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How Does Digital Trade Affect Pollution Control and Carbon Mitigation? Evidence from the Production, Public, and Government Dimensions

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Abstract

Digital trade reflects the convergence of the new technological revolution and traditional trade. Investigating its effectiveness in pollution control and carbon mitigation (PCCM) is crucial for addressing global environmental challenges. This research exploits the rollout of cross-border e-commerce comprehensive pilot zones (CECPZs) as an exogenous policy shock, leveraging double machine learning (DML) methods to assess the impact of digital trade on PCCM using panel data from 280 Chinese prefecture-level cities from 2011 to 2023. The results reveal that digital trade significantly enhances PCCM, mainly by promoting technological innovation, intelligent industrial transformation, and public participation; government emphasis on new quality productive forces and digital government construction positively moderates the link between digital trade and PCCM, while intensified environmental regulation exerts a counteracting inhibitory effect. Heterogeneous outcomes reveal that the promoting effects of digital trade are more evident in large areas, as well as in cities that are neither traditional industrial bases nor resource-based. Further analysis shows that digital trade can deliver a triple dividend in the form of reduced pollution, lower carbon emissions, and sustained economic growth. These findings provide meaningful guidance for promoting a balanced and sustainable relationship between human activities and the natural environment in the digital era.

Keywords: digital trade; cross-border e-commerce comprehensive pilot zones; pollution control; carbon mitigation; double machine learning

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1. Introduction

The dual crises of climate change and pollution are core challenges for global sustainable development. Unlike developed nations that addressed pollution and carbon reduction sequentially, China, as the world's largest emitter bearing some of the heaviest pollution burdens, faces the formidable challenge of tackling both simultaneously [1]. Sharing identical sources and generation processes, air pollutants and greenhouse gases (GHGs) stem mainly from fossil fuel combustion, industrial production, and transportation. This high overlap indicates that addressing both conventional pollutants and carbon emissions simultaneously is highly feasible and can lead to dual emission reductions [2]. Recently, China has rolled out policies to promote pollution control and carbon mitigation (PCCM) as a parallel effort within its green and low-carbon transition framework. However, a

heavy-chemical industrial structure, a coal-dominated energy mix, and regional regulatory disparities have created a deep structural lock-in, causing the marginal benefits of traditional governance approaches to gradually diminish. Therefore, the key to China's achievement of PCCM lies in exploring a new and intensive development model, thereby breaking the path dependency of pollution and high-carbon growth under traditional production and consumption patterns.

Amidst escalating international green trade barriers and China's strategic commitment to "dual-carbon" targets, digital trade, an emerging paradigm capable of reconfiguring production and consumption networks, presents a vital pathway to dismantle the aforementioned structural lock-ins. Specifically, digital trade mitigates emissions at the source by optimizing resource allocation and facilitating green technology spillovers while also inducing a consumer-led transition through enhanced information transparency [3]. Conversely, its reliance on energy-intensive infrastructure and logistics may trigger a "rebound effect" that increases energy consumption [4]. Thus, whether digital trade expansion aggravates environmental burdens or improves environmental quality while driving growth remains highly debated [5,6]. Additionally, for China, pollutant and carbon emissions correspond to environmental quality and low-carbon transition goals, respectively. Since these are two key dimensions of digital trade's environmental effects, examining either in isolation fails to fully reveal the overall impact. In light of this, it is highly warranted to examine the impacts of digital trade on both pollution and carbon emissions within a unified analytical framework and to further scrutinize the underlying transmission mechanisms.

The literature on the trade–environment nexus is closely related to this study. Although this line of research has a long history, a consensus has yet to emerge, with prevailing scholarly views broadly divided into three perspectives. The first is the environmental degradation theory, represented by the "pollution haven hypothesis" [7]. The second is the environmental improvement theory, typified by the "pollution halo hypothesis" [8]. The third is the environmental complexity theory, which lies between the two and is commonly framed as the "Environmental Kuznets Curve (EKC) hypothesis" [9]. Additionally, another strand of research examines the environmental impacts of other economic activities, primarily focusing on the dual dimensions of production and consumption. On the production side, activities such as energy consumption [10], industrial manufacturing processes [11], and building material production are identified as major drivers of environmental degradation [12]. On the consumption side, shifts in household consumption structures and their embodied indirect carbon emissions have also garnered widespread attention [13].

With the rapid expansion of the digital economy, a growing body of literature has begun to explore the nexus between digital trade and the environment. One line of research suggests that by reshaping global trade patterns, structures, and rules, digital trade upgrades traditional industries and fosters new business models [14]. The resulting technological and structural effects help reduce energy consumption and emissions [15]. Conversely, another line argues that digital trade relies on massive data centers, servers, and network equipment for storage and transmission, which inevitably intensifies energy consumption and emissions [16], thereby weakening or even reversing its potential environmental benefits. Furthermore, some scholars explore the environmental impacts of digital trade from the perspective of policy shocks [17]. Certain studies find that digital trade policies lower urban carbon intensity through technological innovation, industrial upgrading, and digital transformation [18]. By contrast, others contend that the expansion of logistics demands and consumption growth induced by digital trade policies render the overall environmental outcomes uncertain [19,20].

In sum, despite these valuable insights, several critical gaps remain in the literature. First, most studies investigate either pollution abatement or carbon reduction in isolation, rarely evaluating both pollution and carbon emissions within a unified framework to explore whether digital trade can simultaneously achieve PCCM. Second, prior research primarily explains the environmental effects of digital trade through production-side processes and consumption-side structural shifts, while the potential roles of public-level environmental participation and green consumption attitudes remain relatively underexplored. Since PCCM constitutes a systemic endeavor spanning the production, consumption, and public spheres, all of which are inextricably linked to digital trade, the underlying transmission mechanisms warrant systematic elucidation. Third, studies have yet to adequately examine whether shifts in the external institutional environment moderate the impact of digital trade on PCCM. Specifically, it remains unclear whether and to what extent institutional factors can amplify or constrain the PCCM effect of digital trade.

To bridge these gaps, this study addresses three key yet underexplored questions: (1) Can digital trade promote both pollution control and carbon mitigation, thereby realizing the PCCM effect? (2) What are the underlying transmission mechanisms through which digital trade influences PCCM? (3) How does the external institutional environment moderate the PCCM effect of digital trade? Addressing these questions is of great significance for understanding how to overcome the dual constraints of sustained environmental quality improvement and intensified carbon emission controls in the digital era.

Guided by these questions, this study leverages the establishment of China's cross-border e-commerce comprehensive pilot zones (CECPZs), a pivotal institutional vehicle for digital trade, as a quasi-natural experiment. Using Chinese city-level panel data, we systematically evaluate the impacts, transmission mechanisms, and moderating effects of digital trade on PCCM. Meanwhile, unlike the majority of the prior literature relying on traditional causal inference methods, such as difference-in-differences (DID), synthetic control method (SCM), or propensity score matching (PSM) [21,22], we employ the double machine learning (DML) framework developed by Chernozhukov et al. [23]. Traditional approaches typically depend on stringent assumptions or specifications: DID requires parallel trends and is vulnerable to functional misspecifications and multicollinearity [24]; SCM has limited applicability [25]; and PSM suffers from subjective covariate selection [26]. By contrast, DML integrates machine learning with orthogonalization to flexibly capture non-linear relationships and control for high-dimensional confounders, thereby mitigating estimation biases from model misspecification and redundant variables [27].

Compared with existing studies, this paper makes two primary contributions: First, we re-evaluate the environmental consequences of digital trade from the perspective of pollution reduction and carbon mitigation. By integrating both carbon emissions and pollutant discharges into a unified analytical framework, this study expands the research frontiers at the interdisciplinary intersection of digital trade and environmental economics. Second, this study establishes a tripartite theoretical framework encompassing the productive, public, and governmental dimensions. Through this lens, we delineate the transmission channels of digital trade's impact on PCCM, highlighting the critical roles of technological innovation, intelligent industrial transformation, and public participation. Furthermore, we delve into the moderating role of the external institutional environment, focusing on the dual facets of local government capacity and behavior. These efforts help systematically identify the critical leverage points of digital trade in facilitating PCCM, thereby providing novel empirical evidence on how to advance green and low-carbon development in the digital era.

The rest of the paper is structured as follows: Section 2 elaborates on the policy background and hypotheses. Section 3 introduces the methodology and data. Section 4 reports the baseline results, heterogeneity tests, underlying mechanisms, and moderating effects. Section 5 provides further analysis, and Section 6 concludes with policy implications.

2. Policy Background and Research Hypotheses

2.1. Policy Background

As a key mode of digital commerce, cross-border e-commerce faces entrenched structural and institutional challenges in its development. Recognizing its importance, China has introduced targeted support policies and established cross-Border e-commerce comprehensive pilot zones (CECPZs) to generate replicable and scalable practices for the healthy growth of the sector nationwide. In March 2015, the first CECPZ was established in Hangzhou. This was followed by six subsequent expansions: 12 cities in January 2016, 22 in July 2018, 24 in December 2019, 46 in April 2020, 27 in January 2022, and 33 in November 2022. By the end of 2022, there were 165 CECPZs across all 31 provinces. All pilot zones make use of local resource endowments to promote technological upgrading, industrial restructuring, and factor reallocation. Meanwhile, greening industrial and supply chains and delivering on peak-carbon and carbon-neutrality goals have become integral aspects of cross-border e-commerce development. These are all key driving forces for curbing emissions and carbon releases.

2.2. Theoretical Framework and Hypotheses

PCCM is a systematic endeavor deeply embedded in economic development, involving production, consumption, and institutional dimensions. By empowering traditional commerce with digital technologies, digital trade reshapes supply-side production and demand-side behaviors, thus exerting environmental impacts through multifaceted channels. Accordingly, by drawing on theories of endogenous growth, knowledge spillover, industrial upgrading, and public environmental governance, this study constructs a unified, three-dimensional "production–public–government" framework to systematically examine the transmission mechanisms and external moderators through which digital trade facilitates pollution and carbon reduction.

Within this framework, producers serve as the drivers and implementers of mitigation efforts; members of the public act as social participants and monitors; and the government functions as the planner and regulator of the external institutional environment. Specifically, by enabling cross-domain flow and data sharing, digital trade eliminates supply–demand information asymmetry, triggering a "technological empowerment–industrial transformation–societal reshaping" chain reaction. This indirectly drives PCCM through technological innovation, intelligent industrial transformation, and public participation. Meanwhile, as an external regulator, the government constructs an institutional triangle of strategic guidance (focusing on new quality productive forces), infrastructure support (digital government), and institutional constraints (environmental regulation), thereby moderating the direction and intensity of PCCM effects. This integrated framework establishes a unified theoretical foundation for subsequent analysis, paving the way for the systematic formulation of testable hypotheses (Figure 1).

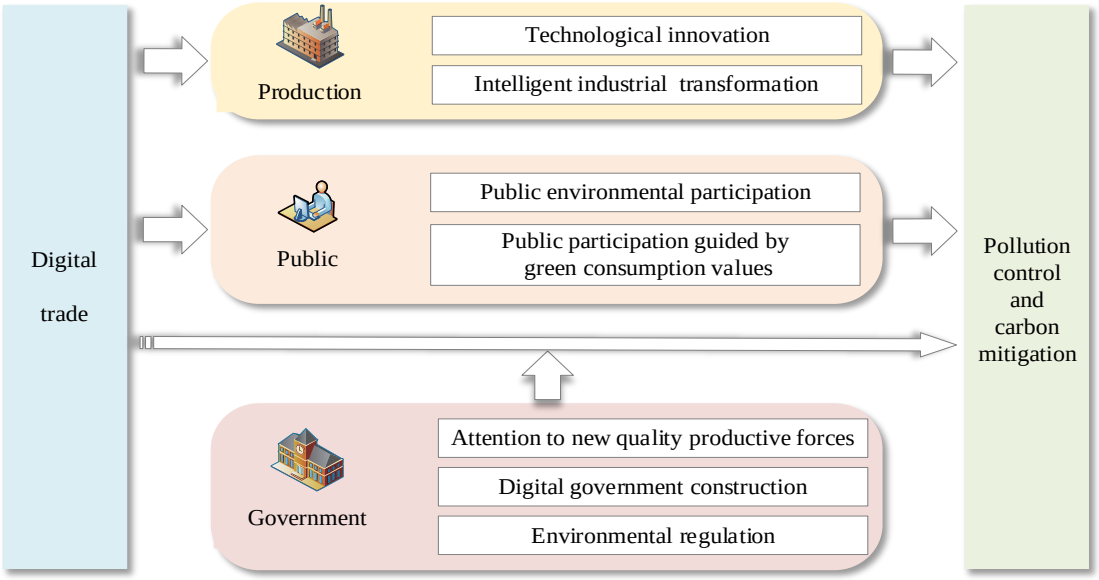


Figure 1. Theoretical framework.

2.2.1. Production Dimension

Digital trade injects new vitality into technological innovation, a critical force for resolving the pollution and carbon dilemmas. Under endogenous growth theory, technological progress, knowledge accumulation, and human capital drive productivity and sustainable development. By harnessing digital platforms, data factors, and cross-border networks, digital trade overcomes geographical and informational barriers, promoting the agglomeration of innovation inputs and knowledge diffusion, which ultimately elevates the innovative capacity of both enterprises and regions [22]. Furthermore, knowledge spillover theory posits that open and networked economic activities facilitate the dissemination of technological knowledge, managerial expertise, and market information among diverse agents. Digital trade development, epitomized by CECPZs, has refined the innovation market system. By dismantling barriers to factor mobility, it effectively aggregates innovative talents, advanced knowledge assets, and digital service inputs. This not only elevates regional innovation levels but also fosters a conducive environment for disruptive innovation, ultimately enabling enterprises to enhance productivity, energy efficiency, and pollution abatement capabilities [28].

Concurrently, digital trade induces green technological innovation by transmitting shifts in international market demand. The trajectory of corporate technological innovation is inherently shaped by variations in market demand, factor prices, and external constraints. Against the backdrop of advancing global climate governance, international markets impose increasingly stringent requirements on green product attributes and supply chain traceability. Leveraging advantages such as rapid information transmission, timely market feedback, and traceable transaction data, digital trade platforms, exemplified by cross-border e-commerce, can swiftly capture shifts in international green demand and low-carbon regulations, thereby transmitting these signals to upstream manufacturers. This incentivizes enterprises within the industrial ecosystem to accelerate innovation in energy-saving, cleaner production, and environmental governance technologies [29]. Such technological innovations reduce the pollution and carbon intensity of production by improving energy efficiency, replacing traditional high-emission processes with low-pollution alternatives, and enhancing pollutant treatment and resource recycling capabilities.

Furthermore, the expansion of digital trade accelerates the innovation and adoption of digital technologies. Within CECPZs, the digitalization of industrial parks, augmented by

the continuous upgrading and pervasive diffusion of technologies such as blockchain, the Internet of Things (IoT), and big data, enables enterprises to dynamically monitor real-time energy consumption and pollutant emissions during the production phase. Consequently, firms can precisely identify energy-saving opportunities and optimize production workflows, logistics routes, and inventory management, thereby driving a green, intensive, and highly efficient corporate transformation [30]. Therefore, by promoting general technological innovation, green technological innovation, and digital technology adoption, digital trade translates these innovative advantages into improved energy efficiency, cleaner production substitution, and enhanced environmental governance capabilities, ultimately curbing environmental pollution and carbon emissions. Thus, we formulate Hypothesis 1.

Hypothesis 1. *Digital trade enhances PCCM by promoting technological innovation.*

As a major milestone in digital trade, CECPZs foster digital supply chains and industrial ecosystems, significantly accelerating intelligent industrial transformation [31]. Under industrial upgrading theory, structural change entails not just rebalancing industry shares but also reshaping production methods, factor allocation, and value creation. As industries shift from high-energy, low-value activities to smart, high-tech, and high-value-added sectors, economic growth gradually decouples from energy use and emissions, triggering a structural abatement effect.

On the one hand, emerging digital trade formats, epitomized by cross-border e-commerce, digitize physical goods, services, and transaction workflows. This digitalization drives the proliferation of novel paradigms, including digital consumption, online services, smart terminals, and the platform economy. This not only expands the market demand for digital products and services but also further catalyzes the growth of advanced intelligent industries, especially those related to electronic equipment manufacturing, software and information technology services, and digital content services [4]. Compared with traditional resource- and energy-intensive industries, digital technology-intensive industries are typically characterized by high knowledge intensity, high added value, and lower energy consumption and emissions per unit of output. As their share in the regional economy increases, the industrial structure gradually becomes smarter, more service-oriented, and more sustainable. This helps reduce regional pollutant and carbon emission levels by lowering the aggregate energy and emission intensities.

On the other hand, digital trade drives the smart upgrading of traditional industries. Traditional trade relies heavily on factor inputs, capital expansion, and offline distribution, which often locks high-energy, high-emission, and low-efficiency firms into path dependency. Conversely, digital trade models like cross-border e-commerce utilize cloud computing, artificial intelligence (AI), big data, and the IoT to support the digital and intelligent upgrading of traditional trade and production. This accelerates the deep integration of smart tech with traditional manufacturing, logistics, and supply chain services. By collaboratively upgrading R&D, manufacturing, logistics, and marketing with smart technologies, traditional firms can streamline production processes and resource allocation, minimizing idle production and energy waste while boosting productivity and energy efficiency. Moreover, intelligent systems allow for real-time monitoring and optimized scheduling of energy use and emissions during production, offering manufacturing units a new technological pathway to meet emission abatement targets [32].

Therefore, digital trade not only upgrades industrial structures by fostering low-energy, high-value-added smart sectors but also boosts energy efficiency and environmental control by digitally enabling traditional industries. This intelligent industrial transformation further lowers regional emission intensity and carbon levels by promoting the greening

of industrial structures and improving production efficiency. Hence, we put forward Hypothesis 2.

Hypothesis 2. *Digital trade enhances PCCM by promoting intelligent industrial transformation.*

2.2.2. Public Dimension

As both consumers and vital actors in environmental governance, the public plays a dual role. Digital consumption modes stemming from digital trade can boost public environmental participation, emerging as a critical path toward pollution and carbon abatement. Under the theory of public participation in environmental governance, improving public environmental awareness, responsibility, and engagement channels strengthens social oversight of both corporate emissions and government environmental performance.

First, digital trade expands public channels for environmental participation. The rise of digital trade models like cross-border e-commerce promotes online transactions and information service platforms alongside digital technologies while driving the proliferation of digital communication tools, including social media, online forums, and consumer feedback systems. By lowering the cost of accessing and sharing environmental information, these platforms accelerate the spread of corporate environmental actions, green product attributes, and low-carbon concepts, ultimately boosting public awareness of and willingness to participate in addressing pollution, carbon emissions, and green production issues [33]. On this basis, the public translates its engagement into external pressure on corporate behaviors and state environmental governance by monitoring information disclosure, signaling green preferences, and generating negative feedback on high-pollution and high-carbon products. Such participation acts as an "invisible environmental regulation" mechanism, driving firms to safeguard their green reputation, refine manufacturing processes, and curtail emissions, thereby contributing to a co-governance framework involving diverse stakeholders [34].

Second, digital trade deepens and empowers public environmental participation by fostering green consumption concepts. This concept extends beyond purchasing green products; it encompasses environmental responsibility, green value judgments, and attention to corporate environmental behavior shaped during the consumption process. Through digital technologies and e-commerce platforms, digital trade improves the availability and transparency of information on product environmental profiles and corporate green reputations, thereby accelerating the internalization of green consumption values [35]. Under the impetus of green consumption values, the public scrutinizes whether manufacturing processes are environmentally friendly and whether firms discharge their environmental duties, while actively signaling their environmental preferences through social sharing and feedback [36]. This consumption-driven participation sends green demand signals and reputational pressures to firms, forcing them to refine production processes, improve environmental disclosure, and minimize high-pollution inputs, which ultimately facilitates emission reduction and decarbonization.

Serving as innovative hubs for digital trade, CECPZs enhance information transparency, thereby empowering the public to access green information, express environmental preferences, and exercise environmental oversight. Therefore, digital trade can foster pollution abatement and carbon reduction by bolstering public environmental participation, which activates demand-side signaling and social oversight. Accordingly, we formulate Hypothesis 3.

Hypothesis 3. *Digital trade enhances PCCM by promoting public participation.*

2.2.3. Government Dimension

The policy effectiveness of CECPZs is shaped not only by the policy design itself but also by the external institutional context. As a major policy platform for digital trade, these pilot zones exert pollution-reducing and carbon-abating effects that are moderated by local government actions and governance capacity.

First, government attention to new quality productive forces helps reinforce the PCCM effect of CECPZs. In essence, new quality productive forces represent an advanced form of productivity that is led by innovation, supported by digital technologies, driven by data elements as key inputs, and anchored in the integration of the digital and real economies [37,38]. During the development of digital trade, data elements can facilitate information flow, optimize resource allocation, and ultimately elevate total factor productivity. On the one hand, governmental focus on new quality productive forces accelerates digital infrastructure construction, data factor mobility, and digital technology integration, collectively lowering cross-border transaction, settlement, logistics, and communication costs and ultimately boosting the operational efficiency of CECPZs. On the other hand, characterized by its orientation toward scientific innovation and green, low-carbon transformation, new quality productive forces can curb the negative environmental externalities of economic activities through green R&D, production process optimization, and enhanced energy utilization efficiency [39]. Consequently, a greater emphasis on new quality productive forces by local governments is highly conducive to unlocking the green development potential of digital trade, which reinforces the PCCM effect.

Second, digital government construction can bolster the PCCM effect of CECPZs. In the context of the digital economy, government digitalization serves as a crucial pathway to enhance governance capacity and optimize institutional supply [29]. On the one hand, the deep integration of government administration and digital technology can streamline administrative approval processes, enhance the efficiency of public services, and lower institutional transaction costs between enterprises and the government, thereby providing more efficient institutional support for the development of new trade formats. On the other hand, digital government construction can improve policy transparency and regulatory precision, helping enterprises better comprehend policy orientations and mitigating innovation uncertainty. Meanwhile, government digital transformation also helps drive urban governance toward intelligent, green, and digitalized paradigms, facilitating enterprises to undertake green transformations across their supply chain, logistics, production, and management processes [40]. Therefore, the higher the level of government digitalization, the more conducive it is to improving the policy implementation efficiency of CECPZs, thereby reinforcing the PCCM effect.

Third, the intensity of environmental regulation may weaken the PCCM effect of CECPZs. Environmental quality is closely linked to local government environmental regulations. Generally speaking, stringent environmental regulations impose tighter pollution emission constraints on firms, prompting them to reduce both pollutant and carbon emissions. However, for CECPZs, excessively stringent environmental regulations may also induce a "cost crowding-out effect". Particularly in the short term, rigorous emission standards and environmental oversight increase firms' environmental investments, equipment retrofits, and compliance costs, thereby squeezing profit margins and eroding their product price advantages [41]. While digital trade inherently possesses the potential to reduce transaction costs, optimize resource allocation efficiency, and foster the green transition, the incremental costs arising from high environmental compliance pressures may offset the efficiency advantages brought by digital trade, crowd out R&D investment, and ultimately impair green innovation efficiency. As a result, an excessively high intensity

of environmental regulation may weaken the PCCM effect. Consequently, we propose Hypothesis 4.

Hypothesis 4. *Government emphasis on new quality productive forces and digital government construction positively moderates the impact of digital trade on PCCM, while environmental regulation imposes a negative moderating effect.*

3. Research Design

3.1. Model Description

Guided by the theoretical analysis above, this paper utilizes the CECPZ policy as a quasi-natural experiment to empirically evaluate the effect of digital trade on PCCM. In the realm of causal inference, traditional econometric models are widely adopted for policy evaluation. Nevertheless, in empirical applications, these conventional approaches are often constrained by rigid assumptions and remain vulnerable to sample selection bias, non-fulfillment of the parallel trend assumption, and misspecification issues. To circumvent these challenges, DML integrates regression with machine learning, automatically selecting high-dimensional variables to enhance causal identification [23]. Consequently, DML has emerged as a popular tool for evaluating economic causal relationships.

DML is highly suited for this study, offering unique advantages in handling high-dimensional controls, capturing non-linear relationships, and enhancing estimation robustness. On the one hand, as PCCM is influenced by diverse factors like social development and industrial restructuring, potential confounders must be strictly controlled. By employing machine learning and regularization algorithms, DML extracts key information to construct highly predictive control variables, thereby avoiding the "curse of dimensionality" and multicollinearity inherent in traditional models [27]. On the other hand, traditional parametric regressions require pre-specified functional forms [24], thereby overlooking potentially complex, non-linear relationships between the CECPZ policy and PCCM. By contrast, DML, as a non-parametric approach, bypasses the need for pre-defined functional relations. This effectively eliminates model misspecification bias, yielding a more precise evaluation of the CECPZ policy's impact on PCCM.

Therefore, we employ the DML framework to investigate the impact of the CECPZ policy on PCCM, specifying the partially linear DML model as follows:

$$Y_{it} = \theta_0 CECPZ_{it} + g(X_{it}) + U_{it} \tag{1}$$

$$E(U_{it}|CECPZ_{it}, X_{it}) = 0 \tag{2}$$

where Y_{it} represents the explained variable of city i in year t; $CECPZ_{it}$ denotes the policy dummy variable of city i in year t; X_{it} denotes a collection of high-dimensional control factors, with their specific form needing to be modeled using machine learning algorithms; U_{it} is the error term, with a conditional mean of 0; and θ_0 denotes the corresponding regression coefficient.

3.2. Variable Selection

3.2.1. Explained Variables

We employ two indicators, namely industrial SO_2 emissions and CO_2 emissions, as the explained variables to reflect the extent of pollution control and carbon mitigation (PCCM). The specific reasons for selecting the indicators and the corresponding measurement methods are as follows: (1) Given that SO_2 represents traditional industrial pollution, shapes perceived quality, and constitutes a crucial government control target, industrial SO_2 emissions (lnpse), adjusted on a population basis, are logarithmically transformed and

used to capture industrial pollution levels [42]. (2) Following Li et al. [4], carbon discharges are captured by the logarithm of per capita CO_2 emissions (lnpce). These two indicators are negatively oriented, with lower values denoting superior PCCM performance.

3.2.2. Main Explanatory Variable

The core explanatory variable is the policy dummy variable representing the establishment of CECPZs. If city *i* is designated as a CECPZ in year t or later, $CECPZ_{it}$ is set to 1; otherwise, it is set to 0. If a pilot zone is established toward the end of a year, we define the policy implementation year as the following year. Since this study covers 2011–2023, cities included in the first six batches of pilot zones can be selected as the treatment group, while all remaining cities constitute the control group.

3.2.3. Control Variables

To account for other factors that may influence PCCM, a set of control variables is introduced following Hu [43] and Xu et al. [44]. Industrial structure (IS) is determined by the share of the secondary industry in the regional GDP. The financial environment (FE) is captured by the balance of deposits and loans of financial institutions to the regional GDP. Internet penetration (NET) is calculated by the count of Internet users per 100 people. Human capital (HC) is measured by the number of higher education students per 100 people. Resource endowment (RE) is measured by the population employed in the mining industry relative to the population employed in urban units. Government intervention (GI) is measured by the ratio of local fiscal expenditure to regional GDP. Population density (lnPD) is measured as the logarithm of population per square kilometer. Opening up (lnFDI) is determined by the logarithm of total actual utilized foreign investment. The input of science and education (ISE) is proxied by the share of scientific research and educational spending within the local government's overall budget. Residential income (lnRI) is expressed as the natural logarithm of the average wage of on-the-job employees in urban units. Material capital accumulation (MCA) is captured by the fraction of fixed asset investment to regional GDP. Since the China City Statistical Yearbook ceased publishing fixed asset investment amounts after 2017, the data from 2018 to 2023 were calculated based on the fixed asset growth rates reported in provincial and municipal statistical yearbooks or statistical bulletins. Finally, transportation development (lnTD) is measured by the logarithmic value of highway passenger volume.

3.3. Data Sources

The empirical sample for this research comprises 280 prefecture-level cities in China, including 121 CECPZ cities. Given that China's digital economy, epitomized by the mobile Internet, took off around 2011, the sample spans 2011 to 2023. Data on $PM_{2.5}$ concentrations are sourced from the ChinaHighAirPollutants (CHAP) dataset [45], maintained by the National Tibetan Plateau/Third Pole Environment Data Center, http://data.tpdc.ac.cn (accessed on 15 October 2025). The carbon emissions data are derived from the Emissions Database for Global Atmospheric Research (EDGAR), while information for other variables was obtained from the China City Statistical Yearbook. Missing values were taken from regional yearbooks, bulletins, or linear interpolation, and continuous variables were winsorized at the 1% and 99% thresholds. Descriptive statistics for most variables are presented in Table 1.

Table 1. Descriptive statistics.

Variables	Description	Obs.	Mean	Std.	Min	Max
lnpse	Per capita SO_2 emissions	3640	−5.631	1.404	−8.988	−2.600
lnpce	Per capita CO_2 emissions	3640	1.853	0.872	−0.442	3.780
CECPZ	Cross-border e-commerce comprehensive pilot zones policy dummy variable	3640	0.146	0.354	0	1
IS	Industrial structure	3640	0.444	0.108	0.162	0.707
FE	Financial environment	3640	2.639	1.220	1.037	7.094
NET	Internet penetration	3640	27.935	19.288	3.754	99.257
HC	Human capital	3640	2.064	2.517	0.103	12.151
RE	Resource endowment	3640	0.046	0.081	0	0.390
GI	Government intervention	3640	0.201	0.094	0.079	0.567
lnPD	Population density	3640	5.755	0.902	2.907	7.452
lnFDI	Opening up	3640	11.805	2.015	6.113	15.907
ISE	Input of science and education	3640	0.194	0.042	0.095	0.294
lnRI	Resident income	3640	11.038	0.379	10.206	11.880
MCA	Material capital accumulation	3640	0.822	0.318	0.206	1.880
lnTD	Transportation development	3640	7.879	1.325	4.094	11.041

4. Examination of Empirical Results

4.1. Benchmark Regression

This study employs DML to estimate the impact of digital trade on PCCM. We divide the sample in a 1:4 ratio and employ the lassocv algorithm for prediction. This ratio is widely used in DML to reduce overfitting and enhance evaluation accuracy. The lassocv algorithm also ensures relatively strong interpretability. Table 2 reports the findings. Models (1) and (2) tested the results of adjusting for temporal and city fixed effects and introducing control variables. The regression coefficients of CECPZs on lnpse and lnpce are all negative at the 1% significance level; that is, digital trade has an inhibitory effect on the city's SO_2 and CO_2, thereby contributing to effective PCCM. Models (3) and (4) further introduce squared values for the control variables, with the regression coefficients remaining notably negative, confirming that digital trade substantially promotes PCCM.

Table 2. Benchmark regression results.

Variables	(1)	(2)	(3)	(4)
	lnpse	lnpce	lnpse	lnpce
CECPZ	−0.178 ***	−0.054 ***	−0.147 ***	−0.035 ***
	(0.029)	(0.008)	(0.030)	(0.008)
Control	YES	YES	YES	YES
$Control^2$	NO	NO	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	3640	3640	3640	3640

Note: *** $p < 0.01$. Parentheses enclose robust standard errors.

4.2. Robustness

4.2.1. Endogeneity Issues

To lessen potential endogeneity due to unobserved variables and reverse impact, we apply a DID design and instrumental variable (IV) tests to verify the robustness of the results.

Based on the CECPZ policy, we introduce a staggered DID model as follows:

$$Y_{it} = \beta_0 + \beta_1 CECPZ_{it} + \lambda X_{it} + a_i + v_t + \varepsilon_{it} \quad (3)$$

where Y_{it}, X_{it}, and $CECPZ_{it}$ are defined as in the benchmark regression. City and temporal fixed effects are captured by a_i and v_t, and ε_{it} is the error term.

Columns (1) and (2) of Table 3 indicate that the staggered DID coefficients remain markedly negative, confirming the robustness of the baseline results. We further corroborate the validity of these findings by conducting parallel trends and placebo tests (See Supplementary Materials S1 and S2).

Table 3. Endogenous test.

Variables	Staggered DID		Internet Users × Post Office		Internet Users × Telephone Sets	
	(1)	(2)	(3)	(4)	(5)	(6)
	lnpse	lnpce	lnpse	lnpce	lnpse	lnpce
CECPZ	−0.168 ***	−0.041 ***	−0.546 ***	−0.154 **	−1.402 ***	−0.198 ***
	(0.029)	(0.009)	(0.179)	(0.063)	(0.299)	(0.077)
Control	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	3640	3640	3640	3640	3640	3640

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

Following Chernozhukov et al. [23], we specify a partial linear IV model within the DML framework.

$$Y_{it} = \theta_0 CECPZ_{it} + g(X_{it}) + U_{it} \quad (4)$$

$$Instrument_{it} = m(X_{it}) + V_{it} \quad (5)$$

where $Instrument_{it}$ denotes the instrumental variable of $CECPZ_{it}$.

We use 1984 per capita post offices and fixed-line telephones as baseline instrumental variables. To obtain panel IVs, we interact these 1984 levels with the lagged number of national Internet users, generating two time-varying instruments [17,18]. Columns (3) to (6) of Table 3 reveal the IV estimates. The coefficients remain negative and significant, affirming that the baseline findings are robust to potential endogeneity.

4.2.2. Substituting the Explained Variables

To assess variable-specific measurement sensitivity, we re-estimate the models with alternative indicators. First, the logarithms of annual average $PM_{2.5}$ concentration (lnpm) and industrial NOx emissions (lnNO) are used as alternative indicators of pollutant emissions. Second, the logarithm of CO_2 emissions (lnce) is used as an alternative indicator for carbon emissions. Columns (1) to (3) of Table 4 reveal that CECPZ maintains a statistically significant mitigating effect on both pollution and carbon emissions, thereby strengthening the robustness of the main outcomes.

Table 4. Robustness test.

Variables	Replace the Explained Variables			Other Policy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	lnpm	lnNO	lnce	lnpse	lnpce	lnpse	lnpce
CECPZ	−0.025 ***	−0.103 ***	−0.017 **	−0.118 ***	−0.027 ***	−0.153 ***	−0.034 ***
	(0.005)	(0.029)	(0.008)	(0.031)	(0.008)	(0.030)	(0.008)
PFTZ				YES	YES		
LCCP						YES	YES
Control	YES	YES	YES	YES	YES	YES	YES

Table 4. *Cont.*

Variables	Replace the Explained Variables			Other Policy			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	lnpm	lnNO	lnce	lnpse	lnpce	lnpse	lnpce
Control[2]	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
N	3640	3640	3640	3640	3640	3640	3640

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

4.2.3. Assessing Other Policy Impacts

During the establishment of CECPZs, other policies can also influence PCCM, such as the pilot free trade zone (PFTZ) program and the low-carbon city pilot (LCCP) policy. Therefore, we added dummy variables for these policies to the benchmark model. The outcomes, presented in columns (4) to (7) of Table 4, show that the PCCM effect of digital trade remained significant.

4.2.4. Additional Robustness Checks

To further examine the reliability of our benchmark estimates, we perform a series of supplementary robustness tests. Specifically, the model is re-estimated using alternative specifications, modified samples, and repeated sampling procedures, with all results affirming the stability of the baseline findings (see Supplementary Materials S3–S5).

4.3. Heterogeneity Assessment

4.3.1. City Size

China's large and medium-sized cities differ considerably in terms of economic development, industrial composition, and digitalization, resulting in uneven progress in pollution and carbon abatement. Accordingly, following the 2014 standards adjustment notice for Urban Size Classification, the sample is divided into large and medium-small cities using a permanent-resident population threshold of one million, and separate regressions are conducted. As shown in Table 5, CECPZ yields significantly negative coefficients on lnpse and lnpce in large cities, while the corresponding coefficients for small and medium-sized cities are statistically insignificant. This pattern indicates that the PCCM benefits of digital trade are more salient in large cities. The underlying rationale lies in the preconditions for CECPZ implementation. Large cities generally feature well-established economic foundations, superior infrastructure, and complete modern industrial systems, creating an enabling environment for the diffusion of digital technologies and the digital upgrading of traditional industries, which amplifies PCCM. However, small and medium-sized cities suffer from resource scarcity, weak technological innovation, and deficient information and logistics infrastructure, thereby limiting the scope for digital trade to deliver PCCM outcomes.

Table 5. Heterogeneity of city size.

Variables	Large Cities		Small and Medium-Sized Cities	
	(1)	(2)	(3)	(4)
	lnpse	lnpce	lnpse	lnpce
CECPZ	−0.131 ***	−0.034 ***	−0.061	0.048
	(0.034)	(0.009)	(0.078)	(0.035)
Control	YES	YES	YES	YES

Table 5. *Cont.*

Variables	Large Cities		Small and Medium-Sized Cities	
	(1)	(2)	(3)	(4)
	lnpse	lnpce	lnpse	lnpce
Control^2	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	2262	2262	1378	1378

Note: *** $p < 0.01$. Parentheses enclose robust standard errors.

4.3.2. Initial Industrial Base

Industrial path dependence rooted in the initial industrial base generates heterogeneous pollution and carbon abatement performance across regions. In line with the National Plan for the Adjustment and Renovation of Old Industrial Bases (2013–2022), we accordingly divide the sample into old industrial base cities and other cities. The results in Table 6 reveal that the estimated coefficients of CECPZ on lnpse and lnpce are all significantly negative in non-old industrial base cities. By contrast, in old industrial base cities, the coefficients on lnpse and lnpce fail to pass the significance test. This indicates that digital trade is more conducive to leveraging PCCM advantages in non-old industrial base cities. The underlying rationale is as follows. Old industrial base cities exhibit a higher share of traditional industries that are energy-intensive and emission-intensive, locking regions into path dependence and thereby inhibiting digital trade development and the associated PCCM effect. By contrast, non-old industrial base cities feature higher economic development levels, more mature market institutions, and elevated public environmental aspirations. These attributes incentivize local governments to prioritize environmental governance and accelerate industrial upgrading, thereby amplifying the PCCM efficacy of digital trade.

Table 6. Heterogeneity of the initial industrial base.

Variables	Old Industrial Base		Non-Old Industrial Base	
	(1)	(2)	(3)	(4)
	lnpse	lnpce	lnpse	lnpce
CECPZ	0.043	−0.001	−0.220 ***	−0.047 ***
	(0.053)	(0.015)	(0.037)	(0.010)
Control	YES	YES	YES	YES
Control^2	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	1209	1209	2431	2431

Note: *** $p < 0.01$. Parentheses enclose robust standard errors.

4.3.3. Resource Dependence

Cities with differing degrees of resource dependence follow distinct development patterns, leading to heterogeneous effects of digital trade on PCCM. In accordance with the National Sustainable Development Plan for Resource-Based Cities (2013–2020), we classify the sample into resource-based and non-resource-based cities for separate regressions. Table 7 shows that, in resource-based cities, CECPZ significantly reduces lnpse but has no statistically significant effect on lnpce (Columns 1–2). By contrast, the estimated coefficients of CECPZ are significantly negative for both lnpse and lnpce in non-resource-based cities (Columns 3–4). This disparity stems from structural endowments. Resource-based cities re-

main locked in mineral and resource path dependence, leaving them short of digital capital and plagued by fragmented chains. The resulting "resource curse" suppresses innovation and reduces digital trade's capacity to promote PCCM. Conversely, non-resource-based cities are characterized by lower resource dependence, more balanced industrial composition, and diversified economic foundations, providing a more fertile environment for digital trade to achieve effective PCCM.

Table 7. Heterogeneity of resource dependence.

Variables	Resource-Based Cities		Non-Resource-Based Cities	
	(1)	(2)	(3)	(4)
	lnpse	lnpce	lnpse	lnpce
CECPZ	−0.108 **	−0.007	−0.143 ***	−0.044 ***
	(0.054)	(0.016)	(0.038)	(0.010)
Control	YES	YES	YES	YES
Control^2	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	1495	1495	2145	2145

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

4.4. Mechanism Analysis and Moderating Effects

4.4.1. Mechanism Analysis from the Production Dimension

For the mechanism of technological innovation, we use patent records sourced from the China Research Data Services Platform (CNRDS) and classify them into three categories: overall, green, and digital innovation. Compared with granted patents, application data avoids bias arising from time lags. Therefore, we adopt invention patent applications per 10,000 residents, disaggregated into overall, green, and digital domains (A_patent, G_patent, and D_patent, respectively), as corresponding innovation proxies [28,46]. As reported in Table 8, the estimated coefficients of CECPZ for A_patent, G_patent, and D_patent are all significantly positive. Meanwhile, the estimated coefficients of A_patent, G_patent, and D_patent for lnpse and lnpce are all significantly negative, indicating that digital trade fosters PCCM through enhancing technological innovation. Hypothesis 1 is verified.

Table 8. Mechanism analysis: technological innovation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	A_patent	lnpse	lnpce	G_patent	lnpse	lnpce	D_patent	lnpse	lnpce
CECPZ	2.974 ***	−0.113 ***	−0.032 ***	0.416 ***	−0.097 ***	−0.029 ***	1.638 ***	−0.103 ***	−0.030 ***
	(0.485)	(0.029)	(0.008)	(0.055)	(0.029)	(0.008)	(0.251)	(0.029)	(0.008)
A_patent		−0.011 ***	−0.001 **						
		(0.002)	(0.000)						
G_patent					−0.118 ***	−0.015 ***			
					(0.013)	(0.003)			
D_patent								−0.027 ***	−0.003 ***
								(0.003)	(0.001)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
Control^2	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3640	3640	3640	3640	3640	3640	3640	3640	3640

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

To capture intelligent industrial transformation, we employ the share of AI enterprises among new registrations (smart) and industrial robot installations (robot) as proxies [47,48]. AI enterprises are identified by screening enterprise business scope descriptions for keywords associated with artificial intelligence technologies, including chips, image recognition, computer vision, voice recognition, and sensors. Newly registered enterprises are distinguished by their incorporation dates. Industrial robot installation data are obtained from the International Federation of Robotics (IFR). As shown in Table 9, the estimated coefficients of CECPZs for smart and robot are both significantly positive. Moreover, the estimated coefficients of smart and robot for lnpse and lnpce are significantly negative, implying that digital trade facilitates PCCM through the intelligent transformation of industries. Hypothesis 2 is verified.

Table 9. Mechanism analysis: intelligent industrial transformation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Smart	**lnpse**	**lnpce**	**Robot**	**lnpse**	**lnpce**
CECPZ	0.006 ***	−0.712 ***	−0.030 ***	1.735 ***	−0.591 ***	−0.081 **
	(0.001)	(0.060)	(0.008)	(0.184)	(0.058)	(0.039)
smart		−8.456 ***	−0.730 ***			
		(0.858)	(0.160)			
robot					−0.095 ***	−0.012 ***
					(0.006)	(0.003)
Control	YES	YES	YES	YES	YES	YES
Control^2	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	3640	3640	3640	3607	3607	3607

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

4.4.2. Mechanism Analysis from the Public Dimension

As the dominant search platform in China, Baidu provides broad user coverage and highly accessible data. By counting keyword search intensity and geographic distribution, we can analyze the level of public participation and its regional trends for specific issues. Accordingly, the Baidu Search Index enables an effective evaluation of public participation in environmental issues [33,34]. First, we use the keyword "haze" to capture public environmental participation and then aggregate the corresponding city-level Baidu Search Indices (lnindex1). Second, following the China Consumers Association's definition of green consumption, we select "green travel", "green food", "garbage classification", and "environmental protection" as core keywords and append "haze" to the list. An equally weighted composite index, lnindex2, is then constructed to measure public participation guided by the green consumption values. The results in Table 10 show that the estimated coefficients of CECPZs for lnindex1 and lnindex2 are both significantly positive and that the estimated coefficients of lnindex1 and lnindex2 for lnpse and lnpce are all significantly negative, implying that digital trade enhances PCCM through promoting public participation. Hypothesis 3 is verified.

Table 10. Mechanism analysis: public participation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	lnindex1	**lnpse**	**lnpce**	**lnindex2**	**lnpse**	**lnpce**
CECPZ	0.100 ***	−0.869 ***	−0.033 ***	0.078 ***	−0.131 ***	−0.032 ***
	(0.018)	(0.058)	(0.008)	(0.013)	(0.029)	(0.008)
lnindex1		−0.049 ***	−0.016 **			
		(0.019)	(0.008)			

Table 10. *Cont.*

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	lnindex1	lnpse	lnpce	lnindex2	lnpse	lnpce
lnindex2					−0.195 ***	−0.034 ***
					(0.044)	(0.012)
Control	YES	YES	YES	YES	YES	YES
Control^2	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	3640	3640	3640	3640	3640	3640

Note: *** $p < 0.01$ and ** $p < 0.05$. Parentheses enclose robust standard errors.

4.4.3. Moderating Effect Analysis from the Government Dimension

Following the theoretical discussion, three government-side moderating variables are constructed. (1) Government attention to new quality productive forces (GAN) is gauged by the share of relevant terms in each city's government work report; a higher share signifies greater attention, reflecting governmental priorities [49]. (2) Digital government construction (DGC) is proxied by a dummy variable equal to 1 for cities covered by the 2014 National Pilot Policy of Information Benefiting the People and 0 otherwise. This policy represents a key Chinese initiative to modernize governance by expanding information and communication technology (ICT) deployment and thereby accelerating digital government construction [50]. (3) Environmental regulation (ER) is proxied by the share of environmental-protection-related keywords appearing in each city's government performance report; this programmatic document provides a panoramic view of the government's regulatory efforts [51]. The results reported in Table 11 indicate that the interaction terms of CECPZ with GAN and DGC have significantly negative coefficients for both lnpse and lnpce. By contrast, the interaction term between CECPZ and ER exhibits significantly positive coefficients for both outcome variables. This finding implies that enhanced government attention to new quality productive forces and improved digital government construction reinforce the PCCM effect of digital trade, while a higher intensity of environmental regulation tends to attenuate this effect. Hypothesis 4 is verified.

Table 11. Regression results for the moderating effect.

Variables	Government Attention to New Quality Productive Forces		Digital Government Construction		Environmental Regulation	
	(1)	(2)	(3)	(4)	(5)	(6)
	lnpse	lnpce	lnpse	lnpce	lnpse	lnpce
CECPZ × GAN	−0.279 ***	−0.051 **				
	(0.096)	(0.024)				
CECPZ × DGC			−0.412 ***	−0.050 ***		
			(0.052)	(0.012)		
CECPZ × ER					0.115 *	0.035 **
					(0.061)	(0.015)
Control	YES	YES	YES	YES	YES	YES
Control^2	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	3602	3602	3640	3640	3623	3623

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. Parentheses enclose robust standard errors.

5. Further Analysis

As previously demonstrated, the expansion of digitally enabled trade, represented by the establishment of CECPZs, has a significant PCCM effect. Meanwhile, the simultaneous development of economic and environmental objectives remains a critical consideration in the digital era. Leveraging digital platforms, CECPZs provide a more convenient customs clearance and logistics environment. This can help enterprises reduce operating costs, enabling them to enter overseas markets and enhance their economic performance. Accordingly, digital trade development is expected to exert a positive driving effect on regional economic growth. This conjecture is corroborated in Supplementary Material S6, with affirmative results. Collectively, these findings suggest that digital trade generates triple dividends in terms of pollution control, carbon mitigation, and economic growth.

6. Conclusions and Policy Implications

6.1. Conclusions

Digital trade is emerging as a new trend in international trade development, offering a fresh perspective for researching how to achieve the goals of PCCM. This study incorporates production, public, and government dimensions into the analytical framework. Using the DML method and against the establishment of CECPZs, employing data from 280 prefecture-level cities in China from 2011 to 2023, it explores the underlying mechanisms and external moderators through which digital trade affects PCCM. The main outcomes are as follows: (1) Digital trade reduces industrial SO_2 and CO_2, thereby generating significant PCCM. (2) Mechanism analysis shows that on the production side, digital trade facilitates PCCM by advancing technological innovation, including both green and digital technology innovations, and by promoting intelligent industrial transformation. At the public level, digital trade facilitates PCCM through public environmental participation and public participation under the green consumption paradigm. From the governmental perspective, enhancing government attention to new quality productive forces and advancing digital government amplify the PCCM effect of digital trade, whereas intensifying environmental regulation attenuates this influence. (3) Heterogeneity tests indicate that the PCCM benefits of digital trade are particularly pronounced in large cities, non-old industrial base cities, and non-resource-based cities. (4) Further analysis demonstrates that digital trade can contribute to pollution reduction, carbon mitigation, and economic growth, thereby facilitating economic expansion and environmental improvement.

6.2. Policy Implications

These results carry notable policy implications for advancing economic and environmental sustainability through digital trade.

First, comprehensive policy packages should be enhanced to support digital trade development, with targeted guidance allocating technology, talent, and capital to the sector. Concurrently, digital technologies must be deployed to transform traditional trade models and organizational structures, while the expansion of emerging platforms such as cross-border e-commerce is actively encouraged.

Second, technological innovation, intelligent industrial transformation, and public participation constitute the three primary channels for advancing PCCM. On the production side, targeted policy incentives, including dedicated innovation funds, credit enhancement instruments, and fiscal subsidies, should be deployed to accelerate enterprises' adoption of digital and green technologies. Meanwhile, the government must optimize industrial structures and spatial layouts, upgrade traditional extensive sectors, and phase out outdated capacity through intelligent systems. On the consumer side, the government should prioritize public environmental satisfaction through transparent mobile information plat-

forms and digital visual education programs that promote green lifestyles and habitual green consumption.

Third, the government should prioritize emerging sectors such as electronic information, new materials, advanced manufacturing, and renewable energy, while systematically allocating high-quality productive factors. In parallel, it should advance digital government through the Internet plus public services paradigm to promote coordination between a productive market and a capable government. Moreover, the efficacy of government policy interventions such as environmental regulation does not increase monotonically with stringency. An evaluation mechanism for environmental policies should be established and refined in response to local realities and circumstances.

Fourth, complementary initiatives must be customized to local conditions, including city size, initial industrial base, and resource dependence. Large cities should strengthen their innovation ecosystem and disseminate proven models of digital trade, while small and medium-sized cities should enhance technology acquisition and collaboration, leveraging their comparative advantages. Old industrial base cities should prioritize intelligent management and green production to accelerate digital transformation and phase out, merge, or repurpose high-energy and high-emission facilities as needed. Resource-dependent cities should encourage green technology innovation and digital transformation in resource-intensive industries to break the "resource curse" and accelerate green transitions.

6.3. Limitations and Future Directions

Realizing that PCCM is a systematic and long-term endeavor, digital trade offers a key opportunity in this regard. Although this study presents a detailed analysis, several limitations remain. First, the CECPZ quasi-experiment captures only one policy dimension of digital trade; future research will construct multi-dimensional indicators and employ robust quantitative models to corroborate our findings. Second, city-level data constrain granular inference on industry structure and firm dynamics; future work should leverage industry- and enterprise-level datasets to extend our findings.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18136408/s1: S1. Parallel Trend Test. S2. Placebo Test. S3. Changing Model Settings. S4. Adjusting Sample. S5. Repeated Sampling. S6. Further Analysis: Procedure and Results. Figure S1: Outcomes of the parallel trend test; Figure S2: Outcomes of the placebo test; Table S1: Regression results under different DML settings; Table S2: Regression results with sample adjustment; Table S3: Regression results with repeated sampling; Table S4: Regression results of further analysis.

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Abbreviations

The abbreviations used in this manuscript are listed below.

PCCM	Pollution Control and Carbon Mitigation
CECPZs	Cross-border E-commerce Comprehensive Pilot Zones
DML	Double Machine Learning

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