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Environmental regulation, pollution reduction and green innovation: The case of the Chinese Water Ecological Civilization City Pilot policy

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ABSTRACT

This paper treats the Water Ecological Civilisation City Pilot (WECCP) policy as a quasi-natural experiment, and integrates environmental regulation, pollution reduction and green innovation into a unified analytical framework. Based on the pollution emission index and green patent data for 283 Chinese cities from 2010 to 2018, we examine the impact of WECCP policy on urban pollution emissions and green innovation by using a difference-in-differences model. The results show that the WECCP policy has significant regional pollution reduction effects, that is, the policy significantly reduces water pollution in the pilot cities, while it has a weak impact on air quality improvement. Also, we find that the WECCP policy significantly promotes the growth of the number of green patent applications in the pilot cities, indicating that the policy can significantly improve urban green innovation capacity. The mediating effect analysis shows that the WECCP policy can improve regional environmental quality by enhancing urban green innovation ability. Furthermore, the heterogeneity analysis demonstrates that the WECCP policy has more significant effects on pollution reduction and green innovation in small cities.

1. Introduction

Water plays a crucial role in the ecosystem, affecting its balance and the evolution of the ecosystem (Grizzetti et al., 2016). Water ecological civilisation is a significant component and a solid guarantee of ecological progress, especially today when urbanisation is accelerating and urban populations continue to grow. Therefore, water ecological civilisation city construction is growing in prominence. However, the world's water ecological environment is under pressure because of overly polluted water, which may have resulted from population growth, food production, economic development and urbanisation (Strokal and Kroeze, 2020). It is worth noting that water pollution has become a major global concern, especially in developing countries where approximately 2.1 billion people lack access to safe drinking water at home and more than twice as many lack access to safe sanitation.[1] Although the overall environmental quality of Chinese surface water has improved in recent years (in 2019, the proportion of Class I-III water was 74.9 %,

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[1] The data is derived from https://www.unicef.org/press-releases/21-billion-people-lack-safe-drinking-water-home-more-twice-many-lack-safe-sanitation.

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and that of Class V water (polluted water) was 3.4 %), the problems of uncoordinated control of water pollution remain prominent. Furthermore, the water environmental conditions existing in some areas, such as Yingkou, Tongchuan and Baicheng, remain severe.[2]

Against this background, many countries established a series of policies and regulations to tackle water pollution problems. In this regard, the United Nations (UN) developed sustainable development goals (SDGs) to improve the quality of the global environment. These are a novel, universal set of goals, targets and indicators that UN member states are expected to use when framing their agendas and political policies over the next 15 years. Furthermore, the Chinese government established a series of regulations to improve the water ecological environment, and the Water Ecological Civilisation City Pilot (WECCP) is one of the most representative water management policies. In 2013, the Chinese Ministry of Water Resources issued *Opinions on Accelerating the Construction of Water Ecological Civilisation*, indicating that the WECCP policy had been officially implemented. At its core, the WECCP policy implemented the strictest water resource management system and adhered to the ideas of 'water-saving priority, spatial balance, system management and two hands efforts' (Chinese Ministry of Water Resources, 2013). Its primary objectives include optimising water resource allocation, strengthening the conservation and protection of water resources and implementing comprehensive water ecological management (Chen, 2014). From 2012–2014, the Ministry of Water Resources successfully established 105 water ecological civilisation pilot cities (Chinese Ministry of Water Resources, 2018). By May 2019, 99 pilot cities had completed the construction tasks and passed the acceptance inspection (Chinese Ministry of Water Resources, 2019). The water resource utilisation rate, water quality compliance rate and water treatment technology have been dramatically improved, indicating that the WECCP policy has achieved remarkable progress (Deng et al., 2019; Tian et al., 2021). In recent years, as the world's largest developing country, China has made greater contributions to the international construction of ecological civilisation and green development by making trade and investment agreements compatible with ecological civilisation principles, goals and practices (Hanson., 2019). Consequently, the WECCP policy is an innovative environmental policy tool for ecological civilisation construction, which may have practical significance for China and other developing countries to improve urban environmental quality and green innovation capacity.

Although researchers have engaged in extensive theoretical discussion and empirical research on the pollution reduction and green innovation effects of environmental regulation, most have not clarified whether environmental regulation affects urban pollution and emissions reduction through improving urban green capability. More importantly, the pilot project of water ecological civilization city is an innovative environmental policy proposed by the Chinese government. Research on the WECCP policy is still in the initial stage and focuses primarily on the fundamental concept, legal basis, implementation strategy and evaluation system (Li et al., 2014; Liu and Wang, 2018; Tian et al., 2021). However, current studies lack theoretical analysis on the pollution reduction and green innovation effects of this policy. Most current studies used the comprehensive evaluation analysis method to evaluate the policy effect of a specific water ecological civilisation pilot city or cities in the urban agglomerations from the perspective of water ecological performance (Ren et al., 2016; Zhang et al., 2020; Tian et al., 2021). More importantly, few studies have evaluated the policy effect of all the pilot cities and compared the differences in the pollution reduction and green innovation effects between pilot and non-pilot cities. Therefore, it is of both academic value and practical significance to explore and identify the impact of the WECCP policy on urban pollution reduction and green innovation capability.

Given this, this paper treats the WECCP policy as a quasi-natural experiment, and utilises a pollution emission index and green patent data for 283 Chinese cities from 2010 to 2018 to examine the impact of WECCP policy on urban pollution reduction and green innovation by using the difference-in-differences (DID) model and a series of robustness tests. This paper's contributions are listed as follows. First, in theory, this paper analyses the logical process regarding the impact of WECCP policy on urban pollution emissions and green innovation ability, and clarifies whether the WECCP policy promotes regional pollution reduction by strengthening urban green innovation capacity. Second, regarding empirical methods, this paper applies the DID model to comprehensively evaluate the pollution reduction effect of the WECCP policy based on the data of the urban water quality, air pollution and composite pollution indexes. Also, green patent data is collected for all enterprises, universities and research institutions located in the same city to measure urban green innovation capacity so that we can conduct an empirical study on the green innovation effect of WECCP policy. Based on this, the mediating effect model is used to verify that the WECCP policy may achieve pollution reduction by improving urban green innovation ability. Third, many developing countries also face severe water pollution problems. Therefore, the research can provide a theoretical reference and empirical support for the Chinese government and other developing countries to perfect environmental governance systems, accelerate the construction of ecological civilisations and achieve sustainable growth.

The remainder of this paper proceeds as follows. Section 2 illustrates the relevant literature. Section 3 introduces the background of WECCP policy and proposes our hypotheses. Section 4 describes the sample selection and methodology used in this study, and Section 5 presents and analyses the empirical results of this research. Section 6 concludes and provides some useful policy implications.

2. Literature review

2.1. Environmental regulation and pollution reduction

Over the past few decades, there has been heated discussion on the impact of environmental regulation on pollution reduction. Early studies mainly used environmental intensity indicators to define environmental regulation, including pollution treatment costs, pollutant emission standards and comprehensive pollution emission indexes (Jaffe et al., 1995; Fu and Li, 2010; Acemoglu et al.,

[2] On January 23, 2020, the Ministry of Ecological Environment informed the media of the national surface water and ambient air quality in 2019, and the website is http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202001/t20200123_760936.html.

2012). However, recent studies pay more attention to the causal relationship between environmental regulation and pollution reduction. For example, many researchers selected energy prices or quasi-natural experiments to define environmental regulation (Ley et al., 2016; Yang et al., 2021; Pan and Tang, 2020).

Environmental pollution is an external behaviour in industrial production and consumption, and pollution emissions behaviour determined by market mechanisms is ineffective, requiring the government to implement environmental protection policies to reduce environmental pollution (Zhang, 2014). Therefore, environmental regulation is an important policy instrument for the government's social governance, targeting enterprises' production and operation activities by imposing administrative penalties, emissions taxes and emissions limits to achieve pollution reduction and sustainable economic development (Zhang, 2014). Existing studies have shown that environmental regulation mainly promotes pollution reduction through cost-effective compliance and innovative compensation (Du and Li, 2020). First, regarding the compliance cost effect, under the constraints of environmental regulation policies, the development and utilisation of fossil fuel energy are strictly restricted. Also, environmental policies may force firms to reduce their consumption of low heating value and high-pollution resources and encourage them to utilise renewable energy, which is conducive to achieving energy conservation and emissions reduction (Floros and Vlachou, 2005; Sohag et al., 2015). Second, regarding innovation compensation effect, the increasing intensity of environmental regulation means that the government imposes more stringent environmental constraints on enterprises. As a result, enterprises focus on developing and applying clean technologies to achieve energy saving and emission reduction goals and higher environmental standards (Acemoglu et al., 2012; Shapiro and Walker, 2018). Cole et al. (2005) utilised a dataset of UK industry-specific emissions for various pollutants from 1990 to 1998 to examine the complex linkages between industrial activities, environmental regulations and air pollution. They found that informal and formal environmental regulations had been successful in reducing pollution intensity.

2.2. Environmental regulation and green innovation

Green innovation is a unique form of technological innovation that can reduce pollution emissions, optimise resource utilisation and improve ecological management (Braun and Wield, 1994). Also, green innovation is characterised by high investments, high risks and long research and development (R&D) cycles. Therefore, enterprises face great difficulties in executing green innovation activities. The existing literature mainly adopts two methods to measure green technological innovation capacity: green total factor productivity (Li and Chen, 2019) and the number of green patent applications (authorisations) (Ley et al., 2016; Qi et al., 2018; Kesidou and Wu, 2020).

Porter and van der Linde (1995) believed that more stringent but properly designed environmental regulation could trigger innovation and enhance competitiveness, namely the 'Porter Hypothesis'. Many scholars have since used various methods and datasets to investigate the impact of environmental regulation on green innovation. The relevant studies can be categorised into three groups. The first theory is the promotion effect. Based on Porter's Hypothesis, Mohr (2002) and Mohr and Saha (2008) pointed out that environmental regulation might motivate enterprises to invest in green technologies, which was conducive to exploiting firms' capacity to innovate. Acemoglu et al. (2012) proposed that environmental regulation promoted innovation in the cleaning sector, and this innovation will continue to exist after the environmental regulation. Ley et al. (2016) and Lanzi et al. (2011) utilised energy sector data from the 18 OECD countries and 23 other countries and selected energy prices as the proxy variable of environmental regulation to investigate whether environmental regulation can affect corporate green innovation ability. They found that increasing energy prices can promote green technological innovation. The second argument is the inhibition effect. Yuan (2018) conducted empirical tests based on China's manufacturing industry data and concluded that environmental regulation would crowd out R&D investments in the manufacturing industry, thus inhibiting substantive and strategic innovation therein. Stoever and Weche (2018) used the DID model to investigate the impact of Germany's water environmental protection policy on firms' competitiveness. In this regard, they found that the policy inhibited enterprise performance and investments in environmental protection, which is not conducive to their green development. The third argument is uncertainty theory. The development level of green innovation varies according to the stringency of countries' environmental regulations (Klaassen et al., 2005). Li and Du (2021) examined the spatial spillover effect of environmental regulations on green innovation efficiency based on Chinese city-level data. The results showed significant spillover effects of environmental regulations on urban green innovation efficiency, reflected in a U-shaped impact that was first suppressed and then promoted. Tao et al. (2021) took China's Target Responsibility System of Environmental Protection as a quasi-natural experiment and discovered that the policy was beneficial to expanding the number of green patent applications, leading to a decline in the quality of green innovation activities.

2.3. Relevant studies regarding WECCP policy

The pilot construction of water ecological civilisation cities is an innovative environmental policy proposed by the Chinese government. Furthermore, theoretical and empirical research linking the WECCP policy and pollution reduction is related to a small but growing body of literature. Li et al. (2014), Tian et al. (2021), and Liu and Wang (2018) conducted a theoretical analysis on the WECCP policy on its basic concept, legal basis, implementation strategy and evaluation system. Water ecological civilisation is a fundamental element of ecological civilisation. It refers to the harmonious development of the water environment and human activities, aiming to realise the sustainable utilisation of water resources, support the harmonious development of the economy and society and ensure a virtuous cycle in the ecosystem (Liu and Wang, 2018). Li et al. (2014) considered that the implementation plan for the WECCP policy should be compiled based on overall urban planning and rely on constructing a modern water network. The local government should then focus on flood control, water conservation and water ecological system construction. Such an approach would facilitate improving urban flood control capacity and the ecological function and would highlight the construction of 'water resources, water ecology, water landscape, water engineering and water management' (Li et al., 2014).

Subsequent empirical research, based on the entropy method, analytic hierarchy process, principal component analysis and other methods, supported the view that the WECCP policy contributed to regional pollution reduction. For example, Zhang et al. (2020) evaluated water ecological civilisation construction conditions in the different urban agglomerations using the entropy method. They found that the impact of the water ecological civilisation construction on urban agglomerations in the Yangtze River Delta and Middle Reaches of the Yangtze River were better than that of Chengyu Urban Agglomeration. Fang and Chen (2021) and Tian et al. (2021) used an analytical hierarchy process to evaluate the quality of Zhongshan City's water environment and 18 pilot cities in the Yangtze River Economic Belt. The former found that the water ecological civilisation construction in Zhongshan City satisfied the emissions standard, and the water environment indexes met the Level II required by the guidelines. The latter believed that the Urban Water Ecological Civilisation Index of urban agglomerations gradually increased along the Yangtze River from west to east, showing noticeable spatial differences. Ren et al. (2016) utilised principal component analysis to evaluate the construction performance of water ecological civilisation in the capital city of the Yangtze River Economic Belt. The results showed significant differences in the comprehensive score of water ecological civilisation in different cities.

2.4. *Brief conclusion*

In general, the existing literature has the following shortcomings: First, most scholars have only analysed the relationship between environmental regulation and pollution reduction or the impact of environmental regulation on green innovation. However, the logical process regarding how the WECCP policy promotes regional pollution reduction through strengthening urban green innovation capacity is yet to be accurately revealed. Second, although the literature regarding WECCP policy mainly focuses on the basic concept, legal basis, implementation strategy and evaluation system of the policy, there is relatively less empirical research on the WECCP policy. Specifically, most current literature used a comprehensive evaluation analysis method to evaluate the policy effect of a specific water ecological pilot city or cities in the urban agglomeration from the perspective of water ecological performance. Also, few studies have evaluated the policy effect of all the pilot cities and compared the differences in pollution reduction and green innovation levels between pilot and non-pilot cities. Finally, it is worth highlighting that those researchers ignored the influence of WECCP policy on other types of pollution, such as water pollution, air pollution and comprehensive pollution. Therefore, this paper clarifies the interaction mechanism among environmental regulation, pollution reduction and green innovation. Methodologically, the WECCP policy is treated as a quasi-natural experiment, and its effects on urban pollution reduction and green innovation are evaluated using detailed data from 283 Chinese cities from 2010 to 2018.

3. Institutional background and theoretical analysis

3.1. *The background of WECCP policy*

Water is the source of life, the essence of production and the basis of ecology. Furthermore, water ecological civilisation is a major component and a solid guarantee for ecological progress (Chen, 2013). However, China's water resources are relatively insufficient, the capacity of the water ecological environment is limited, and water pollution prevention and control is an arduous task. Hence, water ecological civilisation construction and the low utilisation rate of water resources are the primary practical problems requiring an urgent solution in China (Tian et al., 2021).

The Chinese government began to implement the WECCP policy to give full play to the fundamental role of water conservancy in ecological civilisation construction. In October 2012, Jinan was confirmed as the first national pilot city for the water ecological civilisation, reflecting that China was officially embarking on constructing a water ecological civilisation city (Shandong Quality Supervision Bureau, 2012). In January 2013, the Ministry of Water Resources issued *Opinions on Accelerating the Construction of Water Ecological Civilization*, which clarified the concepts, principles, objectives and main contents of the water ecological construction initiative, and formally proposed implementing the WECCP policy nationwide. 'Water ecological civilisation' refers to the harmonious development of the water environment and human activities, which integrates the concept of ecological civilisation into all aspects of water resources development, utilisation, management, allocation, conservation and protection. The main goals of the pilot policy include establishing 'Three Red Lines and Four Regulations' (see Fig. A1 in the Appendix) and a water-saving society, improving the water ecological environment and forming a scientific and reasonable water resources allocation pattern (Chinese Ministry of Water Resources, 2013). The construction of a water ecological civilisation fundamentally requires taking the strictest water resource management system as its core. In this regard, the main responsibilities (see Fig. A2 in the Appendix) of the ecological civilisation include optimising water resource allocation, strengthening the conservation and protection of water resources, promoting the restoration of water ecosystems, improving the ability of security and support, and conducting widespread publicity and education (Chinese Ministry of Water Resources, 2013; Chen, 2014). In August 2013, the Ministry of Water Resources selected 45 cities as the first batch of national water ecological civilisation pilot cities through a series of processes, including independent declaration, government recommendation and expert evaluation. In May 2014, the Ministry of Water Resources selected 59 cities as the second batch of pilot cities to advance the construction of the water ecological civilisation. From 2012–2014, the Ministry of Water Resources established 105 water ecological civilisation pilot cities. After identifying the pilot cities, the Water Resources Department and the local government reviewed the relevant construction plans. The pilot cities passing the review should conduct water ecological civilisation construction by following their plans and achieving the expected goals within the validity period. In addition, each pilot city implemented the strictest water resource protection and management, adopted the ‘Three Red Lines and Four Regulations’ of water resource management as binding indicators and incorporated the water ecological environment into the government’s performance appraisal system. By the end of 2017, 41 pilot cities had completed the inspection and acceptance, and a series of remarkable achievements were made during the pilot construction (Chinese Ministry of Water Resources, 2018). In May 2019, another 58 pilot cities passed the pilot acceptance (Chinese Ministry of Water Resources, 2019)[3] .

The WECCP policy generally aims to improve the urban water ecological environment and is also an important part of Chinese ecological civilisation construction systems (Deng et al., 2019). According to Deng et al. (2019) and Tian et al. (2021), the water resource utilisation rate, water quality compliance rate and water treatment technology in the pilot cities have been dramatically improved, indicating that the WECCP policy achieved demonstrable results.

3.2. Theoretical analysis and hypotheses

3.2.1. Pollution reduction effect

The WECCP policy is essentially an environmental regulation policy that addresses six dimensions: water security, water environmental management, water ecological restoration, water-based economic development, water management implementation and water culture cultivation (Chen, 2013). Each pilot city has pursued the strictest water resource management system and achieved ecological environment restoration by adjusting its economic structure and industrial layout, which helps to improve the quality of the urban ecological environment. Under these rigorous environmental standards, enterprises with excessive emissions will be penalised by the government. Therefore, some enterprises may reduce water pollution emissions by reducing output. Alternatively, others seek to maximise profits through reducing pollution emissions from installing water treatment machines and improving sewage treatment technologies. Furthermore, disseminating the WECCP policy to the public via the media may raise public awareness on environmental protection and subsequently guide entrepreneurs and residents to continuously strengthen their environmental awareness and consciously practice energy conservation and emission reduction (Tao et al., 2021). The main goal of the WECCP policy is to comprehensively improve the water ecological environment rather than improve the urban atmospheric environment. Accordingly, the pilot cities focus on controlling water pollution and pay less attention to reducing air pollution. More importantly, the characteristics of air fluidity lead to the obvious spatial spillover effect of air pollution, and the atmospheric environment is affected by a series of meteorological and geographical factors, such as wind speed, precipitation, temperature, air pressure and altitude (Li et al., 2017). Therefore, the pilot policy produces heterogeneous impacts on different types of pollution. According to the above analysis, the following hypothesis can be formulated:

Hypothesis 1. The WECCP policy has a pollution reduction effect; that is, the pilot policy is beneficial to optimising water quality in the pilot city, while the improvement effect on air quality is relatively weak.

3.2.2. Green innovation effect

The WECCP construction is an urban water environmental governance activity in which the government takes the lead, enterprises assume the main responsibility, and social organisations and the public also participate. Local officials compete over environmental protection and economic growth targets set by the central government for getting promotions (Li and Zhou, 2005). Therefore, they may take punitive and incentive environmental governance measures to improve urban water quality and green innovation capability. For instance, local officials may implement stricter environmental regulations by issuing administrative orders to impose environmental governance pressure on industrial enterprises, such as strengthening the supervision of firms’ pollutant discharge, raising pollution discharge standards and imposing stricter penalties on polluters. Faced with the ‘strong constraints’ of the WECCP policy, rational economic firms may optimise energy consumption structures and production processes by conducting green technological innovation activities to lower environmental costs and achieve sustainable development (Lu et al., 2020). When the compensatory effect of environmental regulations on corporate innovation offsets and exceeds the effects caused by the internalisation of environmental costs, conditions become favourable for enterprises to achieve green innovation (Porter and van der Linde, 1995; Tao et al., 2021). For other firms, local officials may provide environmental and innovation subsidies to support corporate green innovation, especially for high-tech companies and companies in green sectors. Generally, government subsidies compensate for insufficient corporate resources, reduce environmental protection costs, lower environmental investment risks and enhance the enthusiasm of enterprises for environmental protection, thereby motivating them to invest in green innovation activities.

However, with the continuous enhancement of people’s awareness of environmental protection, the stringency of environmental regulation has been increasingly strengthened, and the short-term mandatory emission standards have gradually become the normal constraints. Against this background, enterprises may spare no effort to organise innovative activities and develop clean technologies, which essentially help to promote industrial upgrading and enhance urban green innovation capability. In addition, considering that universities and research institutions are also involved in environment-related innovations, firms may cooperate with universities and research institutes to develop green technologies and green products, and the industry-university-research innovation mode is beneficial for improving the urban green innovation ability. Given the above analysis, it is, therefore, proposed:

Hypothesis 2. The WECCP policy helps to improve urban green innovation capacity.

[3] The relevant data are derived from the website of the Chinese Water Resources Ministry (http://www.mwr.gov.cn/).

3.2.3. The mediating effect of green innovation

Against the background of implementing the WECCP policy, enterprises with certain capital and technological foundations may improve green technological innovation ability by introducing technology or independent innovation. On the one hand, polluting enterprises may purchase water pollution treatment equipment from other eco-friendly enterprises to reduce pollution emissions in the production process. Therefore, the market demand for environmental protection equipment dramatically increases. This scenario may improve environmentally-friendly enterprises' green innovation capacity and then promote the development of eco-friendly industries. In this case, WECCP policy may stimulate eco-friendly firms to develop clean technologies, consequently reducing the pollution emissions of polluting firms and achieving regional pollution reduction. On the other hand, some enterprises tend to increase R&D investments in environmental technologies and organise green innovation activities to reduce pollution emissions since productive expenditure on independent innovation for clean technological innovation can strengthen corporate competitiveness and achieve sustainable development (Ali et al., 2021). Therefore, under the established conditions of environmental regulation, technological innovation development should be conducive to pollution reduction (Acemoglu et al., 2014). Based on the above arguments, the following hypothesis can be proposed:

Hypothesis 3. The WECCP policy can improve regional environmental quality by enhancing urban green innovation capacity.

4. Methodology and data

4.1. Model

4.1.1. Pollution reduction effect of WECCP policy

From 2012–2014, the Ministry of Water Resources established 105 water ecological civilisation pilot cities, which provided a quasi-natural experiment for us to investigate the pollution reduction effect of WECCP policy. The DID estimator compares treatment and control groups in terms of outcome changes over time relative to the outcomes observed for a preintervention baseline. The advantage of DID is that it relaxes the assumption of conditional exogeneity or selection only on observed characteristics. It also provides a tractable, intuitive way to account for selection on unobserved characteristics (Khandker et al., 2009). This paper sets the intensity of urban pollution emissions as the dependent variable and utilises the DID method to estimate the pollution reduction effect of WECCP policy. Meanwhile, we include year-specific and city-specific dummy variables to control nationwide shocks and time-invariant unobserved city characteristics. DID estimation equation is specified as follows:

$$Pollution_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

where subscripts 'i' and 't' refer to a specific city and a year, respectively. *Pollution* represents pollutant emissions, including water pollution index, air pollution index and composite pollution index. $Policy_{it}$ is a dummy variable that equals one in the years after the city i being selected as a pilot city, and equals zero otherwise. The coefficient α_1 indicates the impact of WECCP policy on regional pollution reduction. *CV* represents a series of control variables, including economic growth, industrial structure, infrastructure construction, government intervention degree, fixed asset investment rate and population density. μ_i is the city fixed eff ;ect, capturing cities' time-invariant characteristics, and λ_t measures the year fixed eff ;ect. ε_{it} is a random error term.

4.1.2. Green innovation effect of WECCP policy

Based on the analysis regarding the pollution reduction effect of WECCP policy, this paper selects urban green innovation capacity as the dependent variable to explore the impact of WECCP policy on urban green innovation, and the DID estimation equation is set as follows:

$$Gpatent_{it} = \beta_0 + \beta_1 Policy_{it} + \beta_2 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

where *Gpatent* denotes urban green innovation capacity, which is measured by the number of green patent applications, including the number of total green patent applications (*Gpatent*), green invention patent applications (*IGpatent*) and green utility model patent applications (*UGpatent*). The coefficient β_2 indicates the impact of WECCP policy on urban green innovation. Other variables have the same meaning as before.

4.1.3. Mediating effect of green innovation

The theoretical analysis shows that the WECCP policy may improve urban environmental quality by improving green innovation levels. According to Wang et al. (2021), this paper introduces *Policy* and *Gpatent* as independent variables into Eq. (3) to explore the relationship among WECCP policy, urban pollution reduction and green innovation, and the mediating effect model is set as follows:

$$Pollution_{it} = \gamma_0 + \gamma_1 Policy_{it} + \gamma_2 Gpatent_{it} + \gamma_3 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

where Eqs. (1)–(3) constitute mediating effect models. Eq. (1) represents the total effect of WECCP policy on urban pollution emission levels, and Eq. (2) represents the effect of WECCP policy on urban green innovation capacity. If the coefficient β_1 is positive, it proves that the policy is conducive to improving urban green innovation capacity. The coefficient γ_1 in Eq. (3) measures the policy's direct effect on urban pollution emissions. If Eq. (2) is brought into Eq. (3), the following results can be obtained:

Table 1
Urban pollution emission level evaluation index system.

First-level indicators	Second-level indicators	Third-level indicators	Data source
Composite pollution index (*Pollution*)	Water pollution index (*Wpollution*)	Surface water quality index (*WSI*)	Institute of Public and Environmental Affairs
		Drinking water quality index (*WDI*)	Institute of Public and Environmental Affairs
	Air pollution index (*Apollution*)	PM2.5 concentration per unit of GDP(*PM25*)	Atmospheric Composition Analysis Group
		Industrial SO2 emission per unit of GDP (*SO2*)	China Urban Statistical Yearbook
		Industrial smoke emission per unit of GDP (*Smoke*)	China Urban Statistical Yearbook

$$Pollution_{it} = (\gamma_0 + \beta_0\gamma_2) + (\gamma_1 + \beta_1\gamma_2)Policy_{it} + (\gamma_3 + \beta_2\gamma_2)CV_{it} + \varepsilon_{it} \tag{4}$$

where the coefficient $\beta_1\gamma_2$ measures the mediating effect, that is, the degree that WECCP policy lowers the intensity of pollution emissions by improving urban green innovation capacity.

4.2. Sample selection and data source

During 2012–2014, the Ministry of Water Resources set up 105 pilot cities, including 79 prefecture-level cities, 16 county-level cities and 10 districts (counties) under the jurisdiction of centrally-administered municipalities.[4] This paper takes prefecture-level cities and municipalities as the main research objects, and county-level cities and autonomous prefectures are excluded due to lacking environmental data, such as Yanqing County, Miyun County, Jixian County, Naqu Region and so on. Considering that only Jinan was established as a pilot city in October 2012, this paper includes it in the first batch of pilot cities in 2013. Hence, the implementation time of the WECCP policy is 2013 and 2014. Due to the unavailability of water pollution data at the city level before 2010, this paper selects the research period as 2010–2018, and then compares the differences of pollution emission intensity before and after the implementation of this policy. Consequently, this paper selects 283 cities during 2010–2018 to study the effect of WECCP policy on urban pollution reduction and green innovation, including 75 cities in the treatment group and 208 cities in the control group.

4.2.1. Dependent variable

(1) Pollution emission index (*Pollution*). Environmental pollution mainly includes air pollution, water pollution, solid waste pollution, noise pollution, and electromagnetic pollution, among which air pollution and water pollution are the most harmful to people's health, and they are also the main targets of environmental pollution control in China. In view of this, this paper sets the dependent variable as urban pollution emission intensity, measured by three indicators: water pollution index (*Wpollution*), air pollution index (*Apollution*) and composite pollution index (*Pollution*). To be more specific, the Institute of Public and Environmental Affairs (www.ipe.org.cn) has published a city-level water quality index since 2010, including a surface water quality index (*WSI*), a groundwater quality index (*WGI*), and a drinking water quality index (*WDI)*. The larger the index is, the more severe is the water pollution. Due to the lack of groundwater quality indexes in many cities, this paper selects *WSI* and *WDI* as the proxy variables of the water pollution index, and uses the entropy method to calculate the urban water pollution index. Then, we utilise PM2.5 concentration (*PM25*), industrial sulphur dioxide emissions (*SO2*), and industrial smoke emissions (*Smoke*) per unit of GDP to measure the degree of urban air pollution, and the entropy method is employed to compute the air pollution index. Finally, this paper computes a composite pollution emission index based on various water pollution and air pollution indicators (see Table 1) because of lacking city-level solid pollutant data.

The entropy method is an objective weighting method computing the weight by the overall influence of the relative variation of indicators, which excludes people's interference and reflects the internal differences between the data (Tian et al., 2021). Therefore, the entropy method was applied to calculate the composite pollution index (Fu and Li, 2010; Cheng et al., 2020). There are four steps to calculate the composite pollution index:

The first step is to standardize three-level indicators, so that the value of each index ranges from 0 to 1. The selected indicators have different measurement units. In order to eliminate the influence of dimensions, this paper utilises the normalization method to normalize the values of 5 indicators for each city (Saranya and Manikandan, 2013).

$$x_{ij}^{*} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{5}$$

where i and j denote a city and a third-level pollution indicator, respectively. $x_{ij}*$ is the normalized value of indicator j in city i. $\max(x_{ij})$

[4] A centrally-administered municipality is under the direct control of the state council, and there are 4 municipalities directly under the central government in China, including Beijing, Tianjin, Shanghai and Chongqing.

Table 2
Descriptive statistics.

Variable	Definition	Obs	Mean	Std. Dev	Data source
Wpollution	Water pollution index	2547	0.17	0.18	Institute of Public and Environmental Affairs,
Apollution	Air pollution index	2547	0.07	0.08	Atmospheric Composition Analysis Group, China
Pollution	Composite pollution index	2547	0.10	0.09	Urban Statistical Yearbook
Gpatent	The sum of the number of green invention and green utility model patent applications	2547	6.67	19.69	World Intellectual Property Organization, Incopat
IGpatent	The number of green invention patent applications	2547	3.59	12.04	Database
UGpatent	The number of green utility model patent applications	2547	3.08	7.95	
Policy	Before the implementation of WECCP policy, *Policy* = 0 in all cities, and *Policy* = 1 in pilot cities after the implementation of WECCP policy	2547	0.16	0.37	The Ministry of Water Resources
PGDP	The natural logarithm of actual per capita GDP	2547	10.53	0.60	
Stru	The ratio of the added value of the third industry to that of the second industry	2547	0.93	0.51	
Infrastru	Urban road area per capita	2547	4.89	6.22	China Urban Statistical Yearbook, China Regional
GI	The proportion of government financial expenditure to GDP	2547	0.20	0.13	Economic Development Database
Invest	The proportion of fixed asset investment to GDP	2547	0.81	0.31	
Pop	Total population at the end of the year divided by urban construction land area	2547	4.37	3.44	

and $\min(x_{ij})$ represent the maximum value and minimum value of the indicator j, respectively.

The second step is to determine the entropy value of all third-level indicators through the entropy method. e_j is the entropy value of indicator j, and the specific procedure of the calculation is summarized as follows:

$$p_{ij} = \frac{x_{ij}^{*}}{\sum_{i=1}^{n} x_{ij}^{*}} \tag{6}$$

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{7}$$

where p_{ij} is the characteristic proportion of the city i in the indicator j, e_j is the entropy value of indicator j, and ln(n) refers to the information entropy coefficient.

The third step is to compute the entropy weight of all third-level indicators. w_j is the entropy weight of indicator j, and the specific calculation process is as follows:

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \tag{8}$$

In the final step, we calculate the composite pollution index of all cities.

$$Pollution_i = \sum_{j=1}^{m} \omega_j p_{ij} \tag{9}$$

where $Pollution_i$ is the composite pollution index of city i, which is equal to the sum of entropy value multiplying entropy weight of third-level indicators.

(2) Urban green innovation (*Gpatent*). The number of green patent applications can better reflect the level of environmental technologies, so this paper collects the number of green patent applications for all enterprises, universities, and research institutions in the same city to measure urban green innovation capacity. The reason why we choose the number of green patent applications rather than the number of green patent grants lies in two aspects: (i) it takes 1–2 years from application to authorization for a patent, so the number of green patent applications can better reflect green innovation capacity in the current period; (ii) the number of green patent applications is less affected by external factors, such as the efficiency and preference of patent agencies. The methods of collecting green patents are listed as follows. At first, based on the Green Patent Inventory issued by the World Intellectual Property Organization, we identify the types of green patents and their IPC classification number. Then, we use the *Incopat Database* (www.incopat.com) and input "IPC classification number + city name" in the search box to retrieve the number of green invention patents and green utility model patents applied by all firms, universities, and research institutions in the sample cities during 2010–2018. Finally, we can obtain the total number of green patent applications by summing up each city's green invention patents and green utility model patent applications. In China, patent applications can be divided into three types: invention, utility model and design. The technical level of invention patents is the highest, followed by utility model patents, and the technical content of design patents is the lowest. Therefore, this paper mainly considers green invention and utility model patents, and sequentially sets the dependent variable as the number of green patent applications (*Gpatent*), green invention patent applications (*IGpatent*) and green utility model patent applications (*UGpatent*).

Table 3
The impact of WECCP policy on regional pollution reduction.

Variables	Water pollution index			Air pollution index				Composite pollution index
	(1) *Wpollution*	(2) *WSI*	(3) *WDI*	**(4)** *Apollution*	(5) *PM25*	(6) *SO2*	(7) *Smoke*	(8) *Pollution*
Policy	−0.043***	−2.429**	−1.143***	−0.008	−0.007*	−0.103	0.268	−0.023***
	(0.014)	(1.039)	(0.366)	(0.008)	(0.003)	(0.300)	(0.419)	(0.008)
PGDP	0.022*	3.099***	0.070	−0.033***	−0.029***	−1.006*	−1.082**	−0.008
	(0.013)	(0.882)	(0.287)	(0.010)	(0.006)	(0.550)	(0.431)	(0.008)
Stru	0.022	0.793	0.377	−0.018***	−0.007*	−1.513***	−1.136***	−0.000
	(0.021)	(0.839)	(0.430)	(0.006)	(0.004)	(0.403)	(0.379)	(0.012)
Infrastru	−0.000	−0.074	−0.009	0.003	0.001*	0.100	0.053	0.001
	(0.001)	(0.071)	(0.020)	(0.002)	(0.001)	(0.061)	(0.048)	(0.001)
GI	−0.072**	−3.055	−0.257	0.012	0.036	0.354	−1.983*	−0.026
	(0.029)	(2.676)	(1.022)	(0.038)	(0.038)	(2.377)	(1.126)	(0.024)
Invest	−0.047***	−1.290	−1.916***	0.003	0.019***	0.010	−0.332	−0.008
	(0.016)	(1.099)	(0.577)	(0.009)	(0.006)	(0.554)	(0.635)	(0.009)
Pop	−0.000	0.479***	−0.060	−0.006***	−0.001	−0.357***	−0.421***	−0.004***
	(0.001)	(0.172)	(0.046)	(0.001)	(0.001)	(0.081)	(0.099)	(0.001)
Constant	−0.025	−18.622*	5.151	0.447***	0.333***	16.919***	17.847***	0.206**
	(0.143)	(9.490)	(3.186)	(0.102)	(0.069)	(5.937)	(5.144)	(0.094)
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2547	2547	2547	2547	2547	2547	2547	2547
R^2	0.035	0.063	0.024	0.146	0.238	0.092	0.011	0.039

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

4.2.2. Independent variable

The core independent variable is the WECCP policy (*Policy*), which estimates the difference of outcome variable (pollution emissions or green innovation capacity) between pilot cities and non-pilot cities before and after implementing the WECCP policy. *Policy* is a dummy variable, and the values of *Policy* in the control and treatment groups are equal to 0 before the treated year (2013 or 2014). However, if a city is determined as the pilot city after 2013 (2014), its value of *Policy* turns to 1.

4.2.3. Control variable

The control variables include economic growth (*PGDP*), industrial structure (*Stru*), infrastructure construction (*Infrastru*), government intervention degree (*GI*), fixed asset investment rate (*Investment*) and population density (*Popdensity*), which are measured by the natural logarithm of actual per capita GDP, the ratio of the added value of the third industry to that of the second industry, urban road area per capita, the proportion of government financial expenditure to GDP, the proportion of fixed asset investment to GDP and total population divided by urban construction land area, respectively. Table 2 shows the descriptive statistics of the main variables used in this paper.

5. Results and discussion

5.1. The impact of WECCP policy on regional pollution reduction

According to Eq. (1), this subsection investigates whether WECCP policy plays a role in pollution reduction at the city level. According to Table 3, we can obtain the following main conclusions. First, when the explained variables are water pollution index (*Wpollution*), surface water quality index (*WSI*), drinking water quality index (*WDI*) and composite pollution index (*Pollution*), the coefficients of *Policy* are significantly negative, indicating that implementing the WECCP policy helps to reduce urban pollutant emissions, and plays a more prominent role in water pollution control. This is because WECCP policy requires pilot cities to enhance sewage treatment capacity and optimise the utilisation efficiency of water resources, and the pilot cities must strengthen environmental law enforcement to improve the quality of the water environment. With the improvement of environmental regulation intensity, the emission of other pollutants in the pilot cities will be gradually reduced, and the overall environmental quality will continue to be optimised. Second, when the dependent variable is *PM25*, the coefficient of *Policy* is significantly negative at the 10 % level. However, when the dependent variables are air pollution index (*Apollution*), the emission intensity of industrial sulphur dioxide (*SO2*) and industrial smoke industrial emission (*Smoke*), the coefficients of *Policy* are insignificant. This means that the WECCP policy has a weak effect on improving air quality. The reasons lie in two aspects: (i) the main goal of the WECCP policy is to comprehensively improve urban water ecological environment rather than improve urban air quality, so the effect of the policy on water pollution reduction is more significant; (ii) the air quality is affected by geographical location, atmospheric pressure, wind and other natural factors, and the characteristics of air fluidity lead to the obvious spatial spillover effect of air pollution. Therefore, the WECCP policy may achieve emission reduction targets, and hypothesis 1 is supported.

Table 4
The impact of WECCP policy on urban green innovation.

Variables	Dependent variable: Gpatent		Dependent variable: IGpatent		Dependent variable: UGpatent	
	(1)	(2)	(3)	(4)	(5)	(6)
Policy	16.054***	8.568***	9.428***	5.218***	6.627***	3.350***
	(4.030)	(2.498)	(2.535)	(1.553)	(1.549)	(1.003)
PGDP		10.546***		6.202***		4.344***
		(2.642)		(1.701)		(0.978)
Stru		12.599*		8.194*		4.405**
		(6.756)		(4.621)		(2.147)
Infrastru		0.007		−0.045		0.052
		(0.196)		(0.127)		(0.074)
GI		13.439		7.648		5.791
		(13.194)		(7.783)		(5.430)
Invest		−6.464**		−3.592*		−2.872***
		(2.904)		(1.872)		(1.064)
Pop		1.720***		0.964***		0.756***
		(0.419)		(0.237)		(0.184)
Constant	4.063***	−122.426***	2.057***	−72.762***	2.006***	−49.665***
	(0.638)	(31.655)	(0.358)	(20.533)	(0.287)	(11.500)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	2547	2547	2547	2547	2547	2547
R^2	0.084	0.410	0.077	0.374	0.088	0.442

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

5.2. The impact of WECCP policy on urban green innovation

In this subsection, the dependent variables are successively set as *Gpatent*, *IGpatent*, and *UGpatent*. The DID model is used to test the influence of WECCP policy on urban green innovation capacity. The regression results are shown in Table 4. As seen, we can obtain the following main conclusions. When the dependent variables are *Gpatent*, *IGpatent* and *UGpatent*, the elasticity coefficients of *Policy* are significantly positive at the level of 1%, indicating that implementing WECCP policy promotes the growth of the total number of green patent applications in the pilot areas. In other words, the WECCP policy can significantly improve urban green innovation ability. Overall, hypothesis 2 is validated.

5.3. Parallel trend and dynamic effects

The premise that the results of DID estimation maintain consistency is that the treatment and control groups meet the parallel trend hypothesis. Specifically, without the intervention of exogenous policy, the development trends of outcome variables in the treatment and control groups are consistent. In order to verify the applicability of DID method, this paper uses the Event Study Approach developed by Beck et al. (2010) and Li et al. (2016) to test the parallel trend and dynamic effects of WECCP policy. The relevant model is specified as follows:

$$Pollution_{it} = \phi_0 + \sum\nolimits_{\tau=2010}^{2012} \theta_{-\tau} D_{i,t-\tau} + \theta^* D_{it} + \sum\nolimits_{\tau=2013}^{2018} \theta_{+\tau} D_{i,t+\tau} + \phi_1 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{10}$$

$$Gpatent_{it} = \phi_0 + \sum\nolimits_{\tau=2010}^{2012} \theta_{-\tau} D_{i,t-\tau} + \theta^* D_{it} + \sum\nolimits_{\tau=2013}^{2018} \theta_{+\tau} D_{i,t+\tau} + \phi_1 CV_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{11}$$

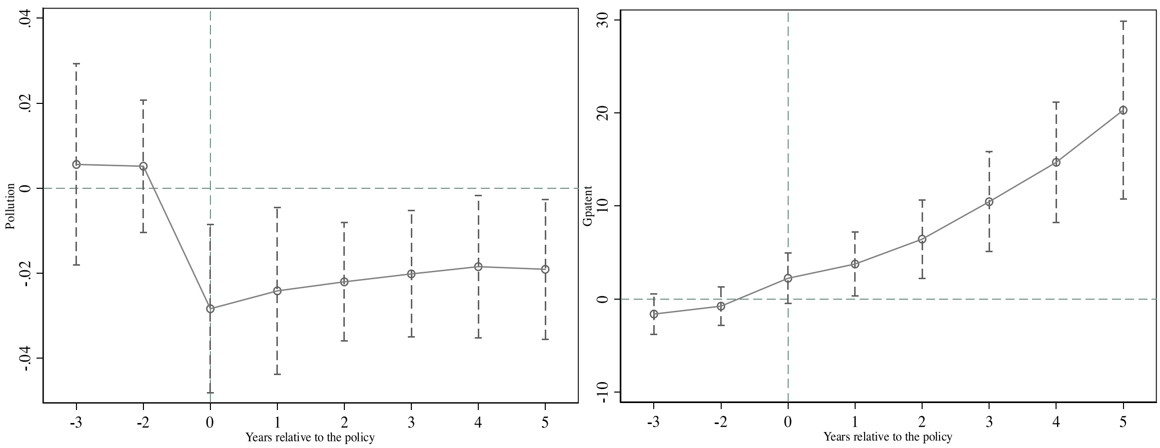
where $\theta_{-\tau}$ represents the impact of WECCP policy on urban pollution reduction or green innovation levels before the implementation of the policy, while $\theta_{+\tau}$ denotes the pollution reduction effect or green innovation effect after implementing the WECCP policy.

This paper sets 2013 and 2014 as implementation time, and the research years can be divided into non-pilot period (2010–2012) and pilot period (2013–2017). The dynamic effect of DID estimation is shown in Table 5 and Fig. 1. According to Table 5, except for column 4 (when the dependent variable is *Apollution*), the coefficients of *Pre2* and *Pre3* in other columns are insignificant, and the coefficients of *Post1-Post5* in other columns are significantly negative or positive. Figs. 1(a) and (b) illustrate the time trend of DID estimation regarding pollution reduction effect and green innovation effect, respectively. As shown, it is clear that both urban pollution emissions and green innovation capacity satisfy the parallel trend hypothesis before implementing the WECCP policy. Also, we find that the WECCP policy helps to reduce pollution emissions in the next few years. As time goes by, the policy effects show an upward trend, and the effects are statistically significant, demonstrating that WECCP policy exerts a significant positive impact on urban green innovation.

Table 5
Parallel trend and dynamic effects.

Variables	Pollution reduction effect			Green innovation effect		
	(1) *Pollution*	(2) *Wpollution*	(3) *Apollution*	(4) *Gpatent*	(5) *IGpatent*	(6) *UGpatent*
Pre3	0.006	0.007	−0.021**	−1.623	−0.926	−0.697
	(0.014)	(0.019)	(0.010)	(1.323)	(0.772)	(0.566)
Pre2	0.005	0.006	−0.008	−0.775	−0.601	−0.174
	(0.009)	(0.015)	(0.005)	(1.262)	(0.744)	(0.538)
Current	−0.028**	−0.052**	−0.011	2.227	1.564	0.663
	(0.012)	(0.024)	(0.008)	(1.646)	(1.012)	(0.671)
Post1	−0.024**	−0.050*	−0.012	3.753*	2.477*	1.277
	(0.012)	(0.026)	(0.008)	(2.077)	(1.283)	(0.838)
Post2	−0.022***	−0.043**	−0.009	6.431**	3.892**	2.539**
	(0.008)	(0.021)	(0.008)	(2.550)	(1.621)	(0.988)
Post3	−0.020**	−0.037***	−0.009	10.452***	6.423***	4.030***
	(0.009)	(0.014)	(0.010)	(3.254)	(2.093)	(1.230)
Post4	−0.018*	−0.040***	−0.005	14.693***	8.939***	5.753***
	(0.010)	(0.014)	(0.012)	(3.910)	(2.561)	(1.484)
Post5	−0.019*	−0.027	−0.008	20.295***	11.433***	8.863***
	(0.010)	(0.018)	(0.011)	(5.798)	(3.401)	(2.596)
PGDP	−0.008	0.021*	−0.032***	10.607***	6.241***	4.366***
	(0.008)	(0.012)	(0.010)	(2.677)	(1.719)	(0.994)
Stru	−0.000	0.022	−0.018***	12.631*	8.214*	4.417**
	(0.012)	(0.021)	(0.006)	(6.814)	(4.654)	(2.172)
Infrastru	0.001	−0.000	0.003	0.000	−0.048	0.049
	(0.001)	(0.001)	(0.002)	(0.195)	(0.126)	(0.074)
GI	−0.026	−0.072**	0.011	13.355	7.604	5.751
	(0.024)	(0.029)	(0.039)	(13.363)	(7.887)	(5.496)
Invest	−0.009	−0.047***	0.005	−6.320**	−3.502*	−2.819***
	(0.009)	(0.016)	(0.009)	(2.921)	(1.883)	(1.068)
Pop	−0.004***	−0.000	−0.006***	1.710***	0.959***	0.751***
	(0.001)	(0.001)	(0.001)	(0.425)	(0.240)	(0.187)
Constant	0.210**	−0.020	0.436***	−123.054***	−73.171***	−49.884***
	(0.090)	(0.138)	(0.104)	(32.156)	(20.806)	(11.724)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	2547	2547	2547	2547	2547	2547
R^2	0.040	0.035	0.149	0.421	0.383	0.455

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.



(a) Pollution reduction effect (b) Green innovation effect

Fig. 1. Parallel trend and dynamic effects of DID estimation.
(a) Pollution reduction effect (b) Green innovation effect

Table 6
Robustness Check I: PSM sample (pollution reduction effect).

Variables	K-Nearest Neighbors Matching			Radius Matching			Kernel Matching		
	(1) *Pollution*	(2) *Wpollution*	(3) *Apollution*	(4) *Pollution*	(5) *Wpollution*	(6) *Apollution*	(7) *Pollution*	(8) *Wpollution*	(9) *Apollution*
Policy	−0.024***	−0.046***	−0.011	−0.022***	−0.041***	−0.010	−0.022***	−0.041***	−0.010
	(0.009)	(0.015)	(0.009)	(0.008)	(0.014)	(0.008)	(0.008)	(0.014)	(0.008)
CV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1761	1761	1761	2481	2481	2481	2482	2482	2482
R^2	0.042	0.038	0.144	0.037	0.030	0.143	0.037	0.030	0.143

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

Table 7
Robustness Check I: PSM sample (green innovation effect).

Variables	K-Nearest Neighbors Matching			Radius Matching			Kernel Matching		
	(1) *Gpatent*	(2) *IGpatent*	(3) *UGpatent*	(4) *Gpatent*	(5) *IGpatent*	(6) *UGpatent*	(7) *Gpatent*	(8) *IGpatent*	(9) *UGpatent*
Policy	6.955***	4.401***	2.554**	7.832***	4.790***	3.042***	7.865***	4.806***	3.059***
	(2.518)	(1.590)	(0.988)	(2.370)	(1.475)	(0.955)	(2.363)	(1.468)	(0.954)
CV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1761	1761	1761	2481	2481	2481	2482	2482	2482
R^2	0.461	0.421	0.496	0.437	0.399	0.469	0.439	0.401	0.472

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

Table 8
Robustness Check II: Alternative measurement of urban green innovation.

Variables	1-year lagged the number of green patent applications			2-year lagged the number of green patent applications			The number of green patent authorizations		
	(1) *LGpatent*	(2) *LIGpatent*	(3) *LUGpatent*	(4) *L2Gpatent*	(5) *L2IGpatent*	(6) *L2UGpatent*	(7) *Grant*	(8) *LGrant*	(9) *L2Grant*
Policy	6.791***	4.102***	2.689***	4.797***	2.818***	1.979***	73.108***	106.096***	109.343**
	(1.976)	(1.270)	(0.729)	(1.675)	(1.063)	(0.625)	(16.499)	(33.538)	(46.749)
CV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2264	2264	2264	1981	1981	1981	2547	2264	1981
R^2	0.275	0.240	0.298	0.220	0.184	0.255	0.087	0.140	0.174

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

5.4. Robustness checks

5.4.1. Propensity score matching

In fact, the selection of water ecological civilisation pilot cities may be not random, but determined by the Ministry of Water Resources. Specifically, the Ministry approved the pilot city according to its economic conditions and ecological environment. Propensity Score Matching (PSM) is a technique that attempts to simulate the random assignment of treatment and control groups by matching treated subjects to untreated subjects that were similarly likely in the same group. In order to avoid sample selection bias and improve the comparability of the treatment and control groups, this paper chooses the PSM method to further verify the impact of water ecological civilisation city construction on urban environmental pollution and green innovation. Considering that the pilot policy is multi-stage, this paper matches firms in the non-pilot cities with those in the pilot cities year by year (Li and Wu, 2018). This paper adopts three matching methods, including k-Nearest Neighbor Matching (k = 4), Radius Matching and Kernel Matching, to match the individuals in the treatment group with those in the control group. Economic development level (*PGDP*), industrial structure (*Stru*), government intervention degree (*GI*) and fixed asset investment rate (*Invest*) are selected as covariates. Tables 6 and 7 show the estimation of the impact of WECCP policy on regional emission reduction and green innovation after PSM treatment, respectively. The

Table 9
Robustness Check III: Excluding municipality samples.

Variables	(1) *Pollution*	(2) *Wpollution*	(3) *Apollution*	(4) *Gpatent*	(5) *IGpatent*	(6) *UGpatent*
Policy	−0.021***	−0.042***	−0.009	5.591***	3.415***	2.176**
	(0.008)	(0.014)	(0.008)	(2.022)	(1.197)	(0.860)
CV	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	2511	2511	2511	2511	2511	2511
R^2	0.051	0.028	0.147	0.378	0.344	0.399

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

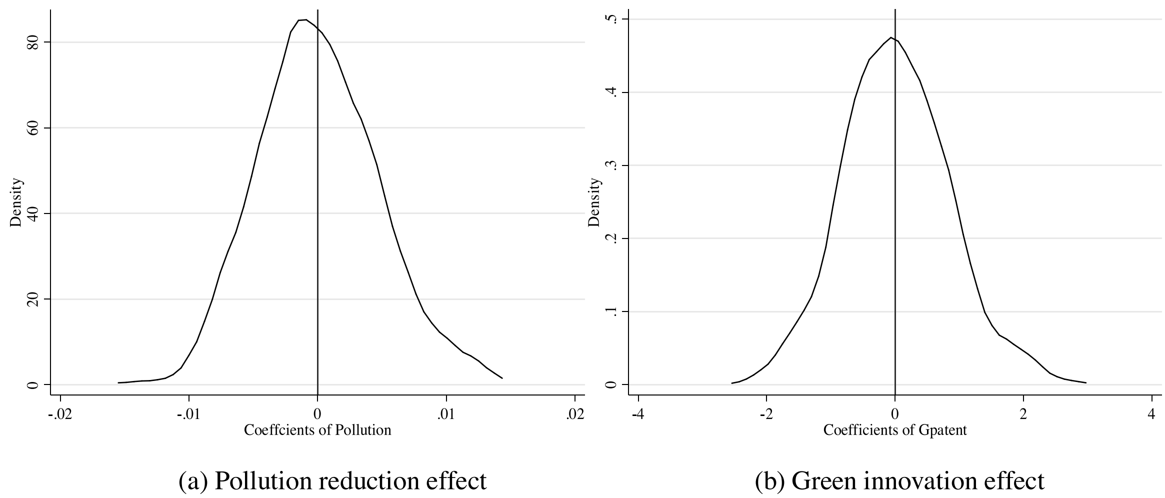


Fig. 2. Placebo test.
Pollution reduction effect (b) Green innovation effect

regression results of the main variables are consistent with the basic regression results after the treatment of multiple PSM methods, implying that the WECCP policy is not only conducive to reducing pollution emissions, but also helps to improve cities' green innovation ability. Therefore, the regression results of this paper are robust.

5.4.2. Alternative measurement of urban green innovation

The patent application procedure in China is relatively complex. It usually takes 1–2 years from application to authorization for a patent. It is worth noting that using the lagged values of explanatory variables and dependent variables may address some concerns of endogeneity and omitted variables (Bhattacharyya and Hodler, 2014). Hence, we replace the dependent variable with 1-year lagged (*LGpatent*, *LIGpatent*, *LUGpatent*) and 2-year lagged (*L2Gpatent*, *L2IGpatent*, *L2UGpatent*) the number of green patent applications, and then conduct DID estimation again. In addition, the patent application needs to go through the substantive examination after being published, and only for patents that meets the authorization conditions can the invention patent be granted. To a certain extent, the number of patent grants can better reflect corporate innovation capacity. Thus, this paper further replaces the dependent variable with the number of green patent authorizations (*Grant*), 1-year lagged (*LGrant*) and 2-year lagged the number of green patent authorizations (*L2Grant*). The results in Table 8 show that after using alternative measurement of urban green innovation, the coefficients of *Policy* are significantly positive at the 1% level, suggesting that the WECCP policy promotes regional green innovation, which further confirms hypothesis 2.

5.4.3. Excluding municipality samples

The Ministry of Water Resources has established some pilot cities within four municipalities, such as Mentougou District of Beijing, Wuqing District of Tianjin, Qingpu District and Minhang District of Shanghai, Yongchuan District of Chongqing, and the economic conditions of municipalities are quite different from those in the prefecture-level cities. More importantly, municipalities tend to gather more economic factors and innovation resources, and the central government may strengthen environmental supervision in the municipalities in comparison with prefecture-level cities. Therefore, there may be a large gap in pollution emission levels and green innovation capacity between municipalities and prefecture-level cities. Therefore, this paper excludes the relevant data of municipality samples from the whole sample to ensure robust estimation results, including Beijing, Shanghai, Tianjin and Chongqing. It can be seen

Table 10
Heterogeneity results based on urban size.

Variables	Big Cities		Small Cities	
	(1) *Pollution*	(2) *Gpatent*	(3) *Pollution*	(4) *Gpatent*
Policy	0.001	17.934*	−0.025***	4.077***
	(0.016)	(9.022)	(0.009)	(1.493)
CV	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	324	324	2223	2223
R^2	0.135	0.533	0.050	0.295

Notes: The parentheses are the clustered standard errors at the city level. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

Table 11
The mediating effect of green innovation on the relationship between WECCP policy and pollution reduction.

Variables	(1) *Pollution*	(2) *Gpatent*	(3) *Pollution*	(4) *IGpatent*	(5) *Pollution*	(6) *UGpatent*	(7) *Pollution*
Policy	−0.019***	8.668***	−0.012**	5.377***	−0.012*	3.291***	−0.014**
	(0.006)	(0.812)	(0.006)	(0.511)	(0.006)	(0.328)	(0.006)
Gpatent			−0.001***				
			(0.000)				
IGpatent					−0.001***		
					(0.000)		
UGpatent							−0.001***
							(0.000)
CV	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2547	2547	2547	2547	2547	2547	2547
R^2	0.570	0.821	0.575	0.811	0.576	0.820	0.573
Z-value of Sobel test	–	−6.074		−7.022		−4.328	
Pecent of total effect that is mediated	–	36.21 %		39.48 %		25.66 %	

Notes: The parentheses are the standard errors. *, ** and *** indicate 10 %, 5% and 1% significance levels, respectively. *City* and *Year* represent city fixed effects and year fixed effects, respectively.

from Table 9 that the regression results are basically the same as before.

5.4.4. Placebo test

To check whether our results are biased due to the unobservable factors, such as environment, economy and politics, this paper constructs artificial treatment and control groups, and then conducts a placebo test. At first, according to Cai et al. (2016), this paper randomly selects 75 cities from a total of 283 cities. Then, we assign them as the pilot cities, and the remaining 208 cities are assigned as the non-experimental cities. Random selection ensures that the double difference term *Policy* has no impact on pollution emissions and green innovation. Simply, if the coefficients of *Policy* are insignificant, there is no deviation in the regression result. Finally, we conduct this random data generating process 500 times to avoid contamination by any rare events. Fig. 2 illustrates the estimated distribution of *Policy* coefficients (α_1 and β_1) from the 500 times of randomization. The results show that the distributions of coefficients' kernel density of pollution reduction effect (α_1) and green innovation effect (β_1) almost obey normal distribution. This means that our results are less affected by other unobservable factors. Therefore, it is ruled out that the improvement of pilot cities' green innovation levels are affected by systemic factors at the city level in the same period, that is, the regression results of this paper are robust.

5.5. Heterogeneity analysis

There are huge gaps in pollution emission intensity and green innovation capacity among different sizes of Chinese cities, and the implementation effect of WECCP policy in different sizes of cities may also be different. Therefore, in order to test whether there are differences in the impacts of WECCP policy among cities of different sizes, this paper defines municipalities directly under the central government, provincial capital cities and vice-provincial cities as big cities; otherwise, the cities are small size cities. According to Table 10, there are certain differences in pollution reduction and green innovation effects among different sizes of cities. Compared to big cities, the WECCP policy has a more significant effect on pollution reduction and green innovation in small cities. The possible reasons are listed as follows. Big cities, with solid economic foundations and abundant innovative firms, are in a leading position in the field of green innovation, and their pollution reduction levels have reached higher environmental standards, so big cities may not

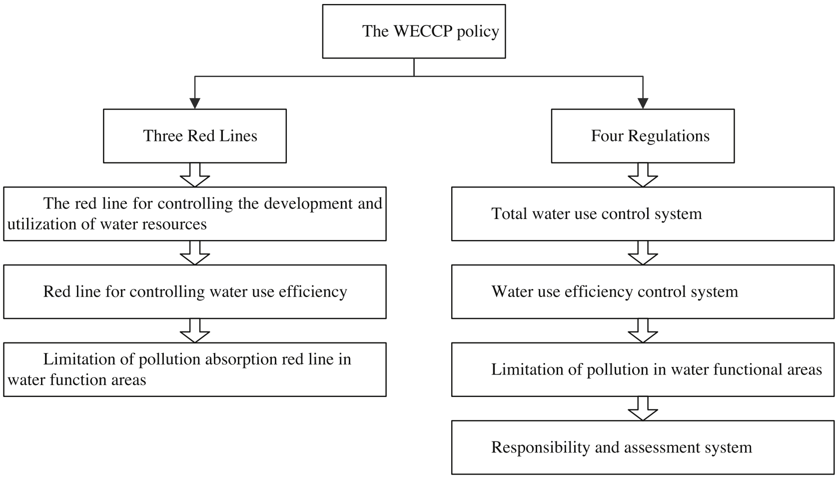


Fig. A1. "Three Red Lines and Four Regulations" of the WECCP policy.

respond sharply to stringent environmental policies.

5.6. The mediating effect analysis

This paper selects the number of green patent applications (*Gpatent*), green invention patent applications (*IGpatent*) and green utility model patent applications (*UGpatent*) respectively as the mediator, and the mediating effect test is conducted according to Eqs. (1)–(3). The regression results are shown in Table 11. As seen, when the mediator is different types of green patent applications (*Gpatent*, *IGpatent* and *UGpatent*), the regression results of the mediating effect tests are basically the same. Taking *Gpatent* as an example, the direct effect of WECCP policy on pollution emission level is -0.019, and the indirect effect (mediating effect) of WECCP policy on pollution emission reduction through green innovation is -0.008668(=-0.001*8.668), and the intermediary effect accounts for 36.21 % of the total effect. Also, this paper uses the Sobel test to verify whether the mediating effect of green innovation is robust. The Z-values of the Sobel tests are less than -2.58, indicating that green innovation plays a mediating role between WECCP policy and pollution reduction, that is, hypothesis 3 is valid.

6. Conclusions and policy implications

This paper takes the WECCP policy as a quasi-natural experiment and integrates environmental regulation, pollution reduction and green innovation into a unified analytical framework. Based on the pollution emission index and green patent data for 283 Chinese cities from 2010 to 2018, this paper examines the impact of WECCP policy on urban pollution emissions and green innovation by using the DID model. The main findings of this paper are as follows: First, the WECCP policy has significant regional pollution reduction effects. To be more precise, the policy significantly lowers water pollution intensity in the pilot cities, while it has a weak impact on air quality improvement. Second, the WECCP policy significantly promotes the growth of green patent applications in the pilot cities, indicating that the policy can significantly improve urban green innovation capacity. Third, the mediating effect analysis shows that the WECCP policy can improve regional environmental quality by enhancing urban green innovation ability. Fourth, compared to big cities, the WECCP policy has more significant effects on pollution reduction and green innovation in small cities.

This paper's conclusions also provide important policy implications regarding achieving a win-win situation between environmental protection and green economic development for China and other developing countries. First, the government should continue to promote the construction of water ecological cities and comprehensively improve the quality of the ecological environment. This paper shows that the construction of the water ecological civilisation city significantly affects pollution reduction. Therefore, the local government should investigate the endowment conditions of water resources and the characteristics of water ecosystems in non-pilot cities and gradually extend the WECCP policy countrywide. Meanwhile, to steadily promote the normal implementation of the construction of the water ecological civilisation city, the government should summarise the mature experience and typical cases of the pilot cities in the early stage and then provide this as a reference for other regions. As the experimental field of ecological civilisation construction in China, the WECCP policy has a demonstration effect, which may guide China and other developing countries to promote ecological progress. Second, all levels of government should formulate scientific and effective green technology support policies and give full play to the positive role of WECCP policy in inducing green innovation. This research shows that the WECCP policy can promote urban green innovation capacity and realise pollution reduction through the green innovation effect. The WECCP policy influences corporate green innovation through local government. Therefore, the local government should formulate effective green technology support policies. On the one hand, the government should establish a series of preferential policies to stimulate corporate green innovation, such as tax incentives and environmental protection subsidies, thereby comprehensively improving urban green innovation ability. On the other hand, the government can also formulate financial support policies, especially green credit

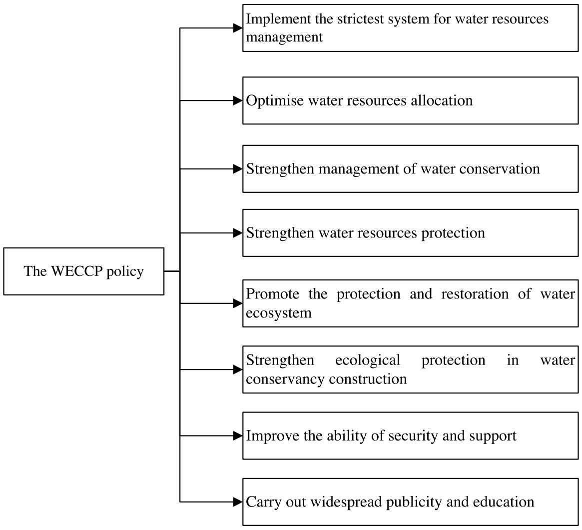


Fig. A2. The main work contents of the WECCP policy.

Table A1
Lists of water ecological civilisation pilot cities.

Batch	Time	Pilot cities
First batch (46 cities)	October, 2012	Jinan
	August, 2013	Miyun County, Wuqing District, Handan, Xingtai, Wuhai, Dalian, Dandong, Jilin, Hegang, Harbin, Qingpu District, Xuzhou, Yangzhou, Suzhou, Wuxi, Ningbo, Huzhou, Wuhu, Hefei, Changting County, Nanchang, Xinyu, Qingdao, Linyi, Zhengzhou, Luoyang, Xuchang, Xianning, Ezhou, Changsha, Chenzhou, Guangzhou, Dongguan, Nanning, Qionghai, Yongchuan District, Chengdu, Luzhou, Qianxinan Autonomous Prefecture, Pu'er, Xi'an, Zhangye, Longnan, Xining, Yinchuan
Second batch (59 cities)	May, 2014	Mentougou District, Yanqing County, Jixian County, Chengde, Hulunbuir, Tieling, Yanbian, Changchun, Baicheng, Mudanjiang, Minhang District, Nantong, Huai'an, Taizhou, Suqian, Yancheng, Wenzhou, Quzhou, Jiaxing, Lishui, Bengbu, Huainan, Quanjiao County, Lixin County, Putian, Nanping, Pingxiang, Binzhou, Tai'an, Yantai, Jiaozuo, Nanyang, Xiangyang, Qianjiang, Wuhan, Fenghuang County, Zhijiang Dong Autonomous County, Zhuzhou, Huizhou, Zhuhai, Yulin, Guilin, Baoting Li and Miao Autonomous County, Bishan County, Liangping County, Suining, Leshan, Guiyang, Qiannan Autonomous Prefecture, Yuxi, Lijiang, Yangling Demonstration Area, Dunhuang, Haibei Autonomous Prefecture, Shizuishan, Loufan County, Tekesi County, Wujiaqu County, Naqu Region

Note: The data are derived from the website of Water Resources Ministry (http://www.mwr.gov.cn/).

policies. Specifically, the government should strictly control the credit investment of high energy consumption and high pollution projects and increase the credit support for energy conservation and environmental protection enterprises or projects. Third, developing countries with severe pollution problems should pay more attention to preserve the ecological environment and develop clean technologies. The governments in these countries should strengthen environmental supervision and set pollution reduction goals to force industrial enterprises to reduce pollution emissions. Also, the government should introduce clean technologies into polluted industries and encourage firms to carry out green innovation activities by formulating innovative support policies.

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Appendix A

Table A1

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