

## Article

# Impact of the Coupling and Coordinated Development of National and Global Value Chains on Green Development: Evidence from China's Manufacturing Industry

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## Abstract

Against the backdrop of China's new development paradigm, this study examines how the coupling coordination between the national value chain (NVC) and the global value chain (GVC) affects regional green development and the mechanisms through which it does so. Focusing on China's manufacturing sector, we employ a coupling coordination model, a high-dimensional fixed effects estimator, two-stage least squares, and bootstrap mediation tests on pooled cross-sectional data covering 31 provincial-level administrative units. The results indicate that greater NVC–GVC coupling coordination exerts a significant and positive effect on green development. Three transmission mechanisms are identified. First, NVC participation, environmental protection investment, and industrial structure upgrading jointly promote green development through a resource allocation and scale effect channel (NVC-led channel). Second, GVC participation operates through a green knowledge spillover and learning paths channel, which on net suppresses green development. Third, GVC participation also operates through an environmental regulations and standards transmission channel, which on net suppresses green development. The aggregate effect is nonetheless positive. Across the 2012, 2015, and 2017 sample years, the resource allocation and scale effect mechanism mediated by NVC participation dominates the knowledge spillover and regulatory transmission mechanism mediated by GVC participation, yielding a significant net stimulus to regional green development.

**Keywords:** national value chain; global value chain; coupling coordination degree; manufacturing industry; green development; transmission mechanism



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## 1. Introduction

Against the backdrop of China's strategic transition to a new development paradigm, one that places a domestic grand circulation at the center and treats the domestic and international circulations as mutually reinforcing, understanding how this strategy interacts with green development is of fundamental importance for reconciling high-quality economic growth with effective environmental stewardship [1]. The smooth functioning of the national value chain (NVC) is the backbone of the domestic economy, while the ongoing restructuring of the global value chain (GVC) underpins the international economy [2]. Although a body of literature has examined the respective impacts of NVCs and GVCs on carbon dioxide emissions, as well as their complementary roles [3], the coupling and coordinating effects of NVCs and GVCs on green development have received far less

attention. Under the dual circulation strategy, domestic and global value chains do not operate in isolation; their synergies or tensions may exert complex influences on the green transition, yet few studies have approached this from a coupling coordination perspective. Moreover, existing work grounded in that perspective typically measures the coupling coordination between two systems without establishing causal identification or testing mechanisms—a gap that partly reflects the difficulty of finding suitable instrumental variables. Identifying valid instruments to achieve causal identification thus constitutes a pressing methodological frontier in this field.

A global value chain is a transnational production network in which multinational firms collaborate across borders with partners, suppliers, and customers, encompassing value-creating activities from design and R&D through production, marketing, and services [4,5]. A national value chain, by contrast, refers to value-creating processes contained within a specific country or region, with emphasis on optimizing the allocation of domestic resources [2,6]. Over the past 2 decades, Chinese manufacturing achieved rapid growth through deep integration into GVCs, while the building of a unified domestic market simultaneously strengthened the NVC. However, this dual embeddedness, though conducive to economic expansion, has also intensified resource consumption and environmental stress [7]. Two urgent questions follow: In what respects does NVC–GVC coupling coordination promote green development, and in what respects does it hinder it? What are the underlying mechanisms?

A useful analogy is the bench press. The NVC is the right arm, the GVC is the left, and their coupling coordination is the pectoralis major, which is responsible for synchronizing the direction and force applied by both arms. Just as an efficient bench press requires both arms working in concert with the pectoral muscles leading the movement, genuine progress in regional green development requires the NVC and GVC to form a productive synergy, with the NVC playing the leading role. Whether this synergistic mechanism holds empirically, and what its magnitude and transmission pathways are, must be established through rigorous causal identification and mechanism testing.

This study aims to analyze theoretically and test empirically the effects of NVC–GVC coupling coordination on regional green development in Chinese manufacturing, to provide appropriate instrumental variables for capturing the underlying causal relationships, and to offer a new perspective on how dual chain dynamics shape green development. Drawing on coupling coordination analysis and provincial pooled cross-sectional data for Chinese manufacturing, we examine how NVC–GVC coupling coordination affects regional green development. The paper makes three principal contributions. First, adopting a dual-chain “coupling coordination” rather than a single-chain lens, we provide a novel perspective and new empirical evidence on the green effects of the dual circulation strategy. Second, we supply two suitable instrumental variables and employ 2SLS to identify the causal effect of NVC–GVC coupling coordination on green development, addressing endogeneity and offering a methodological template for further research in this area. Third, we propose and empirically test three transmission mechanisms—Green Knowledge Spillover and Learning Paths, Environmental Regulations and Standards Transmission, and Resource Allocation and Scale Effect—thereby clarifying the pathways through which dual chain coupling coordination shapes regional green development.

The remainder of the paper proceeds as follows. Section 2 develops the theoretical framework and states the research hypotheses. Section 3 describes the empirical methods, data, variables, and the measurement of NVC–GVC coupling coordination. Section 4 presents and discusses the empirical results. Section 5 concludes and outlines directions for future research.

## 2. Theoretical Analysis and Hypotheses

### 2.1. Theoretical Analysis

#### 2.1.1. Global Value Chain

Global value chain theory identifies two main drivers of global commodity chains: producers and buyers [8]. Producer-driven GVCs are led by large multinational manufacturers that coordinate production networks, with profits mainly derived from scale expansion and technological upgrading in production [9]. In contrast, buyer-driven GVCs are governed by large retailers, marketers, and branded firms from developed countries that leverage branding and sales channels, with profits concentrated in high-value activities such as R&D, design, marketing, and financial services [9,10].

The GVC perspective views chain coordination as a key strategic resource for competitive advantage [9], implying that coordinated development of both GVCs and NVCs enhances competitiveness. In the context of globalization, NVCs are typically embedded in GVCs and rarely operate independently. This embedding occurs either through producer country integration or buyer country integration within global value chains. In China, participation in GVCs has accelerated industrialization and improved resource allocation [11], while engagement in both GVCs and NVCs has jointly promoted economic growth, reflecting their complementarity [2]. However, benefits from GVC participation are uneven, with smaller and less capable countries often disadvantaged [12]. Since value capture requires strong local capabilities [13,14], coordinated development of GVCs and NVCs is crucial, a condition China appears well positioned to sustain.

#### 2.1.2. Coupling Coordination

Coupling theory originated in physics and was first used to describe interactions between systems [15]. It was later introduced into economics to analyze relationships among different systems [16]. With the growing emphasis on sustainable development, coordination among economic growth, environmental protection, and social equity has become a key concern. This shift requires moving beyond simple correlation analysis to evaluate whether systems can develop harmoniously [17]. Accordingly, the coupling coordination theory emerged. It focuses on both the strength of interactions between systems (coupling) and the consistency of their development directions (coordination).

To analyze coupling coordination, scholars developed the coupling coordination degree model. This model measures the joint state of systems by combining the coupling degree and the coordination index [16]. The coupling degree reflects the strength of interaction between subsystems, while the coordination index indicates whether their development trends are aligned [18,19].

For example, when economic development and green development are highly coupled, they strongly influence each other. Faster economic growth is often associated with quicker environmental change. A higher coordination index suggests that economic development and environmental quality improve together. Importantly, this model does not identify causal relationships. Instead, it examines interaction and trend consistency between systems. Therefore, a high coupling coordination degree indicates both strong interaction and aligned development paths. The coupling coordination model has recently been applied to assess the degree of coordination between GVCs and NVCs in China [20]. This provides a new vantage point from which to examine how the interplay between China's global and national value chains shapes regional green development in manufacturing.

#### 2.1.3. Value Chains and Green Development

The concept of the "green economy" was introduced in 1989 [21], marking the emergence of green development. Over the past 3 decades, research in this field has advanced

substantially, generating key theoretical perspectives. These include the resource-based view [22], the sustainable development framework [17], and the triple bottom line theory [23]. All emphasize environmental protection, resource conservation, and sustainable economic growth. In manufacturing, green development refers to the adoption of efficient, low-carbon, and environmentally friendly production methods and technologies. The goal is to improve environmental performance while maintaining or enhancing firm competitiveness [24].

A growing body of recent work examines industrial green development through the lens of GVC–NVC interactions. Evidence from Brazilian firms indicates that GVC participation raises R&D spending and directly stimulates environmental innovation, while NVC participation also increases R&D expenditure but does not independently drive environmental innovation [25]. Other research shows that improving the business environment within China’s domestic value chain enhances resource allocation efficiency, particularly in downstream industries [26]. The most recent evidence suggests that higher NVC and GVC participation rates both accelerate manufacturing upgrading and reduce carbon emissions, with the two exhibiting complementarities in promoting upgrading but substitutability in reducing emissions [3]. Taken together, these findings imply that GVCs and NVCs support green development through distinct channels: GVCs primarily stimulate green innovation, while NVCs improve resource allocation.

#### 2.1.4. An Integrated Theoretical Framework

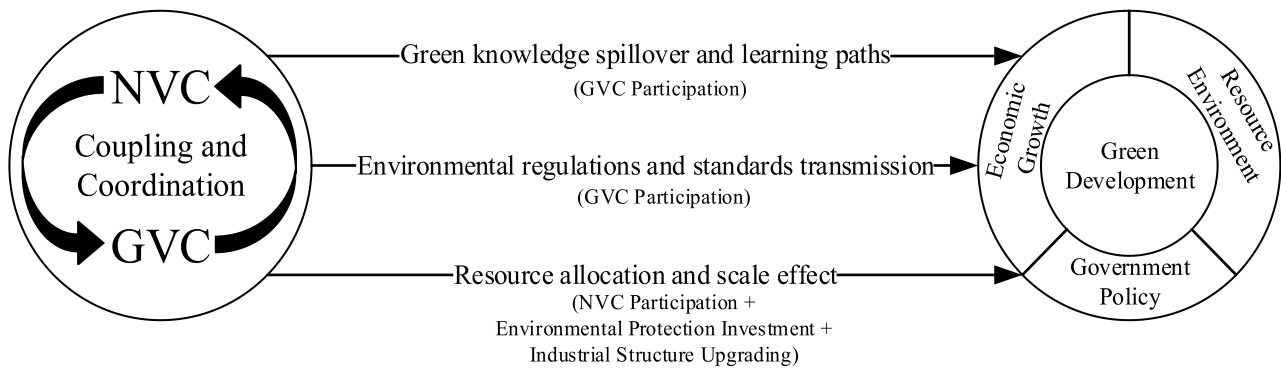
Drawing on the dual embeddedness perspective [2,8], we argue that the pathway to green upgrading for Chinese manufacturing firms runs through simultaneous embedding in both GVCs and NVCs. This dual embeddedness exposes firms to heterogeneous knowledge, resources, and institutional pressures. GVCs primarily transmit frontier green technologies, international environmental standards, and market-driven sustainability imperatives; NVCs principally shape local factor costs, domestic regulatory environments, and inter-regional resource allocation [27,28]. NVC–GVC coupling coordination, at its core, reflects the degree of synergy—or conflict—between the two sets of signals and resources generated by dual embeddedness. This synergy or conflict ultimately affects regional green development through three specific mechanisms: (1) green knowledge spillover and learning paths, (2) environmental regulations and standards transmission; and (3) resource allocation and scale effect. We employ four mediating variables to capture these mechanisms: GVC participation, NVC participation, environmental protection investment, and industrial structure upgrading.

Mechanism 1: Green knowledge spillover and learning path (GVC channel). GVCs are a critical conduit for advanced green technologies, cleaner production practices, and international environmental management know-how [28,29]. By participating in GVCs, multinationals facilitate the knowledge transfer and learning that are central to industrial upgrading [30,31]. When the NVC and GVC are tightly coupled and well coordination, domestic manufacturers can more effectively absorb green knowledge from international markets and diffuse it along domestic supply chains, generating spillover and learning effects. Firms may thus improve their environmental performance through interactions with global partners, a mechanism primarily captured by GVC participation. However, peripheral suppliers often face significant constraints in appropriating value from lead firms [32,33]. Confronted with the green knowledge shock from dominant GVC players, Chinese manufacturers find themselves at a disadvantage and may encounter resource competition, technological lock-in, or pollution-haven effects—all of which can offset positive spillovers and even reduce resource efficiency and environmental performance, thereby dampening green development.

Mechanism 2: Environmental regulation and standards transmission (GVC channel). Within GVCs, lead firms are key transmitters of standards and governance practices [28,34]. GVC participation introduces international environmental standards, green procurement requirements, and consumer preferences for sustainability into domestic markets [35,36]. Environmental regulations and standards transmission is therefore primarily captured by GVC participation. Provinces with deeper GVC integration are the first to encounter international environmental regulations and standards. International standards exert upward pressure on these provinces through GVC linkages, and this pressure subsequently diffuses across regions via the NVC. As the synergies between the NVC and GVC intensify, the dissemination of this external regulatory pressure proceeds more rapidly across China's regions. Nonetheless, the effect of upward pressure from international environmental regulations and standards on green development tends to follow an inverted U pattern. In the short run, more stringent environmental requirements impose costs on Chinese firms—necessitating the adoption of eco-friendly materials, advanced green production processes and equipment, and increased resource and energy consumption—and may force some firms to curtail or cease operations, thereby reducing environmental performance. Furthermore, local governments may respond with protective measures or lukewarm enforcement to safeguard employment and economic stability, further weakening the positive transmission effects. Environmental regulations and standards transmission thus exert a net dampening effect on green development.

Mechanism 3: Resource allocation and scale effects (NVC-led channel). Deeper NVC participation reshapes inter-regional factor flows, the division of labor, and resource allocation [2,37]. This mechanism resonates with the Global Production Networks 2.0 framework, which emphasizes how competitive dynamics shape firm strategies and regional outcomes [27]. Among the adjustments in resource reallocation, environmental investment reflects the deliberate channeling of financial resources toward pollution control and green technology adoption [22]. Resource reallocation and structural upgrading are expected to improve environmental performance and thereby foster green development, consistent with the concepts of “strategic coupling” and “value capture” [38]. When the NVC and GVC couple and coordinate effectively, resources are reallocated toward higher-productivity sectors, incentivizing firms and local governments to increase environmental investment. This process strengthens pollution control capacity and regulatory enforcement, generates scale economies, and drives industrial upgrading—raising the greenness of economic growth. At the same time, deeper NVC participation may in the short run intensify the demand for natural resources, exerting a negative crowding-out effect on environmental carrying capacity. This mechanism is captured by three mediating variables: NVC participation, environmental investment, and industrial structure upgrading. NVC participation reflects the depth of domestic value chain embeddedness; environmental investment captures the directed allocation of resources toward green development; and industrial structure upgrading represents the outcome of improved resource allocation. On balance, the resource allocation and scale effect driven by NVC participation should exert a positive influence on green development.

Figure 1 presents the conceptual framework of the paper, highlighting the effects of NVC–GVC coupling coordination on green development and mapping the three mechanisms onto the four mediating variables.



**Figure 1.** Conceptual framework.

## 2.2. Hypotheses

### 2.2.1. Direct Effect of Dual Chain Coupling Coordination on Green Development

A higher degree of NVC–GVC coupling coordination signifies that domestic and international production networks are converging in the intensity of their interaction and the coherence of their developmental trajectories, enabling two streams of heterogeneous resources and institutional signals to reinforce one another simultaneously across knowledge spillovers, regulatory transmission, and factor allocation, thereby exerting a systemic positive push on regional green development. Existing research indicates that simultaneous participation in NVC and GVC generates complementarity effects, jointly promoting manufacturing upgrading and carbon reduction [2,37]. Coupling coordination further integrates global green pressure with domestic transformation momentum; we therefore expect the co-directional impetus of the two chains on regional green development to be positive. This motivates the following hypothesis:

**H1.** *NVC–GVC coupling coordination exerts a significant and positive effect on regional green development.*

### 2.2.2. Indirect Effect via GVC Participation

As discussed in Mechanisms 1 and 2 of Section 2.1.4, GVC participation serves as the common mediating carrier for both the green knowledge spillover and learning path channel and the environmental regulations and standards transmission channel: rising coupling coordination creates conditions for domestic firms to access green technology and managerial expertise through GVCs, while the international environmental standards and green compliance pressures imposed by GVC lead firms are simultaneously transmitted downstream [28,34]. However, the net outcome of these two effects is not necessarily positive. Chinese manufacturing firms occupying peripheral GVC positions face technological lock-in and pollution-haven risks [32]. The short-run cost shock from international compliance requirements may force some firms to reduce or halt production, and protective local government policies further attenuate the positive transmission effects [35]. In the current period, the shock effect dominates the learning effect, so that GVC participation exerts a net negative influence on regional green development. This gives rise to the following hypothesis:

**H2.** *GVC participation mediates the effect of NVC–GVC coupling coordination on regional green development through a negative indirect channel.*

### 2.2.3. NVC-Led Indirect Effects

As elaborated in Mechanism 3 of Section 2.1.4, effective NVC–GVC coupling coordination redirects resources toward higher productivity sectors, generates scale economies, and simultaneously strengthens incentives for environmental investment and industrial structural adjustment by both firms and local governments [2,37]. This process is captured by three mediating variables, namely, NVC participation, environmental protection investment, and industrial structure upgrading, which collectively constitute the “resource allocation and scale effect” transmission chain.

Regarding NVC participation, deeper embeddedness in the domestic value chain fosters a finer division of labor and reduces production redundancy, with medium-to-long-run improvements in resource efficiency and environmental performance predominating [27]. Regarding environmental protection investment: the scale dividends released by coupling coordination will strengthen firms’ willingness to undertake a green transition and accelerate the diffusion of cleaner production technologies. Regarding industrial structure upgrading, the concentration of factors in higher value added, lower pollution industries structurally reduces energy intensity and improves carbon emission efficiency. These three pathways jointly underpin the positive contribution of the NVC-led channel to green development, motivating the following hypotheses:

**H3a.** *NVC participation positively mediates the effect of NVC–GVC coupling coordination on regional green development.*

**H3b.** *Environmental protection investment positively mediates the effect of NVC–GVC coupling coordination on regional green development.*

**H3c.** *Industrial structure upgrading positively mediates the effect of NVC–GVC coupling coordination on regional green development.*

Table 1 summarizes the hypotheses of the paper.

**Table 1.** Hypotheses summary (DV: green development).

| Hypotheses | Description                                                                                                    | Mechanism                       | Mediator         | Expected Sign |
|------------|----------------------------------------------------------------------------------------------------------------|---------------------------------|------------------|---------------|
| H1         | NVC–GVC coupling coordination positively affects regional green development                                    | Direct effect                   | NVC–GVC          | +             |
| H2         | GVC participation negatively mediates the relationship between NVC–GVC and green development                   | Mechanism 1 and 2 (GVC channel) | <i>GVC_Pat_f</i> | –             |
| H3a        | NVC participation positively mediates the relationship between NVC–GVC and green development                   | Mechanism 3 (NVC-led channel)   | <i>NVC_Pat_f</i> | +             |
| H3b        | Environmental protection investment positively mediates the relationship between NVC–GVC and green development | Mechanism 3 (NVC-led channel)   | <i>Envir</i>     | +             |
| H3c        | Industrial structure upgrading positively mediates the relationship between NVC–GVC and green development      | Mechanism 3 (NVC-led channel)   | <i>Isu</i>       | +             |

“+” indicates a positive expected sign, “–” indicates a negative expected sign.

### 3. Methodology and Data

#### 3.1. Measurement Methods for NVCs and GVCs

Meng et al. [39] and Meng et al. [40] suggest integrating China's inter-regional and international input–output tables to measure NVC and GVC participation within a unified framework. This method clarifies their linkages and allows direct comparison. However, because this study uses the NVC–GVC coupling coordination degree as an explanatory variable, a unified accounting framework may cause endogeneity. To avoid this issue, we measure NVC and GVC participation using separate accounting frameworks.

China's NVC participation is measured using multiregional input–output (MRIO) tables from the CEADs database, while GVC participation is measured using world input–output tables from the OECD. To ensure consistency, we harmonize industry classifications across both datasets and aggregate manufacturing into 17 sectors. The NVC data cover 29 provincial regions, excluding Taiwan, Hong Kong, Macao, Tibet, and Xinjiang. Moreover, the latest versions of publicly available China's MRIO tables are only available for 2012, 2015, and 2017. Therefore, our analysis is limited to these 3 years.

We adopt the GVC decomposition method proposed by Wang et al. [41] to calculate NVC and GVC participation in China's manufacturing sector. The simplified formulas are shown in Equations (1) and (2).

$$NVC_{it} = NVC\_forward_{it} + NVC\_backward_{it} \quad (1)$$

$$GVC_{it} = GVC\_forward_{it} + GVC\_backward_{it} \quad (2)$$

$NVC_{it}$  denotes region  $i$  national value chain participation in year  $t$ .  $NVC\_forward_{it}$  measures upstream participation, indicating the extent to which the region supplies intermediate inputs to other regions.  $NVC\_backward_{it}$  measures downstream participation, indicating the use of intermediate inputs sourced from other regions. Similarly,  $GVC_{it}$  denotes global value chain participation.  $GVC\_forward_{it}$  and  $GVC\_backward_{it}$  measure upstream and downstream participation in global value chains, respectively, following the same definitions as for NVC. NVC and GVC participation are defined in Equations (3) and (4).

$$NVC^{(t)} = NVC_{t,i,j} = \begin{bmatrix} NVC_{t11} & NVC_{t12} & \cdots & NVC_{t1J} \\ NVC_{t21} & NVC_{t22} & \cdots & NVC_{t2J} \\ \vdots & \vdots & \ddots & \vdots \\ NVC_{tI1} & NVC_{tI2} & \cdots & NVC_{tIJ} \end{bmatrix}_{I \times J} \quad (3)$$

$$GVC^{(t)} = GVC_{t,i,j} = \begin{bmatrix} GVC_{t11} & GVC_{t12} & \cdots & GVC_{t1J} \\ GVC_{t21} & GVC_{t22} & \cdots & GVC_{t2J} \\ \vdots & \vdots & \ddots & \vdots \\ GVC_{tI1} & GVC_{tI2} & \cdots & GVC_{tIJ} \end{bmatrix}_{I \times J} \quad (4)$$

In Equations (3) and (4),  $t \in \{2012, 2015, 2017\}$ ,  $i \in \{1, 2, \dots, I\}$ ,  $j \in \{1, 2, \dots, J\}$ .

Specifically,  $t$  denotes time (3 years),  $i$  denotes regions (29 provinces), and  $j$  denotes industries (17 manufacturing sectors).

#### 3.2. Coupling Coordination Degree Model

Because NVC and GVC participation in China's manufacturing sector influence each other, we treat them as a coupled system. Following Zhang et al. [42], we construct a

coupling coordination degree model based on coupling coordination theory to measure their coordination level. The model is specified in Equations (5)–(7).

$$T = \alpha f(NVC) + \beta f(GVC) \quad (5)$$

$$C = \sqrt{f(NVC) \times f(GVC) / (f(NVC) + f(GVC))} \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

In Equations (5)–(7),  $f(NVC)$  and  $f(GVC)$  denote participation in national and global value chains, respectively.  $T$  is the coordination index, while  $\alpha$  and  $\beta$  are their weights. Following Zhang et al. [42] and Tan et al. [43], the sum of the weights  $\alpha$  and  $\beta$  should equal 1. Given the importance of both NVC and GVC participation for China's economic and green development [42,44], we set  $\alpha = \beta = 0.5$  to avoid weighting bias.

In Equations (6) and (7),  $C$  denotes the coupling degree between NVC and GVC participation in China's manufacturing, with higher values indicating stronger mutual influence.  $D$  denotes the coupling coordination degree. Higher values of  $D$  indicate stronger interaction, greater synergy, and better alignment between NVC and GVC development [42,43].

### 3.3. Model Specification

#### 3.3.1. High-Dimensional Fixed Effects Model

To examine the effect of NVC–GVC coupling coordination level in Chinese manufacturing on regional green development, we employ a high-dimensional fixed effects model that controls for industry fixed effects, time fixed effects, and their interaction. The model is specified as follows:

$$Green_{jt} = \alpha + \beta_1 NVC\_GVC_{jt} + \beta_2 Controls + industry + year + industry \times year + \varepsilon_{jt} \quad (8)$$

In Equation (8),  $j$  denotes the manufacturing industry, and  $t$  denotes the year.  $Green_{jt}$  denotes the green development level of industry  $j$  in year  $t$ , and  $NVC\_GVC_{jt}$  denotes the coupling coordination degree of NVC and GVC participation. *Controls* includes all control variables. *industry* and *year* represent industry and time fixed effects, respectively.  $industry \times year$  represent the interaction term of industry and time fixed effects.  $\varepsilon_{jt}$  is the error term,  $\alpha$  is the intercept, and  $\beta_1$  and  $\beta_2$  are slope coefficients.

#### 3.3.2. Mediation Testing Method

This study tests whether GVC participation, NVC participation, environmental protection investment (Envir), and industrial structure upgrading (Isu) mediate the effect of NVC–GVC coupling coordination on green development in Chinese manufacturing. Bootstrap mediation testing procedures are applied throughout [45].

### 3.4. Variables and Data

The study draws on mixed cross-sectional data from 2012, 2015, and 2017.

#### 3.4.1. Dependent Variable

Data are sourced from the 2019 *China Green Development Index Report: Regional Comparison* [46]. We use the aggregate index together with three sub-indices: (1) economic growth greening, (2) resource–environmental carrying capacity; and (3) government policy support. Each year's aggregate green development index equals the sum of the three sub-indices.

The green development index provides a composite assessment of regional performance across resource utilization, environmental governance, ecological protection, and

growth quality. The Ecogreen sub-index measures the degree to which regional economic development is greened. The Resgreen sub-index gauges the capacity of a region's resource endowment, ecological protection, environmental stress, and climate conditions to support future economic activity and human welfare. The Polgreen sub-index reflects the degree to which local governments prioritize and support green development [46,47].

### 3.4.2. Independent Variable

**NVC–GVC Coupling Coordination.** We calculate this variable to measure the degree of coupling and coordination between NVC and GVC participation across 17 manufacturing industries. Based on theoretical analysis, we expect higher NVC–GVC coordination level to be associated with better green development performance. Accordingly, NVC–GVC coupling coordination is expected to be positively related to the green development index. For robustness check, we use the coupling degree and coordination index of NVC and GVC as alternative independent variables.

### 3.4.3. Mediator

The study employs four mediating variables: GVC participation, NVC participation, environmental protection investment, and industrial structure upgrading. Based on the theoretical analysis in Section 2, NVC–GVC coupling coordination encourages Chinese manufacturing to deepen both domestic and global value chain participation. A higher GVC participation rate exposes firms to greater volumes of green knowledge and technology, but also subjects them to larger shocks from international environmental regulations and standards, raising compliance costs and, in the early stages, actually suppressing regional green development. We therefore expect GVC participation to exert a negative indirect effect.

Higher NVC participation improves resource allocation efficiency across China's provincial economies, stimulates local government environmental protection investment, and enhances regional economic and environmental performance, driving industrial structure upgrading. We therefore expect NVC participation, environmental protection investment, and industrial structure upgrading each to generate a positive indirect effect.

The measurement of NVC and GVC participation follows the procedure set out in Section 3.1. This study uses forward participation only for both NVC and GVC, for three reasons. First, as a theoretical focus, the paper centers on the role of Chinese manufacturing as a “supplier”—providing intermediate goods that influence both domestic and foreign production networks—which is precisely what forward participation captures. Second, regarding the Chinese reality, China's manufacturing sector integrates deeply into international fragmentation primarily by supplying intermediate and capital goods to the world, making forward participation the more representative measure. Third, to avoid confounding, total participation encompasses the backward component, which more closely reflects the technology content of imports and is less germane to the supply-side resource allocation and scale effect mechanisms on which this paper focuses.

**Environmental protection investment.** This variable is measured by provincial spending on industrial pollution control. Data are drawn from the EPS China Data platform and the China Environment Statistical Yearbook. Existing research confirms that environmental investment supports sustainable development [48]. Consistent with the theoretical analysis in Section 2, we expect this variable to be positively associated with the green development index.

**Industrial structure upgrading.** Following Zhang et al. [49], this variable is measured using an industrial structure upgrading index. Prior research establishes a mutually reinforcing relationship between industrial upgrading and green development [49]. Consistent

with the theoretical analysis in Section 2, we expect this variable to be positively associated with the green development index.

#### 3.4.4. Control Variables

To enhance the robustness of the results, four control variables are included alongside industry fixed effects, year fixed effects, and their interaction.

**Wastewater treatment capacity.** We measure this variable using the volume of industrial wastewater discharges that meet regulatory standards. Data are from the China Environmental Statistical Yearbook (Regional Edition). Following Su and Sheng [37] and Yao and Niu [50], higher compliant discharge volumes indicate stronger treatment capacity. We therefore expect a positive association with the green development index.

**Waste gas emissions.** This variable is measured using total industrial waste gas from fuel combustion based on data from the China Environmental Statistical Yearbook (Regional Edition). Higher emissions indicate more severe pollution. We therefore expect a negative association with the green development index.

**Solid waste recycling.** We measure this variable by the comprehensive utilization of industrial solid waste, using data from the China Environmental Statistical Yearbook (Regional Edition). Higher utilization reflects less material waste and better resource efficiency. We therefore expect a positive association with the green development index.

**Industrial water use.** This variable is measured using total industrial water consumption, reflecting natural resource use based on data from the China Statistical Yearbook. Manufacturing green development relies on massive water inputs. We therefore expect a positive association with the green development index.

Please refer to the Supplementary Materials or the GitHub repository noted in the Data Availability Statement for the Stata datasets and do-files used in this study.

## 4. Results and Discussion

### 4.1. Descriptive Statistics and Correlation Matrix

All analyses were conducted in Stata MP 17. Table 2 presents descriptive statistics and variable abbreviations. Table 3 shows the correlation matrix for the 15 variables.

**Table 2.** Descriptive statistics.

| Variable                                              | Abbreviations | N    | Mean   | S.D.   | Min   | Max     |
|-------------------------------------------------------|---------------|------|--------|--------|-------|---------|
| 1. Green Development Index                            | Green         | 1479 | 0.390  | 0.070  | 0.280 | 0.680   |
| 2. Economic Growth Greening Sub-index                 | Ecogreen      | 1479 | 0.110  | 0.040  | 0.040 | 0.270   |
| 3. Resource–Environmental Carrying Capacity Sub-index | Resgreen      | 1479 | 0.100  | 0.030  | 0.040 | 0.190   |
| 4. Government Policy Support Sub-index                | Polgreen      | 1479 | 0.180  | 0.040  | 0.090 | 0.320   |
| 5. NVC–GVC Coupling Coordination                      | NVC–GVC (D)   | 1479 | 0.310  | 0.090  | 0.000 | 0.600   |
| 6. Coordination Index of NVC and GVC                  | T             | 1479 | 0.280  | 0.180  | 0.020 | 1.570   |
| 7. Coupling Degree of NVC and GVC                     | C             | 1479 | 0.400  | 0.110  | 0.000 | 0.500   |
| 8. Wastewater Treatment Capacity                      | Water         | 1479 | 83,541 | 80,328 | 5630  | 330,000 |
| 9. Waste Gas Emissions                                | Atmosphere    | 1479 | 13,505 | 15,211 | 795   | 83,434  |
| 10. Solid Waste Recycling                             | Fixed         | 1479 | 11,166 | 11,771 | 156.7 | 61,466  |

Table 2. Cont.

| Variable                                | Abbreviations | N    | Mean  | S.D.  | Min   | Max   |
|-----------------------------------------|---------------|------|-------|-------|-------|-------|
| 11. Industrial Water Use                | Indwater      | 1479 | 45.90 | 46.81 | 2.500 | 250.1 |
| 12. NVC Participation                   | NVC_Pat_f     | 1479 | 0.410 | 0.370 | 0.000 | 3.010 |
| 13. GVC Participation                   | GVC_Pat_f     | 1479 | 0.140 | 0.060 | 0.030 | 0.280 |
| 14. Environmental Protection Investment | Envir         | 1479 | 5.390 | 0.800 | 3.100 | 6.860 |
| 15. Industrial Structure Upgrading      | Isu           | 1479 | 2.370 | 0.130 | 2.180 | 2.800 |

#### 4.1.1. Correlation Between the Dependent and Core Independent Variables

Table 3 reveals significant correlations between NVC–GVC coupling coordination and the aggregate green development index as well as its three sub-indices. Specifically, coupling coordination is significantly and positively correlated with Green ( $b = 0.105$ ,  $p < 0.01$ ), Ecogreen ( $b = 0.125$ ,  $p < 0.01$ ), and Polgreen ( $b = 0.112$ ,  $p < 0.01$ ). By contrast, coupling coordination is significantly and negatively correlated with Resgreen ( $b = -0.098$ ,  $p < 0.01$ ). These patterns indicate that greater NVC–GVC coupling coordination tends to advance regional green development, raise the greenness of economic growth, and encourage local governments to adopt environmental protection policies; however, simultaneously places greater pressure on natural resources and environmental carrying capacity.

In addition, Green is significantly and positively correlated with the coordination index T ( $b = 0.113$ ,  $p < 0.01$ ) but bears no significant relationship with the coupling degree C ( $b = -0.024$ ,  $p > 0.1$ ). This suggests that within the NVC–GVC system, the coordination dimension—not the coupling dimension—is the operative driver. From an economic standpoint, regions in which NVC and GVC participation are better coordinated exhibit higher levels of green development, whereas the sheer intensity of their interaction has no discernible effect.

As the aggregate index is the sum of the three sub-indices, positive correlations with each component are expected and confirmed. Green is strongly and positively correlated with Ecogreen ( $b = 0.889$ ,  $p < 0.01$ ) and Polgreen ( $b = 0.828$ ,  $p < 0.01$ ), indicating that overall green development is primarily driven by green economic growth and policy support. However, Green is significantly and negatively correlated with Resgreen ( $b = -0.136$ ,  $p < 0.01$ ), reflecting a common pattern in China whereby regions with larger resource and environmental endowments tend to have lower levels of economic development and rely on less efficient resource use, which pulls down their aggregate green development index. The negative correlation between Ecogreen and Resgreen ( $b = -0.393$ ,  $p < 0.01$ ) further points to a trade-off between economic greening and resource–environmental carrying capacity.

Table 3 also reveals a significant negative correlation between the coordination index T and the coupling degree C ( $b = -0.325$ ,  $p < 0.01$ ). This implies that when NVC–GVC coordination is high, the coupling intensity tends to be low, and vice versa. This motivates a further robustness check using T and C separately as independent variables.

**Table 3.** Correlation matrix (observations = 1479).

| Variable      | 1.         | 2.         | 3.         | 4.        | 5.        | 6.         | 7.         | 8.        | 9.         | 10.        | 11.       | 12.        | 13.    | 14.       | 15. |
|---------------|------------|------------|------------|-----------|-----------|------------|------------|-----------|------------|------------|-----------|------------|--------|-----------|-----|
| 1. Green      | 1          |            |            |           |           |            |            |           |            |            |           |            |        |           |     |
| 2. Ecogreen   | 0.889 ***  | 1          |            |           |           |            |            |           |            |            |           |            |        |           |     |
| 3. Resgreen   | −0.136 *** | −0.393 *** | 1          |           |           |            |            |           |            |            |           |            |        |           |     |
| 4. Polgreen   | 0.828 ***  | 0.704 ***  | −0.511 *** | 1         |           |            |            |           |            |            |           |            |        |           |     |
| 5. NVC–GVC    | 0.105 ***  | 0.125 ***  | −0.098 *** | 0.112 *** | 1         |            |            |           |            |            |           |            |        |           |     |
| 6. T          | 0.113 ***  | 0.128 ***  | −0.081 *** | 0.111 *** | 0.770 *** | 1          |            |           |            |            |           |            |        |           |     |
| 7. C          | −0.024     | −0.023     | 0.019      | −0.029    | 0.262 *** | −0.325 *** | 1          |           |            |            |           |            |        |           |     |
| 8. Water      | 0.003      | 0.125 ***  | −0.365 *** | 0.127 *** | −0.021    | −0.066 **  | 0.077 ***  | 1         |            |            |           |            |        |           |     |
| 9. Atmosphere | −0.178 *** | −0.197 *** | −0.332 *** | 0.145 *** | −0.046 *  | −0.014     | −0.060 **  | 0.063 **  | 1          |            |           |            |        |           |     |
| 10. Fixed     | −0.156 *** | −0.147 *** | −0.143 *** | −0.005    | 0.016     | 0.005      | 0.004      | 0.279 *** | 0.350 ***  | 1          |           |            |        |           |     |
| 11. Indwater  | 0.020      | 0.133 ***  | −0.245 *** | 0.066 **  | −0.022    | −0.061 **  | 0.061 **   | 0.560 *** | −0.090 *** | −0.010     | 1         |            |        |           |     |
| 12. NVC_Pat_f | 0.114 ***  | 0.128 ***  | −0.082 *** | 0.113 *** | 0.701 *** | 0.986 ***  | −0.393 *** | −0.065 ** | −0.013     | 0.009      | −0.061 ** | 1          |        |           |     |
| 13. GVC_Pat_f | −0.012     | −0.008     | 0.009      | −0.019    | 0.369 *** | 0.026      | 0.419 ***  | −0.003    | −0.006     | −0.020     | 0.004     | −0.143 *** | 1      |           |     |
| 14. Envir     | 0.143 ***  | 0.278 ***  | −0.392 *** | 0.221 *** | 0.099 *** | 0.043      | 0.057 **   | 0.619 *** | 0.084 ***  | 0.516 ***  | 0.457 *** | 0.043 *    | −0.006 | 1         |     |
| 15. Isu       | 0.587 ***  | 0.662 ***  | −0.157 *** | 0.391 *** | 0.080 *** | 0.112 ***  | −0.047 *   | −0.065 ** | −0.044 *   | −0.099 *** | −0.021    | 0.116 ***  | −0.030 | 0.158 *** | 1   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

#### 4.1.2. Multicollinearity Diagnosis for Control Variables and Mediators

Correlation coefficients below 0.6 are generally acceptable [51]. High correlations among the aggregate index and its sub-indices, and among the coordination index, coupling degree, and coupling coordination degree, are to be expected. Following Jiang et al. [52], we computed variance inflation factors (VIFs) after estimation; results are reported in Table 4. The mean VIF is 2.12, and the maximum VIF is 3.60. Both of these values are comfortably below the threshold of 10 [53], confirming the absence of serious multicollinearity. The VIF structure is identical across the four dependent variable models, further validating that the diagnostic conclusions are invariant to the choice of outcome.

**Table 4.** Variance inflation factors (VIFs).

| Variable   | Green | Ecogreen | Resgreen | Polgreen |
|------------|-------|----------|----------|----------|
| NVC–GVC    | 3.60  | 3.60     | 3.60     | 3.60     |
| NVC_Pat_f  | 3.15  | 3.15     | 3.15     | 3.15     |
| Envir      | 2.64  | 2.64     | 2.64     | 2.64     |
| Water      | 2.01  | 2.01     | 2.01     | 2.01     |
| GVC_Pat_f  | 1.84  | 1.84     | 1.84     | 1.84     |
| Fixed      | 1.83  | 1.83     | 1.83     | 1.83     |
| Indwater   | 1.71  | 1.71     | 1.71     | 1.71     |
| Atmosphere | 1.17  | 1.17     | 1.17     | 1.17     |
| Isu        | 1.16  | 1.16     | 1.16     | 1.16     |
| Mean VIF   | 2.12  | 2.12     | 2.12     | 2.12     |

#### 4.2. Baseline Regression

Baseline regressions are estimated using a high-dimensional fixed effects model incorporating industry fixed effects, year fixed effects, and their interaction, together with four control variables, as in Equation (9). Results using the aggregate green development index and each of its three sub-indices as dependent variables are reported in Table 5.

$$\begin{aligned} \text{Green}_{jt} = & \alpha + \beta_1 \text{NVC\_GVC}_{jt} + \beta_2 \text{Water}_{jt} + \beta_3 \text{Atmosphere}_{jt} + \beta_4 \text{Fixed}_{jt} \\ & + \beta_5 \text{Indwater}_{jt} + \text{Industry} + \text{Year} + \text{Industry} \times \text{Year} + \varepsilon_{jt} \end{aligned} \quad (9)$$

Hypothesis H1 predicts that NVC–GVC coupling coordination in Chinese manufacturing promotes regional green development. All models in Table 5 display satisfactory fit, with R-squared values in the range [0.206, 0.575]. NVC–GVC coupling coordination exerts a significant and positive effect on Green ( $b = 0.147, p < 0.01$ ), Ecogreen ( $b = 0.137, p < 0.01$ ), and Polgreen ( $b = 0.093, p < 0.01$ ). It does, however, exert a significant and negative effect on Resgreen ( $b = -0.083, p < 0.01$ ), revealing that dual value chain coupling coordination simultaneously imposes transitional pressure on natural resources and the environment even as it drives regional green transformation—a structural divergence in the interior dimensions of green development. Because the aggregate index Green equals the sum of the three sub-indices for each year, it captures China’s overall regional green development level. Consequently, even though NVC–GVC coupling coordination weakens regional resource–environmental carrying capacity, the net effect on aggregate green development remains positive. These results provide statistical support for Hypothesis H1.

**Table 5.** Baseline regression results (OLS test).

| Variables      | Model 1<br>Green      | Model 2<br>Ecogreen   | Model 3<br>Resgreen    | Model 4<br>Polgreen  |
|----------------|-----------------------|-----------------------|------------------------|----------------------|
| NVC–GVC        | 0.147 ***<br>(5.16)   | 0.137 ***<br>(7.26)   | −0.083 ***<br>(−7.82)  | 0.093 ***<br>(7.17)  |
| Water          | 0.000 **<br>(2.06)    | 0.000 ***<br>(5.19)   | −0.000 ***<br>(−11.51) | 0.000 ***<br>(6.27)  |
| Atmosphere     | −0.000 ***<br>(−5.53) | −0.000 ***<br>(−5.62) | −0.000 ***<br>(−16.28) | 0.000 ***<br>(9.37)  |
| Fixed          | −0.000 ***<br>(−3.35) | −0.000 ***<br>(−4.42) | 0.000<br>(0.82)        | −0.000<br>(−1.54)    |
| Indwater       | −0.000<br>(−0.96)     | 0.000<br>(1.16)       | −0.000 ***<br>(−4.37)  | −0.000<br>(−0.08)    |
| Constant       | 0.358 ***<br>(38.41)  | 0.068 ***<br>(10.95)  | 0.147 ***<br>(42.48)   | 0.143 ***<br>(33.73) |
| Observations   | 1479                  | 1479                  | 1479                   | 1479                 |
| R-squared      | 0.273                 | 0.206                 | 0.424                  | 0.575                |
| Industry (Ind) | Yes                   | Yes                   | Yes                    | Yes                  |
| Year           | Yes                   | Yes                   | Yes                    | Yes                  |
| Ind × Year     | Yes                   | Yes                   | Yes                    | Yes                  |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

#### 4.3. Robustness Check

A series of robustness checks are conducted to validate the findings.

##### 4.3.1. Replacement of Independent Variables

###### (1) Coordination index (T)

First, we substitute the coordination index T—the degree of coordination between NVC and GVC participation—for the coupling coordination degree as the explanatory variable in robustness check 1. Results are reported in Table 6.

**Table 6.** Robustness check 1.

| Variables      | Model 1.1<br>Green    | Model 2.1<br>Ecogreen | Model 3.1<br>Resgreen  | Model 4.1<br>Polgreen |
|----------------|-----------------------|-----------------------|------------------------|-----------------------|
| T              | 0.086 ***<br>(6.10)   | 0.076 ***<br>(8.16)   | −0.037 ***<br>(−7.12)  | 0.047 ***<br>(7.38)   |
| Water          | 0.000 **<br>(2.34)    | 0.000 ***<br>(5.56)   | −0.000 ***<br>(−11.72) | 0.000 ***<br>(6.57)   |
| Atmosphere     | −0.000 ***<br>(−5.87) | −0.000 ***<br>(−6.09) | −0.000 ***<br>(−15.78) | 0.000 ***<br>(8.98)   |
| Fixed          | −0.000 ***<br>(−3.17) | −0.000 ***<br>(−4.15) | 0.000<br>(0.41)        | −0.000<br>(−1.21)     |
| Indwater       | −0.000<br>(−0.83)     | 0.000<br>(1.34)       | −0.000 ***<br>(−4.47)  | 0.000<br>(0.06)       |
| Constant       | 0.379 ***<br>(75.26)  | 0.088 ***<br>(26.46)  | 0.133 ***<br>(70.25)   | 0.158 ***<br>(68.89)  |
| Observations   | 1479                  | 1479                  | 1479                   | 1479                  |
| R-squared      | 0.279                 | 0.213                 | 0.420                  | 0.576                 |
| Industry (Ind) | Yes                   | Yes                   | Yes                    | Yes                   |
| Year           | Yes                   | Yes                   | Yes                    | Yes                   |
| Ind × Year     | Yes                   | Yes                   | Yes                    | Yes                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

As Table 6 shows, the coefficient on T is consistent in sign with the baseline results across all four models and is statistically significant at the 1% level, providing additional support for Hypothesis H1.

#### (2) Coupling degree (C)

Second, we substitute the coupling degree C, which is the intensity of interaction between NVC and GVC participation, for the key independent variable in robustness check 2. Results are reported in Table 7.

**Table 7.** Robustness check 2.

| Variables      | Model 1.2<br>Green    | Model 2.2<br>Ecogreen | Model 3.2<br>Resgreen  | Model 4.2<br>Polgreen |
|----------------|-----------------------|-----------------------|------------------------|-----------------------|
| C              | −0.047 **<br>(−1.99)  | −0.043 ***<br>(−2.67) | 0.018 **<br>(2.04)     | −0.023 **<br>(−2.11)  |
| Water          | 0.000 **<br>(2.06)    | 0.000 ***<br>(5.10)   | −0.000 ***<br>(−11.20) | 0.000 ***<br>(6.12)   |
| Atmosphere     | −0.000 ***<br>(−6.19) | −0.000 ***<br>(−6.51) | −0.000 ***<br>(−15.00) | 0.000 ***<br>(8.32)   |
| Fixed          | −0.000 ***<br>(−2.79) | −0.000 ***<br>(−3.60) | 0.000<br>(0.01)        | −0.000<br>(−0.78)     |
| Indwater       | −0.000<br>(−1.04)     | 0.000<br>(1.02)       | −0.000 ***<br>(−4.14)  | −0.000<br>(−0.21)     |
| Constant       | 0.422 ***<br>(42.89)  | 0.127 ***<br>(19.30)  | 0.114 ***<br>(30.87)   | 0.181 ***<br>(40.07)  |
| Observations   | 1479                  | 1479                  | 1479                   | 1479                  |
| R-squared      | 0.262                 | 0.180                 | 0.401                  | 0.561                 |
| Industry (Ind) | Yes                   | Yes                   | Yes                    | Yes                   |
| Year           | Yes                   | Yes                   | Yes                    | Yes                   |
| Ind × Year     | Yes                   | Yes                   | Yes                    | Yes                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

As Table 7 shows, the coefficients for C are statistically significant across all four models but reverse in sign relative to the baseline. This is consistent with the significant negative correlation between T and C documented in the correlation matrix. These results confirm that the positive effect of NVC–GVC coupling coordination on green development operates primarily through coordination effects, as captured by the coordination index T, rather than through coupling intensity alone, as captured by C. This conclusion is corroborated by robustness checks 1 and 2 jointly.

#### 4.3.2. Winsorization Test (1–99%)

To limit the influence of extreme outliers and sharpen the robustness of the conclusions, all variables are winsorized at the 1st and 99th percentiles, and regressions are re-estimated. Results are reported in Table 8.

As Table 8 shows, the coefficients for the core explanatory variable are consistent in sign with the baseline and remain significant at the 1% level, indicating that the findings are not driven by extreme observations. Hypothesis H1 receives further support.

**Table 8.** Robustness check 3.

| Variables      | Model 1.3<br>Green_w  | Model 2.3<br>Ecogreen_w | Model 3.3<br>Resgreen_w | Model 4.3<br>Polgreen_w |
|----------------|-----------------------|-------------------------|-------------------------|-------------------------|
| NVC–GVC_w      | 0.139 ***<br>(4.83)   | 0.133 ***<br>(6.94)     | −0.084 ***<br>(−7.81)   | 0.090 ***<br>(6.88)     |
| Water_w        | 0.000 **<br>(2.04)    | 0.000 ***<br>(5.16)     | −0.000 ***<br>(−11.50)  | 0.000 ***<br>(6.24)     |
| Atmosphere_w   | −0.000 ***<br>(−5.57) | −0.000 ***<br>(−5.65)   | −0.000 ***<br>(−16.27)  | 0.000 ***<br>(9.32)     |
| Fixed_w        | −0.000 ***<br>(−3.33) | −0.000 ***<br>(−4.41)   | 0.000<br>(0.84)         | −0.000<br>(−1.53)       |
| Indwater_w     | −0.000<br>(−0.97)     | 0.000<br>(1.15)         | −0.000 ***<br>(−4.36)   | −0.000<br>(−0.09)       |
| Constant       | 0.361 ***<br>(38.32)  | 0.069 ***<br>(11.07)    | 0.148 ***<br>(42.19)    | 0.144 ***<br>(33.61)    |
| Observations   | 1479                  | 1479                    | 1479                    | 1479                    |
| R-squared      | 0.272                 | 0.203                   | 0.424                   | 0.574                   |
| Industry (Ind) | Yes                   | Yes                     | Yes                     | Yes                     |
| Year           | Yes                   | Yes                     | Yes                     | Yes                     |
| Ind × Year     | Yes                   | Yes                     | Yes                     | Yes                     |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

#### 4.3.3. Alternative Weights for the Coordination Index

To rule out sensitivity to the weighting scheme used in constructing the coordination index, we recompute the coupling coordination degree under two alternative weight configurations. Setting  $\alpha = 0.7$ ,  $\beta = 0.3$  yields NVC–GVC\_1, with results reported in Table 9. Setting  $\alpha = 0.3$ ,  $\beta = 0.7$  yields NVC–GVC\_2, with results reported in Table 10.

**Table 9.** Robustness check 4:  $\alpha = 0.7$ ,  $\beta = 0.3$ .

| Variables      | Model 1.4<br>Green    | Model 2.4<br>Ecogreen | Model 3.4<br>Resgreen  | Model 4.4<br>Polgreen |
|----------------|-----------------------|-----------------------|------------------------|-----------------------|
| NVC–GVC_1      | 0.123 ***<br>(5.37)   | 0.115 ***<br>(7.61)   | −0.071 ***<br>(−8.33)  | 0.078 ***<br>(7.53)   |
| Water          | 0.000 **<br>(2.10)    | 0.000 ***<br>(5.25)   | −0.000 ***<br>(−11.61) | 0.000 ***<br>(6.33)   |
| Atmosphere     | −0.000 ***<br>(−5.59) | −0.000 ***<br>(−5.70) | −0.000 ***<br>(−16.29) | 0.000 ***<br>(9.34)   |
| Fixed          | −0.000 ***<br>(−3.36) | −0.000 ***<br>(−4.43) | 0.000<br>(0.83)        | −0.000<br>(−1.55)     |
| Indwater       | −0.000<br>(−0.93)     | 0.000<br>(1.21)       | −0.000 ***<br>(−4.43)  | −0.000<br>(−0.04)     |
| Constant       | 0.363 ***<br>(44.38)  | 0.072 ***<br>(13.27)  | 0.145 ***<br>(47.83)   | 0.146 ***<br>(39.25)  |
| Observations   | 1479                  | 1479                  | 1479                   | 1479                  |
| R-squared      | 0.274                 | 0.209                 | 0.427                  | 0.577                 |
| Industry (Ind) | Yes                   | Yes                   | Yes                    | Yes                   |
| Year           | Yes                   | Yes                   | Yes                    | Yes                   |
| Ind × Year     | Yes                   | Yes                   | Yes                    | Yes                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

**Table 10.** Robustness check 5:  $\alpha = 0.3$ ,  $\beta = 0.7$ .

| Variables      | Model 1.5<br>Green    | Model 2.5<br>Ecogreen | Model 3.5<br>Resgreen  | Model 4.5<br>Polgreen |
|----------------|-----------------------|-----------------------|------------------------|-----------------------|
| NVC–GVC_2      | 0.171 ***<br>(4.53)   | 0.158 ***<br>(6.28)   | −0.093 ***<br>(−6.62)  | 0.107 ***<br>(6.23)   |
| Water          | 0.000 **<br>(1.97)    | 0.000 ***<br>(5.04)   | −0.000 ***<br>(−11.32) | 0.000 ***<br>(6.12)   |
| Atmosphere     | −0.000 ***<br>(−5.49) | −0.000 ***<br>(−5.56) | −0.000 ***<br>(−16.16) | 0.000 ***<br>(9.34)   |
| Fixed          | −0.000 ***<br>(−3.30) | −0.000 ***<br>(−4.33) | 0.000<br>(0.73)        | −0.000<br>(−1.47)     |
| Indwater       | −0.000<br>(−1.02)     | 0.000<br>(1.07)       | −0.000 ***<br>(−4.25)  | −0.000<br>(−0.17)     |
| Constant       | 0.355 ***<br>(32.06)  | 0.066 ***<br>(8.91)   | 0.148 ***<br>(35.77)   | 0.141 ***<br>(28.02)  |
| Observations   | 1479                  | 1479                  | 1479                   | 1479                  |
| R-squared      | 0.274                 | 0.209                 | 0.427                  | 0.577                 |
| Industry (Ind) | Yes                   | Yes                   | Yes                    | Yes                   |
| Year           | Yes                   | Yes                   | Yes                    | Yes                   |
| Ind × Year     | Yes                   | Yes                   | Yes                    | Yes                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

In both sets of estimates, the sign of the core explanatory variable is entirely consistent with the baseline and remains significant at the 1% level. These results confirm that the conclusions of the paper are insensitive to the choice of weights for the coordination index, demonstrating strong robustness.

#### 4.3.4. Adding Province Fixed Effects

Given that the effect of NVC–GVC coupling coordination on green development is partly realized through NVC participation, which is itself strongly correlated with inter-provincial differences in economic development levels, policy environments, and resource endowments, the treatment of province fixed effects warrants careful consideration. The baseline regression and preceding robustness checks already incorporate industry fixed effects, year fixed effects, and their interaction. Adding province fixed effects to this high-dimensional specification risks absorbing large volumes of cross-sectional variation in both the core explanatory variable (NVC–GVC coupling coordination) and the key mediating channel (NVC participation) that carry genuine economic content, potentially eliminating the identifying variation and introducing attenuation bias. Notwithstanding these concerns, and to further probe the robustness of the baseline results, province fixed effects (Id) are added alongside the existing fixed effects, and regressions are re-run. Results are reported in Table 11.

The estimates in Models 1.6 and 4.6 indicate that, after controlling for province fixed effects, the coefficient on NVC–GVC coupling coordination remains statistically significant at the 1% level and preserves the sign established in the baseline, further underscoring the robustness of the core findings. The modest narrowing of the absolute magnitude of the NVC–GVC coefficient is consistent with the theoretical expectation that province fixed effects absorb part of the cross-sectional identifying variation. Notably, the coefficient sign reversal for NVC–GVC in Models 2.6 and 3.6 does not undermine the core conclusions; we return to this point in Section 4.6. Overall, Hypothesis H1 receives further statistical support.

**Table 11.** Robustness check 6.

| Variables      | Model 1.6<br>Green   | Model 2.6<br>Ecogreen | Model 3.6<br>Resgreen | Model 4.6<br>Polgreen |
|----------------|----------------------|-----------------------|-----------------------|-----------------------|
| NVC–GVC_2      | 0.023 ***<br>(2.75)  | −0.013 ***<br>(−2.62) | 0.023 ***<br>(4.77)   | 0.013 ***<br>(2.64)   |
| Water          | 0.000<br>(0.18)      | −0.000 ***<br>(−4.68) | −0.000<br>(−0.85)     | 0.000 ***<br>(5.47)   |
| Atmosphere     | 0.000 ***<br>(5.99)  | 0.000 ***<br>(6.74)   | 0.000 ***<br>(7.67)   | −0.000 ***<br>(−3.75) |
| Fixed          | 0.000 ***<br>(6.22)  | −0.000 ***<br>(−3.07) | −0.000<br>(−0.70)     | 0.000 ***<br>(14.52)  |
| Indwater       | 0.000<br>(1.23)      | 0.000 ***<br>(3.64)   | 0.000 ***<br>(2.92)   | −0.000 ***<br>(−3.92) |
| Constant       | 0.357 ***<br>(52.68) | 0.108 ***<br>(27.91)  | 0.079 ***<br>(20.37)  | 0.169 ***<br>(43.24)  |
| Observations   | 1479                 | 1479                  | 1479                  | 1479                  |
| R-squared      | 0.951                | 0.961                 | 0.907                 | 0.954                 |
| Industry (Ind) | Yes                  | Yes                   | Yes                   | Yes                   |
| Year           | Yes                  | Yes                   | Yes                   | Yes                   |
| Ind × Year     | Yes                  | Yes                   | Yes                   | Yes                   |
| Id             | Yes                  | Yes                   | Yes                   | Yes                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses.

#### 4.4. Endogeneity Test

We employ two-stage least squares (2SLS) to address the potential endogeneity between NVC–GVC coupling coordination and green development. Valid instruments must satisfy both a relevance condition and an exclusion restriction. We select Terrain Ruggedness (Topo) and the Historical Count of Confucian Academies (Academy) as instruments for the following reasons.

Regarding terrain ruggedness, the relevance condition holds because topography shapes the cost of transport infrastructure construction and the accessibility of regions, systematically influencing industrial location and factor mobility. Here, flatter terrain implies better developed transport networks, lower logistics costs, and a greater likelihood of deep value chain embeddedness and integration. The exclusion restriction holds because terrain features are determined by geological history, do not change with economic activity over the sample window, and do not directly affect current green development levels [54,55].

Regarding Confucian academy counts, the relevance condition holds because the Confucian cultural tradition shapes social norms, business ethics, and trust mechanisms, influencing the cooperative orientation of regional firms, contract enforcement efficiency, and openness to external exchange, and thereby their willingness to participate in value chain specialization. Historically denser concentrations of academies are associated with deeper Confucian cultural accumulation, effects that continue to permeate the behavioral logic of local economic agents through intergenerational transmission [56]. The exclusion restriction holds because academy counts are historical cultural relics formed centuries ago and bear no direct relationship to current green development levels.

Table 12 reports 2SLS estimates using heteroskedasticity robust standard errors. In the first stage, the coefficient on terrain ruggedness (Topo) is significantly negative at the 1% level across all four specifications (coefficient approximately  $-0.017$ ,  $t = -6.467$ ), indicating that flatter regions exhibit higher levels of value chain coupling coordination. This finding is consistent with theoretical expectations. The coefficient of academy is also negative but fails to reach conventional significance ( $t = -0.921$ ), suggesting limited independent

explanatory power over the endogenous variable. Nevertheless, the joint F-statistic for both instruments is 21.225, substantially exceeding the Stock–Yogo critical value of 10 at the 10% significance level, confirming that the instrument set provides sufficient collective explanatory power and is free from weak instrument concerns.

**Table 12.** 2SLS endogeneity test.

| Stage Variables                           | 2SLS Test 1<br>First<br>NVC–GVC | Second<br>Green        | 2SLS Test 2<br>First<br>NVC–GVC | Second<br>Ecogreen     | 2SLS Test 3<br>First<br>NVC–GVC | Second<br>Resgreen     | 2SLS Test 4<br>First<br>NVC–GVC | Second<br>Polgreen     |
|-------------------------------------------|---------------------------------|------------------------|---------------------------------|------------------------|---------------------------------|------------------------|---------------------------------|------------------------|
| NVC–GVC-hat                               |                                 | 1.126 ***<br>(5.914)   |                                 | 1.262 ***<br>(6.377)   |                                 | −0.756 ***<br>(−6.236) |                                 | 0.618 ***<br>(5.786)   |
| Water                                     | −0.000 *<br>(−1.733)            | 0.000 *<br>(1.761)     | −0.000 *<br>(−1.733)            | 0.000 ***<br>(2.547)   | −0.000 *<br>(−1.733)            | −0.000 ***<br>(−4.612) | −0.000 *<br>(−1.733)            | 0.000 ***<br>(3.628)   |
| Atmosphere                                | −0.000<br>(−1.529)              | −0.000<br>(−0.816)     | −0.000<br>(−1.529)              | 0.000<br>(0.069)       | −0.000<br>(−1.529)              | −0.000 ***<br>(−5.399) | −0.000<br>(−1.529)              | 0.000 ***<br>(4.608)   |
| Fixed                                     | 0.000<br>(0.971)                | −0.000 ***<br>(−3.568) | 0.000<br>(0.971)                | −0.000 ***<br>(−2.986) | 0.000<br>(0.971)                | 0.000 **<br>(2.049)    | 0.000<br>(0.971)                | −0.000 ***<br>(−3.547) |
| Indwater                                  | −0.000<br>(−1.393)              | −0.000<br>(−0.122)     | −0.000<br>(−1.393)              | 0.000<br>(0.929)       | −0.000<br>(−1.393)              | −0.000 **<br>(−2.074)  | −0.000<br>(−1.393)              | 0.000<br>(0.462)       |
| IV_1<br>(Topo)                            | −0.017 ***<br>(−6.467)          |                        | −0.017 ***<br>(−6.467)          |                        | −0.017 ***<br>(−6.467)          |                        | −0.017 ***<br>(−6.467)          |                        |
| IV_2<br>(Academy)                         | −0.000<br>(−0.921)              |                        | −0.000<br>(−0.921)              |                        | −0.000<br>(−0.921)              |                        | −0.000<br>(−0.921)              |                        |
| Constant                                  | 0.338 ***<br>(55.951)           | 0.055<br>(0.923)       | 0.338 ***<br>(55.951)           | −0.282 ***<br>(−4.545) | 0.338 ***<br>(55.951)           | 0.357 ***<br>(9.350)   | 0.338 ***<br>(55.951)           | −0.019<br>(−0.562)     |
| Weak IV Test<br>(F statistic)             | 21.225                          |                        | 21.225                          |                        | 21.225                          |                        | 21.225                          |                        |
| Overidentified<br>Test ( <i>p</i> -value) | 0.223                           |                        | 0.151                           |                        | 0.428                           |                        | 0.163                           |                        |
| Endogeneity<br>Test ( <i>p</i> -value)    | 0.000                           |                        | 0.000                           |                        | 0.000                           |                        | 0.000                           |                        |
| Observations                              | 1479                            | 1479                   | 1479                            | 1479                   | 1479                            | 1479                   | 1479                            | 1479                   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ ; t-statistics noted in parentheses within the first stage; z-statistics noted in parentheses within the second stage.

Instrument validity is supported by Hansen J over-identification test *p*-values of 0.223, 0.151, 0.428, and 0.163 across the four specifications. All of these values far exceed 0.1, so the null hypothesis that the instruments satisfy the exclusion restriction cannot be rejected, confirming both instruments meet the exogeneity requirement. Endogeneity test *p*-values are uniformly 0.000, rejecting the null hypothesis that the key explanatory variable is exogenous at the 1% level and confirming that NVC–GVC coupling coordination is endogenous in its effect on green development, establishing the necessity of 2SLS correction.

In the second stage, the fitted value coefficients for NVC–GVC coupling coordination are 1.126 \*\*\* ( $z = 5.914$ ), 1.262 \*\*\* ( $z = 6.377$ ), −0.756 \*\*\* ( $z = -6.236$ ), and 0.618 \*\*\* ( $z = 5.786$ ) for Green, Ecogreen, Resgreen, and Polgreen, respectively. All of these values are highly significant at the 1% level and entirely consistent in sign with the baseline regression. The significantly negative Resgreen coefficient may reflect structural tension between deep value chain integration and the resource utilization efficiency dimension, a matter warranting further investigation. On the whole, the positive and robust effect of NVC–GVC coupling coordination on regional green development persists after accounting for endogeneity bias, providing further support for Hypothesis H1.

#### 4.5. Mechanism Test (Bootstrap Mediation Analysis)

##### 4.5.1. GVC Participation as Mediator

Table 13 reports results with GVC participation (GVC\_Pat\_f) as the mediator. Regarding indirect effects, the NVC–GVC → GVC\_Pat\_f → Green indirect effect coefficient is −0.017 ( $p = 0.023$ ), with a 95% confidence interval of [−0.032, −0.002] that excludes zero, indicating a statistically significant negative indirect effect at the 5% level. The NVC–GVC

→ GVC\_Pat\_f → Ecogreen coefficient is  $-0.012$  ( $p = 0.013$ ), which is significant and negative. The NVC–GVC → GVC\_Pat\_f → Polgreen coefficient is  $-0.013$  ( $p = 0.003$ ), which is significant at the 1% level and negative. Of particular interest, the NVC–GVC → GVC\_Pat\_f → Resgreen indirect effect coefficient is  $0.007$  ( $p = 0.014$ ), which is significantly positive and opposite in sign to the other three green dimensions. These findings suggest that the GVC channel does provide some positive transmission for resource utilization efficiency, potentially linked to technological spillovers from GVC embeddedness. Regarding direct effects, after controlling for GVC\_Pat\_f, the direct effect of NVC–GVC coupling coordination on all four dependent variables remains highly significant at the 1% level (coefficients 0.093, 0.071,  $-0.046$ , and 0.068), indicating partial mediation across all four dimensions. These results confirm that NVC–GVC coupling coordination exerts significant negative indirect effects on Green, Ecogreen, and Polgreen through the GVC participation channel, supporting Hypothesis H2.

**Table 13.** Bootstrapping test 1.

| Effect Type         | Path                             | Coefficient    | <i>p</i> -Value | 95% CI               |
|---------------------|----------------------------------|----------------|-----------------|----------------------|
| Indirect Effect 2.1 | NVC–GVC → GVC → Green            | $-0.017^{**}$  | 0.023           | [ $-0.032, -0.002$ ] |
| Direct Effect 2.1   | NVC–GVC → Green (control GVC)    | $0.093^{***}$  | 0.000           | [0.051, 0.135]       |
| Indirect Effect 2.2 | NVC–GVC → GVC → Ecogreen         | $-0.012^{**}$  | 0.013           | [ $-0.021, -0.002$ ] |
| Direct Effect 2.2   | NVC–GVC → Ecogreen (control GVC) | $0.071^{***}$  | 0.000           | [0.046, 0.095]       |
| Indirect Effect 2.3 | NVC–GVC → GVC → Resgreen         | $0.007^{**}$   | 0.014           | [0.001, 0.013]       |
| Direct Effect 2.3   | NVC–GVC → Resgreen (control GVC) | $-0.046^{***}$ | 0.000           | [ $-0.061, -0.031$ ] |
| Indirect Effect 2.4 | NVC–GVC → GVC → Polgreen         | $-0.013^{***}$ | 0.003           | [ $-0.021, -0.004$ ] |
| Direct Effect 2.4   | NVC–GVC → Polgreen (control GVC) | $0.068^{***}$  | 0.000           | [0.045, 0.092]       |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ . GVC\_Pat\_f is further abbreviated as GVC.

#### 4.5.2. NVC Participation as a Mediator

Table 14 reports bootstrap mediation test results with NVC participation (NVC\_Pat\_f) as the mediator. Regarding indirect effects, the NVC–GVC → NVC\_Pat\_f → Green indirect effect coefficient is  $0.046$  ( $p = 0.019$ ), with a 95% confidence interval of [0.008, 0.085] that excludes zero, indicating a significant positive indirect effect at the 5% level. The NVC–GVC → NVC\_Pat\_f → Ecogreen coefficient is  $0.034$  ( $p = 0.005$ ) and is significantly positive at the 1% level. The NVC–GVC → NVC\_Pat\_f → Polgreen coefficient is  $0.023$  ( $p = 0.047$ ) and significantly positive at the 5% level. The NVC–GVC → NVC\_Pat\_f → Resgreen coefficient is  $-0.011$  ( $p = 0.081$ ), which is marginally significant and negative at the 10% level, suggesting that the NVC channel exerts some suppressive effect on Resgreen, possibly related to resource consumption pressures accompanying domestic value chain deepening. Regarding direct effects: after controlling for NVC\_Pat\_f, the direct effect of NVC–GVC on Green ( $p = 0.267$ ) and Ecogreen ( $p = 0.132$ ) is no longer significant, indicating full mediation for these two dimensions. The direct effects on Resgreen and Polgreen remain significant, indicating partial mediation. These results confirm that NVC–GVC coupling coordination exerts a positive indirect stimulus on regional green development via the NVC participation channel, supporting Hypothesis H3a.

**Table 14.** Bootstrapping test 2.

| Effect Type         | Path                             | Coefficient | <i>p</i> -Value | 95% CI           |
|---------------------|----------------------------------|-------------|-----------------|------------------|
| Indirect Effect 1.1 | NVC–GVC → NVC → Green            | 0.046 **    | 0.019           | [0.008, 0.085]   |
| Direct Effect 1.1   | NVC–GVC → Green (control NVC)    | 0.030       | 0.267           | [−0.023, 0.082]  |
| Indirect Effect 1.2 | NVC–GVC → NVC → Ecogreen         | 0.034 ***   | 0.005           | [0.011, 0.058]   |
| Direct Effect 1.2   | NVC–GVC → Ecogreen (control NVC) | 0.025       | 0.132           | [−0.007, 0.057]  |
| Indirect Effect 1.3 | NVC–GVC → NVC → Resgreen         | −0.011 *    | 0.081           | [−0.024, 0.001]  |
| Direct Effect 1.3   | NVC–GVC → Resgreen (control NVC) | −0.027 ***  | 0.006           | [−0.047, −0.008] |
| Indirect Effect 1.4 | NVC–GVC → NVC → Polgreen         | 0.023 **    | 0.047           | [0.000, 0.046]   |
| Direct Effect 1.4   | NVC–GVC → Polgreen (control NVC) | 0.033 **    | 0.048           | [0.000, 0.065]   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ . NVC\_Pat\_f is further abbreviated as NVC.

#### 4.5.3. Environmental Protection Investment as a Mediator

Table 15 reports results with environmental protection investment (Envir) as the mediator. Regarding indirect effects, the coefficients for NVC–GVC → Envir → Green (0.032,  $p = 0.000$ ), NVC–GVC → Envir → Ecogreen (0.027,  $p = 0.000$ ), and NVC–GVC → Envir → Polgreen (0.017,  $p = 0.000$ ) are all highly significant and positive at the 1% level, with 95% confidence intervals that exclude zero. The NVC–GVC → Envir → Resgreen coefficient is −0.011 ( $p = 0.000$ ) and significantly negative. This is consistent with the overall sign pattern for Resgreen. Regarding direct effects, after controlling for Envir, the direct effect of NVC–GVC on all four dependent variables remains significant across all specifications, indicating partial mediation. These results confirm that NVC–GVC coupling coordination raises regional green development levels by incentivizing greater environmental protection investment; the indirect effect is robust and highly significant, supporting Hypothesis H3b.

**Table 15.** Bootstrapping test 3.

| Effect Type         | Path                               | Coefficient | <i>p</i> -Value | 95% CI           |
|---------------------|------------------------------------|-------------|-----------------|------------------|
| Indirect Effect 3.1 | NVC–GVC → Envir → Green            | 0.032 ***   | 0.000           | [0.018, 0.047]   |
| Direct Effect 3.1   | NVC–GVC → Green (control Envir)    | 0.043 **    | 0.026           | [0.005, 0.082]   |
| Indirect Effect 3.2 | NVC–GVC → Envir → Ecogreen         | 0.027 ***   | 0.000           | [0.016, 0.037]   |
| Direct Effect 3.2   | NVC–GVC → Ecogreen (control Envir) | 0.032 ***   | 0.004           | [0.010, 0.054]   |
| Indirect Effect 3.3 | NVC–GVC → Envir → Resgreen         | −0.011 ***  | 0.000           | [−0.016, −0.006] |
| Direct Effect 3.3   | NVC–GVC → Resgreen (control Envir) | −0.028 ***  | 0.000           | [−0.042, −0.014] |
| Indirect Effect 3.4 | NVC–GVC → Envir → Polgreen         | 0.017 ***   | 0.000           | [0.009, 0.024]   |
| Direct Effect 3.4   | NVC–GVC → Polgreen (control Envir) | 0.039 ***   | 0.001           | [0.017, 0.061]   |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

#### 4.5.4. Industrial Structure Upgrading as a Mediator

Table 16 reports results with industrial structure upgrading (Isu) as the mediator. Regarding indirect effects, the coefficients for NVC–GVC → Isu → Green (0.035,  $p = 0.003$ ), NVC–GVC → Isu → Ecogreen (0.025,  $p = 0.002$ ), and NVC–GVC → Isu → Polgreen (0.014,  $p = 0.003$ ) are all significant and positive at the 1% level. The NVC–GVC → Isu → Resgreen coefficient is  $-0.005$  ( $p = 0.002$ ) and significantly negative. Regarding direct effects, after controlling for Isu, the direct effect of NVC–GVC on all four dependent variables remains highly significant at the 1% level, confirming partial mediation across all dimensions. These results indicate that NVC–GVC coupling coordination promotes regional green development by driving industrial structure toward higher end, less resource-intensive sectors, effectively reducing the dependence of economic growth on resource consumption and pollution emissions. Hypothesis H3c is supported.

**Table 16.** Bootstrapping test 4.

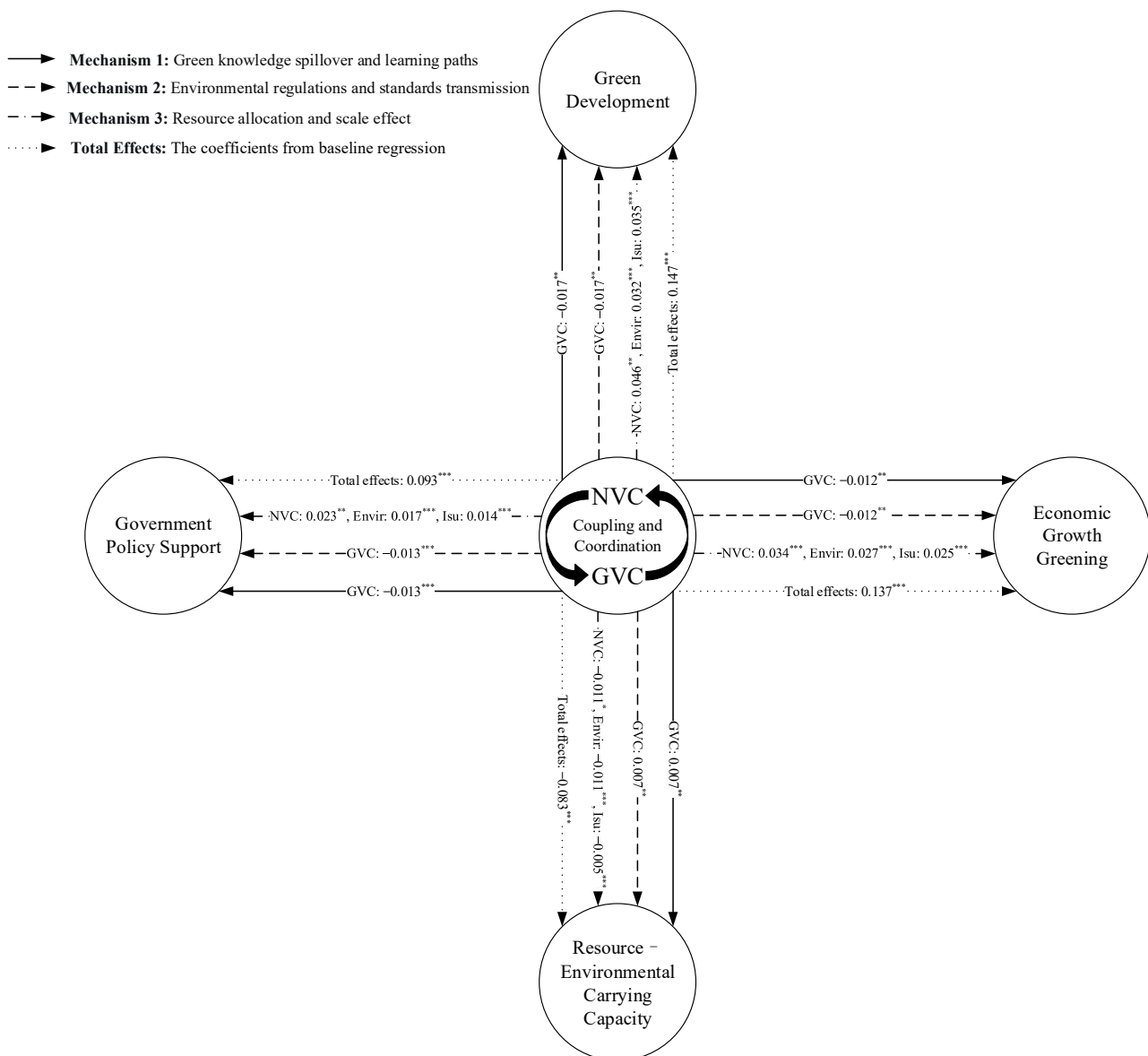
| Effect Type         | Path                             | Coefficient  | $p$ -Value | 95% CI                  |
|---------------------|----------------------------------|--------------|------------|-------------------------|
| Indirect Effect 4.1 | NVC–GVC → Isu → Green            | 0.035 ***    | 0.003      | [0.012, 0.057]          |
| Direct Effect 4.1   | NVC–GVC → Green (control Isu)    | 0.041 ***    | 0.008      | [0.011, 0.072]          |
| Indirect Effect 4.2 | NVC–GVC → Isu → Ecogreen         | 0.025 ***    | 0.002      | [0.009, 0.041]          |
| Direct Effect 4.2   | NVC–GVC → Ecogreen (control Isu) | 0.034 ***    | 0.000      | [0.017, 0.051]          |
| Indirect Effect 4.3 | NVC–GVC → Isu → Resgreen         | $-0.005$ *** | 0.002      | [ $-0.007$ , $-0.002$ ] |
| Direct Effect 4.3   | NVC–GVC → Resgreen (control Isu) | $-0.034$ *** | 0.000      | [ $-0.048$ , $-0.021$ ] |
| Indirect Effect 4.4 | NVC–GVC → Isu → Polgreen         | 0.014 ***    | 0.003      | [0.005, 0.023]          |
| Direct Effect 4.4   | NVC–GVC → Polgreen (control Isu) | 0.042 ***    | 0.000      | [0.020, 0.063]          |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

Table 17 summarizes the direction of each mediating effect and the type of mediation across all four channels, and Figure 2 depicts the three mediating mechanisms and total effect framework. As Table 17 shows, NVC\_Pat\_f exerts full mediation on Green and Ecogreen and partial mediation on Resgreen and Polgreen. GVC\_Pat\_f, Envir, and Isu all display partial mediation across all four green development dimensions. These results collectively corroborate the theoretical logic of NVC–GVC coupling coordination affecting regional green development through multiple channels.

**Table 17.** Mediating effects.

| Variables |   | Green              |   | Ecogreen           |   | Resgreen          |   | Polgreen          |
|-----------|---|--------------------|---|--------------------|---|-------------------|---|-------------------|
| NVC_Pat_f | + | Complete mediation | + | Complete mediation | – | Partial mediation | + | Partial mediation |
| GVC_Pat_f | – | Partial mediation  | – | Partial mediation  | + | Partial mediation | – | Partial mediation |
| Envir     | + | Partial mediation  | + | Partial mediation  | – | Partial mediation | + | Partial mediation |
| Isu       | + | Partial mediation  | + | Partial mediation  | – | Partial mediation | + | Partial mediation |
| NVC–GVC   |   | +                  |   | +                  |   | –                 |   | +                 |



**Figure 2.** Three mediating mechanisms and total effect framework. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

#### 4.6. Discussion

The empirical results provide support—or partial support—for all five hypotheses, while also surfacing several complexities that merit deeper discussion.

##### 4.6.1. Core Findings and Aggregate Effect

The baseline regression (Table 5) and the full battery of robustness checks (Tables 6–11) consistently indicate that NVC–GVC coupling coordination exerts a significant and positive effect on Green, Ecogreen, and Polgreen, whereas it exerts a significant and negative effect on Resgreen. The 2SLS endogeneity test (Table 12) further confirms this causal relationship, supporting Hypothesis H1. These findings indicate that, over the sample period (2012–2017), dual chain coupling coordination in Chinese manufacturing has yielded tangible gains in greening the economy and strengthening policy responsiveness, while simultaneously exerting transitional pressure on natural resource and environmental carrying systems.

#### 4.6.2. Sign Reversals in the Robustness Check: Identifying Variation and Dimensional Heterogeneity

A notable finding is the sign reversal in the coefficients on NVC–GVC coupling coordination for Ecogreen and Resgreen after adding province fixed effects (Table 11, Models 2.6 and 3.6). This reversal does not invalidate the core conclusions; rather, it illuminates the economic implications of alternative identification strategies.

The first economic implication is the change in identifying variation. The baseline regression exploits variation both across provinces (between province) and within individual provinces over time (within province). Adding province fixed effects restricts identification strictly to within-province temporal variation, purging the systematic cross-sectional differences (in factor endowments, industrial foundations, and policy environments) that distinguish provinces. Models 2.6 and 3.6 thus capture the within-province, year-to-year change in NVC–GVC coupling coordination and its net effect on Ecogreen and Resgreen—a fundamentally different object of inference from the cross-provincial comparison embedded in the baseline.

The second economic implication is the divergence between cross-provincial patterns and within-province dynamics. The sign reversals imply that, in cross-provincial comparisons, provinces with higher NVC–GVC coupling coordination tend to display higher Ecogreen and lower Resgreen. In within-province temporal dynamics, however, a short-run increase in coupling coordination may marginally depress Ecogreen by accelerating industrial activity and increasing resource consumption, while simultaneously improving Resgreen by incentivizing environmental technology adoption and governance investment. The cross-provincial effect reflects long-run systemic advantages; the within-province temporal effect captures transitional pressures in dynamic adjustment. The distinct behavior of these two effects across the Ecogreen and Resgreen dimensions reflects an inherent tension between cross-provincial structural differences and short-run within-province dynamics, a manifestation of the dimensional heterogeneity in how NVC–GVC coupling coordination affects green development, warranting further investigation. Crucially, the coefficients on Green and Polgreen retain their sign and merely narrow in magnitude after province fixed effects are added, confirming that the overall positive effect of NVC–GVC coupling coordination on green development is robust.

#### 4.6.3. Coupling Degree vs. Coordination Index: Coordination Matters More than Coupling

Robustness Check 2 (Table 7) shows that the coupling degree  $C$  produces significantly negative coefficients for Green, Ecogreen, and Polgreen—exactly the opposite sign to the coordination index  $T$  and the coupling coordination degree  $D$ . Far from being contradictory, this result validates the adoption of the coupling coordination model.

Statistically, the sign reversal is consistent with the significant negative correlation between  $T$  and  $C$  ( $b = -0.325$ ,  $p < 0.01$ ) documented in the correlation matrix (Table 3). Economically, the coupling degree  $C$  measures only the intensity of the interaction between NVC and GVC, without capturing the coherence of their developmental trajectories or the rationality of resource allocation between them. In the early stages of China's manufacturing development, the NVC depended heavily on the GVC. Their interaction was frequent (high coupling), but the NVC was immature and coordination was low. As domestic industrial chains matured and both NVCs and GVCs developed in step with one another (rising  $T$ ), their mutual dependence may have declined, and competitive dynamics may even have emerged in certain domains, driving  $C$  downward. Consequently, raw high coupling (high  $C$ ) may signal dependence or competition rather than synergy, and may actually impede green development; high coordination (high  $T$ ), by contrast, represents genuine systemic synergy—the true engine of green progress. This finding powerfully

supports one of the paper's central arguments: the quality of co-ordination matters more than the intensity of coupling.

#### 4.6.4. Mediating Mechanisms: The NVC-Led Channel and the Dampening Effect of GVC

The bootstrap mediation results trace out three distinct mechanisms, which can be organized into two broad channels.

The first channel is the green knowledge spillover and environmental regulations transmission channel (GVC channel). GVC participation (GVC\_Pat\_f) mediates the effect of NVC–GVC coupling coordination with a significant negative partial indirect effect on Green, Ecogreen, and Polgreen, supporting Hypothesis H2. Of particular note, the GVC channel exhibits a positive indirect effect in the Resgreen dimension, implying that deepening GVC integration does, to a degree, expose Chinese manufacturers to internationally advanced green technologies and environmental standards and thereby improves the efficiency of ecological resource utilization. This is consistent with the theoretical expectation that GVC participation fosters green innovation. However, the upward compliance pressure imposed by lead firms raises the production costs of many manufacturers, and some may curtail capacity as a result. Furthermore, local governments may enforce international environmental regulations only selectively in order to protect employment and economic growth, further attenuating the positive transmission effects. In buyer-driven GVCs, lead firms capture the lion's share of value, while Chinese manufacturing suppliers face a dual bind of cost pressure and limited functional upgrading opportunities. In some cases, high pollution production stages may even be relocated to China under “pollution haven” dynamics, generating a net drag on overall green development performance [32]. This reflects the likelihood that, over the 2012–2017 sample period, Chinese manufacturing firms were still positioned in the mid-to-lower tier of GVCs—passive recipients whose green dividends from GVC engagement were insufficient to offset the competitive and compliance costs incurred.

The second channel is the resource allocation and scale effect channel (NVC-led channel). NVC\_Pat\_f fully mediates the effect of NVC–GVC coupling coordination on Green and Ecogreen and partially mediates the effect on Resgreen and Polgreen. Envir and Isu partially mediate the effect across all four green development dimensions. NVC\_Pat\_f, Envir, and Isu all generate significant positive indirect effects on Green, Ecogreen, and Polgreen as well as significant negative indirect effects on Resgreen. Hypotheses H3a, H3b, and H3c are all supported. This highly consistent sign pattern strongly supports interpreting these three mediators as components of a unified “resource allocation and scale effect” mechanism. Specifically, NVC deepening drives the reallocation of regional productive factors, promotes structural upgrading toward higher value added, lower pollution industries (Isu), and incentivizes environmental investment (Envir) by both local governments and firms. This process raises the greenness of economic growth and the intensity of policy support while, in the short run, crowding out environmental carrying capacity as industrial expansion and resource consumption accelerate. This is consistent with the broader GVC literature's observation that upgrading often entails short-run costs and trade-offs [30,57].

Taken together, the evidence indicates that over the 2012–2017 sample period, the effect of NVC–GVC coupling coordination on green development in Chinese manufacturing is dominated by the positive impetus of the resource allocation and scale effect mechanism (NVC-led channel), overlaid by the negative dampening of the green knowledge spillover and environmental regulations transmission mechanism (GVC channel). The net aggregate effect is positive, but it is accompanied by pressure on resource–environmental carrying capacity. This finding reflects China's current development stage. Rapid expansion of

domestic circulation improves green economic performance and policy responsiveness but also increases short-term resource and environmental pressure in the absence of effective green governance. This suggests that expanding NVC–GVC coordination alone does not ensure ecological sustainability. Instead, value chain upgrading must be combined with targeted green governance to achieve both economic and environmental gains. These results have important policy implications and suggest directions for future research, discussed in Section 5.

## 5. Conclusions and Future Research

This study investigates the causal effects and mechanisms through which the coupling coordination of national value chains and global value chains shapes green development in Chinese manufacturing. By quantifying NVC–GVC coupling coordination and applying a suite of econometric tools, including high-dimensional fixed effects estimation, two-stage least squares, and bootstrap mediation tests, the analysis yields a rich set of findings that provide novel empirical evidence and theoretical insight into the dynamics of green development in Chinese manufacturing under the new development paradigm.

### 5.1. Conclusions and Theoretical Implications

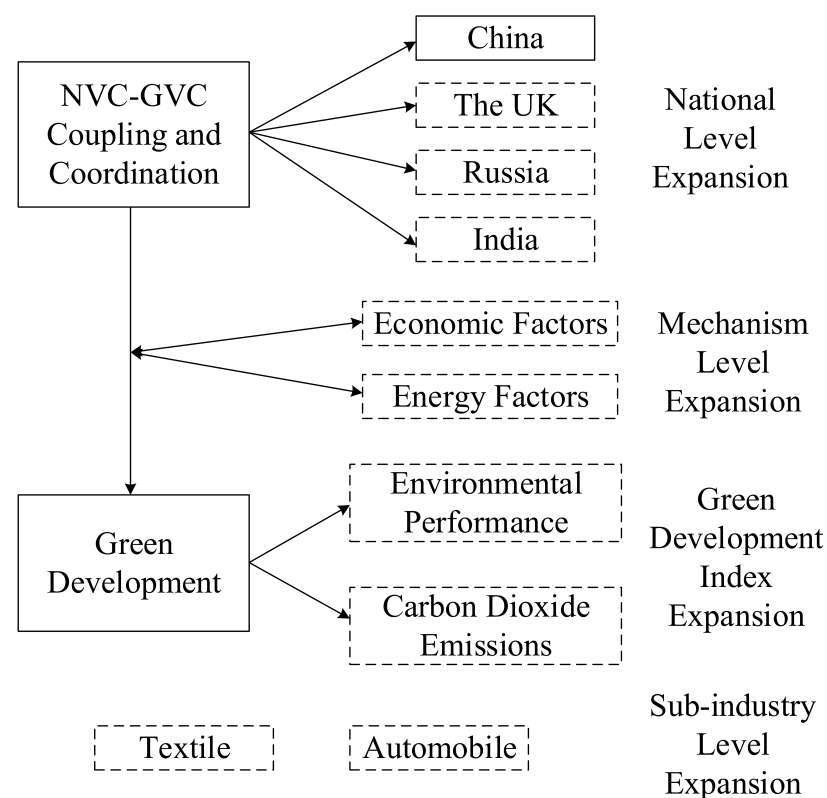
The paper establishes the following. First, NVC–GVC coupling coordination in Chinese manufacturing significantly promotes regional green development, economic green transition, and environmental policy intensity while weakening regional resource–environmental carrying capacity. Second, this effect is driven by coordination and not by coupling intensity, the sign of whose effect is opposite to that of the main finding. Third, three mediating mechanisms govern how NVC–GVC coupling coordination affects green development. Specifically, the resource allocation and scale effect mechanism aligns in sign with the main effect, while the green knowledge spillover and learning paths mechanism and the environmental regulations and standards transmission mechanism each operate in the opposite direction. In the current Chinese context, the NVC\_Pat\_f-led resource allocation and scale effect mechanism is dominant. This NVC-led finding implies that, when assessing the systemic influence of dual value chain dynamics on green development, the “quality of coordination” is more explanatory than the “intensity of interaction.” Furthermore, to our knowledge, this study is the first to propose reliable instrumental variables suitable for identifying the causal effect of NVC–GVC coupling coordination on green development, thereby opening a new avenue for causal inference from this vantage point.

### 5.2. Policy Recommendations

Returning to the bench-press analogy, the findings reveal a pronounced “right-arm dominance” in the way NVC–GVC coupling coordination drives green development in Chinese manufacturing: NVC participation and the resource allocation and scale effect mechanism it carries constitute the primary source of impetus. By contrast, the green knowledge spillover and environmental regulatory effects transmitted through GVC participation have yet to generate sufficient positive traction over the sample period. This implies that China’s manufacturing dual chain coupling currently operates in a “right-handed” mode. Future policy priorities should shift toward “strengthening the left hand”, that is, enhancing the positive green-development transmission capacity of GVC participation and guiding the dual chains from their current dominant–subordinate arrangement toward a more balanced and mutually reinforcing bilateral synergy.

### 5.3. Limitations and Future Research

The model specification retains only four core control variables (wastewater treatment capacity, waste gas emissions, solid waste recycling, and industrial water use). This parsimonious approach is designed to keep the focus on the total effect of NVC–GVC coupling coordination and to avoid over-controlling mediating pathways that would obscure the true causal chain. Green development is, however, shaped by a complex array of factors. Future research can advance along five dimensions. First, at the country level, the analysis will be extended to three additional countries, including the United Kingdom, Russia, and India. Second, at the mechanism level, future work will examine the potential mediating roles of economic and energy-side factors such as energy structure and capital intensity in the pathway from NVC–GVC coupling coordination to green development. Third, at the level of green development indicators, the impact and mechanisms of NVC–GVC coupling coordination on environmental performance and carbon emissions will be examined. Fourth, at the industry level, the relationship between NVC–GVC coupling coordination and green development in key sectors such as textiles and automotive will be studied. Fifth, regarding effect heterogeneity, future research will investigate the dimensional heterogeneity in how NVC–GVC coupling coordination affects green development in greater depth. We also encourage scholars to pursue further investigations along multiple dimensions to deepen our collective understanding of the green development effects of dual value chain synergy. Avenues for future research are illustrated in Figure 3.



**Figure 3.** Future research directions.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/systems14070765/s1>, including all Stata datasets and do-files.

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**Data Availability Statement:** Upon acceptance of this manuscript, all Stata datasets and do-files employed in the empirical analysis will be made publicly available in a GitHub repository at [<https://github.com/Songkaiyang/NVC-GVC-and-green-development-Chinese-manufacturing-industry>] (accessed on 5 June 2026). Further inquiries can be directed to the first author (Kaiyang Song). The raw data of the national value chain presented in the study are openly available in [CEADs database] at [<https://www.ceads.net.cn/data/input-output-tables/provincial/>] (accessed on 5 June 2026). The raw data of the global value chain presented in the study are openly available in [OECD database] at [<https://www.oecd.org/en/data.html>] (accessed on 5 June 2026). The raw data of labor and industrial water use presented in the study are openly available in [the CEInet Statistics Database] at [<https://db.cei.cn/jsps/Home>] (accessed on 5 June 2026) and [China Industry Economic Statistical Yearbook] at [<https://www.stats.gov.cn/sj/ndsj/>] (accessed on 5 June 2026). The raw data of environmental protection investment, wastewater treatment capacity, waste gas emissions, and solid waste recycling presented in the study are openly available in [the CEInet Statistics Database] at [<https://db.cei.cn/jsps/Home>] (accessed on 5 June 2026) and [China Environmental Statistical Yearbook] at [<https://www.stats.gov.cn/sj/ndsj/>] (accessed on 5 June 2026).

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