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Green Industry Agglomeration and Public Environmental Awareness: Dual Mechanisms Accelerating Green Development in Zero-Waste Cities

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Abstract

Zero-waste city (ZWC) construction serves as a vital approach to regional sustainable development amid tightening resource constraints and the dual carbon goals. Examining its impact on urban green development efficiency (UGDE) and the underlying transmission mechanisms bears important theoretical significance and practical value. Drawing on panel data covering 281 Chinese cities from 2008 to 2024, this study adopts the difference-in-differences model to examine how the zero-waste city pilot (ZWCP) policy affects UGDE. The main findings are summarized as follows. (1) ZWCP policy significantly improves UGDE, and this core conclusion remains robust after multiple robustness tests and endogeneity corrections. (2) Mechanism tests confirm that ZWCP elevates the green development efficiency of pilot cities through two intermediate channels: green industrial agglomeration and public environmental awareness. (3) The ZWCP policy exerts positive spatial spillover effects on UGDE improvement. However, the two transmission mechanisms show heterogeneous spatial linkage effects. Green industrial agglomeration acts as the core channel for policy spatial radiation, with inter-city agglomeration diffusion driving UGDE growth in neighboring cities. In contrast, public environmental awareness only exerts a local mediating effect, with no significant spatial spillover on UGDE. (4) The moderation analysis reveals that government environmental attention (GEA) strengthens both transmission paths, exerting a positive moderating effect on the UGDE promotion of ZWCP. (5) Heterogeneous results indicate that the policy's boosting effect is more pronounced in eastern regions, resource-based cities and highly urbanized cities. These findings provide empirical evidence and targeted policy references for advancing urban green development efficiency via the differentiated implementation of zero-waste city initiatives across China. They also offer practical Chinese insights for other developing economies pursuing green urban transition.

Keywords: zero-waste city; urban green development efficiency; government environmental attention; causal mediation analysis

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1. Introduction

The state of the environment is a shared global concern. Since 1987, when the concept of sustainable development emerged from the World Commission on Environment and Development, sustainable development that balances the economic and ecological has gained global attention [1]. "The 2030 Agenda for Sustainable Development", adopted by the United Nations in 2015, encompasses 17 integrated goals, including eradicating poverty, promoting economic growth, and combating climate change. It aims to address global challenges through the synergistic advancement of social, economic, and environmental dimensions. As the world's largest developing country, China has achieved remarkable economic growth during its rapid industrialization and urbanization. However, as a result of the extensive development model, China's industrialization has also led to adverse effects such as low land utilization efficiency, increased emissions of pollution, and deterioration of the ecological environment. Statistics indicate that since 2019, China has been the world's largest producer of solid waste, with an annual generation exceeding 10 billion tons [2]. According to the Environmental Performance Index (EPI) released by Yale University and Columbia University in 2024, China's annual score is only 35.4, ranking 156th [3], indicating an urgent need for improvement in the quality of its ecological environment. Therefore, it is imperative to engage in urgent discussions on how to promote intensive and sustainable development methods, generate greater economic value within limited land resources, and enhance the efficiency of green economic development in order to advance China's environmental goals.

China has rolled out a series of place-based ecological policy pilots to address mounting ecological and environmental pressures, while exploring viable models for sustainable economic development. For example, low-carbon cities [4], smart cities pilot [5], carbon trading pilots [6,7], sulfur dioxide control zones [8], etc. Existing literature has widely examined the environmental outcomes of these pilot policies, with scholarly consensus that such regulatory experiments have effectively improved China's overall ecological quality [9]. In China's system of green development policies, the zero waste city pilot (ZWCP) policy represents a recent experimental initiative in environmental policy. The policy was implemented in 2019, and a second batch of pilot projects was launched in 2022. Currently, over 110 cities have participated in the pilot program for constructing zero-waste city (ZWC). The ZWC constitutes an urban circular economy framework that systematically integrates solid waste management across production, living, and ecological spheres. By leveraging source reduction, resource recovery, and harmless disposal, it establishes circular pathways for industrial solid waste, household waste, and other streams, thereby minimizing pollution and environmental damage stemming from production and everyday activities. Beyond its core focus on solid waste governance, the ZWCP also drives broader industrial green upgrading and comprehensive environmental regulation, which generates spillover effects on the abatement of conventional pollutants such as industrial wastewater and sulfur dioxide. Therefore, investigating the effects of China's ZWCP holds considerable practical value for developing countries seeking to explore green development pathways and advance global sustainability.

In recent years, a growing body of scholarly research has evaluated the development models and implementation outcomes of ZWC initiatives worldwide. Specifically, Bai et al. (2026) systematically reviewed municipal solid waste management patterns across East African countries [10]. Similarly, Leslie et al. (2026) applied text mining to urban solid waste management reports from local governments in Sydney to identify key deficiencies in current local solid waste governance practices [11]. Furthermore, a strand of studies has conducted comprehensive evaluations of China's ZWCP policy from multiple perspectives, including green technological progress effects, pollution reduction performance, carbon emission mitigation outcomes, and energy consumption impacts [12–14]. Despite extensive scholarly discussions on ZWC, most existing studies focus on isolated effect evaluations of either solid waste governance or carbon emission reduction. Comprehensive assessments from the perspective of green efficiency remain scarce, and the holistic impacts of the policy on the coupled resource-environment-economy system have yet to be fully revealed. To fill this research gap, this study employs panel data of 281 Chinese cities covering the period 2008–2024 to investigate the impact of the ZWCP policy on urban green development efficiency (UGDE). Furthermore, it explores the underlying mechanisms through which ZWCP improves UGDE within the circular economy system framework. Additionally, this study examines the moderating effect of government environmental attention (GEA) in the above causal relationship. Our findings provide policymakers with optimized pathways for ZWC development, and offer Chinese empirical evidence for advancing the achievement of Sustainable Development Goal 12 (SDG 12)—sustainable consumption and production patterns.

The marginal contributions of this study are mainly embodied in the following three dimensions. First, most previous studies explored the environmental effects of the ZWCP policy through mechanisms such as green technological innovation, industrial structure upgrading, and environmental regulation intensity, but they overlooked the inherent roles of the market and the public. Therefore, this study integrates ZWC development with the circular economy system, and dissects the underlying mechanisms through which the ZWCP policy affects UGDE from both market and public perspectives. This mechanistic perspective integrated governments, enterprises, and the public into a unified environmental governance framework. Governments focused on top-level institutional design, promoting green industrial agglomeration on the enterprise side and upgrading public environmental awareness on the social side. Meanwhile, the ecological transformation of enterprise production scenarios and growing public green demand formed a positive feedback mechanism. This study revealed the systematic transmission logic of environmental policy effect diffusion, and provided a more holistic theoretical explanation and micro-mechanism support for understanding the multi-stakeholder co-governance model of environmental governance in the Chinese context. Second, in terms of empirical methodology, studies such as Liu et al. (2024) and Guo et al. (2025) used traditional mediation effect models to examine the mechanisms of the ZWCP policy [14,15]. However, these models relied on strict exogeneity assumptions and could only identify correlational rather than causal effects. Therefore, this study adopted a causal mediation analysis method to explore the causal transmission mechanism through which the ZWCP policy affects UGDE. This approach addresses the key limitations of traditional mediation effect models, namely their susceptibility to confounding bias and inability to accurately delineate causal chains. In doing so, it enables more rigorous identification of policy transmission pathways and enhances the robustness of empirical conclusions. Third, this study incorporated governmental environmental attention as a moderating variable into the analytical framework. It systematically examined its positive moderating effect during policy implementation and confirmed that local governance attention served as a critical condition for amplifying the effects of the ZWCP policy. From the perspective of government attention allocation, this research design revealed the conditions under which environmental policy effects were stronger. It not only complemented research on the boundary conditions of ZWCP policy transmission, but also extended the application of the attention-based view to urban environmental governance, providing a new theoretical dimension for understanding the differentiated outcomes of local environmental policy implementation.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 elaborates on the theoretical mechanisms of the study. Section 4 describes the empirical model specification and data sources. Section 5 discusses the empirical results. Section 6 summarizes the main research findings, proposes corresponding policy implications, and discusses the limitations of this study.

2. Literature Review

2.1. Zero-Waste City

Since Palmer first introduced the term "zero-waste" in 1973, the concept of a "zero-waste city" has evolved into a new paradigm for waste management [16]. Subsequently, Canberra, Del Norte County in California, Seattle and other regions gradually introduced zero-waste targets in urban management [17]. At present, the relevant research on ZWC primarily focuses on three aspects: conceptual definition, performance evaluation, and implementation pathways. First, in the debate over the connotation of "zero waste", some scholars concentrated on interpreting its meaning from the perspective of micro-level waste treatment processes, and argued that the effective recycling and reutilization of waste is the ultimate goal in building a zero-waste city [18]. Specifically, Lavee (2007) simulated the solid waste management system in Israel and found that municipal solid waste recycling was a relatively efficient waste management model [19]. At the same time, Asih et al. (2026) argued that domestic solid waste recycling at the community level was an important component of urban solid waste management and contributed to the development of zero-waste cities [20]. Furthermore, some scholars also held that it was necessary to construct a "zero-waste" economic development model at the macro level [21]. Second, in terms of performance evaluation, some scholars developed a comprehensive evaluation index system encompassing macro dimensions such as waste management, government support, economic development, and public awareness [22]. Several studies employed the difference-in-differences (DID) model to evaluate the comprehensive green development effects of the ZWCP policy, and concluded that the policy reduces energy consumption and achieves pollution abatement and carbon emission mitigation primarily through green technological progress, industrial structure upgrading, and strengthened environmental regulation [14,15]. Third, regarding the realization pathways of ZWC, existing studies have widely emphasized the importance of promoting reduction measures at the waste discharge end. Orazalin et al. (2025) argued that green technological innovation reduces waste generation and improves waste recycling efficiency [23]. Simultaneously, Zulkifli and Abd Manaf (2024) stated that efforts should be made to raise public awareness of waste reduction and ecological conservation [24], so as to reduce domestic waste discharge. Meanwhile, relevant studies held that local authorities should actively promote the efficient operation and market-oriented restructuring of the waste management sector. For instance, Seyyedi et al. (2024) proposed that the waste management industry should undergo digital transformation and establish a comprehensive waste life cycle management system [25]. Cheng et al. (2024) suggested that a combination of pricing, fiscal, taxation, financial and other tools should be adopted to build a market-oriented mechanism for waste resource utilization [26]. However, it should be noted that excessive product market competition reduces waste recycling efficiency [27]. Qiao et al. (2026) argued that intergovernmental cooperation should be strengthened to advance cross-regional coordinated disposal of solid waste and the sharing of governance resources [28].

2.2. Urban Green Development Efficiency

The UGDE is an important issue of sustainable development. The relevant studies mainly focus on three aspects: index measurement, evolution characteristics and driving factors. First, in terms of index measurement, the evaluation method has evolved from a single index to a comprehensive index system encompassing economic, social, environmental factors [29]. However, neglecting the characteristics of the input–output relationship is a limitation of the comprehensive index system. The Data Envelopment Analysis method, particularly the Super Slack-Based Model, which takes into account both the desired output (such as economic growth) and the undesired output (such as pollution emissions) in the process of economic development, addresses this limitation and is the predominant method for measuring the green development efficiency [30]. Second, in terms of evolutionary characteristics, relevant studies are primarily analyzed at the national and regional levels. According to research on China, it is generally believed that UGDE in China exhibits a fluctuating upward trend with spatial agglomeration and convergence characteristics [31]. However, there is an obvious regional difference pattern of decreasing in the eastern, central, and western regions [32]. At the regional scale, scholars conducted measurements and analyses of UGDE in the Yellow River Basin [33], the Yangtze River Economic Belt [34], the Beijing–Tianjin–Hebei city cluster [35], the Yangtze River Delta [36], the Guangdong–Hong Kong–Macao Greater Bay Area [37], and other regions. Third, in terms of driving factors, UGDE will be affected by regional economic development level, urbanization level, industrial structure, local government support and other factors. Payasi et al. (2026) demonstrated that the composition of economic development and environmental intensity determine green development efficiency, rather than the pace of economic development [38]. Reckien et al. (2017) argued that rapid urbanization in developing countries intensified environmental pollution [39]. Guo and Qiao (2024) constructed a theoretical and analytical framework to examine the impact of government environmental attention on UGDE [40]. Their findings indicated that the government environmental attention could lead to increased allocation of resources to the ecological sector, thereby enhancing UGDE.

Taken together, existing studies have provided abundant theoretical and empirical insights for the present research. In particular, the literature on ZWCP policy evaluation bears close relevance to this study. However, existing research has yet to conduct an in-depth dissection of the functional mechanisms and transmission pathways of ZWC within the circular economy analytical framework. To address this research gap, this study carries out the following work. First, grounded in the theoretical framework of the circular economy, this paper unpacks the inherent logic through which the ZWCP policy affects UGDE from the dual perspectives of the market and the public. Second, unlike existing studies that employ traditional mediation effect models to analyze transmission mechanisms, this study adopts causal mediation analysis for mechanism testing, which mitigates the endogeneity bias inherent in conventional mediation models. Third, prior studies have generally overlooked the role of government attention in ZWCP policy implementation, and rarely account for policy implementation effectiveness from the perspective of local governance preferences. Accordingly, this study examines the moderating effect of local government environmental attention in the causal link between the ZWCP policy and UGDE, further extending the research scope of micro-mechanisms in zero-waste city governance.

3. Theoretical Analysis

3.1. Urban Green Development Effect of ZWCP

Distinct from isolated solid waste governance measures, zero-waste city pilot (ZWCP) construction goes beyond end-of-pipe treatment. It focuses on city-wide resource allocation and full life-cycle waste management [41], forming a closed loop covering resource consumption, waste disposal, and recycling and reuse, and realizes the deep coupling of urban development and ecological protection [42,43]. While centered on solid waste reduction and resource recycling, this systematic green transition also generates widespread spillover effects on conventional pollutant control and production efficiency improvement. It lays a solid foundation for improving urban green development efficiency (UGDE) through two parallel channels: green industries agglomeration and public environmental awareness.

From the perspective of market industrial entities, the ZWCP policy improves UGDE by fostering industrial agglomeration and industrial restructuring, and building a sound industrial circular economy system. The pilot policy adopts multiple incentive tools including policy support, fiscal subsidies and tax breaks [44]. These tools support the clustered growth of green industries such as waste recycling, renewable resource processing, energy conservation and environmental protection, and solid waste treatment, thus expanding the overall scale of the circular economy [45]. On one hand, industrial agglomeration accelerates the diffusion and upgrading of green production, waste recovery and resource regeneration technologies [46]. It also enhances coordination across upstream and downstream links of the value chain, which directly improves resource utilization efficiency and reduces the emission intensity of conventional industrial pollutants such as wastewater and sulfur dioxide—the core dimensions embedded in the UGDE indicator [47]. On the other hand, the gathering of green industries pushes traditional high-consumption and low-efficiency industries to carry out green transformation. This process optimizes the city's overall industrial structure and lowers the environmental costs of industrial production, further driving the growth of UGDE [48].

From the perspective of the public, ZWCP policy effectively raises public environmental awareness through diversified environmental information dissemination and concept guidance, and further promotes UGDE improvement through urban governance, demand guidance, and social supervision. During ZWCP construction, local governments carry out regular activities including zero-waste concept promotion, waste sorting science training and green lifestyle advocacy [49]. These measures continuously deliver information on solid waste reduction, resource recycling and ecological protection to the public, stimulate public attention and discussion on urban environmental governance, and elevate the overall level of public environmental awareness at the city level. First, growing public environmental awareness reduces resistance to ZWCP implementation. It improves public cooperation with environmental measures such as waste sorting and resource recycling [50,51], lowers the operating cost of domestic waste collection, transportation and disposal, and optimizes the overall operational efficiency of the urban waste governance system. Second, rising public environmental attention translates into consumer preferences for green products and low-carbon services. This guides market factors to flow into green sectors such as energy conservation, environmental protection and renewable resource utilization, expands the scale of green industries and accelerates technological upgrading, and boosts UGDE through the green upgrading of industrial structure. Third, public environmental awareness exerts sustained social supervision pressure. It urges local governments to increase environmental governance investment and optimize the layout of environmental facilities, and pushes industrial enterprises to meet clean production standards and reduce emissions of conventional pollutants such as industrial wastewater and sulfur dioxide, which directly improves UGDE from the governance dimension.

To sum up, we propose the following hypotheses:

Hypotheses 1. *The ZWCP policy significantly improves UGDE.*

Hypotheses 2. *The ZWCP policy boosts UGDE by accelerating green industries agglomeration.*

Hypotheses 3. *The ZWCP policy facilitates the growth of UGDE by driving the public environmental awareness.*

3.2. Moderating Effect of Government Environmental Attention

The impact of the ZWCP on UGDE exhibits notable heterogeneity across cities, as policy effectiveness is largely shaped by local governments' governance priorities and resource allocation. Government environmental attention (GEA) acts as a critical contextual factor that strengthens the two core transmission channels of green industrial agglomeration

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and public environmental awareness, thereby amplifying the causal effect of the ZWCP on UGDE.

In scenarios with low GEA, local governments assign low priority to zero-waste governance and ecological conservation [52]. Policy implementation often suffers from formalism, inadequate supporting resources, and weak supervision and incentive mechanisms. Under such conditions, the ZWCP fails to effectively stimulate green industrial development and public awareness changes. Its spillover effects on resource efficiency improvement and conventional pollution abatement are substantially weakened, and thus its promoting effect on UGDE is greatly diminished. By contrast, when local governments maintain high environmental attention, ecological governance becomes a core regional development priority. Local governments proactively roll out supporting policies covering special fiscal funds, land supply, and talent incentives [53], and improve the business environment to foster the agglomeration of green industries such as solid waste recycling and renewable resource utilization [54]. This accelerates the development of the industrial circular economy system, and in turn generates stronger gains in production efficiency and pollution reduction, translating into a more pronounced improvement in UGDE. Meanwhile, high GEA motivates local governments to carry out regular zero-waste publicity, waste sorting guidance, and green lifestyle promotion. These efforts expand the coverage and depth of environmental education, help cultivate public awareness of zero-waste and environmental protection, and foster consistent green and low-carbon living habits, which improves the circular operation of urban daily life systems [55]. Through enhanced public cooperation and demand-side guidance, the policy's spillover effects on urban green operation efficiency are further strengthened, contributing to a larger increase in UGDE.

Therefore, we propose the following hypotheses:

Hypotheses 4. *GEA exerts a positive moderating effect on the mediation pathway linking the ZWCP policy to UGDE improvement.*

Figure 1 shows the theoretical framework based on the above analysis.

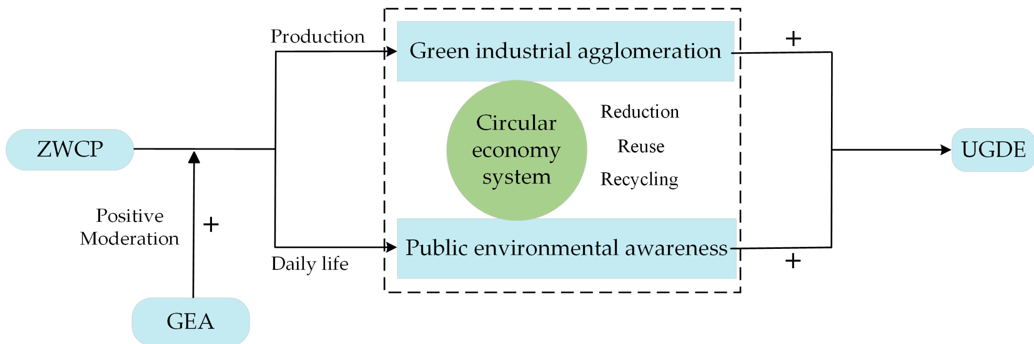

Figure 1. The impact mechanism of ZWCP on UGDE.

4. Methodology and Data

4.1. Methodology

4.1.1. Difference-in-Differences Model

To analyze the impact of ZWCP on UGDE, this study uses the difference-in-differences (DID) model for empirical test. The model is as follows:

$$y_{it} = \alpha_0 + \beta_1 zwcp_{it} + \delta X_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{1}$$

where the subscripts i and t represent the city and year, respectively. y_{it} is the dependent variable that denotes the UGDE in city i in year t. $zwcp_{it}$ is the core independent variable and indicates whether city i was established as a ZWCP city in year t. X_{it} is other control variables that affect the UGDE, including economic development level ($lnpgdp$), government support intensity ($lngov$), foreign direct investment ($lnfdi$), financial development level ($lnfin$), and green technology innovation ($lngpa$). μ_i represents individual effects. τ_t denotes time effects. ε_{it} is the residual term.

4.1.2. Causal Mediation Analysis

Traditional mediation analysis is based on linear structural equation systems. It judges whether a mechanism holds by testing the significance of estimated parameters and conducting the Sobel test. However, this method ignores uncontrolled confounders that may exist among the treatment variable, mediator, and outcome variable [56]. This issue weakens the interpretability of the estimated mediation effects. To address this problem, this study adopts the potential outcomes framework proposed by Imai et al. (2010) [57]. It uses causal mediation analysis to identify the transmission mechanism through which ZWCP affects UGDE. Compared with traditional mediation models, causal mediation analysis decomposes the average treatment effect (ATE) into two components. The first is the natural indirect effect (NIE), which is transmitted through the mediator. The second is the natural direct effect (NDE), which reflects the effect of the treatment variable when the mediator stays at its natural value. This decomposition can more clearly describe the explanatory power of different mechanisms.

Under the potential outcomes framework, cities with $zwcp = 1$ serve as the treatment group, while those with $zwcp = 0$ serve as the control group. $y_{it}(zwcp)$ denotes the observed UGDE under a given $zwcp$ status. Since counterfactual outcomes cannot be directly observed, we introduce the average treatment effect (ATE), which is presented in Equation (2).

$$ATE = E[y_{it}(1) - y_{it}(0)] \tag{2}$$

Building on this framework, we introduce the mediator variable M_{it}. Since M_{it} can also be affected by the policy shock, cities in different groups have two potential values of the mediator: $M_{it}(1)$ and $M_{it}(0)$. Following Nguyen et al. (2021), the ATE can be decomposed into the NIE and NDE [58], as presented in Equations (3) and (4).

$$NIE = E[y_{it}(zwcp, M_{it}(1)) - y_{it}(zwcp, M_{it}(0))] \;\; zwcp = 0, 1 \tag{3}$$

$$NDE = E[y_{it}(1, M_{it}(zwcp)) - y_{it}(0, M_{it}(zwcp))] \;\; zwcp = 0, 1 \tag{4}$$

Equation (3) defines the NIE under two scenarios. When $zwcp = 1$, it measures the indirect effect of the mediator shifting from the control state to the intervention state, while samples remain under the policy intervention condition. When $zwcp = 0$, it measures the indirect effect of the same mediator shift, while samples stay in the control condition. Equation (4) defines the NDE under two corresponding scenarios. When $zwcp = 1$, it captures the direct effect of the policy shock on UGDE, with the mediator held fixed at the policy intervention state. When $zwcp = 0$, it captures the direct effect of the policy shock on UGDE, with the mediator held fixed at the control state.

4.1.3. Spatial Econometric Model

Spatial econometric models can capture the spatial effects of policy impacts. This study further examined the spatial effects of the ZWCP policy and its two transmission mechanisms using the Spatial Durbin Model (SDM). The specific model specification is as follows:

$$y_{it} = \alpha_0 + \rho W y_{it} + \beta_1 zwcp_{it} + \varphi_1 W zwcp_{it} + \delta X_{it} + \varphi W X_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{5}$$

$$M_{it} = \alpha_0 + \rho WM_{it} + \beta_1 zwcp_{it} + \varphi_1 Wzwcp_{it} + \delta X_{it} + \varphi WX_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{6}$$

$$y_{it} = \alpha_0 + \rho Wy_{it} + \beta_1 zwcp_{it} + \varphi_1 Wzwcp_{it} + \beta_2 M_{it} + \lambda WM_{it} + \delta X_{it} + \varphi WX_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{7}$$

Equation (5) tests whether the ZWCP policy has a spatial spillover effect on UGDE, while Equation (6) tests for such an effect on the mediating variables. Equation (7) extends Equation (5) by further incorporating the mediating variable and its spatial lag term, to examine whether this mediating variable affects the UGDE of neighboring cities through spatial correlation effects. In these equations, W denotes the spatial weight matrix. This study used an adjacency matrix (W_1) and a geographic distance matrix (W_2) to capture the spatial effects of the policy, as shown in Equations (8) and (9). Wy_{it} and WM_{it} are the spatial lag terms of the dependent variables in the three equations, respectively. $Wzwcp_{it}$ is the spatial lag term of the ZWCP policy, and WX_{it} is the spatial lag term of the control variables. ρ, φ_1, and φ are the spatial lag parameters for the dependent variable, policy variable, and control variables, respectively. All other variables and symbols are the same as those defined earlier.

$$W_1 = \begin{cases} 1, \text{ if city } i \text{ is adjacent to city } j \\ 0, \text{ if city } i \text{ is not adjacent to city } j \end{cases} \tag{8}$$

$$W_2 = \begin{cases} \frac{1}{d_{ij}^2}, & i \neq j \\ 0, & i = j \end{cases} \tag{9}$$

Equation (8) defines the adjacency matrix (W_1), which takes a value of 1 if two cities share a common border and 0 otherwise. Equation (9) defines the geographic distance matrix (W_2), where d_{ij} denotes the straight-line distance between two cities. For W_2, diagonal elements are 0 and off-diagonal elements equal the reciprocal of the squared distance.

4.1.4. Moderation Model

This study adopts the interaction term approach to test the moderating effect of GEA on the relationship between ZWCP and UGDE. The model is presented as follows:

$$M_{it} = \alpha_0 + \beta_1 zwcp_{it} + \beta_2 lngea_{it} + \beta_3 zwcp_{it} \times lngea_{it} + \delta X_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{10}$$

where the M_{it} represents the mediator variables in this study, including green industrial agglomeration ($lngia$), and public environmental awareness ($lnpea$) respectively. $lngea_{it}$ is the moderator variable, which reflects local governments' attention to environmental protection. β_3 is the core parameter of interest in Equation (10). If β_3 is positive and statistically significant, it indicates that GEA positively moderates the effect of ZWCP on the mediator variable. This in turn helps drive the improvement of UGDE.

4.2. Variables

Dependent variable: urban green development efficiency (y). The variable reflects the sustainable development principles of maximizing economic output while minimizing environmental impact during urban development, particularly at a defined technical level. It emphasizes the importance of increasing output efficiency and prioritizing environmental protection in land use. This paper uses Super-SBM model to measure the efficiency of urban green development. This method's strength is its capacity to decompose and categorize effective decision-making units (DMU), considering undesired outputs, which improves the precision and applicability of efficiency assessments [59]. The calculation method is as follows:

$$y = min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x_i}}{x_{i0}}}{\frac{1}{t_1+t_2}\left(\sum_{r=1}^{t_1}\frac{\overline{h_r}^g}{h_{r0}^g}+\sum_{r=1}^{t_2}\frac{\overline{h_i}^b}{h_{r0}^b}\right)} \tag{11}$$

$$s.t.\begin{cases} \overline{x} \geq \sum_{j=1,\neq k}^{n} x_{ij}\theta_j \\ \overline{h}^g \leq \sum_{j=1,\neq k}^{n} h_{rj}^g\theta_j \\ \overline{h}^b \geq \sum_{j=1,\neq k}^{n} h_{rj}^b\theta_j \\ \overline{x} \geq x_0, \overline{h}^g \leq h_0^g, \overline{h}^b \geq h_0^b, \overline{h}^g \geq 0, \theta_j \geq 0 \end{cases} \tag{12}$$

where y is the efficiency value, and the higher the value, the higher UGDE. m represents the type of input factor. t_1 is the type of desired output and t_2 is the type of undesired output. n is the number of DMU, that is, the number of cities. Each DMU contains factor input, desired output and undesired output. x denotes an element of the factor input matrix. h^g signifies an element within the matrix of desired outputs. h^b indicates an element within the matrix of undesired outputs. θ is the weight of the linear program. Table 1 shows the input–output index framework adopted by UGDE. Notably, constrained by the limited availability of city-level solid waste statistics, we do not include solid waste-related indicators such as industrial solid waste output and municipal domestic waste in undesirable outputs. Instead, we select industrial wastewater discharge and sulfur dioxide emissions as the core measures. These two pollutants have continuous long-panel data and consistent statistical calibers across cities, and are widely used as standard undesirable outputs in studies on urban green development efficiency. We explicitly clarify that the UGDE indicator in this paper measures the overall green production efficiency of cities, rather than the specific performance of zero-waste core targets. As a comprehensive environmental governance policy, the ZWCP generates spillover effects on conventional pollutant reduction through industrial green upgrading and full-chain environmental regulation. The selected indicators can therefore effectively capture the comprehensive green performance brought by the policy implementation.

Table 1. Input–output indicator framework.

Indicator Type	Tier 1 Indicator	Tier 2 Indicator	Tier 3 Indicator
Input	Capital	Fixed capital	Capital stock calculated using the perpetual inventory method (constant 2008 prices)
	Labor	Number of employees	The total employment in the secondary and tertiary industries
	Resource	Energy, land	Energy consumption and urban construction land area
Output	Desired output	Economic benefits	Total value added of the secondary and tertiary industries (constant 2008 prices)
	Undesired output	Environmental pollution	Industrial wastewater emissions, industrial sulfur dioxide emissions

Core independent variable: zero-waste city pilot (*zwcp*). The indicator is represented by a dummy variable. *zwcp* takes the value of 1 in that year and subsequent ones if city i is established as an ZWCP city in the year t. Otherwise takes the value of 0.

Mediator variables: (1) Green industrial agglomeration (*lngia*). Aina et al. (2026) argued that green industrial clusters are a key model for urban circular economy development [60]. Using data from the China Industrial and Commercial Enterprise Registration Database, we define an enterprise as a circular economy enterprise if its business scope covers “waste”, “wastewater”, “waste gas”, or “renewable resources”. Then, using enterprise addresses from the database, we obtained the corresponding longitude and latitude coordinates via Baidu map application programming interface (API) and constructed intra-city enterprise distance matrices accordingly. Meanwhile, we adopt the DO index developed by Duranton and Overman (2005) to measure the level of green industrial agglomeration [61]. Appendix A presents the specific calculation formula. (2) Public environmental awareness (*lnpea*). This variable is measured by the logarithm of residents' attention to zero-waste cities in each city. This study uses residents' attention to zero-waste cities as a proxy for their environmental awareness. Specifically, we collect the Baidu Search Index for three terms at the city level: zero-waste cities, waste sorting, and green consumption. We sum up the three index values and take the logarithm to measure residents' zero-waste awareness. In recent years, many studies have used the Baidu Search Index to quantify public environmental awareness. For example, Yu and Jin (2022) examined the impact of environmental information disclosure on public environmental awareness [62]. Jin and Deng (2024) explored the effect of public environmental awareness on the urban-rural economic gap [63].

Moderator variable: government environmental attention (*lngea*) is measured by the natural logarithm of the frequency of environmental protection words in the annual Government Work Report of each city [64].

Control variables: (1) Economic development level (*lnpgdp*) is expressed by the natural logarithm of per capita GDP. The level of urban economic development reflects its own development potential and has an impact on the efficiency of green development. (2) Government support intensity (*lngov*) is measured by the natural logarithm of the ratio of government fiscal expenditure to GDP. Government intervention in regional economic development significantly affects the trajectory of local economic growth, thus influencing the degree of sustainable development achieved [65]. (3) Foreign direct investment (*lnfdi*) is quantified by the natural logarithm of the ratio of foreign direct investment to GDP. FDI exerts dual effects on local economies. On one hand, it can promote the improvement of local technology and management skills, which in turn boosts the level of green development [66]. On the other hand, there is a risk that it may transform the area into a sanctuary for polluting investments, thereby reducing the economy's green development standards [67]. (4) Financial development level (*lnfin*) is measured by the natural logarithm of the ratio of the annual loan volume of financial institutions to GDP. The development of the financial market facilitates the adjustment of capital flow direction, thereby influencing the level of green economic development [68]. (5) Green technology innovation (*lngpa*). This study employs the natural logarithm of one plus the count of green invention patents as a metric to measure the green technology innovation. Innovation in green technology aids energy conservation and emission reduction in corporate production, thereby improving the efficiency of sustainable development [69].

4.3. Data

The primary data of this study are collected from China Urban Statistical Yearbook. Green invention patents are derived from the patent data of the China National Intellectual Property Administration. Data on circular economy enterprises come from the China Industrial and Commercial Enterprise Registration Database. Data on residents' zero-waste awareness come from the Baidu Search Index. Data on government environmental attention come from government work reports released on official city websites. A small number of missing indicator values are filled using the linear interpolation method. The descriptive statistics of each variable are shown in Table 2.

Table 2. Descriptive statistics of variables.

Variables	Obs	Mean	Std.Dev	Min	Max
y	4777	0.204	0.169	0.010	1.414
zwcp	4777	0.054	0.225	0.000	1.000
lngia	4777	3.298	1.998	0.000	6.997
lnpea	3934	7.617	2.482	0.000	11.003
lngea	4777	0.335	0.143	0.018	1.300
lnpgdp	4777	10.615	0.684	4.595	13.056
lngov	4777	−1.739	0.468	−4.176	0.454
lnfdi	4777	−4.580	1.452	−13.499	6.456
lnfin	4777	−0.175	0.534	−2.586	2.264
lngpa	4777	2.590	1.978	0.000	10.161

Note: The Baidu Search Index platform was officially launched in 2011, and city-level data were first made publicly available in the same year. As a result, no valid observations for the public environmental awareness indicator (*lnpea*) are available for all sample cities over the 2008–2010 period. This systematic left truncation of data along the time dimension does not introduce selection bias at the individual city level.

5. Results

5.1. Results of Benchmark Regression

Table 3 presents the estimation results of ZWCP on UGDE. The results show that the coefficients of *zwcp* consistently exhibit statistically significant positive values at the 1% level. This indicates that ZWCP led to an average increase in UGDE of 0.045 units compared to the control city. Therefore, Hypothesis 1 is supported.

Table 3. The result of benchmark regression.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
zwcp	0.053 ***	0.072 ***	0.059 ***	0.056 ***	0.054 ***	0.045 ***
	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)
lnpgdp		0.095 ***	0.056 ***	0.056 ***	0.051 ***	0.051 ***
		(0.014)	(0.014)	(0.016)	(0.015)	(0.015)
lngov			−0.093 ***	−0.097 ***	−0.082 ***	−0.074 ***
			(0.012)	(0.013)	(0.013)	(0.012)
lnfdi				−0.001 *	−0.001	−0.001
				(0.0005)	(0.001)	(0.005)
lnfin					−0.038 ***	−0.037 ***
					(0.009)	(0.009)
lngpa						0.018 ***
						(0.002)
Constant	0.201 ***	−0.805 ***	−0.559 ***	−0.570 ***	−0.490 ***	−0.525 ***
	(0.001)	(0.149)	(0.145)	(0.153)	(0.152)	(0.146)
City FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Observations	4777	4777	4777	4777	4777	4777
R^2	0.717	0.729	0.736	0.736	0.737	0.742

Note: ***, * mean significance at the level of 0.01 and 0.1, respectively. Robust standard errors in parentheses.

5.2. Robustness and Endogeneity Tests

5.2.1. Parallel Trend Test

Ensuring the parallel trend assumption is met is crucial when applying the DID model to policy evaluation. In other words, maintaining similar developmental trends in the outcome variables between the treatment and control groups prior to policy implementation is crucial. The purpose of this test is to eliminate the potential impact of unobserved factors on the dependent variable. Therefore, drawing on the research method of Beck et al. (2010) [70], we use the event study method to conduct parallel trend test. The method is as follows:

$$y_{it} = \alpha + \beta_1 zwcp_{it}^{t-4} + \beta_2 zwcp_{it}^{t-3} + L + \beta_9 zwcp_{it}^{t+4} + \delta X_{it} + \tau_t + \mu_i + \varepsilon_{it} \tag{13}$$

The superscript t in $zwcp$ denotes the period during which the treatment group initiated the pilot construction of the ZWCP. $zwcp^{t-k}$ equals one for cities in the k year before ZWCP, and is zero for all other time periods. $zwcp^{t+k}$ equals one for cities in the k year after ZWCP, and is zero for all other time periods. In addition, Roth (2022) pointed out that the parallel trend assumption is more critical for periods closer to policy implementation [71]. Periods far from the policy may be affected by other structural changes. The estimated coefficients for these periods have larger variances and are likely to be misleading. Therefore, this study only examines the trend characteristics from 4 years before to 4 years after ZWCP implementation. Figure 2 shows the estimated coefficients of $zwcp^{t-k}$. The results show that the coefficients of $zwcp^{t-4}$, $zwcp^{t-3}$, $zwcp^{t-2}$ and $zwcp^{t-1}$ are statistically insignificant, implying that the UGDE exhibits a similar trend before the implementation of ZWCP for both the treatment group and the control group. The findings confirm that the parallel trend hypothesis is valid. In terms of the dynamic effects of policy implementation, the coefficients of $zwcp^{t}$ and $zwcp^{t+1}$ are not statistically significant, while those of $zwcp^{t+2}$, $zwcp^{t+3}$, and $zwcp^{t+4}$ are significantly positive. This result indicates that the ZWCP policy exerts its effect with a two-year lag.

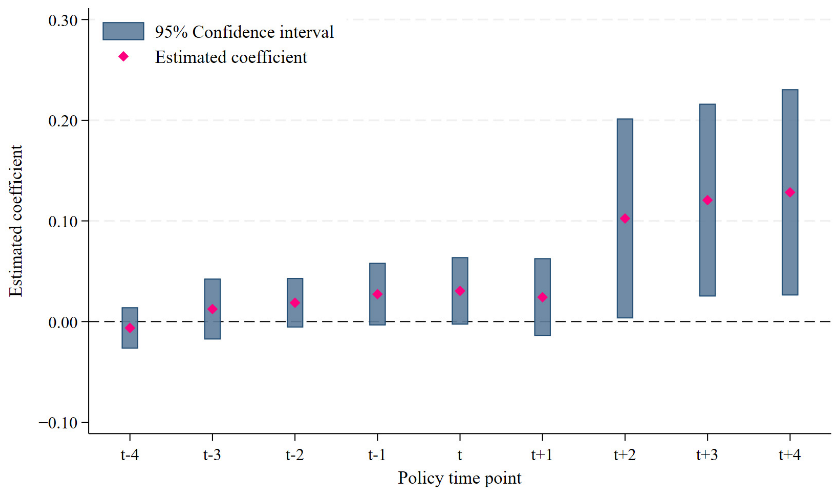

Figure 2. Parallel trends test.

5.2.2. Placebo Test

Besides the ZWCP, a multitude of other factors may also influence the urban green development efficiency. To reduce the influence of other factors, this study utilizes a randomized placebo test methodology for the cities in the treatment group, ensuring that the observed effects are attributable to the policy intervention rather than chance factors. Specifically, we randomly selected a new set of cities, matching the number in the original treatment group, to serve as the new treatment group, and subsequently estimated the policy's impact. And the aforementioned random selection process was repeated 1000 times. If the average policy effect coefficient estimated after randomization closely matches the actual effect, it implies that the improvement in urban green development efficiency might not be due to ZWCP policy alone, indicating the presence of other potentially influential factors. If the average policy effect coefficient after randomization is much smaller than the actual estimation coefficient, it suggests that random factors do not substantially influence the efficiency of urban green development, thereby supporting the effectiveness of the ZWCP policy from a counterfactual perspective. Figure 3 shows a kernel density plot of 1000 randomization policy effect coefficients. The figure indicates that the average policy effect coefficient after randomization is very close to 0, which is significantly lower than the actual policy effect coefficient of 0.045. The findings indicate that random factors do not exert a significant influence on the dependent variables. That is, the enhancement of urban green development efficiency in the experimental group is largely attributed to the implementation of ZWCP policy.

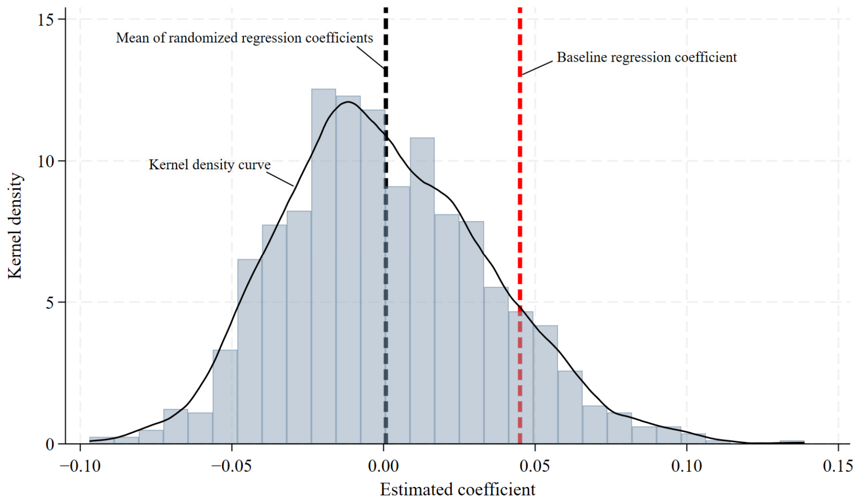

Figure 3. Results of the placebo test.

5.2.3. Other Robustness Tests

This paper also attempts to use other methods to test the robustness of the benchmark model. To eliminate interference from other relevant policies during the same period, we extend the benchmark model by adding controls for policies related to the low-carbon city pilot (*lccp*), smart city pilot (*scp*), e-commerce demonstration city (*edc*), and domestic waste classification pilot city (*dwcpc*). The results of this robustness test are reported in Table 4. Columns (1)–(4) are the regression results of adding other policy dummy variables separately, and column (5) is the regression results of adding all policy dummy variables simultaneously. In general, after controlling the influence of other policies, the estimated coefficient of *zwcp* is still significantly positive, and the coefficient size does not change significantly. It shows that other relevant policies do not affect the causal relationship between ZWCP policy and UGDE.

Additionally, other robustness test results are shown in Table 5. In column (1), we reduced the sample data by trimming the top and bottom 1% to mitigate the impact of outliers on the estimation results. In column (2), samples from sub-provincial cities, provincial capitals, and municipalities directly under the Central government are excluded in order to control for the potential influence of city administrative levels on the estimated results. In columns (3) and (4), this paper employed propensity score matching (PSM) method to mitigate the disparities in economic and social characteristics between the treatment group and the control group. The ZWCP was rolled out in two separate batches. The first was launched in 2019, and the second in 2022. We therefore examine the policy effects of the first and second batches in columns (5) and (6) respectively. In addition, given that the COVID-19 pandemic in 2020 and 2021 may confound the identification of the net effect of the ZWCP policy, column (7) further presents the regression results after excluding sample observations from 2020 and 2021. Overall, the regression results in Table 5 show that the coefficients of *zwcp* are significantly positive, indicating that the benchmark regression results are robust.

Table 4. Estimates excluding the effects of other policies.

Variables	(1)	(2)	(3)	(4)	(5)
zwcp	0.044 ***	0.045 ***	0.042 ***	0.049 ***	0.049 ***
	(0.012)	(0.012)	(0.012)	(0.013)	(0.013)
lccp	0.014 ***				0.004
	(0.005)				(0.004)
scp		0.004			0.004
		(0.005)			(0.005)
edc			0.032 ***		0.017 **
			(0.008)		(0.008)
dwcpc				0.062 ***	0.055 ***
				(0.011)	(0.011)
Constant	−0.531 ***	−0.524 ***	−0.589 ***	−0.564 ***	−0.589 ***
	(0.147)	(0.146)	(0.153)	(0.178)	(0.182)
Control variables	✓	✓	✓	✓	✓
City FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
Observations	4777	4777	4777	4777	4777
R^2	0.743	0.742	0.743	0.748	0.749

Note: ***, ** mean significance at the level of 0.01 and 0.05, respectively. Robust standard errors in parentheses.

Table 5. Results of other robustness tests.

Variables	1% Trimming	Remove Cities with High Levels of Administration	PSM-DID (1:1)	PSM-DID (Kernel)	The First Batch of ZWCP	The Second Batch of ZWCP	Excluding the Impact of the COVID-19 Pandemic
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
zwcp	0.042 ***	0.031 **	0.025 **	0.032 **	0.082 ***	0.036 **	0.051 ***
	(0.011)	(0.012)	(0.012)	(0.014)	(0.022)	(0.014)	(0.014)
Constant	−0.667 ***	−0.802 ***	−1.209 ***	−1.079 ***	−0.484 ***	−0.560 ***	−0.591 ***
	(0.116)	(0.186)	(0.085)	(0.091)	(0.160)	(0.153)	(0.167)
Control variables	✓	✓	✓	✓	✓	✓	✓
City FE	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓
Observations	4777	4199	2234	4095	3042	4362	4215
R^2	0.752	0.728	0.655	0.596	0.729	0.741	0.737

Note: ***, ** mean significance at the level of 0.01 and 0.05, respectively. Robust standard errors in parentheses.

Notably, the policy coefficients estimated separately for the two batches in columns (5) and (6) are all significantly positive, with the first batch yielding a significantly larger policy effect coefficient than the second. This finding carries two implications. On the one hand, policy effects remain detectable for the second batch of pilots despite their shorter observation window. On the other hand, the coefficient patterns indicate that the ZWCP policy's effect on UGDE improvement accumulates over time. The initial launch of projects and policy implementation delivers relatively modest improvement effects, while long-term industrial transformation and public environmental awareness better facilitate the sustained release of policy effects. Furthermore, the policy effect coefficient in column (7), which drops sample observations from 2020 and 2021 to eliminate COVID-19 interference, is comparable to the baseline regression coefficient. This suggests that the pandemic did not diminish the policy's effect. This is because the pandemic-affected years coincided with the two years after the launch of the first batch of pilots. This was a preparatory phase focused on rolling out the policy framework and building key projects, and the policy's governance effects had not yet become apparent. Accordingly, the COVID-19 pandemic did not exert a significant negative impact on the ZWCP policy's effectiveness. This finding also aligns logically with the dynamic effect analysis from the parallel trend test presented earlier.

5.2.4. Endogeneity Tests

Baseline findings indicate that the ZWCP policy improves UGDE. However, cities with a solid foundation in green development efficiency tend to have more mature industrial support and governance capacity. They are thus more likely to be selected as zero-waste pilot cities. As a result, a bidirectional causal relationship exists between ZWCP and UGDE. This relationship causes endogeneity problems in the baseline regression. Therefore, the instrumental variable method is employed in this paper to estimate and correct for potential endogenous bias.

Drawing on the research method of Zhang et al. (2022) [72], we construct the first instrumental variable (iv_{-1}) as the interaction term of two variables: *law* and *post*. The variable *law* is equal to 1 if the city implemented environmental legislation between 1963 and 1985, and 0 otherwise. The variable *post* is a global time indicator that takes the value of 1 for all years from 2019 onward, when the first batch of the ZWCP was officially launched nationwide, and 0 for years before 2019. We select this instrumental variable for the following reasons. First, the relevance assumption is satisfied. Cities with early environmental legislation have accumulated more mature environmental governance frameworks and administrative capacities. After the national launch of the ZWCP in 2019, such cities are significantly more likely to be selected as pilot sites, whether in the first or second batch. The interaction term of *law* and *post* is therefore strongly correlated with the actual implementation status of the ZWCP at the city-year level. Second, the exclusion restriction holds theoretically. The period from 1963 to 1985 represents the initial stage of environmental governance in China. Environmental legislation of this era was formulated entirely under the planned economic system, with its core goal limited to end-of-pipe pollution control for state-owned industrial enterprises. It did not involve institutional concepts such as circular economy or green development. As a time-invariant historical feature, *law* cannot directly drive year-on-year changes in contemporary UGDE after more than three decades. Meanwhile, *post* captures the national timeline of policy rollout and acts as a common time shock across all cities. It does not independently determine the UGDE performance of individual cities. Accordingly, the interaction term affects UGDE only through its influence on the actual implementation of the ZWCP policy, with no direct effect through other channels. This theoretically validates the exclusion restriction.

In addition, following Guo et al. (2025), the interaction term between urban terrain relief and time trend is adopted as an additional instrumental variable ($iv_{\_2}$) [14]. On the one hand, cities with greater terrain relief bear higher costs for solid waste governance, making traditional end-of-pipe disposal unsustainable. These regions have stronger incentives to promote source reduction and resource utilization through ZWC construction. Moreover, most cities with high terrain relief have better ecological endowments and stricter ecological protection requirements, so local governments have stronger willingness to apply for the pilot program. On the other hand, average urban terrain relief is a natural geographic feature. It has no direct link to UGDE and is an exogenous indicator.

Table 6 presents the regression results of instrumental variable. The first stage regression results show that the coefficients of both instrumental variables are significantly positive, indicating that $iv_{\_1}$ and $iv_{\_2}$ are positively correlated with the ZWCP policy. From the results of the second stage regression, the coefficient of *zwcp* remains significantly positive after adjusting for the endogenous bias in the model. This result further supports the conclusion of benchmark regression.

Table 6. Instrumental variable regression.

Variables	Instrumental Variable 1		Instrumental Variable 2	
	The First Stage	**The Second Stage**	**The First Stage**	**The Second Stage**
	zwcp	***y***	***zwcp***	***y***
zwcp		1.154 *** (0.267)		0.865 *** (0.129)
$iv_{\_1}$	0.069 *** (0.014)			
$iv_{\_2}$			0.005 *** (0.001)	
Constant	0.310 *** (0.091)	−0.937 *** (0.157)	−0.059 * (0.034)	0.172 *** (0.030)
Control variables	✓	✓	✓	✓
City FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Observations	3920	3920	4777	4777
R^2	0.763	0.360	0.154	0.168

Note: ***, * mean significance at the level of 0.01 and 0.1, respectively. Robust standard errors in parentheses.

5.3. Mechanism Analysis

In this study, we use causal mediation analysis to examine whether ZWCP improves UGDE through two mechanisms: green industrial agglomeration and public environmental awareness. To ensure the comparability of results across the two causal mediation analyses, all regressions in this section are based on a unified balanced panel sample covering the 2011–2024 period. The results of the mechanism test are shown in Table 7. Column (1) presents the causal mediation results for the green industrial agglomeration mechanism. The results show that the NIE is 0.015 ($p < 0.01$), and the indirect effect accounts for 33.33% of the total effect. This finding indicates that green industrial agglomeration plays a significant partial mediating role in the UGDE improvement effect of ZWCP. Hypothesis 2 is therefore supported. Empirical evidence from the ZWCP policy confirms that environmental policies can improve UGDE by guiding green capital. Column (2) presents the causal mediation results for the public environmental awareness mechanism. The results show that the NIE is 0.006 ($p < 0.05$), and the indirect effect accounts for 12.50% of the total effect. This finding indicates that public environmental awareness plays a significant partial mediating role in the UGDE improvement effect of ZWCP. Hypothesis 3 is therefore supported. Overall, the mediating effect of the green industrial agglomeration mechanism accounts for 33.33% of the total policy effect, while that of the public environmental awareness mechanism accounts for 12.50%. In relative terms, green industrial agglomeration on the production side exerts a stronger transmission effect in the process whereby the ZWCP promotes urban green development. Public environmental awareness on the consumption side serves as an important micro-level supplementary channel, delivering a relatively more limited yet non-negligible mediating effect.

Table 7. Estimation results of causal mediation analysis.

Effect (Variables)	**UGDE**	**Green Industrial Agglomeration Mechanism**	**Public Environmental Awareness Mechanism**
	(1)	**(2)**	**(3)**
zwcp	0.043 *** (0.011)		
NIE		0.015 *** (0.004)	0.006 ** (0.003)
NDE		0.030 *** (0.006)	0.042 *** (0.016)
TE		0.045 *** (0.009)	0.048 *** (0.017)
Constant	−0.857 *** (0.173)		
Proportion mediated		33.33%	12.50%
Control variables	✓	✓	✓
City FE	✓	✓	✓
Year FE	✓	✓	✓
Observations	3934	3934	3934

Note: Column (1) reports the baseline DID regression results based on the identical sample used in the causal mediation analysis. ***, ** mean significance at the level of 0.01 and 0.05, respectively. Robust standard errors in parentheses.

The validity of causal mediation analysis relies heavily on the sequential ignorability assumption. Sensitivity analysis is a standard method to evaluate how strongly unobserved confounders may affect the conclusions of mediation effects. Figures 4a and 4b present the sensitivity analysis results for green industrial agglomeration and public environmental awareness, respectively. For the green industrial agglomeration mechanism, the sensitivity parameter ρ equals 0.402. This indicates that the NIE would drop to exactly zero only if unobserved confounders increased the correlation between residuals of the mediator model and the outcome model to 0.402. In other words, the existence of the green industrial agglomeration mediation effect can only be fully overturned by very strong omitted variables, which supports the high validity of this mediation channel. For the public environmental awareness mechanism, the sensitivity parameter ρ is 0.188. This result also shows that relatively strong unobserved confounders are required to invalidate this mediation mechanism, confirming the robustness of the public environmental awareness mediation effect.

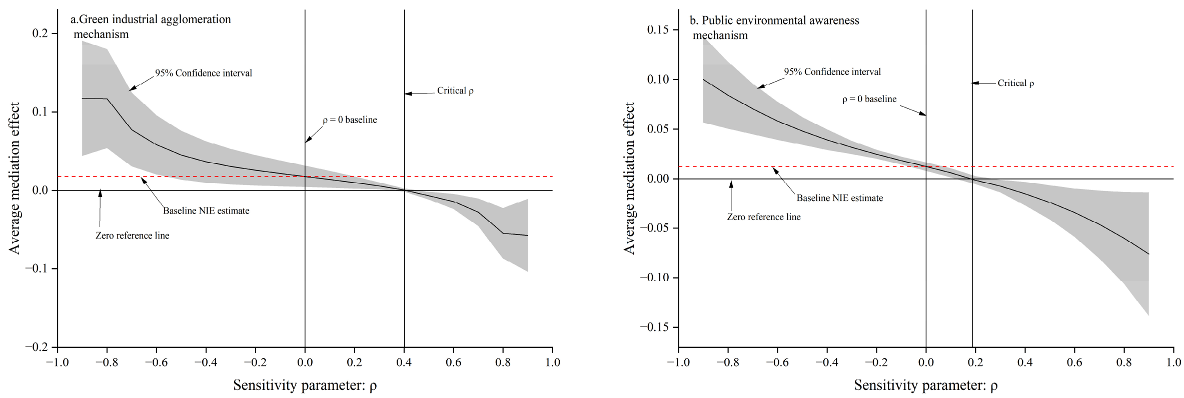

Figure 4. Sensitivity analysis.

5.4. Spatial Spillover Effects Analysis

Baseline regressions and mechanism analyses confirm that the ZWCP policy improves UGDE in pilot cities through two channels: green industrial agglomeration and public environmental awareness. However, these analyses do not account for the spatial externalities common in regional economic activities. The UGDE improvement effect of ZWC construction may spill over to neighboring cities. Meanwhile, green industrial agglomeration and public environmental awareness driven by the ZWCP may also affect the UGDE of adjacent cities through spatial linkage mechanisms. Therefore, we employ Equations (5)–(7) to identify the spatial transmission channels through which the ZWCP enhances UGDE.

Table A1 in Appendix A presents the regression results of Equations (5)–(7). Specification tests show that both the Wald test and LR test reject simplifying the SDM into a spatial lag model (SLM) or spatial error model (SEM), confirming that the SDM is a reasonable choice for this analysis. Given that regression coefficients from spatial econometric models cannot directly capture the marginal effects of explanatory variables, Tables 8 and 9 present the decomposed effects of the policy variable (*zwcp*) and mediator variables (*lngia* and *lnpea*) in Equations (5)–(7) under the two spatial weight matrices, respectively.

Table 8. SDM Marginal Effect Decomposition (Weight Matrix W_1).

Variable	Effect	(1) Equation (5) *y*	(2) Equation (6) *lngia*	(3) Equation (7) *y*	(4) Equation (6) *lnpea*	(5) Equation (7) *y*
zwcp	LR_Direct	0.050 ** (0.022)	0.925 *** (0.139)	0.032 (0.022)	0.031 ** (0.014)	0.040 * (0.023)
	LR_Indirect	0.094 ** (0.043)	1.121 *** (0.352)	0.039 (0.044)	0.109 *** (0.039)	0.115 ** (0.047)
	LR_Total	0.144 *** (0.047)	2.046 *** (0.402)	0.071 (0.048)	0.140 *** (0.045)	0.155 *** (0.052)
lngia	LR_Direct			0.016 *** (0.002)		
	LR_Indirect			0.020 *** (0.004)		
	LR_Total			0.036 *** (0.004)		
lnpea	LR_Direct					0.054 *** (0.010)
	LR_Indirect					−0.022 (0.019)
	LR_Total					0.032 (0.021)

Note: ***, **, * mean significance at the level of 0.01, 0.05, and 0.1, respectively. Robust standard errors in parentheses.

Table 9. SDM Marginal Effect Decomposition (Weight Matrix W_2).

Variable	Effect	(1) Equation (5) *y*	(2) Equation (6) *lngia*	(3) Equation (7) *y*	(4) Equation (6) *lnpea*	(5) Equation (7) *y*
zwcp	LR_Direct	0.051 ** (0.022)	0.651 *** (0.142)	0.003 (0.022)	0.050 *** (0.005)	0.035 * (0.018)
	LR_Indirect	0.455 *** (0.073)	1.037 * (0.614)	−0.023 (0.071)	0.174 *** (0.020)	0.371 *** (0.071)
	LR_Total	0.506 *** (0.072)	1.688 *** (0.642)	−0.020 (0.072)	0.222 *** (0.021)	0.406 *** (0.073)
lngia	LR_Direct			0.012 *** (0.002)		
	LR_Indirect			0.038 *** (0.007)		
	LR_Total			0.050 *** (0.006)		
lnpea	LR_Direct					0.062 *** (0.009)
	LR_Indirect					−0.032 (0.039)
	LR_Total					0.030 (0.041)

Note: ***, **, * mean significance at the level of 0.01, 0.05, and 0.1, respectively. Robust standard errors in parentheses.

In Tables 8 and 9, columns (1), (2) and (3) constitute the spatial transmission path of green industrial agglomeration, while columns (1), (4) and (5) form the spatial transmission path of public environmental awareness. For the transmission path of green industrial agglomeration, the effect decomposition results in column (1) show that the direct, indirect and total effects of the ZWCP on UGDE are all significantly positive. The positive indirect effect indicates that the UGDE improvement effect of the ZWCP is not confined to pilot cities. Local pilot construction can exert a significant positive spillover effect on the green development efficiency of neighboring cities through channels such as policy demonstration effects and industrial linkage transmission. The results in column (2) demonstrate that the ZWCP significantly promotes green industrial agglomeration in both local and surrounding cities. The results in column (3) further show that both the direct and indirect effects of green industrial agglomeration on UGDE are significantly positive at the 1% level. Green industrial agglomeration can not only directly promote UGDE in local cities, but also generate positive spillovers to neighboring cities through channels such as industrial spatial linkages and collaborative diffusion of industrial chains. Meanwhile, the direct, indirect and total effects of the ZWCP in column (3) all become statistically insignificant, indicating that green industrial agglomeration plays a full mediating role at both the local level and the spatial spillover level in the process of the ZWCP affecting UGDE. Both the local governance effect and the inter-city radiation effect of the policy are mainly transmitted through green industrial agglomeration.

For the spatial transmission path of public environmental awareness, the results in column (4) show that the ZWCP significantly enhances public environmental awareness in both local and neighboring cities. The results in column (5) further indicate that public environmental awareness significantly promotes UGDE only at the local level, while its indirect effect at the spatial level is not statistically significant. Meanwhile, the direct effect of the ZWCP exhibits a decline in both coefficient magnitude and statistical significance, suggesting a partial local mediating pattern of public environmental awareness. In contrast, its indirect effect shows no attenuation, indicating that public environmental awareness cannot carry the inter-city transmission effect of UGDE through spatial spillovers and only exerts a partial mediating role within cities.

5.5. Moderation Analysis

To examine the moderating effect of GEA on the UGDE improvement effect of ZWCP, Equation (10) is adopted for estimation. The results are shown in Table 10. In addition, Figure 5 presents the marginal effects of the ZWCP policy on green industrial agglomeration at the 10th, 50th, and 90th percentiles of GEA.

Table 10. Estimation results of the moderating effect.

Variables	*lngia*	*lnpea*
	(1)	**(2)**
zwcp	0.204	0.025
	(0.298)	(0.139)
lngea	0.261 ***	0.174 ***
	(0.082)	(0.056)
zwcp × *lngea*	1.969 ***	0.431 ***
	(0.590)	(0.237)
Constant	−9.766 ***	−5.811 ***
	(0.631)	(0.281)
Control variables	√	√
City FE	√	√
Year FE	√	√
Observations	4777	3934
R^2	0.618	0.739

Note: *** means significance at the level of 0.01. Robust standard errors in parentheses.

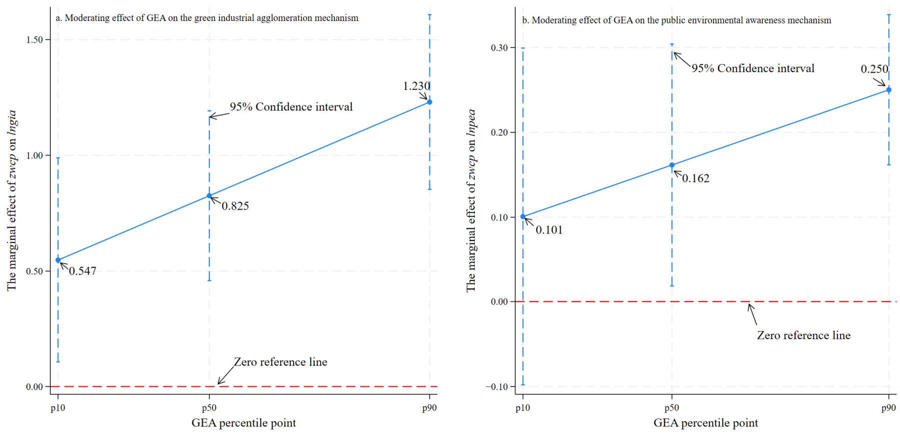

Figure 5. Marginal effects at different percentiles of GEA.

Column (1) in Table 10 uses green industrial agglomeration as the dependent variable. The coefficient of *zwcp* × *lngea* captures how GEA moderates ZWCP's driving effect on green industrial agglomeration. The results show that the coefficient of *zwcp* × *lngea* is 1.969 and statistically significant at the 1% level. This finding indicates that GEA has a significant positive moderating effect on ZWCP's role in promoting green industrial agglomeration. As shown in Figure 5a, when GEA stays at the low 10th percentile, the improvement effect of ZWCP on green industrial agglomeration is 0.547. As GEA rises to the medium 50th percentile, the policy's agglomeration-driving effect increases to 0.825. When GEA reaches the high 90th percentile, the marginal effect of ZWCP climbs to 1.230, and the effect remains statistically significant across all percentile levels.

Column (2) in Table 10 uses public environmental awareness as the dependent variable. The coefficient of $zwcp \times lngea$ reflects how GEA moderates ZWCP's driving effect on public environmental awareness. The results show that the coefficient of $zwcp \times lngea$ is 0.431 and statistically significant at the 1% level. This finding indicates that government environmental attention has a significant positive moderating effect on ZWCP's role in driving public environmental awareness. Figure 5b presents the marginal effects of the ZWCP policy on public environmental awareness at the 10th, 50th, and 90th percentiles of GEA. At the low 10th percentile of GEA, ZWCP produces an improvement effect of 0.101 on public environmental awareness, which is statistically insignificant. As GEA rises to the medium 50th percentile, the policy's promoting effect increases to 0.162 and is significant at the 5% level. When GEA reaches the high 90th percentile, the marginal effect of ZWCP climbs to 0.250.

Overall, GEA positively moderates the UGDE improvement effect of ZWCP. Hypothesis 4 is thus supported.

5.6. Heterogeneity Analysis

5.6.1. Regression Analysis of Different Geographic Locations

Regarding the benchmark regression, it analyzes the impact of ZWCP policy on UGDE in an average sense. It concludes that ZWCP policy remarkably contributes to the improvement of UGDE. However, regions differ in their economic and environmental characteristics. As a result, the policy effects of ZWCP may show heterogeneity. Accordingly, following the official classification criteria for China's regional economic belts issued by the National Bureau of Statistics, we categorized the sample cities into three regions: eastern region, central region, and western region. As shown in Table 11, in the regression results in columns (1)–(3), the impact of the ZWCP policy on UGDE is significantly positive in the eastern region, but not statistically significant in the central and western regions.

Table 11. The result of the heterogeneity test.

Variables	Eastern	Central	Western	RBCs	NRBCs	LUCs	HUCs
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
zwcp	0.069 ***	0.030	−0.004	0.040 **	0.033 **	0.037 ***	0.052 ***
	(0.019)	(0.019)	(0.020)	(0.020)	(0.014)	(0.012)	(0.018)
Constant	−1.145 ***	−0.336 **	−0.614 *	−0.508 **	−0.413 **	−0.177	−1.665 ***
	(0.289)	(0.146)	(0.334)	(0.203)	(0.200)	(0.121)	(0.241)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Chow test				3.21 *		3.77 *	
				[0.073]		[0.052]	
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1700	1700	1377	1870	2907	2261	2244
R^2	0.758	0.761	0.685	0.712	0.749	0.773	0.716

Note: ***, **, * mean significance at the level of 0.01, 0.05, and 0.1, respectively. RBCs, Resource-based cities; NRBCs, Non-resource-based cities; LUCs, Low-urbanization cities, HUCs, High-urbanization cities; *p*-values in square brackets.

5.6.2. Regression Analysis of Different Urban Resource Endowment

The resource endowment characteristics of a city can influence its path of industrial development. Specifically, cities dependent on natural resources for their economic development, particularly those where mineral extraction is the dominant industry, often exhibit high levels of pollution emissions and comparatively low achievements in green development. The sample cities were classified as resource-based and non-resource-based cities based on the "National Sustainable Development Plan for Resource-Based Cities (2013–2020)", to verify whether heterogeneity exists in the impact of ZWCP policies on UGDE with different resource endowment characteristics. The regression results are displayed in column (4) and column (5) of Table 11. The estimated coefficients of *zwcp* are 0.040 in resource-based cities (RBCs) and 0.033 in non-resource-based cities (NRBCs). Both are statistically significant at the 5% level. Meanwhile, the Chow test for group differences shows a significant difference between the two coefficients. The green development effect of ZWCP is relatively stronger in RBCs.

5.6.3. Regression Analysis of Different Urbanization Levels

The degree of urbanization can impact the magnitude of the scale effect on pollutant control. To objectively distinguish differences in urbanization levels and avoid the subjectivity of manually set grouping thresholds, and following common practice in existing studies, the urbanization rate is measured as the share of urban population in the total population of prefecture-level cities [73]. The full sample is split into two subgroups using the median urbanization rate of sample cities in the year of policy implementation as the cutoff: cities with rates below the median are classified as low-urbanization cities (LUCs), and those above the median as high-urbanization cities (HUCs). The regression results are displayed in column (6) and column (7) of Table 11. The estimated coefficients of *zwcp* are 0.037 in LUCs and 0.052 in HUCs. Both are statistically significant at the 1% level. Meanwhile, the Chow test for group differences shows a significant difference between the two coefficients. It is evident that the promotional impact of ZWCP on UGDE is more pronounced in HUCs.

6. Discussion

6.1. Discussion on the Impact of ZWCP on UGDE

This study demonstrates that the ZWCP exerts a significant positive effect on UGDE. This finding is consistent with the results of Chai et al. (2025) and Wang (2025) [13,74]. Their studies found that the ZWCP policy had synergistic effects on pollution and carbon reduction, and boosted urban green development to a certain extent. However, analysis of the dynamic policy effects reveals that the promotional impact of the ZWCP on UGDE is characterized by a two-year time lag. This phenomenon can be explained from three perspectives: institutional design, infrastructure investment, and resident participation. First, from the institutional perspective, although the first batch of pilot cities was announced in April 2019, the specific implementation plans for each city were not finalized until November 2019. Meanwhile, it took roughly six months to formulate and roll out supporting arrangements, including departmental responsibilities, detailed implementation rules, and assessment systems. This means the first year of policy implementation focused mainly on building the institutional framework, while substantive governance tasks had not been fully launched. As a result, policy effects could not emerge immediately in the same year. Second, in terms of infrastructure investment and construction, the upgrading of solid waste disposal facilities and the launch of resource utilization projects are generally characterized by large scale, long construction cycles, and slow effect delivery. This feature also restricts the timely manifestation of ZWCP policy effects. For example, among the first batch of pilot cities, Tongling launched several projects for co-processing of solid waste in cement kilns after obtaining ZWCP approval, with a total investment of 390 million yuan. After equipment installation, commissioning, and acceptance procedures, the projects did not reach full operation and deliver tangible results until 2021. Third, from the perspective of residents' zero-waste behaviors, domestic waste sorting is an important component of ZWC construction. However, existing studies show that the development of residents' environmental behavior habits is typically a gradual process, and such effects cannot be observed immediately after policy rollout [75]. Stable environmental habits can only be formed through sustained institutional strengthening, daily scenario promotion, and positive feedback. Furthermore, studies evaluating the effects of other environmental policies have also identified similar lag effects, which is consistent with the findings of this paper. Dong et al. (2023) found that the carbon emission reduction effect of China's low-carbon city policy had a one-year lag period [76]. Zhao and Xu (2026) observed a two-year lag in the emission reduction effect of China's carbon trading pilots [77]. This finding implies that for green transition policies to exert their full effectiveness, policymakers must maintain strategic resolve, deploy supporting measures proactively, and establish a long-term evaluation orientation, thereby ensuring the full delivery of policy value.

6.2. Discussion on Transmission Mechanisms

Causal mediation analysis confirms that green industrial agglomeration and public environmental awareness serve as two effective channels through which the ZWCP drives improvements in UGDE. In terms of the green industrial agglomeration channel, Rizzitello et al. (2025) demonstrate that environmental policies can stimulate corporate green investment and accelerate the formation of green industrial agglomeration [78]. Gajera et al. (2026) further note that urban solid waste management, functioning as a resource flow, fosters more circular economy enterprises via green technology innovation and thus propels green economic development [79]. With respect to the public environmental awareness channel, the ZWCP establishes diversified publicity and guidance systems, improves supporting facilities for green living, and implements guiding policies such as waste sorting and plastic restriction regulations [80], all of which help strengthen public environmental awareness. Existing studies have verified that enhanced public environmental awareness improves waste management efficiency [81]. In particular, public environmental awareness reduces urban pollutant generation and end-of-pipe treatment costs [82], thereby indirectly facilitating UGDE improvement.

Furthermore, analysis of the spatial effects of the transmission mechanisms reveals that green industrial agglomeration exerts a mediating effect at both the local and spatial spillover levels, whereas the mediating effect of public environmental awareness is confined exclusively to the local level. This spatial pattern is consistent with the conclusions of Liu et al. (2024) [15], who find that the ZWCP generates spatial spillover effects on neighboring cities and promotes green development in surrounding areas through demonstration effects and industrial linkages, which provides empirical support for the cross-city transmission of the green industrial agglomeration channel. In contrast, public environmental awareness bears strong localized social attributes: its formation and diffusion are highly dependent on local cultural contexts, community governance and living circles, and lack effective carriers for cross-city dissemination. Unlike green industries that achieve rapid inter-city spillovers via industrial chain linkages and cross-city enterprise layout, the inter-city transmission of residents' environmental awareness relies on slow processes such as population mobility and social interaction with weak transmission intensity, and thus fails to achieve cross-city spillover effects through the ZWCP. This finding indicates that policymakers should leverage the spatial spillover effects of green industrial agglomeration to strengthen inter-city industrial synergy, and roll out targeted local cultivation and guidance measures in light of the localized nature of public environmental awareness.

6.3. Discussion on the Moderating Effect of GEA

Moderation analysis demonstrates that GEA exerts a positive moderating effect on the causal pathways underlying the ZWCP's promotion of UGDE. In terms of the green industrial agglomeration channel, higher GEA enables pilot cities to roll out targeted supporting measures such as industrial subsidies and green approval fast tracks, directing production factors toward green sectors and reinforcing the policy's agglomeration effect. This finding aligns with existing evidence that cities with greater environmental attention can better capitalize on policy dividends to foster advanced green industrial agglomeration [83]. For the public environmental awareness channel, sufficient GEA underpins the sustained rollout of publicity and guidance initiatives, facilitating the enhancement of public environmental awareness. This result is consistent with Zhang et al. (2024), who note that inadequate governmental attention weakens policy signal penetration and limits improvements in residents' environmental perceptions [84].

This finding demonstrates that the effectiveness of environmental policies is highly contingent on the prioritization of local governance resources. The moderating effect of GEA on the green industrial agglomeration channel can be conceptualized as a factor supply logic, whereby governments deploy supporting measures such as industrial subsidies and land use guarantees to reduce the institutional transaction costs of green industries, channel production factors toward green sectors, and amplify the industrial empowerment effects of the policy. The moderating effect of GEA on the public environmental awareness channel can be framed as a signal transmission logic, in which governments integrate environmental governance into routine governance agendas and deliver sustained publicity guidance and scenario construction to strengthen public perception of policy signals and facilitate the translation of environmental concepts into individual behaviors. However, both governmental resource allocation and governance attention are subject to aggregate constraints, making it infeasible to sustain high-intensity investment across both pathways simultaneously. Resources should thus be allocated differentially in line with urban development foundations to balance the priorities between the short-term outcomes of industrial transformation and the long-term value of public awareness cultivation.

6.4. Discussion on the Heterogeneity

Heterogeneity analysis reveals that the ZWCP exerts heterogeneous effects on UGDE across urban location, resource endowment, and urbanization level, providing valuable empirical guidance for policymakers to roll out targeted zero-waste measures.

Regarding geographic location heterogeneity, the ZWCP demonstrates a significantly positive effect in eastern regions, whereas its effect remains statistically insignificant in central and western regions. This is consistent with the research results of Wang (2025) [74]. Two main factors explain this heterogeneity. First, differences in industrial structure. Compared with eastern regions, central and western regions have a higher proportion of resource-based and heavy chemical industries and exhibit stronger path dependence on the traditional extensive development model [4], which cannot be fundamentally reversed in the short term. Moreover, these regions possess a weak foundation for green industries and incomplete industrial chain support [85], preventing the rapid formation of large-scale green industrial agglomeration. Consequently, the policy effect transmitted through the industrial channel is considerably weakened. Second, differences in resource constraints. Cities in central and western regions are generally weaker than those in eastern regions in fiscal capacity, technological reserves, and the supply of environmental professionals [12,86], thus failing to provide adequate support for zero-waste city construction.

In terms of heterogeneity in urban resource endowments, the ZWCP exerts a more pronounced facilitating effect in RBCs. This finding aligns with the results reported by Xu and Hu (2025) [87]. RBCs are dominated by mining, metallurgy, and chemical industries and generate substantial amounts of bulk industrial solid waste. Given that the ZWCP is designed to promote solid waste recycling and industrial circular transformation, it directly addresses the critical development challenges of RBCs. As a result, these cities possess considerably greater room for marginal improvement than NRBCs, where waste originates mainly from domestic and commercial sources. In addition, the high geographic concentration of upstream and downstream enterprises in RBCs and the centralized nature of their waste emissions facilitate the construction of large-scale networks for waste exchange and cascade utilization [88], thereby fostering efficient green industrial agglomeration. Notably, RBCs generally face pressures from resource depletion and forced transformation, which motivates them to adopt the zero-waste pilot as a core policy instrument for urban transformation and to implement the policy with greater intensity and responsiveness. Overall, the ZWCP exerts a stronger impact on urban green development efficiency in RBCs than in NRBCs.

Regarding urbanization level heterogeneity, the ZWCP exerts a more pronounced promoting effect in cities with high urbanization levels. One possible explanation is that HUCs are characterized by highly concentrated populations and industries along with centralized waste generation, which facilitates the construction of large-scale systems for waste sorting and resource recycling [73], substantially reducing unit treatment costs and amplifying the policy's marginal benefits. Second, HUCs possess stronger fiscal capacity and can allocate sufficient funds to advanced solid waste disposal facilities and smart supervision platforms, thereby rendering the green development effect of the ZWCP more notable. In contrast, LUCs often face constraints such as funding shortages and weak environmental infrastructure [89], which to a certain extent limit the green development effect of the ZWCP.

7. Conclusions and Policy Implications

As the environment deteriorates and natural resources become increasingly constrained, the concept of zero-waste can motivate the government to refine the sustainable development policy framework, drive clean production reforms in enterprises, and endorse a lifestyle that is both simple and environmentally conscious. Building on the ZWCP policy in China, this study examines the impact and mechanisms of ZWCP on UGDE using the panel data from 281 Chinese cities between 2008 and 2024. The following conclusions have been reached.

First, ZWCP policy can effectively improve UGDE. After accounting for robustness testing and endogeneity issues, this core conclusion remains valid. This finding extends existing research on ZWCP policy effect evaluation. It expands the analytical scope from policy outcomes focused on end-of-pipe pollution reduction and carbon governance to the dimension of comprehensive economic efficiency.

Second, from the perspective of the mechanism, ZWCP policy improves UGDE through two channels: green industrial agglomeration and public environmental awareness. At the same time, GEA strengthens the positive effects of ZWCP on these two mediating variables. This finding goes beyond the prevailing paradigm of existing environmental policy mechanism research, which focuses heavily on supply-side pathways including green technology innovation and command-and-control environmental regulation. This study builds a green development effect framework for ZWCP from the market and public dimensions. Furthermore, it introduces the attention-based view into the analysis of conditions for environmental policy transmission, revealing that local governments' discretionary allocation of governance resources amplifies policy effectiveness. This enriches the theoretical connotation of the transmission mechanisms of environmental policies.

Third, the spatial effect analysis shows that the UGDE improvement effect of the ZWCP presents significant spatial spillover effects. Among them, policy-driven green industrial agglomeration has clear spatial transmission capacity, and can drive the green economic development of neighboring cities through cross-regional industrial linkages and collaborative diffusion of industrial chains. In contrast, public environmental awareness only exerts a mediating role within cities, and its spatial spillover effect is not statistically significant. This finding refines research on the transmission mechanism of spatial spillover effects of environmental policies, and confirms that the ZWCP is not a closed governance practice limited to individual cities. Its spatial diffusion presents differentiated characteristics of "strong industrial-level coordination and weak social-level diffusion". This provides empirical evidence for the regional collaborative practice of urban green transformation, and also enriches the theoretical connotation of regional collaborative environmental governance.

Fourth, further heterogeneity analysis reveals that the enhancing effect of ZWCP policy on UGDE in eastern region, resource-based cities, and high-urbanization cities is the most pronounced. This conclusion reveals that resource endowments and development stages bound the effectiveness of the ZWCP policy. It shows that the policy's effects are not homogeneous. Instead, they are highly adapted to cities' industrial foundations, resource characteristics, and urbanization levels. This finding provides more detailed empirical support for the theory of differentiated environmental governance and lays the theoretical foundation for category-specific policy design.

The study presents several practical policy recommendations based on the findings.

In the short term: (1) Building on the practical experience of the first two batches of ZWCP, RBC and industrial cities in central and western China with prominent transformation pressure should be prioritized for inclusion in the candidate pilot list. Special fiscal funds should be allocated to address gaps in environmental infrastructure, laying a solid foundation for improving urban green development efficiency. Targeted initiatives should be rolled out according to regional endowments and city types. Eastern regions should leverage their industrial and technological strengths to build replicable demonstration models for urban green development. Central regions should prioritize the green transformation of traditional industries and reduce pollutant emissions from heavy chemical sectors. Western regions, serving as ecological barriers, should strictly control new pollutant generation and consolidate their ecological carrying capacity. For city-level differentiation, RBC should prioritize large-scale, high-value utilization of industrial solid waste to drive industrial green upgrading. NRBC should promote circular transformation of industrial parks and cleaner production audits for key enterprises. HUC should optimize the refined construction waste recycling system. LUC should improve the three-tier waste collection and transportation network covering counties, townships, and villages. These targeted measures can directly tackle core governance bottlenecks of different city types and deliver tangible improvements in green development efficiency in the short run. (2) Special support funds for solid waste resource utilization should be established. A number of specialized circular economy industrial parks focusing on energy conservation, waste recycling, and remanufacturing should be planned and deployed, supported by shared R&D platforms and centralized environmental infrastructure. Meanwhile, the development level of green industrial clusters should be included in the annual assessment indicators for ZWC construction. This will strengthen local governments' attention to environmental governance and quickly unlock the industrial scale effect.

In the long term: (1) A full-cycle management system with a three-tier gradient cultivation structure should be established. This system includes three tiers, namely candidate pilots, formal pilots, and demonstration benchmarks, and implements standardized procedures for selection, cultivation, evaluation, and exit. This will promote the transition of ZWC construction from phased pilot programs to routine urban governance. Unified national standards and market rules for cross-regional solid waste disposal should be formulated to remove administrative barriers and build a long-term coordination mechanism for regional collaborative governance. Meanwhile, a long-term category-specific assessment system should be developed for different city types, replacing short-term one-size-fits-all task targets. This will create a long-term governance framework adapted to each city's development stage. (2) The zero-waste concept should be integrated into the national education system and grassroots community governance systems, forming a multi-stakeholder governance pattern guided by the government, led by the market, and with broad public participation. This will drive public green behavior to shift from being policy incentive-driven to being internal awareness-driven. A two-way feedback loop will then take shape between upgraded green consumption demand and upgraded green industry supply, consolidating the long-term social foundation for urban green development from both the supply and demand sides.

This study has several limitations. First, this paper takes cities as the basic research unit and verifies the promotion effect and transmission channels of ZWCP on UGDE from a macro perspective. However, it does not decompose the micro mechanisms of the policy at the firm and resident levels. Future research can shift the research focus to enterprises and residents. At the firm level, we will examine how ZWCP affects corporate investment in clean production and green technological innovation, so as to provide micro evidence for the macro policy effects. At the resident level, micro survey data can be adopted to analyze the specific impacts of ZWCP on residents' waste sorting habits and green consumption preferences. This will enrich the micro empirical foundation of the public environmental awareness mediation channel. Second, due to data constraints at the city level, solid waste-related indicators are not included as undesirable outputs in the UGDE estimation. Accordingly, the estimated UGDE cannot fully capture the policy-specific targets of ZWC construction, such as solid waste reduction. Instead, it primarily reflects the overall promotion effect of the policy on the comprehensive green development performance of cities. To address this limitation, we will carry out in-depth case studies of typical pilot cities in follow-up research. Solid waste emission data will be collected through field surveys to develop a UGDE measurement framework more aligned with the core goals of the ZWCP policy. Alternatively, as city-level statistical data improve, solid waste-related indicators can be integrated into the efficiency measurement system to refine the UGDE evaluation framework. Third, this study adopts the DID model and only estimates the average policy effect, without an in-depth analysis of policy tools and implementation intensity. To fill this gap, we plan to collect official implementation plans of ZWCP in follow-up research. Text analysis will be used to sort out different types of policy tools and measure their implementation strength. Continuous difference-in-differences models will then be adopted to capture heterogeneous effects of varied policy intensities and tool combinations on urban green development efficiency, which helps pinpoint the most effective policy measures.

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the datasets cannot be made publicly accessible and will be shared upon reasonable academic request in compliance with relevant data usage constraints.

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Abbreviations

The following abbreviations are used in this manuscript:

ZWC	Zero-waste city
ZWCP	Zero-waste city pilot
UGDE	Urban green development efficiency
GEA	Government environmental attention
ATE	Average treatment effect
NIE	Natural indirect effect
NDE	Natural direct effect
SDM	Spatial Durbin model
SLM	Spatial lag model
SEM	Spatial error model
DMU	Decision-making units
DID	Difference-in-Differences
API	Application programming interface
PSM	Propensity score matching
RBCs	Resource-based cities
NRBCs	Non-resource-based cities
LUCs	Low-urbanization cities
HUCs	High-urbanization cities

Appendix A

In this study, the DO index developed by Duranton and Overman (2005) is adopted to measure the level of green industrial agglomeration in each city [61]. This index characterizes the distribution of pairwise distances between enterprises through kernel density estimation. It is then compared with a counterfactual benchmark of random spatial distribution to assess the degree of industrial spatial agglomeration. The specific calculation steps are as follows.

Step 1: Kernel density estimation.

$$K(d) = \frac{1}{n(n-1)h} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} f\left(\frac{d - d_{ij}}{h}\right) \quad (A1)$$

where n denotes the number of enterprises, d_{ij} refers to the pairwise distance between enterprises, $f(\ )$ is the Gaussian kernel function, and the bandwidth h is determined by Silverman's rule of thumb.

Step 2: Construction of counterfactual experiments.

In reality, enterprise locations are not completely randomly distributed in space. We first construct a set containing the actual location information of all enterprises in each city for each year. The same number of enterprise points are then randomly sampled without replacement from this set, and the simulated spatial distribution curve of enterprises is computed following the procedure in Step 1. This process is repeated 500 times.

Step 3: Construction of global confidence intervals.

The global confidence interval represents a joint estimate of local extrema across multiple distance scales. Specifically, the values at the 5th and 95th percentiles of the 500 simulation results at each given distance are used as the lower and upper bounds of the local confidence interval. Notably, simulation results are not interpretable for all distance settings. Following the approach of Koh and Riedel (2014), this study takes the median of pairwise distances between enterprises within each city as the upper bound of the distance interval [90].

Step 4: Calculation of the agglomeration index.

Building on the above steps, the formula for the agglomeration index is given by:

$$gia(d) = \max\left(K(d) - \widetilde{K}(d), 0\right) \tag{A2}$$

where $\widetilde{K}(d)$ denotes the upper bound of the global confidence interval. For city-year observations with no identified circular economy enterprises, the agglomeration index is set to 0. Meanwhile, to mitigate data skewness, this study uses the natural logarithm of one plus the agglomeration index to measure green industrial agglomeration.

Appendix B

Table A1 presents the regression results and diagnostic test results for the SDM.

Table A1. Estimation results of SDM.

Variables	W_1					W_2				
	y	*lngia*	*lnpea*	*y*	*y*	*y*	*lngia*	*lnpea*	*y*	*y*
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
zwcp	0.044 **	0.835 ***	0.022 *	0.029	0.034	0.036 *	0.618 ***	0.043 ***	0.003	0.022 *
	(0.022)	(0.133)	(0.011)	(0.022)	(0.022)	(0.021)	(0.138)	(0.005)	(0.022)	(0.012)
Wzwcp	0.058 *	0.215	0.045 **	0.024	0.080 **	0.188 ***	−0.006	0.035 ***	−0.014	0.163 ***
	(0.034)	(0.218)	(0.022)	(0.036)	(0.036)	(0.039)	(0.264)	(0.009)	(0.043)	(0.040)
Wy	0.283 ***			0.252 ***	0.283 ***	0.559 ***			0.433 ***	0.543 ***
	(0.017)			(0.018)	(0.019)	(0.021)			(0.025)	(0.024)
lngia				0.016 ***					0.011 ***	
				(0.002)					(0.002)	
Wlngia		0.488 ***		0.012 ***			0.634 ***		0.017 ***	
		(0.015)		(0.004)			(0.019)		(0.005)	
lnpea					0.056 ***					0.063 ***
					(0.010)					(0.010)
Wlnpea			0.534 ***		−0.032 **			0.649 ***		−0.050 **
			(0.014)		(0.016)			(0.019)		(0.020)
Control variables	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
WX	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
City FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Observations	4777	4777	3934	4777	3934	4777	4777	3934	4777	3934
R^2	0.694	0.262	0.235	0.704	0.628	0.678	0.305	0.352	0.708	0.616
Wald test SAR	132.98 ***	44.14 ***	53.08 ***	105.12 ***	38.69 ***	109.61 ***	60.71 ***	73.26 ***	95.31 ***	44.63 ***
Wald test SEM	197.89 ***	139.17 ***	240.51 ***	180.21 ***	51.06 ***	149.28 ***	119.54 ***	182.72 ***	154.89 ***	108.94 ***
LR test SAR	131.35 ***	44.28 ***	52.43 ***	104.23 ***	81.32 ***	108.44 ***	61.07 ***	72.70 ***	94.61 ***	44.29 ***
LR test SEM	207.73 ***	145.69 ***	282.38 ***	189.74 ***	121.54 ***	176.72 ***	140.32 ***	263.05 ***	184.06 ***	138.40 ***

Note: ***, **, * mean significance at the level of 0.01, 0.05, and 0.1 respectively. Robust standard errors in parentheses.

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