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# RETRACTED: Achieving Carbon Neutrality – The Role of Heterogeneous Environmental Regulations on Urban Green Innovation

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This article examines the impact of heterogeneous environmental regulations on urban green innovation using panel data from 285 prefecture-level cities in mainland China from 2008 to 2019. From the perspective of green patents, this article utilizes a two-way fixed-effect model and the mediation effect model to examine the mechanism of the impact of heterogeneous environmental regulations on urban green innovation in China. Results show that the urban green innovation development in China is relatively slow and can be easily influenced by national policies. More specifically, the relationship between the command-based environmental regulation and urban green innovation presents an inverted non-linear U-shaped model, whereas the relationship between the market-based and voluntary environmental regulation presents a positive U-shaped model. Further investigation of this mechanism concludes that the progression of regional green innovation is primarily accelerated by technological development, effective energy allocation, and industrial structural upgrading. However, the implementation of relevant environmental regulations varies, resulting in various green innovation progression rates. Therefore, in order to achieve the carbon neutrality goal that China proposes, the effectiveness of environmental regulation implementation should be improved. Moreover, the development of various environmental regulation tools should be better coordinated.

**Keywords: carbon neutrality, heterogeneous environmental regulation, green innovation, green patent, two-way fixed model, mediation effect**



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RETRACTED

## HIGHLIGHTS

- We measure the level of green innovation in Chinese cities from the perspective of green patents.
- We subdivide the types of environmental regulation into three types: command, market, and voluntary.

- We find an inverted U-shaped non-linear relationship between command-based environmental regulations and urban green innovation, while market-based and voluntary environmental regulations have a positive U-shaped non-linear relationship with them.
- We find that environmental regulations promote the level of green innovation in cities mainly by exerting technological progress, energy allocation and structural upgrading effects.
- We find that environmental regulation implementation has a heterogeneous impact on urban green innovation.

## INTRODUCTION

Since the economic reform and the 1978 Open Door Policy, China's economy has experienced decades of rapid growth. However, this extensive GDP-based development model has resulted in significant resource waste and environmental damage (Tian et al., 2016). To address the problems caused by the extensive development model with high energy consumption, China's economic development has gradually shifted from high-speed growth to high-quality growth (Fu et al., 2021; Khan et al., 2022). The main challenge of long-term economic development has been balancing environmental regulation and economic benefits during the transformation process (Sun et al., 2021; Llanos et al., 2022). Because of the high externality of environmental problems, the government must use regulation to restrain business pollution behavior in policy evaluation (Su and Jiang, 2021; Cui Y. et al., 2022). According to the "Porter hypothesis," "adequate environmental regulation will stimulate technological innovation (Karmaker et al., 2021; Zhu et al., 2021)." Therefore, in order to achieve coordinated economic growth and environmental protection, it is critical to accelerate the transformation of innovative ways to break through the current development bottleneck (Usman et al., 2022).

To address the environmental pollution problem caused by a resource-intensive economic development model, the Chinese government has enacted a series of policies to strengthen environmental control (Sun and Wang, 2021). However, the impact of environmental control falls short of expectations. At the same time, due to regional differences in development, spatial agglomeration of environmental pollution becomes a pressing issue, making government governance more difficult (Du and Li, 2021; Gan et al., 2021; Hu et al., 2022). Resolving the contradiction between economic development and environmental pollution is critical for the green and high-quality development of regional economies (Shuai and Fan, 2020; Weng et al., 2020; Zhou D. et al., 2022). As an essential component of carbon-neutral development, urban green innovative development has significant theoretical and practical significance (Ley et al., 2016; He, 2019). As a result, strengthening cities' green innovation capabilities has emerged as a key driver of long-term economic growth (Zhao X. et al., 2022). However, there are few market incentives for green innovation due to the externality of the technology and financial markets (Fang et al., 2022; Li Y. et al., 2022; Yuan and Cao, 2022). At the same time, due to the path-dependent effect, a large amount of R&D resources flow to polluting technologies may lead to technology lock, making it difficult to meet social needs (Blackman, 2010; Aghion et al., 2016; Stern and Valero, 2021). To intervene and regulate, the government must implement appropriate policy measures.

Besides, the government's informal environmental regulations actively guide green innovation (Wang and Jiang, 2021; Qiu et al., 2022). With the advancement of information technology, informal environmental regulation has gradually demonstrated a positive impact on green innovation through the use of media (Tziva et al., 2020; Din Dar et al., 2021). Informal and formal environmental regulations led by the government both play important roles in promoting regional green innovation and development (Desheng et al., 2021; Zhao L. et al., 2022). Consequently, based on the development of a carbon-neutral background, we attempt to relate research results at home and abroad based on an analysis of formal and informal environmental regulation's influence on urban green innovation and its mechanism of action (Yasmeen et al., 2020). Looking for the "double win" of economic growth and environmental protection path. has significant practical significance for China's long-term and stable economic growth and sustainable development (Shen et al., 2020).

This manuscript may make the following theoretical contributions to existing research: First, from a micro perspective, this manuscript explains the impact of heterogeneous environmental regulation at the city level on green innovation and identifies the factors influencing the growth of urban green innovation. Second, this manuscript explains the mechanisms of formal and informal environmental regulation on green innovation from a city-level perspective. Finally, this manuscript examines the impact of environmental regulation implementation in the context of geographical and scale heterogeneity. This study's findings may provide theoretical support for promoting carbon neutrality and a carbon peak in China and the rest of the world.

## LITERATURE REVIEW

In the extant literature, scholars have focused on three aspects of environmental regulation and regional green development (Wei et al., 2017; Sun et al., 2022; Zhu and Tan, 2022). First, they support the Porter hypothesis, which argues that reasonable environmental regulation policies can stimulate the innovation potential of enterprises and increase their productivity levels (He et al., 2020; Nie et al., 2021). The implementation of environmental regulations has a significant impact on green total factor productivity (Zhang et al., 2011; Tang et al., 2020). Furthermore, scholars have discovered that the stronger the environmental regulation policies introduced by the government, the lower the emissions of pollutants can be observed (Laplante and Rilstone, 1996; Dasgupta et al., 2001). Meanwhile, the external pressure exerted by environmental regulation on firms can effectively overcome firms' organizational inertia, thus creating a mutually reinforcing relationship with the firms' internal governance mechanisms (Ambec and Barla, 2002; Ma and Li, 2021). Secondly, neoclassical economists suggest that environmental regulation exacerbates the level of additional capital investment by firms (Cai and Ye, 2020; Gallen and Winston, 2021), which gradually reduces the funds available for R&D and innovation, thereby inhibiting technological innovation and discouraging productivity and market competitiveness (Fisher and Peterson, 1976; Chen Y.-E. et al., 2021). This is a reflection of the "compliance cost effect" of environmental regulation (Ding et al., 2022). From the perspective of the cost of environmental management, it is argued that the implementation of environmental regulation policies is detrimental to the improvement of environmental quality, and that strict environmental regulation policies have a negative impact on the emission reduction and corporate performance of pollution-intensive firms (Greenstone, 2001; Lanoie et al., 2007). Third, there is uncertainty about the impact of environmental regulation on regional green development, with environmental regulation stimulating environmental R&D but showing a crowding-out effect on non-environmental R&D (Kneller and Manderson, 2012). Meanwhile, there is also significant regional variability in the impact of environmental regulation policy implementation on green total factor productivity in China due to different political attributes of cities (Li and Wu, 2017).

Researchers are divided on the relationship between environmental regulation and regional green development (Kemp and Pontoglio, 2011; Kneller and Manderson, 2012). Some academics fail to recognize the heterogeneity created by various environmental regulation tools, as well as the critical role that heterogeneous environmental regulation tools play (Wei et al., 2017). Some scholars have also studied the impact of heterogeneous environmental regulations on green total factor productivity (Luo et al., 2021), urban environmental pollution (Lu et al., 2021), and corporate green technological innovation (Shen et al., 2019), improving the research on the economic and social impacts of environmental regulations. However, few scholars have explored from the perspective of green patenting to discuss the impact of heterogeneous environmental regulations on urban green innovation in depth (Xie et al., 2017; Guo and Yuan, 2020). Therefore, this manuscript uses panel data from prefecture-level cities in China from 2008 to 2019 to reflect the level of urban green innovation based on green patent information, and analyzes the impact and mechanism of heterogeneous environmental regulation on urban green innovation using a bidirectional fixed effect model and intermediary effect. More discussion of the various impacts of different geographical locations and city scales is required in order to develop reasonable environmental governance policies for the region, promote regional green development, and achieve carbon neutrality goals.

## THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

Achieving the goal of carbon neutrality requires not only a strong public awareness of environmental protection and resource conservation, but also the introduction of relevant government policies and measures by the government (Wang X. et al., 2022; Yamazaki, 2022). There has been discussion about whether the innovation compensation effect or the cost effect of environmental regulation should be used as an important regulatory tool for limiting businesses' pollution emission behavior (De La Peña et al., 2022; Liu X. et al., 2022). To facilitate an in-depth analysis of the differences in the effects of different types of environmental regulations on urban green innovation, this manuscript further classifies environmental regulations into command-based, market-based, and voluntary environmental regulations (Li and Du, 2021; Wu and Lin, 2022). In the short term, the implementation of these policies may increase the input costs of enterprises and have a negative impact on their economic efficiency and green development (Li et al., 2019). However, from a long-term perspective, this will help enterprises to improve their production processes and advance their green technologies (Wei and Wang, 2021), thus enhancing the overall sustainable development of the region (Wang and Wang, 2021; Lim et al., 2022). The market-based environmental regulation focuses on the emissions trading mechanism and subsidies for energy saving and emission reduction proposed by the government and uses market forces to promote win-win development for both economic efficiency and emission reduction (Yu et al., 2022). Voluntary environmental regulation, on the other hand, emphasizes people's opinions on the supervision and implementation of environmental pollution control (Yang et al., 2020; Liu Z. et al., 2022), and is more of a spontaneous act (Hamamoto, 2006; Hu et al., 2020). Considering the variability in the impact of different types of environmental regulation on regional green development and the fact that improving urban green development requires disruptive technological innovation, this manuscript proposes the following hypothesis.

> *Hypothesis 1: Heterogeneous environments have a significant effect on the level of green innovation in cities, and there may be a non-linear relationship.*

To achieve green and innovative development in a region, we must not only increase investment in technological R&D, but also adjust and optimize the structure of energy production and consumption (Ouyang et al., 2020). During this process, the technology progress effect, energy allocation effect, and structural upgrading effect all play a role in promoting urban green innovation (Kellogg and Reguant, 2021). As a result, this manuscript considers its indirect impact as well.

(1) The technological progress effect. With the introduction and implementation of government policies on environmental regulation, higher requirements are imposed on enterprises' emission standards and equipment (Wang H. et al., 2022; Xiang et al., 2022). Forcing them to carry out technological innovation to fulfill their emission reduction targets and responsibilities, thereby achieving more effective low-carbon development of the regional economy (Chen Z. et al., 2021; Wang and Feng, 2021). On the one hand, environmental regulations may lead to an increase in the cost of treatment and a serious imbalance in the efficiency of inputs and outputs at the early stage of policy implementation, thus aggravating the degree of

resource mismatch (Hao et al., 2020; Peng et al., 2021). On the other hand, environmental regulations can help promote technological innovation, improve production efficiency and environmental protection awareness, fully reflecting the innovative compensation effect of environmental regulation (Cui S. et al., 2022; Zhong and Peng, 2022). It can also be seen that improving the level of technological progress plays an important role in raising the level of green innovation in cities (Fan et al., 2021). In addition, relevant studies have confirmed the positive and significant effect of green technological innovation on environmental performance (Liu Y. et al., 2020; Lv et al., 2021), which further reflects the indispensable status of improving the level of technological progress.

(2) The energy allocation effect. Controlling the use of fossil energy such as coal and increasing the proportion of clean energy is an effective way to achieve green development in the regions (Jie et al., 2021). The energy allocation effect is mainly reflected in the fact that environmental regulations can influence the energy structure of enterprises and encourage enterprises to increase the proportion of the usage of clean energy to reduce carbon emissions (Chen et al., 2022; Li W. et al., 2022). While the use of clean energy mainly involves the power industry, in order to improve the efficiency of energy use in the power industry more effectively (Miniard and Attari, 2021), it is necessary to use energy-saving and emission-reducing technologies and equipment to promote clean and low-carbon development in the regions.

(3) The structural upgrading effect. The main effect of structural upgrading is that environmental regulation can affect the imbalance of inter-industrial structure (Zhang et al., 2019), promote the transformation and upgrade the industrial structure (Yu and Shen, 2020), and then improve the advanced level of industrial structure (Zhou et al., 2020). The implementation of environmental regulation policies can have a positive impact not only on the proportion of different industries, but also on each industry's labor productivity (Zhang et al., 2022a). Furthermore, it can increase the proportion of the tertiary industry, promote green transformation and secondary industry development (Zhou and Tang, 2021), and gradually reduce regional carbon emissions, all of which contribute to the goal of coordinated emission reduction and green development (Zheng et al., 2019; Zhang et al., 2021). To this end, this manuscript puts forward the following hypotheses.

*Hypothesis 2: Heterogeneous environmental regulation promotes the improvement of green innovation levels in cities by increasing the level of technological progress.*

*Hypothesis 3: Heterogeneous environmental regulations promote green innovation in cities by optimizing energy allocation.*

*Hypothesis 4: Heterogeneous environmental regulation promotes a higher level of green innovation in cities by facilitating the upgrading of industrial structures.*

## RESEARCH DESIGN

### Model Construction

In order to explore the interaction between environmental regulation and urban green innovation, this manuscript builds up a model to study different types of environmental regulation accordingly, and considers the possible linear and non-linear factors of environmental regulation on urban green innovation. The specific model is set up as follows.

$$lngreen_{it} = \alpha_0 + \alpha_1 \sum_{j=1}^{3} En_{jit} + \alpha_2 control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

$$lngreen_{it} = \beta_0 + \beta_1 \sum_{j=1}^{3} En_{jit} + \beta_2 \sum_{j=1}^{3} En_{jit}^2 + \beta_3 control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

Where $i$ and $t$ represent city and year, respectively. $green_{it}$ represents the level of green innovation in the city; $En$ represents the level of environmental regulation and $j$ represents the type of environmental regulation; $En^2$ represents the quadratic term of environmental regulation; $control_{it}$ represents a set of control variables; $\mu_i$ is the individual city fixed effect, i.e., it also reflects the regional fixed effect; $\gamma_t$ is the time fixed effect; and $\varepsilon_{it}$ is the random error term.

### Selection and Description of Variables

Explanatory variable: urban green innovation (green). The explained variable in this manuscript is the level of urban green innovation. Previous research has found that the level of patented technology is an important indicator of a region's ability to innovate (Milani and Neumann, 2022). Green innovation focuses on the development of environmental protection and economic growth (Yin and Xu, 2022). Hence, based on previous research, relevant data on green patents in prefecture-level cities is collected as a proxy variable to measure urban green innovation (Zhang et al., 2022b; Zhou G. et al., 2022).

Core explanatory variables: (i) command-based environmental regulation ($En_1$), the number of environmental agency employees in each region is used to characterize the model; (ii) market-based environmental regulation ($En_2$), the number of sewage charges levied in each region is chosen as a proxy; (iii) voluntary environmental regulation ($En_3$), the number of environmental proposals made by the National People's Congress and the Environmental Protection Association in each region is chosen as a proxy.

Control variables: In order to avoid the omission of variables that may produce errors in the model regression results, the following control variables are selected for this study. (1) the level of economic development (*pgdp*), the strength of a region's economic development will have an important impact on the level of regional innovation input, so this manuscript uses each city's current year's GDP and year-end resident population to measure; (2) the urbanization rate (*urban*), using each city's current year's urban population and year-end total resident population to measure; (3) The level of industrial structure (*IS*), characterized by the share of the secondary sector in the total gross industrial product of each prefecture; (4) level of transport infrastructure (*road*), characterized by the area occupied by roads per capita in each prefecture-level city.

## Data Sources

This manuscript investigates panel data from Chinese prefecture-level cities. The data came primarily from the China Urban Statistical Yearbook, the China Statistical Yearbook, the China Environmental Statistical Yearbook, prefectural city statistical yearbooks, and official government websites. Some prefecture-level cities have been removed due to significant data gaps, and some missing data has been supplemented using the interpolation method. Finally, this study includes 285 prefecture-level cities' data in China from 2008 to 2019. To avoid the effects of dimensional error, the raw data were logarithmically processed, and all price data was treated as constant price in 2008 as the base period. The results of descriptive statistics for the variables are shown in **Table 1**.

# ANALYSIS OF THE EMPIRICAL RESULTS

## Direct Effect Test Results

This manuscript conducts regression analysis from both linear and non-linear aspects in order to more effectively analyze the differences in the effects of different types of environmental regulations on urban green innovation. The regression results are shown in **Table 2**.

The results of the direct effects of different types of environmental regulation on urban green innovation in **Table 2** reveal that for the linear regression results of model (1), command-based environmental regulation, being significantly positive at the 5% level, has a more significant contribution to the increase in the level of urban green innovation. Market-based environmental regulation also contributes to the increase

**TABLE 2 |** Test results for linear and non-linear effects of environmental regulation on urban green innovation.

| Variables | (1) | (2) |
|---|---|---|
| $En_1$ | 0.109** (2.302) | 0.085** (2.127) |
| $En_2$ | 1.013** (2.014) | 0.054** (2.419) |
| $En_3$ | −0.089* (−1.851) | 0.964** (2.043) |
| $En_1{}^2$ | | 0.548* (1.916) |
| $En_2{}^2$ | | 1.254*** (2.724) |
| $En_3{}^2$ | | 1.228** (2.450) |
| pgdp | 1.528*** (3.125) | 0.873** (2.501) |
| urban | −0.547** (−2.147) | −0.752** (−2.210) |
| us | −1.128** (−2.051) | −0.642* (−1.953) |
| road | −0.223** (−2.062) | −0.347** (−2.127) |
| Cons | 3.185** (2.148) | 4.042** (2.429) |
| $R^2$ | 0.463 | 0.628 |
| F-statistic values | 5.426 | 7.253 |
| Sample size | 3420 | 3420 |

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

of urban green innovation, while voluntary environmental regulation has an inhibitory effect on urban green innovation. From the non-linear regression results in model (2), the relationship between command-based environmental regulation and green innovation shows an inverted U-shape, while the relationship between market-based and voluntary environmental regulation and green innovation shows a positive U-shape (Liu J. et al., 2020). The possible reason is that the government's initial policy intensity will show a downward trend, and market-based environmental regulation measures will gradually stabilize and increase the promotion effect on the level of urban green innovation (Liu Y. et al., 2020). Simultaneously, the popularization and development of Internet technology raise public awareness of environmental protection and supervision, thereby contributing to the region's promotion of green development (Huang and Chen, 2022).

Among the control variables, the level of economic development has a significant positive contribution to urban green innovation, while the urbanization rate, the level of industrial structure and the level of transport infrastructure have a negative relationship with green innovation, which indicates that the long-term innovative development of a region cannot be achieved without the support of economic strength. Meanwhile, it is also necessary to accelerate the optimization of the level of industrial structure upgrading, and reduce the environmental pollution which may be generated in the process of urbanization.

**TABLE 1 |** Descriptive statistics of the selected variables.

| Variables | Sample size | Maximum value | Minimum value | Mean value | Variance |
|---|---|---|---|---|---|
| Green | 3420 | 3.657 | 0 | 0.149 | 0.282 |
| $En_1$ | 3420 | 1.236 | 0.036 | 0.124 | 0.092 |
| $En_2$ | 3420 | 2.575 | 0.923 | 0.983 | 0.832 |
| $En_3$ | 3420 | 1.028 | 0.012 | 0.234 | 0.362 |
| pgdp | 3420 | 13.053 | 4.425 | 9.082 | 1.082 |
| Urban | 3420 | 0.952 | 0.275 | 0.558 | 0.091 |
| Us | 3420 | 0.923 | 0.09 | 0.326 | 0.132 |
| Road | 3420 | 8.236 | 2.634 | 4.023 | 2.917 |

## Endogeneity and Robustness Tests of the Model

### Endogeneity Discussion

When analyzing the impact of environmental regulation on urban green innovation, endogenous problems should be taken into account during the model-building process. The main reason for this is that there is a reverse causal relationship between the three types of environmental regulation tools in the explanatory variables and the level of green innovation in the explained variables, which causes the model estimation coefficient to be biased or inconsistent, affecting the accuracy of the estimation results. Therefore, this manuscript builds upon the ideas of previous studies and considers the lagged period of the three environmental regulation tools as the instrumental variable for analysis for the first time. Secondly, considering that only using the lagged period of data for regression may not be convincing, this manuscript further adopts the area of rivers in each region as the instrumental variable. This is because areas with more rivers are more likely to discharge wastewater, and other wastes into rivers, and for this reason, the government reduces the discharge of wastes by formulating corresponding policy measures. Furthermore, there are significant differences in the discharge capacity of rivers in areas with different intensities of environmental regulation. At the same time, changes in river area do not have a direct impact on a region's level of green development, and there is no endogeneity problem in choosing the river area as an instrumental variable.

**Table 3** shows the regression results for the two-stage least squares test of endogeneity, with IV(1) and IV(2) showing the estimates using the lag and river area of different types of environmental regulation instruments as instrumental variables, respectively, and IV(3) showing the regression results using the lag and river area of environmental regulation instruments together as instrumental variables. As can be seen, the significance of the coefficients on the lagged term of environmental regulation, river area and the interaction term does not differ significantly when the endogeneity of the model is verified, which also indicates the robustness of the regression results.

### Robustness Tests

After discussing the possible endogeneity of the model set, there is still a need to consider whether there is any impact on the accuracy of the regression results due to the unreasonable selection of variable indicators and selective errors in the sample. Therefore, the method of replacing the explanatory variables and samples was used to conduct the robustness test analysis.

**TABLE 3** | Regression results for the instrumental variables approach.

| Variables | IV (1) | IV (2) | IV (3) |
|---|---|---|---|
| $En_1$ | 0.205** (2.204) | 0.319** (2.413) | 0.115*** (2.745) |
| $En_2$ | 0.098** (2.054) | 1.425** (1.995) | 1.082** (2.253) |
| $En_3$ | −0.342* (−1.721) | −0.573* (−1.840) | −0.263* (−1.826) |
| pgdp | 1.413** (2.296) | 1.208** (2.005) | 0.909*** (2.702) |
| Urban | −0.603** (−2.184) | −1.008** (−2.325) | −0.815**(−2.092) |
| Us | −1.108* (−1.814) | −0.765** (−2.015) | −1.013** (−2.014) |
| Road | −0.345* (−1.726) | −0.453* (−1.853) | −0.853* (−1.905) |
| Cons | 2.258** (2.427) | 3.109*** (3.048) | 1.047*** (2.835) |
| Phase I *F*-value | 15.236*** | 20.361*** | 18.013*** |
| Phase I *P*-value | 0.000 | 0.000 | 0.000 |
| $R^2$ | 0.563 | 0.642 | 0.758 |

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

(1) Substitution of explanatory variables. The size of a region's green innovation level is not only reflected in the output of patents, but also has an important impact in terms of R&D investment. To this end, this manuscript uses the share of R&D investment in total GDP for each region to conduct the analysis. The regression estimation results are shown in columns (1) and (2) in **Table 4**, where (1) is using the fixed effects model and column (2) is the regression analysis result of 2SLS. It can be seen that the regression coefficients of urban green innovation are all significantly positive at the 5% level, confirming the robustness of the regression results.

(2) Analysis of the excluded samples. Since the data sample of municipalities directly under the Central Government has a high strength of economic development, it may have a biased impact on the regression results, as this manuscript further excludes these special samples and conducts the regression again. The regression results are shown in columns (3) and (4) of **Table 4**, and the regression coefficients are still significantly positive, indicating the reasonableness of the regression results.

## Testing the Indirect Effect Mechanism

The previous sections have conducted an in-depth study on the impact of different types of environmental regulations on urban green innovation, but the mechanism behind it still needs to be explored further.

$$lngreen_{it} = \delta_0 + \delta_1 \sum_{j=1}^{3} En_{jit} lntec_{it} + \delta_2 \sum_{j=1}^{3} En_{jit} lnes_{it} + \delta_3 \sum_{j=1}^{3} En_{jit} lnsu_{it} + \mu_i + \gamma_t + \varepsilon_{it} + \delta_4 control_{it} \quad (3)$$

Among them, *tec, es,* and *su* are mediating variables. tec represents the effect of technological progress, which is represented by the number of patents granted per capita in each region; es represents the effect of energy allocation, which is represented by the share of coal energy consumption in total energy consumption in each region; *su* represents the effect of structural upgrading, which is represented by the share of industrial value-added in total GDP in each region.

**Table 5** shows the regression results of the indirect effects of different types of environmental regulations on urban green innovation. This may be because local enterprises rely more on policy or market-driven actions are lacking a sense of spontaneity. For the energy allocation effect, all three types of environmental regulation tools have positive contributions to the transformation of the regional energy structure. In terms of the energy allocation effect, all three types of environmental regulation tools promote regional energy structure transformation. To achieve green urban development, we must first transform the traditional industrial structure, which is marked by high energy consumption, pollution, and emissions, and

**TABLE 4 |** Regression results of robustness tests.

| Variables | Green | | Green | |
|---|---|---|---|---|
| | FE | 2SLS | FE | 2SLS |
| | (1) | (2) | (3) | (4) |
| $En_1$ | 0.341** (2.214) | 0.369** (2.204) | 0.418** (1.993) | 0.247** (2.218) |
| $En_2$ | 0.142** (2.068) | 0.245** (2.342) | 0.312** (2.304) | 0.328** (2.360) |
| $En_3$ | −0.478** (−2.061) | −0.617** (−2.247) | −0.327** (−2.259) | −0.365** (−2.107) |
| pgdp | 0.952** (2.201) | 0.847** (2.218) | 0.642* (1.717) | 0.542** (2.305) |
| Urban | −0.542* (−1.768) | −0.238** (−2.341) | −0.413** (−2.218) | −0.340** (−2.042) |
| Us | −0.978** (−2.042) | −0.704* (−1.742) | −0.849** (−2.240) | −0.865** (−2.118) |
| Road | −0.449** (−2.014) | −0.508** (−2.246) | −0.679** (−2.342) | −0.457** (−2.149) |
| Individual effects | YES | YES | YES | YES |
| Year effects | YES | YES | YES | YES |
| *N* | 3420 | 3420 | 3372 | 3372 |
| $R^2$ | 0.758 | 0.769 | 0.801 | 0.657 |

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

then gradually increase the clean energy input and use ratio. As a result, whether through policy formulation and implementation, market competition, or public oversight, it plays a critical role in promoting a region's long-term development. Simultaneously, the correlation coefficient of command environmental regulation on urban green innovation is insignificant in terms of impact on industrial structure upgrading, because policy implementation has a lag, and industrial structure transformation and upgrading also takes time. Market-based environmental regulation and voluntary environmental regulation take changes in the market environment and regional development strategy into account, and optimize industrial upgrading to increase the level of urban green innovation.

## Heterogeneity Analysis

(1) Impact of regional heterogeneity on urban green innovation.

Because of China's vast land area, it is necessary to focus on regional differences in economic development strength, resource endowment, and geographic location, which will result in some opposition to environmental regulation policies. Eastern China, for example, has a robust economy and a well-balanced industrial structure, whereas the central and western regions are still in the early stages of development. Based on this, the sample's prefecture-level cities are further subdivided into eastern, middle, and western cities, and regression is run sequentially to investigate differences in regression results.

(2) The impact of city size heterogeneity on urban green innovation.

**TABLE 5 |** Examining the mechanisms by which environmental regulation affects urban green innovation.

| Variables | Technological progress effect | Energy allocation effect | Structural upgrading effect |
|---|---|---|---|
| $En_1$ | 0.425** (2.018) | 0.347** (2.452) | 0.253 (1.415) |
| $En_2$ | 0.230*** (2.818) | 0.249** (2.215) | 0.302* (1.746) |
| $En_3$ | 0.302 (1.542) | 0.446* (1.813) | 0.346** (2.260) |
| pgdp | 0.982*** (3.327) | | |
| Urban | −0.823** (−2.342) | | |
| Us | −1.225** (−2.054) | | |
| Road | −0.354** (−2.304) | | |
| Cons | 3.185** (2.058) | 2.825*** (3.249) | 4.237*** (4.315) |
| *N* | 3,420 | 3,420 | 3,420 |
| $R^2$ | 0.768 | 0.742 | 0.847 |

**, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.*

In addition to regional heterogeneity, the size of cities and changes in population may also have an impact on the effect of environmental regulations in promoting the development of regional green innovation. For this reason, this manuscript refers to previous studies and classifies cities into five types, including medium, large, type II, type I, and megacities, based on their population size, and uses a benchmark regression model to verify the results, which are finally shown in **Table 6**.

**Table 6** shows the heterogeneous effects of different types of environmental regulation instruments on regional levels of green innovation. By comparing the differential results across geographical locations and city sizes, it can be seen that there are significant differences in the effects of environmental regulation. Firstly, in terms of the effect of regional heterogeneity, the promotion effect of command-based environmental regulation on urban green innovation is significantly stronger in the western region than in the eastern and central regions, probably because the western region relies more on policy guidance and implementation due to its weaker economic development strength, resource endowment and technological innovation level, while the level of openness to the outside world in the western region is also prone to problems. At the same time, due to the geographical distribution of the western region, the level of openness to the outside world is easily restricted, which also results in stronger command-based environmental regulation than market-based and voluntary environmental regulation. From the perspective of city size heterogeneity, the impact of environmental regulations on the level of green innovation varies significantly between cities of different sizes. From the regression results, the increasing size of cities leads to a diminishing role of command and voluntary environmental regulations, while the effect of market-based environmental regulations tends to increase. This could be due to increased city size resulting in a more pronounced concentration of different factors and resources, but it also

**TABLE 6 |** Heterogeneity regression results of environmental regulation on urban green innovation.

| Variables | Different geographical locations | | | Different city sizes | | | | |
|---|---|---|---|---|---|---|---|---|
| | East | Central | West | Medium | Large | Type II | Type I | Extra large |
| $En_1$ | 0.625* | 0.529** | 0.436*** | 1.753*** | 1.532** | 0.872** | 0.658** | 0.779* |
| | (1.725) | (2.108) | (2.913) | (3.352) | (2.142) | (2.036) | (1.985) | (1.826) |
| $En_2$ | 0.817*** | 0.704** | 0.532* | 1.941** | 1.026** | 1.172*** | 0.672*** | 0.824*** |
| | (2.718) | (2.362) | (1.942) | (2.143) | (2.242) | (2.632) | (2.728) | (3.126) |
| $En_3$ | −1.248** | −0.935** | −1.462 | −1.425** | −0.834** | −0.472** | −0.564* | −0.823* |
| | (−2.023) | (−2.247) | (−1.515) | (−2.350) | (−2.213) | (−2.032) | (−1.883) | (−1.726) |
| Control variables | YES | YES | YES | YES | YES | YES | YES | YES |
| Time effects | YES | YES | YES | YES | YES | YES | YES | YES |
| Area effects | YES | YES | YES | YES | YES | YES | YES | YES |
| $R^2$ | 0.752 | 0.814 | 0.802 | 0.741 | 0.653 | 0.692 | 0.641 | 0.608 |

*, **, ***Indicate significant at the 10, 5, and 1% levels, respectively, with t-statistics in brackets.

comes with increased difficulties in city management, more prominent environmental pollution emissions, and less apparent technological spillover effects.

## CONCLUSION AND POLICY RECOMMENDATIONS

### Research Conclusions

Cities are in a pioneering position in achieving the goal of carbon neutrality, and it is important to accelerate the development of green transformation in cities and enhance technological progress to promote high-quality regional economic development. Therefore, this manuscript starts from the perspective of green patent, based on the panel data of 285 prefecture-level cities in mainland China from 2008 to 2019, uses a two-way fixed-effects model and a mediating-effects model to study the changes in the influence of different types of environmental regulation tools on urban green innovation. It also analyses the mechanism of their impacts and draws the following main conclusions: (1) Overall, the development of urban green innovation in China is slow and heavily influenced by national policies. (2) The impact of different types of environmental regulation tools on urban green innovation differs, with command-based environmental regulation promoting the level of urban green innovation and an inverted U-shaped non-linear relationship between the two. Furthermore, market-based environmental regulation can improve the level of urban green innovation and a positive U-shaped non-linear relationship exists. There is a positive U-shaped non-linear relationship between the two; and voluntary environmental regulations have a suppressive effect on urban green innovation, and the suppressive effect gradually decreases as time advances. (3) The analysis of the influence mechanism shows that environmental regulations mainly enhance the level of green innovation in cities through technological progress, energy allocation and structural upgrading. (4) Heterogeneity analysis shows that the impact of environmental regulation on urban green innovation varies significantly across different geographical locations and city sizes, and the effects of different environmental regulation tools are also different.

### Policy Recommendations

Based on the above findings, the following recommendations are made: (1) Enhance the implementation of environmental regulation policies and stimulate the potential of regional green development. Relevant government departments should actively formulate corresponding green development strategies, consider the actual local development situation to formulate appropriate environmental regulation policies, deepen institutional reform, and improve cities' overall green development level from a strategic level. (2) When implementing environmental regulation policies, it is critical to fully consider the characteristics of various types of environmental regulation tools as well as the effects of heterogeneous environmental regulation. In order to gradually eliminate the cost effect, subsidies for low-emission and low-pollution businesses should be increased in command-based environmental regulations. Simultaneously, improve the market's driving force for regional innovation by fostering a favorable market competition environment for the development of regional enterprises. Furthermore, for market-based and voluntary environmental regulations to effectively promote regional green innovation, public awareness of environmental protection and oversight should be increased. (3) Further improve technological innovation capabilities, focus on improving the coordination and balance of industrial structures between regions, and adjust the proportion of energy structures. Specifically, the role of heterogeneous environmental regulations for urban green innovation is mainly achieved by raising the level of technological progress, optimizing energy allocation and promoting structural upgrading. Therefore, it is necessary to increase the level of investment and innovation in relevant technological research and development, actively develop green technologies, set reasonable and effective entry thresholds for industries, and vigorously develop green environmental protection and energy-saving industries. At the same time, regions should also actively plan low-carbon energy development strategies, draw on advanced technologies and experiences, and improve the output efficiency of green patents, thereby accelerating regional green transformation and effectively promoting the achievement of carbon neutrality targets.

### Shortcomings and Prospects

This manuscript analyzes the impact of heterogeneous environments on urban green innovation and the mechanisms of action, and subsequent research can be conducted at the firm level. Also, the impact of interactions between different types of environmental regulatory instruments can be considered.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://www.stats.gov.cn/.

## AUTHOR CONTRIBUTIONS

BL contributed to the conceptualization, methodology, software, and writing–original draft the preparation. JW contributed to the validation and formal analysis. RYML revised, edited, and completed the manuscript. RYML and LP revised and completed the manuscript. LM revised and formatted the manuscript. All authors read and agreed to the published version of the manuscript.

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