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KEYWORDS	ABSTRACT
Urbanization; Digitalization; PM2.5 exposure; Internet use; Renewable energy; Asian economies; Sustainable urban development	The high level of urbanization in Asia is causing unprecedented pressures on air quality and exposure to PM2.5 is a persistent environmental challenge. Meanwhile, digitalization is booming and it remains uncertain if more digital connectivity is necessarily clean urban growth. The study investigates the moderating effect of digitalization between urbanization and PM2.5 exposure for 12 selected Asian economies from 2000 to 2021. Digitalization is proxied using World Development Indicators: Internet use, as the core control, as well as industrialization and renewable-energy consumption are included, while trade openness is used as the robustness analysis. Heteroskedasticity, serial correlation and cross-sectional dependence are addressed by using fixed-effects estimation with Driscoll–Kraay standard errors. The result indicates that there is a positive and significant interaction between urbanization and digitalization, such that increased digitalization reduces the negative relationship between the urbanization and PM2.5 exposure. This relationship is strongest for low digitalization, weaker for the mean, and not statistically significant for high digitalization levels, in keeping with marginal effects. A higher level of industrialization is linked to an increase in PM2.5 exposure, while an increase in renewable-energy consumption is linked to a decrease in PM2.5 exposure. The results reveal that digital expansion is not enough to ensure clean urban development; it needs to be supported by cleaner energy systems and sustainable urban policies.
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Introduction

One of the most significant elements of economic and social change in Asia has been urbanization. Rapid urban growth can generate significant environmental pressures, while also providing opportunities for increasing productivity, employment, infrastructure, and access to public services. Increasing transportation, building, industrial activity, energy consumption, and population density can all negatively impact air quality. Fine particulate matter with aerodynamic diameter of 2.5 micrometers or smaller (PM_{2.5}) is one of the key pollutants as it is directly linked to air pollution and exposure of human being (Wang, Gillani, Balsalobre-Lorente, et al., 2025). However, the relationship between urbanization and PM_{2.5} is not necessarily consistent. Recent studies indicate that the impacts of urban development may vary over different aspects and phases of urbanization. Huang et al. (2023) analyze 283 Chinese cities and find that urbanization can have both negative and positive impacts on PM_{2.5} and even that the relationship between urbanization and PM_{2.5} changes with different stages of urban development.

This is the variation that should make urbanization a part of a wider source of environmental stress. The environmental impacts of urban expansion may be conditioned on the technical, institutional and structural nature of urban development (Sharif et al., 2026; Xie et al., 2026; Zhang et al., 2026). Digitalization is one condition that keeps on rising. The internet and other information and communication technologies can impact the functioning and activities of households, firms, public agencies, transport, and urban services (Li et al., 2026). Digital technologies can contribute to better access to information, to lower transaction costs, to help monitor the environment, to provide online public services, and to better coordinate transport and energy systems. They can also enable more productive production and enhance governments and firms' capacity to address environmental issues (Sun et al., 2025).

There is some empirical evidence for these potential benefits. Chatti and Majeed (2022) conclude that the use of ICTs in urban areas can be beneficial to improving environmental quality through a panel of developed and developing economies. Meanwhile, they demonstrate that the environmental advantage is comparatively low in developing economies, pointing to the potential impact of digitalization being tied to the broader development setting. Likewise, the empirical evidence of Chinese cities suggests the Internet development can also be a positive influence on the environmental quality, and notable spatial spillovers of PM_{2.5} in urban areas. The results reveal that digitalization can have direct impacts on environmental outcomes, though it is possible for this impact to be different depending on the local economic and institutional environment (Sui et al., 2026).

Recent research has further increased the focus on the link between digital development and air pollution. Wei et al. (2024) study how digital-economy development affects PM_{2.5} pollution in China and reveal that digitalization is a risk-reduction leverage for pollution, where industrial structure optimization and green innovation are key channels. They also find significant variations in the level of digitalization between economic subregions and urban agglomerations, reflecting spatial variation in the digitalization-pollution relationship. Yuan et al. (2024) find that digital-

economy development also can alleviate environmental pollution via the panel data of 267 cities in China from 2012 to 2021, and they stress the significance of spatial effect. Overall, these studies point to a growing role for digitalization in the environmental performance, especially in the dynamic city economy.

However, digitalization does not necessarily have a positive impact on the environment. Digital infrastructure will need electricity, and increased digital connectivity can drive electricity consumption, delivery services, logistics, data storage and demand for electronic devices. The environmental impacts of ICTs might, therefore, be dependent on the energy structure and level of development. Indeed, Huang et al. (2022) report significant differences in the E-7 and G-7 economies. The association between ICT and ecological pressure is higher in the E-7 group while the association between environmental outcomes and ICT is higher in the G-7 group. Their results show that environmental impacts of digital development are highly dependent on the context. This mixed evidence makes it hard to predict a priori that greater digitalization will lead to a greenification of urbanization.

Hence, an important gap exists in the existing literature. The direct link between the rise of urbanization and environmental pollution has been a topic of study for a long time, and there is an increasing literature on the independent impact of digitalization on environmental quality. Less research was conducted on the effect of digitalization on the urbanization-PM_{2.5} exposure relationship. This is significant, as digitalization can also have a direct environmental impact, and can also change the relationship between urban development and pollution. Chatti and Majeed (2022) show that, while ICT can be linked to urbanization in influencing its outcomes, the linkage is stronger in developing economies compared to its developed counterpart. It is therefore useful to conduct an examination of this moderating role in the wider Asian context.

Another shortcoming of the recent literature is the heavy focus on the data at the city level in China. Studies by (Huang et al., 2023; Wei et al., 2024; Zhong et al., 2021) and Yuan et al. (2024) offer insights that are specifically applicable to cities in a single national institutional setting. There is significant variation between Asian economies in terms of income, industrial structure, consumption of renewable energy, urbanization, digital connectivity, and governance of the environment (Wang, Gillani, Sharif, et al., 2025). The moderating effect of digitalization can thus be further explored using a multi-country view up to whether it goes beyond the China city-level variation.

In the context of this background, this study aims to investigate the interaction between the urbanization process and PM_{2.5} exposure in the selected Asian economies for the 2000–2021 period, while accounting for the effect of digitalization. The percentage of urban residents is used to measure urbanization, and the percentage of people using the Internet is used to proxy digitalization. In addition to the baseline controls of industrialization and consumption of renewables, trade openness is added in the robustness specification. This analysis is not causal, but rather investigates statistical associations. The final model is estimated with country and year fixed effects and Driscoll–Kraay standard errors due to heteroskedasticity, serial correlation, and cross-sectional dependence.

The study has three key contributions. First, it links the literature on urbanization and air pollution to the increasing literature on digitalization and environmental quality. Secondly, it focuses on digitalization as a moderator and not just as a standalone explanation variable. Third, it offers evidence from a multi-country Asian panel, complementing the recent focus of research on Chinese cities. This is especially so, as the environmental effects of digitalization can be related to variations in economic structures, energy systems and urban development stages.

The rest of this paper is organized as follows. In Section 2, the pertinent literature is reviewed and the hypotheses are formulated. The data, variable measurement, model specification and econometric approach are presented in Section 3. In Section 4 the empirical results are reported including the descriptive evidence, the panel diagnostics, the unit root tests, the main estimates, the robustness analysis and the marginal effects. The results are presented in Section 5 and policy implications, limitations, and avenues for future research are presented in Section 6.

Literature Review

Urbanization and Air Pollution

Air pollution has the potential to be affected by urbanization in several competing ways. Population and economic activity become denser and thus more demand is created for housing, transport, building, electricity and industrial production. In urban areas, environmental regulation is limited, and urban expansion can lead to increasing particulate emissions, if such activities are highly dependent on fossil fuels. Meanwhile, the development of cities can be advanced, which can help to enhance public transport, improve infrastructure, environmental monitoring, energy consumption and access to cleaner technologies). Urbanization's impact on the environment will, therefore, vary by country and by level of development (Wang et al., 2024).

Empirical studies in recent years have confirmed this idea. Based on information from 283 Chinese cities, Huang et al. (2023) demonstrated that various aspects of urbanization have varying effects on PM_{2.5} levels. Air pollution is influenced differently by population, economic, social, spatial and ecological urbanization and some impacts of urbanization even reverse in their direction of action with increasing level of urbanization. The authors' results show that the urbanization–PM_{2.5} relationship is multi-dimensional and stage dependent. Spatial structure of cities also is important. Researchers in China have analyzed the PM_{2.5} pollution levels of 369 cities and have discovered that increased polycentricity is correlated with increased air pollution, but that this strengthens the link only up to a certain number of people. Urban development can have additional effects on the environment. According to the research of 174 Chinese cities, infilling growth has shown to diminish air pollution in some cases, but compact growth and urban shrinkage have shown to cause air pollution under certain conditions. The findings support the larger premise about the environmental impact of urbanization that the effects of urbanization are not just about the share of the population living in urban areas but are also a function of the nature of urbanization.

Previous research on cross country confirmed these findings. Chatti and Majeed (2022) assert that uncontrolled urbanization is likely to decrease the strength of environmental protection, but the use of appropriate information and communication technology can partly mitigate the environmental costs. They found that there are also significant disparities between developed and developing economies in their findings. This diversity is significant especially in Asia, where there are marked variations between countries in their urban infrastructure, industrial characteristics, energy systems and economic development.

Thus, the evidence is not sufficient to conclude that urbanization should always be accompanied by an increase in PM_{2.5}. For more developed urban systems, technological, infrastructure, environmental regulation and energy efficiency can decrease the pollution density of urban growth (Yang et al., 2025; X. Yang, M. N. Shafiq, A. Sharif, et al., 2024). The direction of the average urbanization effect is left as an empirical question because the countries and regions in the present sample are at different stages of urbanization transformation.

H1: Urbanization is significantly associated with PM_{2.5} exposure in selected Asian economies.

Digitalization and Air Pollution

The importance of digitalization in the environmental-economics literature is growing. Digital technologies can have an impact on environmental quality in a number of ways: better information flows, better resource allocation, better production efficiency, better logistics, better environmental monitoring and access to government services. Green innovation and industrial upgrading could also be achieved through digital platforms. Digitalization, however, can have environmental costs, such as increased electricity demand, data infrastructure, production of electronic devices, use of the internet and delivery activity. It is not always a positive environmental impact, however. There is specific evidence from the Internet development that benefits the environment in many settings. Based on the data of 283 Chinese cities, Zhong et al. (2021) show that Internet development has a positive effect on urban environmental quality, and that PM_{2.5} pollution shows significant spatial spillovers. They are also able to recognize nonlinear and heterogeneous effects, which means that the relationship will change depending on local conditions.

Later studies have shifted from simple metrics of Internet access to larger ones of the digital economy. Yuan et al. (2024) examine the environmental impacts of the development of the digital economy in 267 cities in China from 2012 to 2021 and conclude that digital-economic development lowers environmental pollution, particularly in central cities. Their findings show: market development, green technological innovation and industrial upgrading are relevant channels. In the same vein, Li and Yang (2024) based on 285 cities, find that the development of the digital economy has a positive impact on urban environmental quality and that this impact is different in various regions.

The relationship is more significant for PM_{2.5}, Wei et al. (2024) conclude that the digital economy plays a significant role in China's PM_{2.5} mitigation. From the analysis, they find that the spatial spillover effect is greater than the direct local effect, and industrial-structure optimization

and green innovation is an important channel. This is also reflected in the strength of these relationships across economic subdivisions and urban agglomerations. It implies that, digital development could have an impact on pollution outside the area where digital investment is being put.

Expansive studies based on more comprehensive environmental measures yield similar results. Lai et al. (2024) analyze China's national comprehensive pilot zone for big data and conclude that the development of the digital economy has a positive effect on city eco-efficiency, which partly manifests in the reduction of the misallocation of resources and the promotion of green technological progress. They also indicate that the impact is more pronounced in the old industrial cities, resource-based cities, and the energy intensive cities. Liu et al. (2024) not only show that the digital economy is beneficial for sustainable development of cities, but also reveal its potential in green innovation and human-capital improvement, and environmental regulation is an important threshold effect.

Further evidence from recent space is also based on the idea that digitalization has impacts outside the city. Based on 284 prefecture-level cities in China, S. Yang et al. (2024) find that the development of the digital economy can enhance urban sustainable development and create spatial spillovers of its development beyond the boundary of the urban region. They also detect more intense effects in China's eastern parts and in the country's big urban centers. The study of Wang and Xue (2023) at the provincial level indicates that the development of the digital economy has a positive impact on green total factor productivity, though this impact differs between coastal and inland areas, and partly on technological innovation and institutional conditions. Likewise, Lian et al. (2024) find that a positive effect of digital development on green total factor productivity is also observed and that digital development both reinforces the positive effect of environmental regulation and vice versa.

Nevertheless, the evidence in this field is still largely positive, but new studies warn not to take digitalization for granted as automatically environmentally positive. Inverting the U relationship, Kang et al. (2025) find an inverted-U relationship for 272 cities in China. Most importantly, the way digital technology and urban form, city size, connectivity and economics interact can exacerbate pollution under certain conditions. The relevance of this evidence for the present study lies in the fact that it implies that the environmental impact of digitalization could be linked to the interplay with other structural features. Therefore, the direct association of digitalization with PM_{2.5} is considered one that may be relevant in some countries, but not necessarily in others.

H2: Digitalization is significantly associated with PM_{2.5} exposure in selected Asian economies.

Moderating Role of Digitalization

The main research question of this study is whether the digitalization alters the correlation between urbanization and exposure to PM_{2.5}. This is not a question of whether or not to use the Internet to directly improve the air quality. A moderator affects the magnitude or direction of the relationship between two other variables. Digitalization could change the effects of urbanization

in the current context. The pollution cost of urbanization might be reduced through digitalization via a number of mechanisms. Digital technologies can enhance the coordination of traffic, the monitoring of the environment, energy management, delivery of public services and information sharing (Gillani et al., 2026). They can also stimulate the upgrading of industries and green innovation (Nazir et al., 2023). Wei et al. (2024) prove that digitalization can decrease the PM_{2.5} levels partly by optimizing industries and innovating technologies. Lai et al. (2024) also demonstrate the benefits of eco-efficiency that can be achieved by resource reallocation and green technological development. These mechanisms imply that urban growth taking place in a more digitally developed environment could, in principle, generate less pollution than similar urban growth in a less digitally connected economy.

There is direct support from Chatti and Majeed (2022) to consider this interaction. They find that ICT uptake in cities can be beneficial for the environmental performance and that it can partly shape the environmental impacts of urbanization as they cross-nationally analyze the effects. But they also discover that these advantages are significantly lower in developing countries. In addition to being connected digitally, energy structure, institutions, technology, and income level are also crucial (Nazir et al., 2026; Yang et al., 2026). New data support regarding the moderation as an empirical instead of an a priori relationship. Under certain circumstances, the coupling of digital technology and urban attributes can exacerbate PM_{2.5}, according to (Kang et al., 2025). Digitalization can lead to an increase in electricity consumption, delivery activity, freight traffic, need for electronic equipment and data processing requirements. Such gains in efficiency due to the use of digital technologies could partially be realized at the expense of increased energy and transport demand, especially if these activities are reliant on carbon- and pollution-intensive energy systems.

Thus, there is no clear theoretical impact. While urban digitalization is a potential solution to manage urban congestion, resources, emissions and infrastructure more efficiently, it also has the potential to generate rebound effects and offset the positive environmental benefits. This uncertainty is particularly pertinent to economies in Asia, where the adoption of digital technologies has been swift, while electricity systems, industrial architecture and environmental governance is very uneven. The present study thus does not impose a directionality moderation hypothesis.

H3: The relationship between urbanization and PM_{2.5} exposure is significantly moderated by digitalization in the selected economies of Asia.

Research Gap

The literature has developed quickly but some gaps still exist. First, many of the recent studies on digitalization and PM_{2.5} are conducted at the provincial or the prefecture level of Chinese cities. The studies conducted by (Huang et al., 2023; Li & Yang, 2024; Wei et al., 2024; Yuan et al., 2024; Zhong et al., 2021) and Kang et al. (2025) offer useful evidence, but are carried out in a single national institutional and policy context. Second, the majority of studies explored a direct environmental impact of either urbanization or digital development. Fewer studies explicitly

address how digitalization affects the urbanization–pollution relationship itself. It is important because a statistically weak direct digitalization effect does not preclude the possibility of an important moderating effect. Third, there is growing evidence that there are heterogeneity, thresholds, nonlinearities, and spatial spillovers. This is because the idea that digitalization will automatically lead to cleaner urban development is overly simplistic. This is an interesting question when it comes to the Internet, as many countries in Asia have varying degrees of Internet penetration, urbanization, industrialization, renewable energy use, and economic development. The current study aims to fill these gaps by exploring how the relationship between urbanization and PM2.5 exposure varies by the 12 selected Asian economies between 2000 and 2021. The study gives a new test to the interaction between digitalization and the positive environmental effects of urban development, rather than assuming that digitalization has to help strengthen them.

Data and Methodology

Data and Sample

This study employs annual panel data for the 12 selected Asian economies between 2000 and 2021. These countries include Bangladesh, China, India, Indonesia, Japan, South Korea, Malaysia, Pakistan, the Philippines, Thailand, Türkiye and Vietnam. The sample was carefully selected to include significant urbanization and digital connectivity, industrial structure, renewable-energy use, and PM2.5 exposure. Data sources are World Development Indicators (WDI) provided by the World Bank. The PM2.5 indicator reflects the national level of exposure to ambient PM2.5 based on population weighting, including urban and rural populations.

Variable Measurement

The dependent variable is the natural logarithm of the mean annual exposure to PM2.5 (lnPM25). The urbanization rate (URB, the proportion of the population living in urban areas) is the major explanatory variable. Before creating the interaction term, mean-centering provides the advantage of making the interpretation of the constituent terms easier and reduces non-essential multicollinearity between the interaction and the constituent terms.

Table 1: Variable Measurement

Variable	Symbol	Measurement
PM2.5 exposure	PM2.5	PM2.5 air pollution, mean annual exposure ($\mu\text{g}/\text{m}^3$), population-weighted national exposure
Urbanization	URB	Urban population (% of total population)
Digitalization	INT	Individuals using the Internet (% of population)
Industrialization	IND	Industry (including construction), value added (% of GDP)
Renewable energy	RNE	Renewable energy consumption (% of total final energy consumption)
Trade openness	TRD	Trade in goods and services (% of GDP)
GDP per capita	GDP	GDP per capita (constant 2015 US\$)

Population density	POPD	Population density (people per km ² of land area)
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Note. All indicators are from the World Bank's World Development Indicators (WDI).

Model Specification

The baseline model is:

$$\ln PM25_{it} = \beta_0 + \beta_1 URB_{it} + \beta_2 INT_{it} + \beta_3 (URB \times INT)_{it} + \beta_4 IND_{it} + \beta_5 RNE_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where i denotes country and t denotes year, μ_i represents country specific effects and λ_t represents a common year shock. The coefficient β_3 is the most important coefficient to observe. If the interaction is found to be statistically significant, it means that the link between urbanization and PM2.5 vary at the different levels of digitalization.

Econometric Strategy

The fixed-effects estimator is utilized because the unobserved country-specific characteristics are likely to be correlated with regressors. Fixed effects are also supported by the Hausman test, but with a caveat as the test gave a warning about a covariance matrix. The diagnostic tests show groupwise heteroskedasticity, first order serial correlation and cross-sectional dependence. The Modified Wald test is significant, the Wooldridge test does not reject any first-order autocorrelation and the Pesaran (2007) CD test does not reject cross sectional independence. Thus, the final model is based on fixed effects and Driscoll–Kraay standard errors (Driscoll & Kraay, 1998), and with a lag length of one. This estimator is used widely in panel settings where there is heteroskedasticity, serial correlation, cross sectional dependence and, recently, in environmental applications.

As there is cross sectional dependence, second generation CADF/CIPS unit-root tests are also conducted. The levels of urbanization are not stationary; the levels of PM2.5 and Internet use and after the first difference as well as the levels of industrialization and renewable energy. In direct unit root testing, extra care should be taken when testing for unit roots in the presence of population density and constructed interaction. The study therefore does not make causal interpretations about the end level estimates, but rather panel associations, conditional to the other variables being held constant.

Empirical Results

Descriptive Statistics and Correlations

The descriptive statistics are presented in Table 2. The mean value of $\ln PM2.5$ is 3.410 and the mean urbanization is 52.43%. Internet usage ranges from 7.79% to 76.19% among the population, with significant differences in use between countries and years. Industrial-value added accounts on average for 33.17% of GDP and renewable-energy use accounts on average for 24.29% of total final energy use. The variations are adequate in terms of cross-country and time-series differences for the analysis of the moderating effect of digitalization.

Table 2: Descriptive Statistics

Variable	N	M	SD	Minimum	Maximum
lnPM2.5	264	3.410	0.488	2.419	4.373
URB	264	52.425	20.951	23.315	91.874
INT	262	35.800	29.931	0.071	97.571
IND	264	33.172	7.609	17.159	48.530
RNE	264	24.292	16.181	0.700	60.200
TRD	264	71.526	46.188	19.275	220.407

The correlation matrix results presented in Table 3 that indicate the urbanization, Internet use and industrialization were negatively correlated with lnPM2.5, and renewable-energy consumption, was positively correlated and the mean VIF is 3.98.

Table 3: Pairwise Correlations and Variance Inflation Factors

Variable	1	2	3	4	5	6	VIF
lnPM2.5	1.000						—
URB	-.775***	1.000					8.24
INT	-.641***	.815***	1.000				3.54
IND	-.325***	.111	.095	.203***	1.000		1.60
RNE	.666***	-.863***	-.785***	-.917***	-.339***	1.000	6.75
TRD	-.294***	.009	.176**	.106	.544***	-.262***	—

*Note. Correlations are based on the original variables, mean VIF = 3.98, ** $p < .01$, *** $p < .001$.*

Model Selection and Diagnostic Tests

The preliminary model is fixed-effects, suggesting very high level of country-specific heterogeneity, and the joint test of country effects is very significant. The Hausman test also confirms the rejection of the null of systematic similarity between the fixed- and random-effects estimates, but with a caveat: the warning in the covariance-matrix test suggests the result should be taken with a grain of salt. More diagnostics result in strong inference that presented in Table 4. The Modified Wald test identifies groupwise heteroskedasticity, the Wooldridge test identifies first-order serial correlation and the Pesaran CD test indicates cross-sectional dependence. The results confirm the use of fixed effects and Driscoll-Kraay standard errors.

Table 4: Panel Diagnostic Tests

Test	Statistic	p
Modified Wald: groupwise heteroskedasticity	$\chi^2(12) = 62.11$	< .001
Wooldridge: first-order serial correlation	$F(1, 11) = 10.891$	.007
Pesaran CD: cross-sectional independence	$CD = -3.185$	.0014
Average absolute off-diagonal residual correlation	0.356	—

Note. The joint presence of heteroskedasticity, serial correlation, and cross-sectional dependence motivates the use of fixed effects with Driscoll–Kraay standard errors for the main specification

Unit-Root Results

The CADF/CIPS tests show mixed orders of integration that presented in Table 5. The levels of urbanization, lnPM2.5, Internet use, industrialization, and renewable energy, and PM2.5 become stationary after first differencing.

Table 5: CADF/CIPS Unit-Root Results

Variable	Level	p	1st-diff.	p	Order of integration
lnPM2.5	−0.102	.459	−6.326	< .001	I(1)
URB	−6.074	< .001	—	—	I(0)
INT	1.113	.867	−1.846	.032	I(1)
IND	−0.911	.181	−4.184	< .001	I(1)
RNE	1.545	.939	−3.409	< .001	I(1)

Note. Tests use one lag and a constant.

Main Regression Results

Table 6 reports the final fixed-effects estimates with Driscoll–Kraay standard errors. Urbanization has a negative and statistically significant coefficient, whereas the direct effect of digitalization is negative but statistically insignificant. The most important result is that the urbanization–digitalization relationship is positive and statistically significant. This validates H3 and suggests that the urbanization–PM2.5 relationship is altered due to digitalization. Renewable-energy consumption is negatively associated with PM2.5, and industrialization has a positive and significant association with PM2.5. The results are in line with the hypothesis that industrial growth is likely to lead to higher pollution pressure, and a reduction in exposure to PMs is correlated with cleaner use of energy.

Table 6: Main Fixed-Effects Estimates with Driscoll–Kraay Standard Errors

Variable	Coefficient	DK SE	t	p
URB	−0.004483*	0.002140	−2.10	.048
INT	−0.000654	0.001369	−0.48	.638
URB × INT	0.000116**	0.000036	3.23	.004
IND	0.012230**	0.003770	3.24	.004
RNE	−0.007664**	0.002022	−3.79	.001

*Note. Dependent variable = lnPM2.5. Driscoll–Kraay standard errors are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. *p < .05. **p < .01.*

Robustness and Marginal Effects

The robustness model incorporates the indicator of trade openness that finding presented in Table 7. The interaction coefficient is almost the same as 0.0001164 and statistically significant at 1%,

whereas trade is not significant. This means that the moderating effect does not change significantly when we add the trade openness.

Table 7: Robustness with Trade Openness

Variables	Coefficient	DK SE	t	P
URB	-0.004305	0.002261	-1.90	.071
INT	-0.000819	0.001474	-0.56	.584
URB × INT	0.000116**	0.000036	3.22	.004
IND	0.010370*	0.004113	2.52	.020
RNE	-0.007377**	0.001897	-3.89	.001
TRD	0.000632	0.000656	0.96	.346

Note: * $p < .05$. ** $p < .01$

The marginal effects give a better interpretation that presented in Table 8. The impact of urbanization is negative and significant at low digitalization. It is still negative, but milder, at the mean level of digitalization. The effect is not very strong at high digitalization and is not statistically significant. Overall, digitalization does not make the urbanization effect more negative. However, as the degree of digitalization increases, this negative correlation between urbanization and PM2.5 becomes increasingly weak until it is not measurably different from zero.

Table 8: Marginal Effect of Urbanization across Levels of Digitalization

Digitalization level	Marginal effect	SE	t	p
Low digitalization (-1 SD)	-0.007959**	0.001978	-4.02	.001
Mean digitalization	-0.004483*	0.002140	-2.10	.048
High digitalization (+1 SD)	-0.001007	0.002751	-0.37	.718

Note. Marginal effects are calculated from the final Driscoll–Kraay fixed-effects model. Low and high digitalization correspond to one standard deviation below and above the sample mean of Internet use ($SD = 29.9308$). The negative urbanization–PM2.5 association weakens as digitalization rises. * $p < .05$. ** $p < .01$.

Discussion

The findings support the hypothesis that the urbanization–PM2.5 exposure relationship is dependent on the degree of digitalization. The relationship between urbanization and PM2.5 is negative and significant at the mean value of digitalization, which lends credibility to the hypothesis H1. This finding should not be taken as an indicator of the pollution mitigating effect of urbanization. Instead, it follows the idea that environmental impacts from urbanization are different when it is at various stages and in different forms (X. Yang, M. N. Shafiq, R. Nazir, et al., 2024). For instance, according to Huang et al., (2023) urbanization in different dimensions and stages may have positive or negative impacts on PM2.5.

The direct effect of Internet use is negative, although not statistically significant, and is not supported by the final model (H2). While this is in contrast to a number of recent studies at city level that find a direct pollution-reducing effect of digital development. The digital economy not only alleviates environmental pollution in 267 cities in China but also demonstrates a significant decrease in PM_{2.5} pollution related to the development of the digital economy, partly due to industrial optimization and green innovation (Wei et al., 2024; Yuan et al., 2024). A possible reason for the difference might be measurement. While many recent studies rely on composite digital-economy indices reflecting aspects of infrastructure, digital industries, finance and more, the present study relies on Internet penetration as a broad proxy for digitalization. This cross-country context of the study also yields more variation in terms of energy systems and economic structures compared to single-country city panels.

The most important finding is on the interaction term. The positive and significant coefficient strengthens H3, indicating that the negative urbanization-PM_{2.5} relationship weakens with an increase in digitalization. This is reinforced by the marginal effects. The estimated urbanization is at low digitalization, -0.00796; at mean digitalization, -0.00448; and at high digitalization, -0.00101, and not statistically significant. This therefore does not validate the general assumption that the more connected digital societies are, the more positive the impact of urbanization on the environment.

This is significant in the context of the recent evidence. Kang et al. (2025) demonstrate that the individual effect of digital technology on PM_{2.5} can be nonlinear, and that the combined effects of digital technology with urban size, compactness, connectivity and other socioeconomic factors can exacerbate pollution. So, digitalization can create efficiency gains and at the same time use up more electricity, logistical resources and internet consumption, and so on. These mechanisms are not directly identified in the present results; however, the present results indicate that digital connectivity should not be considered as a *de facto* mechanism for clean urban development.

The control variables also yield valuable results. Industrialization is positively related with PM_{2.5}, while Renewable Energy consumption has significant negative association. The renewable-energy finding is in line with (Chen et al., 2023), who discover a decrease in air pollution in China that comes with the deployment of renewable energy, and Xie et al. (2023), who uncover significant air-quality benefits from large-scale renewable deployment. In general, the results indicate that digitalization alone does not definitively influence the environmental aspects of digital development but rather the urban, industrial and energy environments (Jiang et al., 2026).

Conclusion and Policy Implications

Conclusion

This paper investigates whether urbanization-PM_{2.5} exposure relationship is altered by digitalization in 12 selected Asian economies from 2000 to 2021. The analysis involves country and year fixed effects and Driscoll Kraay standard errors, which account for heteroskedasticity, serial correlation and cross-sectional dependence. The results indicate that at a medium level of

digitalization, the negative effect of urbanization is statistically significant, while the direct effect of use of the Internet is not. The main finding is the positive and significant interaction between urbanization and digitalization. The results of marginal-effect estimation reveal that the relationship between urbanization and PM_{2.5} is negative and significant at low digitalization, negative and less significant at the mean digitalization, and insignificant at high digitalization.

The results of this study show that digitalization does not necessarily make environmental gains from urban development more robust. Rather, its impact seems to be related to the overall economic and energy system. The findings thus lead to a more nuanced narrative on digitalization: more connectivity can open up opportunities for cleaner urban governance, but not a foregone certainty. Renewable energy consumption is significantly negatively associated with PM_{2.5}, whereas the industrialization is positively associated with PM_{2.5}. This further confirms the need to take into account industrial and energy aspects when assessing the impact of urban and digital transition.

Policy Implications

These findings indicate that digital expansion should not be seen as a policy in and of itself. The positive impacts of greater Internet penetration on access to information and ability to provide intelligent services will be dependent on the way digital technology will be paired with transport, energy, industrial and environmental policies, but the environmental impact is also probable.

For one, digitalization needs to be more closely tied to environmental management. Digital platforms can be implemented to facilitate real-time pollution monitoring, traffic management, public transport coordination, energy-efficiency programs and environmental information systems. The goal should be to make a contribution to the environmental efficiency of urban development by leveraging digital infrastructure instead of connectivity.

Second, the high positive relationship between industrialization and PM_{2.5} suggests the need for cleaner industrialization. Policies promoting energy efficiency, cleaner technologies, upgrading industry, and improved emission controls can mitigate the pollution pressure of economic growth.

Third, the negative linkage between renewable-energy usage and PM_{2.5} has implications for increased incorporation of renewables in urban and industrial systems. This aligns with recent research showing that, besides carbon savings, the deployment of renewable energy can also provide substantial air-quality benefits (Chen et al., 2023; Xie et al., 2023).

Policies need to take into account variations in countries. Sample economies have markedly different levels of development, digital infrastructure, and energy structure, as well as urban conditions. It is therefore improbable that a uniform digital or urban strategy will have the same environmental impact across the board.

Limitations and Future Research

There is certain caution to be considered. First, Internet use is a general measure of digitalization and does not reflect specific aspects like digital infrastructure quality, artificial intelligence,

digital finance, smart-city investments or e-government. Multidimensional digital-development indices could be used in future studies. Second, PM_{2.5} is not specifically urban PM_{2.5}. The results would be more spatially explicit if the future research were conducted with the city-level or the satellite-based pollution data. Third, the study looks for associations and not causal relationships. Endogeneity cannot be ruled out entirely, although some kinds of omitted-variable bias are eliminated by country and year fixed effects.

Lastly, the sample comprises 12 countries, which is rather small. Research can be expanded to a more robust sample of Asian or developing countries and explore if the impact of digitalization on the moderating effect varies by income level, energy structure, institutional quality, and degree of urbanization. In conclusion, the evidence indicates that digitalization should be considered as a component of the urban and environmental transition and cannot be regarded as a solution to air pollution. The environmental value is linked to the effectiveness of digital development linked with the use of cleaner energy, industrial transformation and sustainable urban management.

References

- Chatti, W., & Majeed, M. T. (2022). Information communication technology (ICT), smart urbanization, and environmental quality: Evidence from a panel of developing and developed economies. *Journal of Cleaner Production*, 366, 132925. <https://doi.org/10.1016/j.jclepro.2022.132925>
- Chen, X. H., Tee, K., Elnahass, M., & Ahmed, R. (2023). Assessing the environmental impacts of renewable energy sources: A case study on air pollution and carbon emissions in China. *Journal of Environmental Management*, 345, 118525. <https://doi.org/10.1016/j.jenvman.2023.118525>
- Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *The Review of Economics and Statistics*, 80(4), 549–560. <https://doi.org/10.1162/003465398557825>
- Gillani, S., Wang, F., Sharif, A., Rexhepi, G., & Shafiq, M. N. (2026). The Role of Environmental Concern in Shaping Support for Green Business Practices: Evidence From the World Values Survey. *Business Strategy and the Environment*. <https://doi.org/10.1002/bse.70852>
- Huang, Y., Haseeb, M., Usman, M., & Ozturk, I. (2022). Dynamic association between ICT, renewable energy, economic complexity and ecological footprint: Is there any difference between E-7 (developing) and G-7 (developed) countries? *Technology in Society*, 68, 101853. <https://doi.org/10.1016/j.techsoc.2021.101853>
- Huang, Z., An, X., Cai, X., Chen, Y., Liang, Y., Hu, S., & Wang, H. (2023). The impact of new urbanization on PM_{2.5} concentration based on spatial spillover effects: Evidence from 283 cities in China. *Sustainable Cities and Society*, 90, 104386. <https://doi.org/10.1016/j.scs.2022.104386>
- Jiang, W., Shafiq, M. N., Gillani, S., & Saeed, M. (2026). Green electricity adoption as a catalyst for mitigating the ecological pressure of economic complexity in BRICS economies. *Scientific Reports*. <https://doi.org/10.1038/s41598-026-65971-x>

- Kang, T., Zhao, J., Li, Z., Han, Q., & Ding, F. (2025). Unraveling PM2.5 pollution drivers through digitalization-climate-urban form interactions in Chinese cities. *Environmental Technology & Innovation*, 40, 104515. <https://doi.org/10.1016/j.eti.2025.104515>
- Lai, A., Li, Z., Hu, X., & Wang, Q. (2024). Does digital economy improve city-level eco-efficiency in China? *Economic Analysis and Policy*, 81, 1198–1213. <https://doi.org/10.1016/j.eap.2024.02.006>
- Li, D., Bhatti, M. A., & Shafiq, M. N. (2026). Digital transformation, governance, and economic growth: a dynamic panel and quantile regression analysis. *Humanities and Social Sciences Communications*, 13(1), 1388. <https://doi.org/10.1057/s41599-026-08295-5>
- Li, H., & Yang, Z. (2024). Does digital economy development affect urban environment quality: Evidence from 285 cities in China. *PLOS ONE*, 19(2), e0297503. <https://doi.org/10.1371/journal.pone.0297503>
- Lian, Y., Dong, H., & Cao, H. (2024). The effect of digital economy and environmental regulation on green total factor productivity: Evidence from China. *Global Finance Journal*, 62, 101010. <https://doi.org/10.1016/j.gfj.2024.101010>
- Liu, Y., Xie, Y., & Zhong, K. (2024). Impact of digital economy on urban sustainable development: Evidence from Chinese cities. *Sustainable Development*, 32(1), 307–324. <https://doi.org/10.1002/sd.2656>
- Nazir, R., Gillani, S., & Shafiq, M. N. (2023). Realizing direct and indirect impact of environmental regulations on pollution: A path analysis approach to explore the mediating role of green innovation in G7 economies. *Environmental Science and Pollution Research*, 30(15), 44795–44818. <https://doi.org/10.1007/s11356-023-25399-6>
- Nazir, R., Gillani, S., Shafiq, M. N., Nasrullah, M. J., & Shahzad, M. F. (2026). Fiscal and monetary policy for green growth: the role of institutional quality in South Asia. *Environment, Development and Sustainability*, 1–35. <https://doi.org/10.1007/s10668-026-07422-1>
- Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, 22(2), 265–312. <https://doi.org/10.1002/jae.951>
- Sharif, A., Shafiq, M. N., Gillani, S., Harymawan, I., & Cahyono, S. (2026). Industrial robot adoption and environmental sustainability: Technological and institutional pathways to sustainable development. *Technological Forecasting and Social Change*, 233, 124874. <https://doi.org/10.1016/j.techfore.2026.124874>
- Sui, X., Sun, Z., Gillani, S., & Shafiq, M. N. (2026). FinTech and resource utilization: a governance-driven approach to managing ecological footprint in top emerging markets. *Humanities and Social Sciences Communications*. <https://doi.org/10.1057/s41599-026-08446-8>
- Sun, X., Dong, Y., Shafiq, M. N., Gago-de Santos, P., & Gillani, S. (2025). Economic policy uncertainty and environmental quality: unveiling the moderating effect of green finance on sustainable environmental outcomes. *Humanities and Social Sciences Communications*, 12(1), 801. <https://doi.org/10.1057/s41599-025-05212-0>
- Wang, F., Gillani, S., Balsalobre-Lorente, D., Shafiq, M. N., & Khan, K. D. (2025). Environmental degradation in South Asia: Implications for child health and the role of institutional quality and globalization. *Sustainable Development*, 33(1), 399–415. <https://doi.org/10.1002/sd.3124>

- Wang, F., Gillani, S., Razzaq, A., Nazir, R., Shafiq, M. N., & Li, B. (2024). Synergistic impacts of technological advancement and environmental hazards on social change and human well-being in South Asia. *Technological Forecasting and Social Change*, 208, 123721. <https://doi.org/10.1016/j.techfore.2024.123721>
- Wang, F., Gillani, S., Sharif, A., Shafiq, M. N., & Farooq, U. (2025). Balancing well-being and environment: The moderating role of governance in sustainable development amid environmental degradation. *Journal of Environmental Management*, 386, 125803. <https://doi.org/10.1016/j.jenvman.2025.125803>
- Wang, S., & Xue, Z. (2023). Has the development of the digital economy improved green total factor productivity in China?—A study based on data at the provincial level in China. *Frontiers in Environmental Science*, 11, 1073997. <https://doi.org/10.3389/fenvs.2023.1073997>
- Wei, G., Yang, Y., Li, R., Liu, Y., & He, B.-J. (2024). Digital economy exhibits varying degrees of mitigation of air pollution in China: Total cities-economic subdivisions-urban agglomerations. *iScience*, 27(6), 110091. <https://doi.org/10.1016/j.isci.2024.110091>
- Xie, F., Zhang, M., Shafiq, M. N., & Mahmood, H. (2026). From Complexity to Sustainability: The Environmental Regulation Puzzle in Emerging Economies. *Sustainable Development*, 34(3), 3457–3476. <https://doi.org/10.1002/sd.70527>
- Xie, Y., Xu, M., Pu, J., Pan, Y., Liu, X., Zhang, Y., & Xu, S. (2023). Large-scale renewable energy brings regionally disproportional air quality and health co-benefits in China. *iScience*, 26(8), 107459. <https://doi.org/10.1016/j.isci.2023.107459>
- Yang, S., Li, H., Liu, X., Wei, Y., Shen, J., & Cheng, B. (2024). Spatial analysis of the digital economy's influence on urban sustainable development: A decade-long study of Chinese prefecture-level cities. *Ecological Indicators*, 166, 112338. <https://doi.org/10.1016/j.ecolind.2024.112338>
- Yang, X., Shafiq, M. N., & Gillani, S. (2026). Towards sustainable development: the synergistic impact of economic complexity, environmental regulation, and renewable energy on environmental performance in G20 economies. *International Environmental Agreements: Politics, Law and Economics*, 26(2), 387–416. <https://doi.org/10.1007/s10784-026-09717-0>
- Yang, X., Shafiq, M. N., Nazir, R., & Gillani, S. (2024). Unleashing the influence mechanism of technology innovation and human development for ecological sustainability in emerging countries. *Emerging Markets Finance and Trade*, 60(10), 2276–2299. <https://doi.org/10.1080/1540496X.2024.2308180>
- Yang, X., Shafiq, M. N., Nazir, R., & Gillani, S. (2025). Economic complexity and the green transition: integrating energy efficiency and digital technologies for sustainable restructuring. *Economic Change and Restructuring*, 58(6), 92. <https://doi.org/10.1007/s10644-025-09932-w>
- Yang, X., Shafiq, M. N., Sharif, A., Gillani, S., & Zeng, X. (2024). Balancing progress and preservation: analyzing the role of technological innovation in mitigating environmental degradation caused by energy consumption in China. *Economic Analysis and Policy*, 84, 391–409. <https://doi.org/10.1016/j.eap.2024.09.001>

- Yuan, H., Liu, J., Li, X., & Zhong, S. (2024). The impact of digital economy on environmental pollution: Evidence from 267 cities in China. *PLOS ONE*, 19(1), e0297009. <https://doi.org/10.1371/journal.pone.0297009>
- Zhang, J., Zhang, Y., Shafiq, M. N., Saeed, M., & Gillani, S. (2026). Economic Complexity, Green Innovation, and Environmental Performance: Evidence on Heterogeneity and Structural Relationships in G20 Economies. *Complexity*, 2026(1), 5165968. <https://doi.org/10.1155/cplx/5165968>
- Zhong, X., Xie, R., Chen, P., & Ke, K. (2021). Internet development and environmental quality—Evidence from the development of Chinese cities. *Sustainability*, 13(20), 11308. <https://doi.org/10.3390/su132011308>