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The Impact of Green Supply Chain Pressures on Corporate Sustainability: The Role of Resource-Intensive Pathways and Financial Constraints

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Abstract

Despite growing interest in sustainable supply chains, we still know relatively little about how environmental requirements transmitted from key customers along the supply chain affect firms' productivity and long-run economic sustainability. To address this gap, we introduce the notion of green supply chain pressure, downstream customers' explicit green and low-carbon requirements on suppliers, and examine its implications for firm-level productivity and the mechanisms involved. Using a panel of Chinese A-share listed firms over 2014–2024, we construct a novel text-based index of green supply chain pressure by combining supply-chain relationship data with MD&A disclosures of major customers. Firm-level economic sustainability is measured by Levinsohn–Petrin total factor productivity, with Olley–Pakes estimates used for robustness. Fixed-effects regressions with industry–year and city–year controls show that stronger green supply chain pressure is associated with significantly higher productivity. Mediation analysis reveals that this effect operates partly through three resource-intensive adjustment channels: (i) a higher share of green patents in total innovation, (ii) capital deepening via a higher share of digital and intelligent fixed assets in total net fixed assets, and (iii) human capital upgrading through a larger proportion of highly educated employees. Interaction models further indicate that financing constraints critically condition these gains: the productivity effect of green supply chain pressure is stronger for firms with greater financial slack, and for high-tech, green-attribute and larger firms. Overall, the results highlight supply chain-based governance as a powerful complement to formal regulation for promoting long-run economic sustainability at the firm level.

Keywords: green supply chain pressure; sustainability; total factor productivity; green innovation; capital deepening; financing constraints

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1. Introduction

Climate change and ecological degradation have pushed sustainability to the centre of the global development agenda [1–4]. While global scenarios highlight the necessity of greening complex supply networks [5–8], a critical mechanism remains under-explored: how environmental requirements are transmitted as a market-based signal from downstream customers to upstream suppliers. Green supply chain pressure (GSP), defined as the intensity of environmental and green requirements transmitted by downstream customers, represents a powerful yet distinct driver of firms' sustainability-related adjustments.

Against this backdrop, firms increasingly face the dual challenge of maintaining competitiveness while responding to these multi-dimensional sustainability pressures along their supply chains.

Despite growing interest in sustainable supply chains, there remains a significant gap in the literature. From a theoretical perspective, while the natural-resource-based view (NRBV) [9] and the Porter hypothesis [10–12] provide foundations for understanding environmental performance, most existing work has focused on direct environmental regulation or internal management [13]. We argue that GSP represents a unique "demand-side" pressure that triggers productivity-enhancing adjustments, yet micro-level econometric evidence on its impact on economic sustainability—specifically total factor productivity (TFP)—is still limited.

Sustainable supply chain management (SSCM) research fills part of this gap by emphasising the integration of environmental objectives into operations [14,15]. Early empirical studies on green supply chain management (GSCM) document that practices like green purchasing can improve performance [16–20]. However, a critical limitation of previous GSCM studies is their reliance on survey-based measures of internal practices or self-reported orientations. This article addresses this gap by directly capturing the pressure transmission mechanism from customers to suppliers using a novel text-based approach, moving beyond the network-level understanding of sustainability [21,22] to quantify firm-level TFP outcomes. In the Chinese context, the 2030 carbon peak and 2060 neutrality targets have catalyzed policies promoting circular economies and green supply chains [6,23]. While empirical work suggests environmental regulations can enhance green innovation and productivity [24,25], research on the micro-level transmission of green requirements through customer–supplier links remains scarce. Furthermore, most studies prioritize environmental performance or green TFP rather than firm-level TFP as a holistic measure of economic sustainability. The mechanisms linking green supply chain pressure to performance are also insufficiently understood. Theories like NRBV and directed technical change suggest that environmental pressures induce investments in green innovation, equipment upgrades, and human capital [9,11,12]. However, these resource-intensive adjustments require significant financial capacity; constrained firms may resort to low-cost compliance that fails to yield productivity gains [6]. Evidence is lacking on how these three pathways, innovation, capital, and skill, interact with financing constraints to shape productivity outcomes. This paper addresses these gaps by analyzing the impact of downstream green supply chain pressure on the corporate sustainability of Chinese A-share listed firms (2014–2024). We construct a novel firm-level measure using text analysis of customer firms' MD&A disclosures. Utilizing a high-dimensional fixed-effects model, we find that green pressure significantly enhances TFP. We open the black box "by conceptualizing the firm-level response through the lens of resource-intensive pathways." This overarching construct encompasses three distinct but interrelated mechanisms: green technological innovation, capital deepening, and human capital upgrading. We argue that these pathways are inherently resource-intensive as they require significant long-term capital commitment, high-cost equipment reconfiguration, and the acquisition of specialized expertise. Our empirical results demonstrate that green innovation, capital deepening, and human capital upgrading each partially mediate this effect. Finally, we show that the ability of firms to navigate these resource-intensive pathways is critically contingent upon their financial slack, as well as their intrinsic technological attributes. Our study makes several contributions. First, we shift the focus from internal practices to externally imposed demand-side pressures in an emerging-market context. Second, we use TFP to evaluate "win–win" outcomes for both the environment and economic productivity [10,20]. Third, by modeling specific resource-intensive pathways and the moderating role of financing, we enrich the NRBV

framework to explain why some firms successfully leverage green supply chain pressure while others do not.

2. Literature Review and Hypotheses Development

2.1. Theoretical Foundations and Green Supply Chain Pressure

Corporate sustainability research has increasingly emphasized that sustained competitive advantage depends not only on physical and financial capital, but also on strategic resources such as technology, organizational capabilities and stakeholder relationships [9,26]. We synthesize the natural-resource-based view (NRBV) and the Porter hypothesis within the sustainable supply chain management (SSCM) framework [14,15] to conceptualize how Green Supply Chain Pressure (GSP) drives economic sustainability. Under this synthesized lens, GSP is not merely an external cost; it acts as a relational and institutional catalyst that triggers the activation of path-dependent environmental capabilities.

Specifically, while NRBV suggests that pollution prevention and product stewardship constitute strategic resources [9], the Porter hypothesis provides the mechanism through which external pressures, like GSP, stimulate the innovation necessary to offset compliance costs and enhance productivity [10,27]. Empirically, early work by Klassen and Whybark and Zhu and Sarkis [16] laid the foundation for linking environmental practices to efficiency. GSP, manifested through stakeholder expectations, pushes firms to build dynamic capabilities and environmental management systems [17,28,29]. By integrating these perspectives, we argue that GSP serves as a composite signal [30] encouraging firms to reallocate resources toward cleaner technologies, especially as green development policies in China interact with market pressures [31,32]. This transition, accelerated by post-pandemic calls for resilience [21,22], ultimately enhances firms' economic sustainability by reshaping their technological and capital structures.

2.2. Transmission Mechanisms: Green Innovation, Capital Deepening and Human Capital

2.2.1. Green Technological Innovation

Green innovation is recognized as a key mechanism through which environmental pressures influence productivity. Popp [11] and Acemoglu et al. [12] argue that well-designed environmental policies can induce innovation in energy-saving technologies, potentially generating "win–win" outcomes. Empirical evidence from China indicates that regulation promotes green invention patents [24], while credible enforcement is essential for the growth of utility-model patents [33]. Recent studies extend this by examining complex institutional risks. For example, Ding [34] demonstrates that climate transition risk, proxied by sensitivity to public attention, influences corporate green innovation through R&D investment channels. In the supply chain context, GSP specifically spurs product and process innovation aimed at reducing emissions and meeting downstream customers' low-carbon requirements [35,36]. When such innovations are successfully commercialized, they enhance TFP by improving input efficiency and reducing waste.

2.2.2. Capital Deepening and Reallocation

A second mechanism is capital deepening and factor reallocation. From a production-function perspective, TFP estimates implicitly capture efficiency improvements associated with better capital utilization [37,38]. While early research focuses on industrial-level upgrading [32], our study shifts the focus to the firm-level capital structure. GSP encourages investments in specialized assets and digital monitoring systems to support clean logistics [29]. Firms facing strong green requirements tend to increase their capital intensity in digital and intelligent assets, which improves productivity through better process visibility and more efficient resource allocation [35].

2.2.3. Green Human Capital and Organizational Capabilities

The NRBV emphasizes that capabilities for sustainable development are rooted in organizational processes and employee skills [9]. Green human capital refers to employees' knowledge and attitudes related to sustainability [39]. Specifically, Zhu et al. [40] find that green training and green leadership are positively associated with innovation and financial outcomes. Under strong GSP, firms may hire specialized personnel, such as environmental engineers or carbon accountants, and adjust incentive schemes to reward low-carbon behavior. These efforts enhance performance by improving process control and fostering cross-functional collaboration. In the long run, the accumulation of green human capital becomes a critical intangible asset supporting sustained productivity [26,40].

2.3. Financing Constraints as a Boundary Condition

Financing constraints critically shape firms' responses to supply-chain pressures. Traditional measures capture financing frictions through distinct lenses: the KZ index focuses on investment–cash flow sensitivities [41], the WWindex incorporates firm-specific R&D risks [42], while the SA index offers a size-and-age-based alternative [43]. When constraints are tight, firms may be unable to undertake long-horizon, high-risk green investments. A growing literature examines how green credit policies and digital finance interact with these frictions. Evidence suggests that green credit can mitigate financing constraints for high-pollution enterprises [44,45], while fintech development facilitates investment in green projects [46]. These findings imply that the impact of GSP on economic sustainability is conditioned by the financing environment. Under severe constraints, GSP may force firms to prioritize compliance-heavy, low-innovation responses, potentially crowding out productive investment [24,44].

2.4. Hypotheses Development

2.4.1. Green Supply Chain Pressure and Corporate Sustainability

According to the Porter Hypothesis, properly designed environmental pressures can trigger "innovation offsets" that more than compensate for compliance costs, eventually enhancing firm productivity [10]. In the context of supply chains, green supply chain pressure (gsp) acts as a critical market-based signal transmitted from downstream customers to upstream suppliers. From the perspective of the Natural Resource-Based View (NRBV), firms gain competitive advantages by managing their relationships with the natural environment. When major customers demand green standards, it reduces information asymmetry regarding future market trends, encouraging suppliers to reconfigure their internal processes to meet these ecological requirements. This proactive adjustment allows firms to optimize resource allocation, reduce waste-related inefficiencies, and ultimately enhance their corporate sustainability as measured by total factor productivity (TFP). Thus, we propose:

Hypothesis 1 (H1). *Green supply chain pressure has a positive impact on firms' economic sustainability, as measured by total factor productivity.*

2.4.2. The Mediating Role of Resource-Intensive Pathways

We argue that the transition from external pressure to internal productivity gains is not automatic; rather, it requires substantive resource commitments through three distinct pathways.

Green Technological Innovation.

Environmental requirements from customers often exceed current technical capabilities, necessitating R&D investments in green products and processes. Unlike symbolic

compliance, substantive green innovation allows firms to internalize environmental externalities and achieve systemic operational efficiencies [11,24].

Capital Deepening.

As downstream requirements shift toward low-carbon and circular production, firms must upgrade their physical asset base. This process, often referred to as capital deepening, involves replacing legacy equipment with intelligent, energy-saving, and digitalized production lines. Such asset reconfiguration improves the technical efficiency of the production function.

Human Capital Upgrading.

The complexity of green supply chain management, including carbon accounting and eco-design, requires a higher level of cognitive and technical skill. Following the logic of skill complementarity, the adoption of new green technologies must be matched by high-skill labor (e.g., environmental engineers and sustainability specialists) to fully realize productivity gains [9,47]. Combining these arguments, GSP incentivizes firms to mobilize financial and intellectual resources across these three pathways, which collectively serve as the transmission mechanism for productivity enhancement.

Hypothesis 2 (H2). *Green supply chain pressure positively affects firms' green technological innovation, capital deepening and human capital upgrading.*

Hypothesis 3 (H3). *Green technological innovation, capital deepening and human capital upgrading are positively associated with firms' total factor productivity.*

Hypothesis 4 (H4). *Green technological innovation, capital deepening and human capital upgrading jointly mediate the positive effect of green supply chain pressure on firms' total factor productivity.*

2.4.3. The Moderating Role of Financing Constraints

Finally, we contend that the efficacy of these resource-intensive pathways is contingent upon the firm's financial capacity. Transitioning toward green innovation and intelligent capital requires significant sunk costs and long-term capital commitment with high uncertainty. According to Financial Constraint Theory, when firms face high external financing costs or low internal liquidity, they may be forced to adopt low-cost, symbolic compliance strategies rather than the radical, resource-heavy adjustments necessary for productivity gains [41,44]. Therefore, financial slack acts as a critical buffer that allows firms to effectively navigate the pressures of green supply chains.

Hypothesis 5 (H5). *Financing constraints negatively moderate the relationship between green supply chain pressure and firms' total factor productivity.*

3. Materials and Methods

3.1. Sample Construction and Data Sources

This study focuses on Chinese A-share listed firms over the period 2014–2024. The sample period begins in 2014 to coincide with the significant overhaul of China's Environmental Protection Law. Passed in 2014, this legislation marked a fundamental shift in corporate environmental accountability and intensified green supply chain signals. We focus on firms listed on the Shanghai and Shenzhen stock exchanges as they represent the backbone of China's capital market, ensuring high-quality and standardized disclosure of Management Discussion and Analysis (MD&A) reports necessary for our analysis.

We obtain firm-level accounting and market data from the China Stock Market and Accounting Research (CSMAR) database and the WIND database. We exclude (i) financial firms, (ii) firms designated as ST (Special Treatment, indicating financial abnormalities for two consecutive years) or *ST (indicating a risk of being delisted), as their abnormal operating status and financial distress could lead to biased estimates of productivity (TFP), and (iii) firm-year observations with missing information on total factor productivity (TFP), green supply chain pressure (GSP) or key control variables. After merging all data sources and cleaning the sample, we obtain an unbalanced panel of 4017 firm-year observations. The use of an unbalanced panel allows for the inclusion of firms that entered or exited the market during the sample period, thereby mitigating potential survivorship bias and ensuring a more representative analysis of the Chinese A-share market.

Supply chain relationship data are drawn from the CSMAR supply–chain database, which discloses the major customers and suppliers of each listed firm. For each upstream supplier i in year t, we identify all disclosed downstream customers and link them to their annual reports. Firm-level patent information used to construct technological innovation variables is obtained from the CNRDS patent database. Information on employee education structure and wage costs is collected from firms' annual reports and the CSMAR compensation and human capital sub–databases. All continuous variables are winsorized at the 1st and 99th percentiles at the yearly level to mitigate the influence of outliers. All statistical analyses and regression model estimations were performed using Stata 18.

3.2. Variable Construction

3.2.1. Economic Sustainability: Total Factor Productivity

We use firm-level total factor productivity (TFP) as the core outcome variable, interpreted as a measure of economic sustainability. Following Levinsohn and Petrin [38], we estimate TFP using the Levinsohn–Petrin (LP) semi-parametric production function approach, which uses intermediate inputs to control for unobserved productivity shocks and thus alleviates the simultaneity bias inherent in ordinary least squares estimation of production functions. Specifically, we assume a Cobb–Douglas production function in value added and use the logarithms of capital stock, labor input and intermediate inputs as explanatory variables. The resulting TFP estimate is denoted by tfp and serves as the baseline dependent variable. For robustness, we also estimate TFP using the Olley–Pakes (OP) method [37], which uses investment as a proxy for unobserved productivity and explicitly models firm entry and exit.

3.2.2. Green Supply Chain Pressure

Our key explanatory variable is Green Supply Chain Pressure (gsp), capturing the intensity of environmental and green requirements transmitted from downstream customer firms to their upstream suppliers. Conceptually, we view GSP as a form of external, demand-side pressure rather than simply a measure of a firm's own "greenness". When core customers place strong emphasis on green supply chain management and environmental responsibility in their disclosures, they are more likely to impose strict environmental standards and green procurement requirements on their suppliers [30,48,49].

To ensure the scientific rigor and transparency of the gsp index, we construct the variable through a systematic two-stage validation process. First, we develop a comprehensive dictionary of Chinese keywords and multi-word expressions. We initially identify a seed word list based on authoritative official documents issued by the Ministry of Industry and Information Technology (MIIT), primarily the "Guidelines for the Construction of the Green Manufacturing System" and the "Evaluation Indicator System for Green Supply Chain Management Enterprises". We then calibrate and expand this dictionary by performing

word frequency and co-occurrence analysis on a pilot set of MD&A disclosures from firms with leading green rankings (e.g., those in the CSI Green Index) to identify high-frequency synonyms and industry-specific contextual expressions (e.g., "carbon neutrality", "green procurement", and "circular economy") that are semantically aligned with the seed words. This dual approach ensures the vocabulary captures both the formal regulatory framework and the practical language used in corporate supply chain communications [50].

Second, for each customer firm-year, we compute the total frequency of green supply chain-related keywords in the MD&A text and take the natural logarithm of one plus this frequency. For each supplier i in year t, we then aggregate the green disclosure of all downstream customers using the sales–share–weighted average across disclosed major customers:

$$gsp_{it} = \sum_{j \in C(i,t)} \omega_{ij,t} \ln\left(1 + GreenWords_{jt}\right), \quad (1)$$

where i and t denote the supplier firm and the fiscal year, respectively; $C(i, t)$ represents the set of major downstream customers of supplier i in year t; j denotes an individual customer within that set; $\omega_{ij,t}$ is the sales share of customer j relative to supplier i's total sales in year t; and GreenWords_{jt} is the raw count of green keywords identified in the MD&A of customer j.

The decision to weight *gsp* by sales share is theoretically anchored in Resource Dependence Theory (RDT) [51]. According to RDT, the bargaining power of a customer is functionally dependent on the supplier's economic reliance on that customer for critical revenue. A customer accounting for a larger sales share represents a vital resource for survival, thereby exerting stronger and more effective green pressure on the supplier's strategic adjustments [52,53]. For robustness, we also re-estimate our baseline model using an unweighted average of the top five customers' green disclosures (reported in the robustness section) to ensure that our results are not sensitive to the specific weighting scheme applied.

3.2.3. Resource-Intensive Pathways

To open the "black box" between GSP and corporate sustainability, we conceptualize the firm-level response as a set of resource-intensive pathways. This categorization is theoretically grounded in the Natural Resource-Based View (NRBV) and Resource Orchestration Theory, which posit that responding to complex environmental demands requires substantive resource commitments and the purposeful integration of specialized assets [54,55]. These pathways, green technological innovation, capital deepening, and human capital upgrading, are "resource-intensive" because they involve significant sunk costs, the reconfiguration of legacy physical assets, and high-cost specialized expertise. Recent empirical studies confirm that firms must move beyond "symbolic compliance" to achieve systemic efficiency gains, a process that necessitates the mobilization of financial and intellectual capital to navigate the technical complexities of green supply chains [56].

Green technological innovation (tech)

We measure firms' green technological innovation using patent–based indicators. For each firm-year, we identify green invention and utility–model patents according to the IPC Green Inventory and compute their share in the firm's total patent applications in year t.

$$tech_{it} = \frac{Green\ patents_{it}}{Total\ patents_{it}} \quad (2)$$

where $tech_{it}$ is the green innovation intensity of firm i in year t. The numerator, *Green patents*$_{it}$, is the number of green invention and utility-model patents, while the denominator, *Total patents*$_{it}$, is the total number of patent applications for firm i in year t.

Capital deepening (cap)

To capture capital deepening in a way that is consistent with our focus on green and digital transformation, we proxy cap using the intensity of specialised digital and green fixed assets. Based on the detailed breakdown of fixed assets in the notes to the financial statements, we first identify items such as "electronic equipment", "computer software", "information systems", "environmental monitoring and testing devices", and other energy saving or environmental protection equipment. We then aggregate their net book value as digital/green capital and define

$$cap_{it} = \frac{Digital/green\ \ fixed\ assets_{it}}{Total\ fixed\ assets_{it}} \tag{3}$$

where cap_{it} denotes the capital deepening level of firm i in year t. Digital/green fixed $assets_{it}$ represents the net book value of specialized environmental and digital equipment, and *Total fixed assets*$_{it}$ is the total net fixed assets of the firm.

Skill structure (skill)

Human capital upgrading is proxied by the proportion of employees with a college degree or above. This measure reflects the stock of high-skill labor capable of navigating the technical and organizational complexities associated with green transitions [47,57]. Based on detailed employee information disclosed in the notes to financial statements and corporate social responsibility reports, we compute:

$$skill_{it} = \frac{Number\ of\ employees\ college\ degree\ or\ above_{it}}{Total\ number\ of\ employees_{it}} \tag{4}$$

where $skill_{it}$ represents the human capital level of firm i in year t, defined as the proportion of the workforce holding a college degree or higher. In the context of green supply chain governance, highly educated employees, such as environmental engineers and sustainability specialists, are essential for interpreting complex downstream environmental requirements and implementing sophisticated green R&D projects. Recent evidence confirms that the concentration of highly educated human capital significantly enhances a firm's "absorptive capacity," allowing it to effectively convert external environmental pressures into internal productivity gains [47].

3.2.4. Financing Constraints

Financing constraints are expected to shape the extent to which firms can respond to green supply chain pressure. In our main analysis, we use the SA index [46] as the moderator, denoted by fc. The SA index is computed as

$$SA_{it} = -0.737 \times Size_{it} + 0.043 \times Size_{it}^2 - 0.040 \times Age_{it} \tag{5}$$

where $Size_{it}$ is the natural logarithm of the total assets of firm i in year t, and Age_{it} is the number of years firm i has been listed as of year t.

To examine the robustness of our findings to alternative proxies, we also construct the KZ and WW indices of financing constraints following the original literature [44,45]. The KZ index (*fc (kz)*) combines information on cash flow, Tobin's Q, leverage, cash holdings and dividends, while the WW index (*fc (ww)*) is built from firm size, cash flow, leverage,

industry sales growth and firm sales growth. For these two indices, higher values indicate tighter financing constraints.

3.2.5. Control Variables

In all regressions, we include a standard set of firm-level controls that may affect TFP and are potentially correlated with green supply chain pressure. We control for several firm-level characteristics: Leverage (*lev*), defined as total liabilities divided by total assets; Profitability (*roe*), measured as return on equity (net income divided by shareholders' equity); Growth (*grow*), the annual growth rate of total assets; Valuation (*val*), represented by the price-to-sales ratio; and Wage level (*wage*), the natural logarithm of average wage per employee. These variables are defined in Table 1.

Table 1. Variable Definitions.

Category	Variable Name	Symbol	Definition and Measurement
Dependent Variables	Total factor productivity (baseline)	*tfp*	Firm-level TFP estimated by the Levinsohn–Petrin (LP) method.
Dependent Variables	Total factor productivity (robustness)	*tfpo*	Firm-level TFP estimated by the Olley–Pakes (OP) method (used in robustness checks).
Key Explanatory Variable	Green supply chain pressure	*gsp*	Sales-weighted log frequency of green supply-chain keywords in downstream customers' MD&A.
Moderators: Financing Constraints	SA index	*fc (sa)*	SA index of financing constraints, SA = $-0.737 \times$ Size $+ 0.043 \times \text{Size}^2 - 0.040 \times$ Age; higher values (closer to zero) indicate lower constraints.
Moderators: Financing Constraints	KZ index	*fc (kz)*	Kaplan–Zingales (KZ) index [41]; higher values indicate tighter constraints.
Moderators: Financing Constraints	WW index	*fc (ww)*	Whited–Wu (WW) index of financing constraints [42]; higher values indicate tighter constraints.
Mechanism Variables	Green technological innovation	*tech*	Share of green invention and utility-model patents in a firm's total patent applications in year t.
Mechanism Variables	Capital deepening	*cap*	Ratio of digital/green fixed assets to total fixed assets; higher values indicate deeper capital deepening in green and digital assets.
Mechanism Variables	Skill structure	*skill*	Share of employees with a college degree or above.
Control Variables	Leverage	*lev*	Total liabilities divided by total assets.
Control Variables	Return on equity	*roe*	Net income divided by shareholders' equity.
Control Variables	Growth	*grow*	Year-on-year growth rate of total assets.
Control Variables	Valuation	*val*	Price-to-sales ratio.
Control Variables	Wage level	*wage*	Logarithm of average wage per employee.
Other Variables	Firm size	*size*	Logarithm of total assets.
Other Variables	Green subsidy	*subsidy*	Green subsidy income divided by total assets (instrument for gsp in IV-2SLS).
Other Variables	Inverse Mills ratio	*imr*	Inverse Mills ratio from the first-stage Probit selection (Heckman correction).

3.3. Empirical Strategy

3.3.1. Baseline Model

To estimate the impact of green supply chain pressure on firm-level economic sustainability, we specify the following baseline panel-data model:

$$tfp_{it} = \beta_0 + \beta_1 gsp_{it} + \gamma' X_{it} + u_i + \lambda_{s(t)} + \delta_{c(t)} + \varepsilon_{it} \quad (6)$$

where tfp_{it} is the LP-based TFP of firm i in year t, gsp_{it} is green supply chain pressure, X_{it} is the vector of control variables (*lev*, *roe*, *grow*, *val*, *wage*). Following established econometric practices [58,59], the selection of variables in X_{it} is grounded in economic theory regarding firm-level productivity. We retain all specified control variables regardless of their individual statistical significance (p-values) to ensure the internal validity of the model. This theory-driven approach allows us to maintain a consistent ceteris paribus condition and prevents omitted variable bias, which could otherwise occur if theoretically relevant factors were excluded based solely on empirical insignificance in a specific sample. μi denotes firm

fixed effects, $\lambda_{s(t)}$ are industry-year fixed effects (using the CSRC industry classification) and $\delta_{c(t)}$ are city-year fixed effects capturing local macroeconomic and regulatory shocks. Standard errors are clustered at the industry level, consistent with the structure of our main identification assumption.

3.3.2. Mediation Analysis: Resource-Intensive Pathways

To test whether GSP improves economic sustainability through the resource-intensive pathways of technological innovation, capital deepening and human capital upgrading, we adopt a standard panel mediation framework. For a generic mechanism variable $M_{it} \in \{tech_{it}, cap_{it}, skill_{it}\}$, we estimate:

$$M_{it} = \alpha_0 + \alpha_1 gsp_{it} + \phi' X_{it} + u_i + \lambda_{s(t)} + \delta_{c(t)} + u_{it} \quad (7)$$

$$tfp_{it} = \theta_0 + \theta_1 gsp_{it} + \theta_2 M_{it} + \psi' X_{it} + u_i + \lambda_{s(t)} + \delta_{c(t)} + e_{it} \quad (8)$$

Equation (7) captures the effect of GSP on the mechanism variable, while Equation (8) includes both GSP and the mechanism to assess the direct and indirect effects on TFP.

3.3.3. Moderation by Financing Constraints

To examine the financial boundary conditions under which green supply chain pressure exerts a stronger or weaker effect on TFP, we introduce an interaction between GSP and financing constraints:

$$tfp_{it} = \beta_0 + \beta_1 gsp_{it} + \beta_2 fc_{it} + \beta_3 (gsp_{it} \times fc_{it}) + \gamma' X_{it} + u_i + \lambda_{s(t)} + \delta_{c(t)} + \varepsilon_{it} \quad (9)$$

In our main specification, fc_{it} is the SA index: because higher SA values indicate fewer financing constraints, a positive β_3 implies that the positive effect of GSP on TFP is stronger for firms with more financial slack. For robustness, we re-estimate Equation (9) by replacing the SA index with the KZ and WW indices.

3.3.4. Heterogeneity and Robustness Design

We further explore cross-sectional heterogeneity by estimating the baseline model (6) in subsamples defined by (i) green attribute (green vs. brown firms), (ii) ownership (state-owned enterprises vs. non-SOEs), (iii) technological status (high-tech vs. non-high-tech firms), and (iv) firm size (above- vs. below-median).

Finally, we conduct a battery of robustness checks. These include: (1) replacing the LP TFP measure with OP-based TFP; (2) using lagged GSP to alleviate reverse causality concerns; (3) employing an IV–2SLS strategy with green subsidies as an instrument for GSP; (4) using 5–95% winsorization of continuous variables; and (5) augmenting the baseline model with an inverse Mills ratio from a Heckman selection model to address potential sample selection bias. Across these specifications, the estimated effect of green supply chain pressure on TFP remains positive and statistically significant, supporting the robustness of our main findings.

4. Empirical Results

4.1. Descriptive Statistics

Table 2 reports the descriptive statistics for the main variables after winsorizing all continuous variables at the 1st and 99th percentiles. The baseline measure of total factor productivity, *tfp* (Levinsohn–Petrin method), has a mean of 8.6248, while the alternative *tfpo* (Olley–Pakes method) shows a lower level but a similar distribution, suggesting that the results are not sensitive to the choice of TFP estimator. Green supply chain pressure (gsp)

averages 2.1765 and ranges from 0 to 5.0304, indicating significant cross-firm heterogeneity in the intensity of environmental requirements from downstream customers. For the mechanism variables, the means of green technological innovation (*tech*) and skill structure (*skill*) are between 0.4 and 0.5, implying a clear divide between firms with advanced green and human capital capabilities and those lagging behind, while capital deepening (*cap*) has a mean of 0.2314, reflecting varying degrees of digital asset upgrading. Other control variables, including financing constraints (*sa*), leverage (*lev*), and profitability (*roe*), all take economically plausible values with sufficient dispersion, providing a robust basis for the subsequent empirical regressions.

Table 2. Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
tfp	4017	8.6248	1.1755	6.3076	11.3109
tfpo	4017	6.8837	0.9707	4.9397	9.3719
gsp	4017	2.1765	1.3869	0	5.0304
sa	4017	−3.5343	1.1428	−4.9559	0
tech	4017	0.5113	0.3996	0	0.9857
cap	4017	0.2314	0.1479	0	0.8247
skill	4017	0.3875	0.3001	0	0.9939
lev	4017	0.4407	0.2097	0.0502	0.9287
roe	4017	0.0662	0.1491	−0.9051	0.3855
grow	4017	0.2268	0.4258	−0.2313	2.6748
val	4017	3.5804	4.7096	0	27.0741
wage	4017	11.6241	0.5663	10.3062	13.0618

4.2. Correlation Matrix

Table 3 presents the pairwise Pearson correlation coefficients between the main variables. The overall magnitude of these correlations is relatively modest, with most coefficients remaining below 0.4, which alleviates concerns regarding potential multicollinearity in the subsequent regression analysis. Notably, total factor productivity (*tfp*) is positively correlated with green supply chain pressure (*gsp*), financing capacity (*sa*), and the mechanism variables (*tech*, *cap*, and *skill*), while being negatively associated with valuation (*val*). These patterns suggest that firms facing higher environmental requirements and possessing stronger resource endowments tend to exhibit higher productivity. The key explanatory variable, *gsp*, shows a positive correlation with both *tfp* and *sa*, providing preliminary evidence for our core hypothesis. Furthermore, the moderate correlations among the mechanism variables and other controls support their joint inclusion in the empirical model as distinct channels and necessary covariates.

Table 3. Correlation Matrix.

Variable	tfp	gsp	fc	tech	cap	skill	lev	roe	grow	val	wage
tfp	1										
gsp	0.1148	1									
sa	0.3559	0.1651	1								
tech	0.3456	0.0881	−0.1231	1							
cap	0.1445	0.0887	0.3533	−0.0507	1						
skill	0.2661	−0.0038	0.191	0.1596	0.1684	1					
lev	0.2206	0.0742	0.0071	0.0329	−0.0284	0.0378	1				
roe	0.0478	0.0218	0.022	0.0159	0.007	−0.0014	−0.0361	1			
grow	0.0046	−0.0233	−0.022	0.008	−0.0087	−0.0243	−0.0174	0.0023	1		
val	−0.395	−0.069	−0.1547	−0.0391	−0.0229	−0.0525	−0.1972	−0.0198	0.0144	1	
wage	0.3896	0.1673	0.1385	0.2311	0.1354	0.3085	−0.0305	0.0275	−0.0051	−0.0097	1

4.3. Baseline Results

Table 4 presents the baseline panel regression results regarding the impact of green supply chain pressure on firm-level total factor productivity. Across all specifications (Columns 1–5), as control variables and high-dimensional fixed effects are added sequentially, the coefficient on gsp remains positive and statistically significant at the 1% level. In the fully specified benchmark model (Column 6), the coefficient of gsp is 0.0133, remaining significant at the 5% level after accounting for firm, industry-year, and city-year fixed effects. To provide a more intuitive understanding of the economic impact, we contextualize this coefficient using its standard deviation (1.3869) from Table 2. A one-standard-deviation increase in green supply chain pressure corresponds to a 1.84% increase in firm-level TFP ($1.3869 \times 0.0133 = 0.0184$). Given that average annual productivity growth in manufacturing is often modest, this 1.84% enhancement indicates that green requirements from downstream customers serve as a significant economic driver for upstream productivity, rather than a negligible compliance burden. The control variables exhibit plausible signs: leverage (*lev*) and valuation (*val*) are negatively associated with productivity, while profitability (*roe*) and wage levels (*wage*) show positive correlations, consistent with economic intuition. Overall, these findings provide strong empirical support for the positive role of green supply chain pressure in promoting economic sustainability.

Table 4. The Impact of Green Supply Chain Pressure on TFP.

	(1)	(2)	(3)	(4)	(5)	(6)
gsp	0.0361 ***	0.0362 ***	0.0358 ***	0.0357 ***	0.0362 ***	0.0133 **
	(0.0092)	(0.0091)	(0.0092)	(0.0092)	(0.0091)	(0.0057)
lev		−0.0089	−0.0081	−0.0082	−0.0405	−0.0427 **
		(0.0690)	(0.0691)	(0.0691)	(0.0729)	(0.0201)
roe			0.0032 *	0.0032 *	0.0036 **	0.0036 **
			(0.0017)	(0.0016)	(0.0017)	
grow				−0.0006 *	−0.0005	−0.0002
				(0.0003)	(0.0004)	(0.0010)
val					−0.0297 ***	−0.0234 ***
						(0.0020)
wage					(0.0055)	0.4890 ***
						(0.0190)
Constant	8.6105 ***	8.6146 ***	8.6151 ***	8.6155 ***	8.7343 ***	3.0834 ***
	(0.0200)	(0.0411)	(0.0412)	(0.0413)	(0.0472)	(0.6699)
Observations	4017	4017	4017	4017	4017	4017
Within R2	0.2150	0.2165	0.2190	0.2202	0.2458	0.3124

Note: The dependent variable is total factor productivity (fp) estimated by the Levinsohn-Petrin method. All regressions include firm fixed effects as well as industry-year and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.4. Resource-Intensive Pathways

4.4.1. Resource-Intensive Pathways: Green Technological Innovation

Table 5 investigates whether green technological innovation (tech) serves as a critical pathway through which green supply chain pressure enhances productivity. Column (1) reaffirms the baseline total effect of *gsp* on TFP (0.0133, $p < 0.05$). Column (2) shows that *gsp* significantly promotes green innovation (0.0132, $p < 0.01$), suggesting that environmental requirements from downstream customers incentivize firms to increase the share of green patenting in their R&D portfolios. In Column (3), both *gsp* and tech are included in the regression. The coefficient of tech is positive and highly significant (0.1515, $p < 0.01$), confirming its role in boosting productivity. Meanwhile, the coefficient of *gsp* remains significant at the 5% level but decreases from 0.0133 to 0.0122. This result is consistent

with a partial mediation effect, indicating that while a direct impact of *gsp* persists, the stimulation of green technological innovation constitutes a substantial channel through which green supply chain pressure fosters economic sustainability.

Table 5. Resource-Intensive Pathways of Green Supply Chain Pressure: Green.

	(1) Total Effect	(2) Mechanism (X → M)	(3) Direct Effect
gsp	0.0133 **	0.0132 ***	0.0122 **
	(0.0057)	(0.0044)	(0.0057)
tech			0.1515 ***
			(0.0268)
lev	−0.0427 **	0.0143	−0.0460 **
	(0.0201)	(0.0164)	(0.0200)
roe	0.0036 **	−0.0007	0.0037 **
	(0.0017)	(0.0014)	(0.0017)
grow	−0.0002	0.0007	−0.0003
	(0.0010)	(0.0008)	(0.0010)
val	−0.0234 ***	0.0040 ***	−0.0236 ***
	(0.0020)	(0.0015)	(0.0020)
wage	0.4890 ***	0.1991 ***	0.4619 ***
	(0.0190)	(0.0150)	(0.0194)
Observations	4017	4017	4017
Within R2	0.3124	0.2467	0.3389

Note: Column (1) reproduces the fully specified baseline regression with TFP as the dependent variable. Column (2) reports the effect of green supply chain pressure on green technological innovation (tech). Column (3) includes both gsp and tech in the TFP regression. All regressions control for firm fixed effects, industry-year fixed effects, and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. ** $p < 0.05$, *** $p < 0.01$.

4.4.2. Resource-Intensive Pathways: Capital Deepening

Table 6 examines capital deepening (cap) as the second resource-intensive pathway. Column (1) restates the baseline total effect, while Column (2) shows that *gsp* is positively associated with capital deepening (0.0378, $p < 0.10$), suggesting that green requirements from downstream customers encourage firms to upgrade toward digital and intelligent fixed assets. In Column (3), both *gsp* and cap are included in the regression. The coefficient of cap is positive and highly significant (0.0143, $p < 0.01$), confirming that the adoption of technology-intensive assets enhances productivity. The coefficient of *gsp* remains significant at the 5% level but decreases slightly from 0.0133 to 0.0128, consistent with a partial mediation pattern. This suggests that capital deepening serves as a viable channel through which green supply chain pressure fosters economic sustainability, even though a substantial direct effect remains.

Table 6. Resource-Intensive Pathways of Green Supply Chain Pressure: Capital.

	(1) Total Effect	(2) Mechanism (X → M)	(3) Direct Effect
gsp	0.0133 **	0.0378 *	0.0128 **
	(0.0057)	(0.0227)	(0.0057)
cap			0.0143 ***
			(0.0049)
lev	−0.0427 **	−0.0413	−0.0424 **
	(0.0201)	(0.0840)	(0.0201)
roe	0.0036 **	−0.0005	0.0036 **
	(0.0017)	(0.0073)	(0.0017)
grow	−0.0002	0.0002	−0.0002

Table 6. *Cont.*

	(1) Total Effect	(2) Mechanism (X → M)	(3) Direct Effect
val	(0.0010) −0.0234 ***	(0.0043) 0.0002	(0.0010) −0.0233 ***
wage	(0.0020) 0.4890 ***	(0.0076) 0.1881 **	(0.0020) 0.4863 ***
	(0.0190)	(0.0768)	(0.0190)
Observations	4017	4017	4017
Within R2	0.3124	0.1984	0.3389

Note: Column (1) reproduces the fully specified baseline regression with TFP as the dependent variable. Column (2) reports the effect of green supply chain pressure on capital deepening (cap). Column (3) includes both gsp and cap in the TFP regression. All regressions control for firm fixed effects, industry-year fixed effects, and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.4.3. Resource-Intensive Pathways: Human Capital Upgrading

Table 7 investigates human capital upgrading (*skill*) as the third resource-intensive pathway. Column (1) reaffirms the baseline total effect, while Column (2) shows that gsp significantly improves the skill structure of the workforce (0.0124, $p < 0.01$), suggesting that green requirements incentivize firms to increase their share of highly educated employees. In Column (3), the coefficient of *skill* is positive and significant (0.1007, $p < 0.05$), confirming that human capital is a key driver of productivity. The coefficient of *gsp* remains significant at the 5% level, decreasing slightly from 0.0133 to 0.0127. This consistent partial mediation pattern demonstrates that human capital upgrading is an important mechanism through which green supply chain pressure enhances economic sustainability, operating alongside the direct effects.

Table 7. Resource-Intensive Pathways of Green Supply Chain Pressure: Human Capital Upgrading.

	(1) Total Effect	(2) Mechanism (X → M)	(3) Direct Effect
gsp	0.0133 ** (0.0057)	0.0124 *** (0.0043)	0.0127 ** (0.0057)
skill			0.1007 ** (0.0406)
lev	−0.0427 ** (0.0201)	0.2874 *** (0.1036)	−0.0418 ** (0.0201)
roe	0.0036 ** (0.0017)	0.0003 (0.0016)	0.0037 ** (0.0017)
grow	−0.0002 (0.0010)	−0.0006 (0.0007)	−0.0002 (0.0010)
val	−0.0234 *** (0.0020)	−0.0070 *** (0.0016)	−0.0231 *** (0.0020)
wage	0.4890 *** (0.0190)	0.0944 ** (0.0396)	0.4761 *** (0.0197)
Observations	4017	4017	4017
Within R2	0.3124	0.2241	0.3452

Note: Column (2) regresses the human capital variable (skill) on green supply chain pressure and controls. Column (3) includes both gsp and skill in the TFP regression. All models include firm fixed effects, industry-year fixed effects, and city-year fixed effects. Standard errors are clustered at the industry level. ** $p < 0.05$, *** $p < 0.01$.

Notably, the hierarchy of mediating effects shows that green technological innovation (coeff = 0.1515) exerts a much stronger impact on TFP than human capital upgrading (0.1007) or capital deepening (0.0143). This hierarchy implies that while firms adjust their input structures (capital and labor) in response to green pressure, the predominant reaction is through fundamental technological investments. From the perspective of the Porter

Hypothesis, innovation-led responses allow firms to achieve "innovation offsets", systemic efficiency gains that more effectively internalize environmental costs compared to mere marginal adjustments in factor intensity.

4.5. Financial Boundaries: Moderating Effect

Table 8 examines the moderating role of financial boundaries using three alternative proxies for financing constraints: the SA, KZ, and WW indices. In Columns (1)–(2), using the SA index (where higher values denote lower constraints), the positive and significant interaction term *gsp* × *fc(sa)* indicates that greater financial slack amplifies the productivity-enhancing effect of green supply chain pressure. Conversely, using the KZ and WW indices in Columns (3)–(6) (where higher values indicate tighter constraints), the negative and significant interaction terms confirm that financing constraints weaken this relationship. These consistent results across all three proxies highlight that financial slack serves as a vital strategic buffer. High-slack firms can leverage this buffer to treat green pressure as a window for radical technological upgrading, effectively absorbing the high risks of green R&D. In contrast, for firms with low financial slack, external green demands may impose a "liquidity strain" that crowds out other productive investments. This bifurcated response underscores that the productivity-enhancing effect of GSP is contingent upon a firm's internal financial resilience.

Table 8. Financial Boundaries: Alternative Measures of Financing Constraints.

	SA Index		**KZ Index**		**WW Index**	
	(1) Base	**(2) Interaction**	**(3) Base**	**(4) Interaction**	**(5) Base**	**(6) Interaction**
gsp	0.0134 **	0.0102 *	0.0129 **	0.0091 *	0.0131 **	0.0094 *
	(0.0057)	(0.0059)	(0.0058)	(0.0057)	(0.0056)	(0.0058)
fc (sa)	0.0285 *	0.0247 **				
	(0.0168)	(0.0119)				
gsp × fc (sa)		0.0041 **				
		(0.0019)				
fc (kz)			−0.0245 *	−0.0208 *		
			(0.0190)	(0.0162)		
gsp × fc (kz)				−0.0034 *		
				(0.0019)		
fc (ww)					−0.0278 **	−0.0240 **
					(0.0148)	(0.0131)
gsp × fc (ww)						−0.0037 **
						(0.0018)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4017	4017	4017	4017	4017	4017
Within R2	0.3200	0.3321	0.3183	0.3310	0.3190	0.3336

Note: The dependent variable is total factor productivity (tf *p*) estimated by the Levinsohn-Petrin method. Each pair of columns uses a different proxy for financing constraints: the SA index, the KZ index, and the WW index, respectively. Base columns include gsp, the corresponding financing constraint proxy, and control variables; Interaction columns additionally include the interaction term between gsp and the financing constraint measure. For the SA index, higher values indicate lower financing constraints, while for the KZ and WW indices higher values indicate tighter financing constraints. All regressions include firm fixed effects, industry-year fixed effects, and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$.

4.6. Heterogeneity Analysis

Table 9 reports subsample analyses across four dimensions to identify which firms benefit most from green supply chain pressure. In Panel A, the sample is split into green and brown firms. While the coefficient on *gsp* is positive and significant for both groups, the impact is nearly twice as large for green firms (0.0182, $p < 0.01$) compared to brown firms

(0.0104, $p < 0.10$). This disparity suggests that firms with intrinsic green attributes possess superior "absorptive capacity", their existing technological foundations and organizational routines are highly compatible with environmental requirements. Consequently, green firms can translate downstream pressure into productivity gains more efficiently and at lower marginal adjustment costs. Conversely, brown firms may face significant legacy costs when reconfiguring their carbon-intensive production processes, leading to a more muted productivity response to external green demands.

Table 9. Heterogeneity Analysis: The Impact of Green Supply Chain Pressure on TFP.

	Panel A: Green Attribute		**Panel B: Ownership**		**Panel C: Technological Status**		**Panel D: Firm Size**	
	Green	**Brown**	**Non-SOE**	**SOE**	**High-Tech**	**Non-High-Tech**	**Large**	**Small**
gsp	0.0182 ***	0.0104 *	0.0168 ***	0.0087	0.0195 ***	0.0111 *	0.0176 ***	0.0092
	(0.0061)	(0.0060)	(0.0056)	(0.0081)	(0.0063)	(0.0060)	(0.0057)	(0.0066)
lev	−0.0300	−0.0500 *	−0.0410 *	−0.0200	−0.0450 *	−0.0380 *	−0.0400 *	−0.0360
	(0.0250)	(0.0270)	(0.0210)	(0.0400)	(0.0230)	(0.0220)	(0.0210)	(0.0230)
roe	0.0035 **	0.0033 **	0.0037 **	0.0025	0.0040 **	0.0033 **	0.0038 **	0.0030 *
	(0.0018)	(0.0016)	(0.0016)	(0.0025)	(0.0018)	(0.0017)	(0.0016)	(0.0018)
grow	−0.0003	−0.0001	−0.0002	−0.0004	−0.0001	−0.0003	−0.0002	−0.0001
	(0.0011)	(0.0011)	(0.0010)	(0.0015)	(0.0011)	(0.0010)	(0.0010)	(0.0011)
val	−0.0210 ***	−0.0245 ***	−0.0225 ***	−0.0180 ***	−0.0240 ***	−0.0220 ***	−0.0230 ***	−0.0215 ***
	(0.0035)	(0.0038)	(0.0030)	(0.0050)	(0.0033)	(0.0034)	(0.0031)	(0.0036)
wage	0.4720 ***	0.4560 ***	0.4950 ***	0.4300 ***	0.5050 ***	0.4700 ***	0.5000 ***	0.4600 ***
	(0.0280)	(0.0300)	(0.0250)	(0.0450)	(0.0290)	(0.0270)	(0.0260)	(0.0280)
Observations	1520	2497	2950	1067	1680	2337	2008	2009
Within R2	0.3340	0.3050	0.3325	0.3080	0.3350	0.3075	0.3330	0.3065

Note: The dependent variable is total factor productivity (tfp) estimated by the Levinsohn-Petrin method. Each column reports the coefficient estimates from regressions estimated on the indicated subsample. All specifications include leverage, profitability, growth, valuation, and wage as control variables, as well as firm fixed effects, industry-year fixed effects, and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Panel B distinguishes between ownership types. The effect of gsp on TFP is positive and highly significant for non-SOEs (0.0168, $p < 0.01$), whereas the coefficient for SOEs is smaller and statistically insignificant. This reflects the higher market responsiveness of private enterprises to customer-side requirements. Regarding technological status, Panel C indicates that high-tech firms leverage *gsp* more effectively (0.0195 vs. 0.0111), further supporting the role of innovation as a primary driver. Panel D demonstrates that the positive impact of *gsp* is concentrated among large firms (0.0176, $p < 0.01$), suggesting that superior resource endowments and organizational capabilities are essential for successfully converting green pressure into productivity gains.

Finally, Panel E investigates regional heterogeneity by splitting the sample into Eastern and Central/Western regions. The results show that the impact of *gsp* is positive and significant for firms in the Eastern region (0.0192, $p < 0.01$), whereas it is statistically insignificant for firms in the Central and Western regions. This geographical disparity likely stems from the superior institutional environment and supply chain infrastructure in Eastern China. Firms in these areas are more integrated into global value chains and face higher local environmental compliance standards, which enhances their responsiveness and efficiency when adapting to downstream green requirements.

4.7. Robustness Checks

Table 10 provides a series of robustness checks to confirm the stability of the baseline results. Replacing the LP measure with the Olley–Pakes (OP) estimator (Column 1) and utilizing lagged *gsp* (Column 2) both yield positive and significant coefficients, mitigating concerns about estimator sensitivity and reverse causality. The IV–2SLS estimation in Column 3, using green subsidies as an instrument, addresses potential endogeneity

and suggests that the baseline may even understate the effect due to measurement error. Further tests demonstrate that the results are robust to stricter outlier control through 5% winsorization (Column 4) and sample selection bias correction via the inverse Mills ratio (Column 5). Finally, to address the methodological concern regarding our weighting scheme, Column (6) re-estimates the baseline model using an unweighted average of the green pressure keywords across the top five customers (*gsp_unw*). This test evaluates whether our results are sensitive to the assumption that larger customers exert proportionally higher pressure. The coefficient remains positive and significant (0.0128, $p < 0.01$), confirming that the positive impact of green supply chain pressure on productivity is a consistent phenomenon regardless of whether the indicator is aggregated by sales shares or a simple average. Across all robustness checks, the estimated impact of green supply chain pressure on firm-level TFP remains positive and statistically significant, reinforcing the credibility of our baseline findings.

Table 10. Robustness Checks.

	(1) TFP (OP)	(2) Lagged GSP	(3) IV-2SLS	(4) Winsor 95%	(5) Heckman
gsp	0.0115 **		0.0165 **	0.0129 ***	0.0124 **
	(0.0049)		(0.0078)	(0.0047)	(0.0058)
L.gsp		0.0117 **			
		(0.0055)			
lev	−0.0390 *	−0.0415 *	−0.0380 *	−0.0410 **	−0.0420 **
	(0.0215)	(0.0218)	(0.0225)	(0.0208)	(0.0205)
roe	0.0031 **	0.0034 **	0.0033 **	0.0035 ***	0.0036 **
	(0.0015)	(0.0016)	(0.0016)	(0.0015)	(0.0017)
grow	−0.0001	−0.0002	−0.0002	−0.0002	−0.0002
	(0.0010)	(0.0010)	(0.0010)	(0.0010)	(0.0010)
val	−0.0190 ***	−0.0225 ***	−0.0210 ***	−0.0230 ***	−0.0232 ***
	(0.0022)	(0.0021)	(0.0023)	(0.0020)	(0.0020)
wage	0.4550 ***	0.4780 ***	0.4720 ***	0.4860 ***	0.4880 ***
					(0.0192)
imr	(0.0215)	(0.0205)	(0.0220)	(0.0198)	−0.0065
					(0.0118)
Observations	4017	3683	4017	4017	4017
Within R2	0.3046	0.3185	0.2900	0.3120	0.3591

Note: The dependent variable in column (1) is total factor productivity estimated by the Olley–Pakes (OP) method; in columns (2)–(5) it is tfp estimated by the Levinsohn–Petrin method. Column (2) uses lagged green supply chain pressure (L.gsp) to mitigate reverse causality. Column (3) reports IV-2SLS estimates using green subsidies as an instrument for gsp. Column (4) re-estimates the baseline specification after winsorizing all continuous variables at the 5th and 95th percentiles. Column (6) uses an alternative *gsp* indicator calculated as the unweighted average of the top five customers' green disclosures. All regressions include leverage, profitability, growth, valuation and wage as control variables, as well as firm fixed effects, industry-year fixed effects and city-year fixed effects. Standard errors clustered at the industry level are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5. Discussion

5.1. Green Supply Chain Pressure and the Porter Hypothesis

Our first main finding is that green supply chain pressure from downstream customers is positively associated with firm-level total factor productivity (TFP), which we interpret as an indicator of economic sustainability. This result is broadly consistent with the "Porter hypothesis" that appropriately designed environmental pressures can spur innovation and offset compliance costs by improving efficiency and competitiveness [10,27]. It also resonates with the natural-resource-based view, which emphasises how firms can convert environmental challenges into strategic resources and capabilities [9].

Within the sustainable supply chain management literature, early work largely focused on how green practices adopted by focal firms relate to environmental or operational performance [14–17]. Our results add a cross-tier perspective by documenting that customers' green emphasis, as captured by our textual measure of downstream green supply chain discourse, can translate into higher upstream productivity. This complements recent evidence

that green supply chain integration and dynamic capabilities are important drivers of both environmental and economic performance [60,61] and that green logistics and supply chain practices are increasingly recognised as key levers for improving sustainability outcomes along the value chain [62].

Moreover, our evidence of a positive link between green supply chain pressure and TFP is consistent with broader work showing that environmentally oriented policies and pressures can enhance green total factor productivity at the regional or industry level when accompanied by innovation and structural upgrading [11,12,63]. By focusing on customer-driven pressure, we show that similar "win–win" mechanisms can emerge not only from formal regulation, but also from private governance within supply chains.

5.2. Text-Based Measurement and the Information Channel

A distinctive feature of our study is the construction of green supply chain pressure using text-based analysis of downstream customers' MD&A disclosures. Prior research has shown that the tone, intensity and specificity of environmental disclosure conveymeaningful information about firms' environmental strategies and constraints [30]. Recent work on Chinese firms further documents that richer, more transparent environmental disclosure can improve access to external finance and align stakeholders' expectations [48].

By aggregating customers' green supply chain-related language with sales-based weights, our measure captures both the salience of green issues in customers' narratives and their economic importance for the supplier. This approach complements inventory or survey-based measures of green supply chain management [16,17] and aligns with the growing use of textual methods in sustainability research [61]. It also highlights an information channel: when customers repeatedly stress green procurement, circular economy and low-carbon requirements in their public disclosures, upstream firms face stronger reputational and relational incentives to invest in green and productivity-enhancing adjustments, even when formal contractual clauses are not directly observable.

5.3. Resource-Intensive Pathways: Innovation, Capital and Skills

Our mediation analysis provides evidence that green supply chain pressure improves economic sustainability through three resource-intensive pathways: green technological innovation, capital deepening and human capital upgrading. The positive association between green supply chain pressure and the share of green patents in total patenting is consistent with the idea that external environmental demands redirect innovation efforts toward cleaner technologies [10,12]. It also echoes the growing empirical literature linking environmental regulation and green finance to green innovation and productivity in China [63,64].

The finding that capital deepening partly mediates the effect of green supply chain pressure suggests that upgrading production equipment and processes is an important response channel. This aligns with studies documenting that firms often need to invest in cleaner technologies, advanced monitoring equipment and more efficient production lines to meet tighter environmental and supply chain standards [15,17].

Similarly, the human capital channel we uncover is consistent with work showing that dynamic capabilities and organisational learning are crucial for translating environmental pressures into improved environmental and circular-economy performance [61,65]. Our results indicate that firms exposed to stronger green supply chain requirements tend to increase the share of highly educated employees, and that a more skilled workforce is associated with higher TFP. In summary, these findings support the view that customer-driven green pressure fosters a bundle of resource accumulations, in technology, physical capital and skills, that form the backbone of sustainable competitive advantage [9,14].

5.4. Financial Boundaries and Heterogeneous Effects

The moderation analysis shows that financing constraints significantly shape the strength of the productivity gains from green supply chain pressure. Using the SA, KZ and WW indices, which capture different dimensions of firm-level financial frictions [41–43], we find that the positive effect of green supply chain pressure on TFP is stronger for firms with more financial slack and weaker for firms facing tighter constraints. This pattern is consistent with recent evidence that green innovation and productivity-enhancing responses to environmental policies are more likely when firms can access sufficient financial resources, including targeted green finance instruments [64].

In combination with the mediation results, these findings suggest a mechanism in which green supply chain pressure raises the demand for lumpy investments in green technology, capital equipment and skilled labour, but the ability to undertake these investments is conditional on financing capacity. This framework helps explain the heterogeneity we observe across ownership types, technological status and firm size. Non-SOEs, high-tech firms and larger firms, which typically have better access to external finance and more internal resources, exhibit stronger productivity responses to green supply chain pressure than SOEs, non-high-tech firms and smaller firms. These patterns align with recent studies documenting that the benefits of green supply chain initiatives for sustainability performance vary with firms' internal capabilities and external institutional environments [60,62,66,67].

6. Conclusions

6.1. Summary of Findings

Our empirical evidence reveals that green supply chain pressure (*gsp*) significantly enhances firms' economic sustainability. Specifically, the baseline results indicate that a one-standard-deviation increase in *gsp* leads to a 1.84% increase in TFP (coefficient 0.0133, $p < 0.05$), suggesting that downstream environmental requirements serve as a substantive economic driver rather than a mere compliance cost. We identify three resource-intensive pathways, green technological innovation, capital deepening, and human capital upgrading, as significant partial mediators, with tech showing the strongest associated impact on productivity (coefficient 0.1515, $p < 0.01$). Furthermore, the moderating analysis across SA, KZ, and WW indices consistently demonstrates that the productivity-enhancing effect of *gsp* is contingent upon financial capacity, where financing constraints significantly weaken the transition from green pressure to productivity gains. Finally, heterogeneity tests show that these benefits are more pronounced for non-SOEs, high-tech firms, and larger enterprises.

6.2. Managerial and Policy Implications

In light of these findings, our study provides several practical implications for corporate managers. First, the identified hierarchy of mechanisms implies that managers should prioritize green R&D and fundamental process innovation over simple equipment replacement to achieve long-term "innovation offsets." Second, regarding human capital, firms should invest in specialized expertise, such as hiring environmental engineers and carbon accountants—and implement cross-functional training to bridge the gap between compliance and productivity gains. Finally, managers in firms with high financial slack should leverage their resource buffer for radical technological upgrading, while those in resource-constrained firms should actively utilize green finance instruments, such as green bonds, to ensure that external pressure catalyzes innovation rather than depleting operational resources.

6.3. Limitations and Future Research

Despite the robust findings, this study has limitations that offer avenues for future research. First, our measure of GSP relies on textual analysis of MD&A reports. While this captures firms' perceived environment, it is sensitive to reporting styles and may reflect "rhetorical conformity" or symbolic compliance with sustainability discourse rather than actual operational shifts. Future studies could cross-validate these textual proxies with third-party environmental audits or direct supplier-level surveys.

Second, our sample is exclusively composed of Chinese A-share companies. Given the unique institutional and regulatory context of China, the external validity of our results may be limited. Future research should test the model in developed economies or other emerging markets to explore how different institutional maturities moderate these effects. Finally, the transmission of green pressure may vary across industries with different supply chain lengths.

Beyond these limitations, a significant future challenge for this case study lies in the evolving nature of green compliance, shifting from voluntary disclosure toward mandatory life-cycle carbon accounting. As international frameworks like the EU's Carbon Border Adjustment Mechanism (CBAM) become operational, Chinese upstream suppliers will face the dual challenge of harmonizing fragmented global standards while managing the transparency costs of multi-tier supply chain traceability. Future research should investigate how these "hard" regulatory shifts and the digital-green "twin transition" redefine the frontiers of firm-level productivity.

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