansion can support growth and sustainability. But this requires alignment with urban planning and institutional capacity. Our Asia-wide results add to this perspective. Urbanization magnifies the environmental costs of internet adoption. Innovation, renewable energy, or governance reforms must balance this effect (Sheng et al., 2019; Kusiyah et al., 2024).

6 Conclusion

In Conclusion, these findings support three main insights. First, the environmental impact of digitalization depends on context. Demographics, space, and income differences shape it. Second, urbanization acts as a conditional amplifier by strengthening or weakening the environmental effect of digitalization based on shocks and policies. Third, sustainable digital growth needs strategies that connect ICT expansion, urban development, and environmental management. Asian economies must tailor policies to city size, income tier, and institutional readiness. They should avoid uniform paths.

The evidence demonstrates that digitalization alone does not create environmental sustainability. Outcomes rely on how urbanization and income structures interact with technology. Policymakers must design distinct strategies. They should support digital inclusion, strengthen urban resilience, and add environmental safeguards. Emerging economies can align modernization with stability by bridging these areas. This helps digital growth contribute to long-term ecological balance.

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