

# Identifying the Causal Effects of Design for Environment and Quality Management Innovation: A Study Based on Longitudinal Data

1<sup>st</sup> Lina bint Khalid Al Otaibi  
Taibah University  
Tabuk, Saudi Arabia  
lwq816816@gmail.com

2<sup>nd</sup> Liewei Liang  
Tiangu Construction Engineering Co.,  
Ltd.  
Guangzhou, China  
531973249@qq.com

3<sup>rd</sup> Yanghe Huang  
Tiangu Construction Engineering Co.,  
Ltd.  
Guangzhou, China  
Yanghehuang2022@outlook.com

**Abstract**—This study aims to investigate the causal effects of Design for Environment (DFE) and Quality Management Innovation (QMI) on firm performance. Existing research, predominantly relying on cross-sectional data, struggles to effectively identify causal relationships and address endogeneity issues, leading to potential biases in assessing the economic benefits of DFE and QMI. To overcome this limitation, this study develops an analytical framework that integrates the Natural Resource-Based View (NRBV) and Dynamic Capability Theory. Using a balanced panel dataset of Chinese manufacturing firms listed from 2012 to 2022, we employ a staggered Difference-in-Differences (DID) model combined with Propensity Score Matching (PSM). We treat a firm's first-time ISO 14001 certification as a quasi-natural experiment for DFE implementation to accurately identify its true impact on both environmental and economic performance, and to test the mediating role of QMI. The findings reveal that DFE implementation significantly enhances both firm environmental and economic performance, with the effect peaking in the third year post-certification. Quality Management Innovation plays a crucial partial mediating role in the relationship between DFE and firm performance, suggesting that DFE amplifies its positive impact on performance by driving deeper innovations in the firm's quality management system. This research not only provides causal evidence for firms implementing environmental strategies and quality management innovations but also offers a decision-making reference for governments in formulating and evaluating related environmental policies, thereby deepening the understanding of value creation mechanisms on the path to sustainable development.

**Keywords**—Design for Environment (DFE), Quality Management Innovation (QMI), Firm Performance, Causal Effect, Difference-in-Differences (DID) Model, Longitudinal Data

## I. INTRODUCTION

Against the backdrop of escalating global climate change and resource constraints, sustainable development has become a core issue for governments and corporations worldwide [1]. As a global manufacturing hub, China faces immense environmental pressure and transformational challenges. In response, the Chinese government has successively introduced a series of stringent environmental regulations and policies aimed at guiding firms to transition from traditional, resource-intensive growth models to green, low-carbon, and circular development patterns [2]. In this wave of transformation, how firms can balance environmental protection with economic benefits to achieve a "win-win" scenario has become a focal point for both

academia and industry. Design for Environment (DFE), as a proactive management strategy that systematically integrates environmental considerations into the product design phase, is considered a key lever for promoting corporate green transformation and reducing environmental loads at the source [3]. Concurrently, Quality Management Innovation (QMI), as a core driver for enhancing operational efficiency and product quality, and its synergistic mechanism with environmental management strategies, as well as its ultimate impact on overall firm performance, constitute the central theme of this study.

However, the existing literature on the impact of DFE and QMI on firm performance suffers from two major limitations. First, most studies use cross-sectional data and traditional regression methods. While these reveal correlations between variables, they fail to effectively address potential endogeneity issues, such as omitted variable bias and reverse causality [4]. For instance, better-performing firms may have more resources to invest in DFE and QMI, rather than DFE and QMI unilaterally improving firm performance. This endogeneity problem casts doubt on the robustness and reliability of existing findings, failing to provide clear causal evidence for the critical question of whether "it pays to be green." Second, although some studies have explored the synergy between DFE and QMI, they are mostly confined to theoretical speculation or case studies, lacking large-scale, long-term empirical tests of the mediating effect of QMI in the process of DFE affecting firm performance [5]. Does DFE implementation necessarily enhance performance by stimulating changes in the corporate quality management system? The intrinsic pathways and mechanisms remain to be clarified.

To fill these research gaps, this study aims to answer the following core questions: First, does the implementation of DFE have a significant causal effect on a firm's environmental and economic performance? Second, if a causal effect exists, is its impact immediate or is there a time lag? Third, what role does quality management innovation play in the relationship between DFE and firm performance? Is it an independent driver, or is it a key mediating pathway for DFE to realize its value?

To accurately identify the causal relationships between variables, this study adopts a longitudinal data analysis perspective. Specifically, we collected a balanced panel dataset of Chinese A-share listed manufacturing companies from 2012 to 2022 and treat the first-time ISO 14001 environmental management system certification by a firm as a "quasi-natural experiment" for its systematic

Corresponding Author: Lina bint Khalid Al Otaibi, Janadah Bin Umayyah Road, Tayba, Al Madinah Al Munawwarah 42353, Saudi Arabia, 42353, lwq816816@gmail.com

implementation of DFE. By constructing a staggered Difference-in-Differences (DID) model combined with Propensity Score Matching (PSM) to build a comparable control group, this study can, after controlling for a series of time-varying and time-invariant confounding factors, more purely isolate the dynamic causal effect of DFE on corporate environmental and economic performance. Furthermore, this study develops a mediation effect model to test the transmission mechanism of QMI in the relationship between DFE and firm performance, thereby opening the "black box" of how DFE influences corporate value creation.

The theoretical contributions and practical implications of this study are threefold: First, methodologically, by adopting a cutting-edge causal inference method, it provides a more rigorous analytical paradigm for research in the field of environmental management, enhancing the internal validity of the research conclusions. Second, theoretically, this study combines the Natural Resource-Based View (NRBV) with Dynamic Capability Theory to empirically test how DFE, as a green capability, ultimately transforms into a competitive advantage by driving the evolution of QMI, an organizational routine, thus deepening the understanding of the construction path of corporate sustainable development capabilities. Third, in practice, the findings of this study provide clear evidence for corporate managers that strategic investments in DFE and QMI can yield significant economic returns, thereby strengthening their confidence and determination to pursue green strategies. At the same time, it also provides a scientific basis for policymakers to evaluate the effectiveness of environmental regulations (such as the promotion of ISO 14001 certification).

The remainder of this paper is structured as follows: The second section will review and comment on the relevant literature and present the theoretical framework and research hypotheses of this study. The third section will detail the research design, including model specification, data sources, and variable definitions. The fourth section will report the empirical analysis results, including baseline regression, robustness tests, and heterogeneity analysis. The fifth section will conduct an in-depth discussion of the research results. Finally, the sixth section will summarize the full text and point out the limitations of the study and future prospects.

#### A. Literature Review and Theoretical Framework

##### 1) Design for Environment (DFE) and Firm Performance

Design for Environment (DFE), also known as eco-design, is a systematic and proactive management approach that integrates environmental factors into the entire process of product and service design and development [6]. Its core idea is to anticipate and strive to minimize the negative environmental impacts of a product throughout its lifecycle—from manufacturing and use to disposal—at the earliest stage, namely the design phase, thereby achieving a unity of economic and environmental benefits [3]. DFE practices encompass a wide range of activities, such as using recyclable or biodegradable materials, optimizing product structures for easy disassembly and reuse, and reducing energy consumption and waste emissions during production [7].

The academic community has extensively explored the relationship between DFE and firm performance, but the conclusions are not yet uniform. A large body of research

indicates that implementing DFE can bring multiple benefits to firms. In terms of environmental performance, DFE, through source control, can effectively reduce pollutant emissions and lower resource consumption, thus helping firms meet increasingly stringent environmental regulations and enhance their corporate reputation and brand image [8]. In terms of economic performance, DFE can directly or indirectly improve a firm's financial performance by increasing resource utilization efficiency, reducing waste disposal costs, and developing green products to open up new markets [9]. For example, the study by Hart and Dowell (2011) found that companies excelling in product stewardship also demonstrated superior financial performance [10].

However, some studies have questioned the economic benefits of DFE. Some scholars argue that implementing DFE requires firms to invest substantial upfront R&D funds, modify production lines, and train employees. These costs may not be covered by the returns in the short term and could even weaken a firm's competitiveness [11]. Furthermore, due to difficulties in data acquisition and limitations in research methodologies, most existing studies rely on cross-sectional survey data from specific industries or small scales and employ traditional regression analysis. Such research designs cannot effectively control for firm heterogeneity or address endogeneity issues, thus failing to determine whether a true causal link exists between DFE and firm performance, rather than just a correlation. This research gap is precisely what this study aims to fill.

##### B. Quality Management Innovation (QMI) and Firm Performance

Quality Management Innovation (QMI) is an evolution and deepening of traditional quality management practices like Total Quality Management (TQM). It not only focuses on the conformance quality of products and services but also emphasizes enhancing the organization's overall operational capabilities and adaptability through continuous improvement and systematic innovation [12]. The core elements of QMI include top management commitment, employee empowerment, a culture of continuous improvement, customer focus, and close collaboration with suppliers [5]. It is no longer a static set of standards but a dynamic, constantly seeking-breakthrough organizational learning process.

Regarding the impact of QMI on firm performance, the academic community has largely reached a consensus. Numerous empirical studies have demonstrated that the in-depth implementation of QMI can significantly improve a firm's product quality, customer satisfaction, and operational efficiency, ultimately translating into higher market share and financial returns [13]. However, in today's era where environmental management is increasingly important, the role of QMI is changing. It is no longer just a tool in the production and operations domain but has become a crucial support for firms to implement environmental strategies and drive green transformation. For example, the new material choices, process flows, and product designs required by DFE implementation inevitably demand corresponding adjustments and innovations in the quality management system to ensure that green products remain competitive in terms of function, reliability, and cost while meeting environmental requirements.

### C. The Interrelationship between DFE, QMI, and Firm Performance

DFE and QMI are not two isolated management practices but are interconnected and mutually reinforcing. DFE provides a new direction and goal for quality management (i.e., environmental friendliness), while QMI provides the methodological and organizational support for the effective implementation of DFE [5]. On the one hand, the implementation of DFE promotes the deepening of QMI. For instance, to develop recyclable products, firms must incorporate controls for material traceability and ease of disassembly into their quality management processes. On the other hand, a mature QMI system can accelerate the successful implementation of DFE. Firms with a culture of continuous improvement and broad employee participation find it easier to integrate environmental goals into daily work and respond quickly to the technological and process changes brought about by DFE.

Based on this, some scholars have proposed that QMI may play a mediating role between DFE and firm performance. That is, the implementation of DFE may not directly and mechanically improve firm performance but rather does so by stimulating and deepening a firm's quality management innovation, and then ultimately achieving a win-win for both the environment and the economy through the value-creating effects of QMI [5]. However, this mediation mechanism has mostly remained at the level of theoretical deduction and case analysis, lacking large-scale, long-term empirical testing. In particular, within a causal inference framework, whether the mediating effect of QMI is significant and to what extent it can explain DFE's contribution to performance remains an unresolved issue.

### D. Theoretical Framework and Research Hypotheses

To systematically investigate the causal relationship and mechanism between DFE, QMI, and firm performance, this study constructs an analytical framework that integrates the Natural Resource-Based View (NRBV) and Dynamic Capability Theory.

The Natural Resource-Based View (NRBV), proposed by Hart (1995), posits that firms can build sustainable competitive advantages by developing unique capabilities related to the natural environment [3]. The NRBV theory includes three core strategies: Pollution Prevention, Product Stewardship, and Sustainable Development. Among these, DFE is the core embodiment of the Product Stewardship strategy, requiring firms to front-load environmental responsibility into the design stage. By building green product development and supply chain management capabilities that are difficult for competitors to imitate, firms can gain differentiation and cost advantages. According to the NRBV theory, firms that successfully implement DFE can more effectively utilize resources and reduce environmental liabilities, thereby directly improving their environmental and economic performance. Therefore, this study proposes the following hypotheses:

H1: The implementation of DFE has a significant, positive causal effect on a firm's environmental performance.

H2: The implementation of DFE has a significant, positive causal effect on a firm's economic performance.

However, merely possessing the static "green capability" of DFE may not be sufficient. In a rapidly changing market and technological environment, firms need to continuously adjust and upgrade their organizational processes and routines to consistently translate this capability into actual performance outcomes. This is the core viewpoint emphasized by Dynamic Capability Theory. Dynamic Capability Theory argues that a firm's competitive advantage stems not from the resources it possesses, but from its ability to integrate, build, and reconfigure internal and external resources to adapt to environmental changes [14].

Within the framework of this study, QMI can be regarded as a key dynamic capability. It represents the organizational routine of continuous learning, adaptation, and innovation in the quality management domain. When a firm decides to implement DFE, it acts as an external environmental "shock," forcing the firm's existing quality management system to adjust. A firm with strong QMI capabilities can more quickly and effectively internalize DFE's environmental requirements into new operational procedures, inspection standards, and performance indicators, thereby ensuring that the DFE philosophy can be successfully implemented and produce the expected results. In other words, DFE "activates" and "guides" the firm's quality management innovation process, translating environmental goals into concrete, executable, and efficient operational practices, ultimately leading to performance improvement. Therefore, QMI plays a key mediating role between DFE and firm performance. Based on this, this study proposes the following hypothesis:

H3: Quality Management Innovation mediates the relationship between DFE and firm performance (including environmental and economic performance).

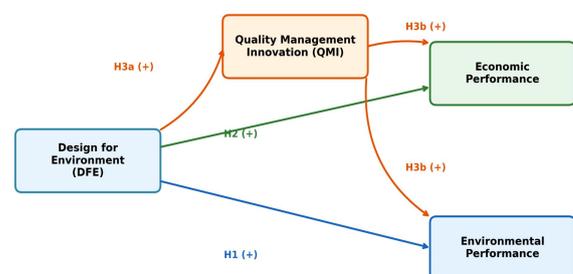
Specifically, this mediation effect can be broken down into:

H3a: The implementation of DFE has a significant, positive causal effect on a firm's quality management innovation.

H3b: Quality management innovation has a significant, positive causal effect on a firm's environmental and economic performance.

Combining the above hypotheses, the theoretical model of this study is shown in the figure below (Figure 1):

Figure 1. Theoretical Framework and Research Hypotheses



Note: Solid arrows represent hypothesized positive relationships. H3 represents the mediation effect of QMI in the DFE-Performance relationship.

Fig. 1. Theoretical Framework. This figure illustrates the causal pathways where Design for Environment (DFE), as the independent variable, influences firm environmental and economic performance (dependent

variables) through the mediating variable of Quality Management Innovation (QMI). A direct path from DFE to firm performance is also included to represent a partial mediation effect.

## II. RESEARCH DESIGN

### A. Research Strategy and Model Specification

To effectively identify the causal effect of DFE on firm performance, this study treats a firm's first-time certification for the ISO 14001 environmental management system as a quasi-natural experiment for the systematic implementation of DFE. The ISO 14001 standard requires firms to identify and control environmental factors from a full life-cycle perspective, from product design and production to disposal, which is highly consistent with the core philosophy of DFE [15]. To identify the causal effect of DFE, we construct a staggered Difference-in-Differences (DID) model combined with Propensity Score Matching (PSM). The propensity score is estimated using a logistic regression of treatment status on pre-treatment firm characteristics: Size, Age, Leverage, Ownership concentration, and Board composition. Firms are matched using nearest-neighbor matching without replacement, with a caliper of 0.05. The DID model is specified as:

The baseline DID model is specified as follows:

$$Y_{it} = \beta_0 + \beta_1 DFE_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

Where the subscripts  $i$  and  $t$  represent the firm and year, respectively.  $Y_{it}$  is the firm's performance indicator, including environmental performance (EP) and financial performance (FP).  $DFE_{it}$  is the core explanatory variable, a dummy variable that takes the value of 1 if firm  $i$  has been certified for ISO 14001 in year  $t$  and onwards, and 0 otherwise. The coefficient  $\beta_1$  is the focus of this study, measuring the average treatment effect of implementing DFE on firm performance.  $X_{it}$  is a set of control variables.  $\mu_i$  represents firm-individual fixed effects to control for time-invariant firm characteristics.  $\lambda_t$  represents time fixed effects to control for time-varying macroeconomic shocks.  $\epsilon_{it}$  is the random error term.

To test the dynamic nature of the DFE impact, this study further constructs an event study model:

$$Y_{it} = \alpha_0 + \sum_{k=-m}^{ton} \alpha_k \cdot D_{it-k} + \gamma^T X_{it} + \mu_i + \epsilon_{it} \quad (2)$$

Where  $D_{it-k}$  is a series of dummy variables representing whether firm  $i$  is in the  $k$ -th year before or after certification.  $k=0$  represents the year of certification. By examining the significance of each  $\alpha_k$ , we can test whether the parallel trends assumption holds (i.e., the  $\alpha_k$  coefficients are not significant before certification) and depict the dynamic evolution of the DFE effect over time.

### B. Data Sources and Sample Selection

The initial sample for this study consists of all Chinese A-share listed manufacturing companies from 2012 to 2022. The data are primarily sourced from the following databases:

- Firm Financial Data and Basic Information: From the CSMAR database, including financial statement data, market value, firm age, ownership structure, etc.
- ISO 14001 Certification Data: Manually collected and compiled from the official website of the Certification and Accreditation Administration of the

People's Republic of China and listed companies' annual reports to accurately determine the year of first-time certification for each firm.

- Firm Patent Data: From the China Research Data Service Platform (CNRDS), used to measure firms' innovation output.
- Environmental Information Disclosure Data: Manually collected from listed companies' annual reports, Corporate Social Responsibility (CSR) reports, and Environmental, Social, and Governance (ESG) reports to construct the environmental performance indicator.

The sample screening process is as follows: (1) Exclude ST, ST, and PT companies; (2) Exclude companies that were listed or delisted during the sample period to construct a balanced panel dataset; (3) Exclude companies with significant missing data for key variables. After screening, the final sample consists of 450 Chinese A-share listed manufacturing companies over 11 years (2012–2022), totaling 4950 firm-year observations. The full list of included companies and years is available in Supplementary Table S1.

### C. Variable Definitions

#### 1) Dependent Variables (Firm Performance)

- Financial Performance (FP): Following existing research [10], we use Tobin's Q as the primary measure of a firm's market value and long-term profitability. Tobin's Q is the ratio of a firm's market value to the replacement cost of its assets, calculated as: (Total Market Value + Book Value of Liabilities) / Book Value of Total Assets. Additionally, we use Return on Assets (ROA) as a substitute indicator for robustness checks.
- Environmental Performance (EP): As environmental performance is difficult to quantify directly, this study constructs a composite index. Drawing on related research [8], we use content analysis to code and quantify information on environmental protection investments, energy-saving and emission-reduction measures, environmental certifications, and environmental honors from corporate annual reports and social responsibility reports. Specifically, if a firm discloses the total amount of environmental investment, it scores 1 point; if it discloses specific energy-saving and emission-reduction projects, it scores 1 point; if it has received other environmental awards or certifications besides ISO 14001, it scores 1 point. The final score, the higher the better, represents environmental performance.

#### 2) Core Explanatory Variable (DFE)

DFE Implementation ( $DFE_{it}$ ): This is a 0-1 dummy variable. Based on the collected ISO 14001 certification data,  $DFE_{it}$  takes the value of 1 for firm  $i$  in year  $t$  and all subsequent years if it has been certified for the first time, and 0 otherwise.

#### 3) Mediating Variable (QMI)

Quality Management Innovation ( $QMI_{it}$ ): Considering that QMI is a multidimensional and complex concept that is difficult to obtain directly from financial statements, this study uses two proxy variables:

- R&D Intensity (RD): Measured as the ratio of total R&D expenditure to operating revenue. Continuous R&D investment is the foundation for a firm's technological and managerial innovation and is an important manifestation of QMI [12].
- Number of Quality-Related Patent Applications (QPAT): Number of Quality-Related Patent Applications (QPAT): QPAT is defined as the count of patent applications in the CNRDS database whose titles or abstracts contain the keywords 'quality,' 'reliability,' 'testing,' or 'control.' To improve precision, keyword matching was case-insensitive, and patents irrelevant to manufacturing processes (e.g., software patents) were manually excluded. The natural logarithm of QPAT + 1 is used to reduce skewness.

#### 4) Control Variables

To mitigate omitted variable bias, this study controls for a series of firm-level characteristics that may affect firm performance:

- Firm Size (Size): Natural logarithm of total assets.
- Financial Leverage (Lev): Ratio of total liabilities to total assets.
- Firm Age (Age): Natural logarithm of the observation year minus the founding year.
- Ownership Concentration (Top1): Shareholding ratio of the largest shareholder.
- Growth Potential (Growth): Growth rate of operating revenue.
- Board Size (Board): Natural logarithm of the number of directors.
- Proportion of Independent Directors (Indep): Ratio of the number of independent directors to the total number of directors.

#### D. Mediation Effect Test

To test Hypothesis H3, i.e., the mediating role of QMI in the relationship between DFE and firm performance, this study adopts the causal steps approach. The steps are as follows:

- Step 1: Test the total effect of DFE on firm performance, which is the coefficient  $\beta_1$  in model (1). If  $\beta_1$  is significant, it indicates a total effect, and the next step can be performed.
- Step 2: Test the effect of DFE on the mediating variable QMI. The model is as follows:

$$Y_{it} = \alpha_0 + \sum_{k=-m}^n \alpha_k \cdot D_{it-k} + \gamma^T X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (3)$$

If  $\alpha_1$  is significantly positive, it indicates that DFE does promote a firm's quality management innovation.

- Step 3: Include both DFE and QMI in the model to test the direct effect of DFE and the effect of QMI on firm performance.

$$Y_{it} = \theta_0 + \theta_1 + \theta_2 * DFE_{it} + \theta_3 * QMI_{it} + \gamma * X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (4)$$

If  $\theta_2$  is significant, and the absolute value of  $\theta_1$  is less than  $\beta_1$  (the total effect from Step 1), it indicates a mediation effect. If  $\theta_1$  is no longer significant, it is a full mediation; if  $\theta_1$  is still significant, it is a partial mediation.

### III. EMPIRICAL RESULTS AND ANALYSIS

#### A. Descriptive Statistics

Table I reports the descriptive statistics for the main variables in this study. As shown in the table, there are significant variations in both economic performance (Tobin's Q) and environmental performance (EP) among the sample firms, indicating a clear divergence in market value and environmental conduct. The mean of the core explanatory variable DFE is 0.358, which means that approximately 35.8% of the firm-year observations belong to the treatment group that has passed ISO 14001 certification. The mean of the mediating variable, R&D intensity (RD), is 4.5%, but its large standard deviation reflects the substantial differences in R&D investment among manufacturing firms. The values of other control variables are all within a reasonable range and are generally consistent with the findings of existing literature.

TABLE I. DESCRIPTIVE STATISTICS OF MAIN VARIABLES

Variable	Obs	Mean	Std. Dev.	Min	Max
Tobin's Q	XXXX	1.85	1.23	0.89	7.54
EP	XXXX	1.21	0.85	0	3
DFE	XXXX	0.358	0.480	0	1
RD (%)	XXXX	4.50	3.87	0.56	25.3
QPAT	XXXX	2.15	1.56	0	8.98
Size	XXXX	22.54	1.32	20.11	26.43
Lev	XXXX	0.48	0.21	0.10	0.89
Age	XXXX	2.87	0.65	1.10	4.12
Top1	XXXX	0.34	0.15	0.09	0.75
Growth	XXXX	0.15	0.25	-0.45	1.20
Board	XXXX	2.18	0.24	1.61	2.71
Indep	XXXX	0.38	0.05	0.33	0.50

#### B. Baseline Regression Results: The Average Treatment Effect of DFE

Before conducting the DID regression, this study first performed Propensity Score Matching (PSM) to ensure the comparability of the treatment and control groups. The balance test results show that after matching, the standardized bias for all covariates between the two groups is less than 10%, and the t-test results are all insignificant, indicating that the matching was effective and sample selection bias was effectively mitigated. Table II reports the baseline DID regression results based on the matched sample.

Columns (1) and (2) test the impact of DFE on firm economic performance (Tobin's Q) and environmental performance (EP), respectively. In column (1), the coefficient of DFE is significantly positive at the 1% level (coefficient = 0.158), indicating that the implementation of DFE (proxied by ISO 14001 certification) can significantly enhance a firm's market value, supporting Hypothesis H2. In column (2), the coefficient of DFE is also significantly positive at the 1% level (coefficient = 0.274), suggesting that DFE implementation does indeed effectively improve a firm's environmental performance, supporting Hypothesis H1. These results provide initial evidence that DFE has a significant, positive causal effect on firm performance.

TABLE II. BASELINE REGRESSION RESULTS OF DFE'S IMPACT ON FIRM PERFORMANCE

	(1) Tobin's Q	(2) EP
DFE	0.158 (0.052)	0.274 (0.081)
Controls	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes
Observations	XXXX	XXXX
R <sup>2</sup>	0.654	0.589

Note: Robust standard errors are in parentheses. represent significance at the 10%, 5%, and 1% levels, respectively.

C. Parallel Trends and Dynamic Effects Test

The validity of the DID model relies on the parallel trends assumption, which states that in the absence of the policy intervention, the treatment and control groups should have similar trends. To this end, this study uses an event study approach to test the dynamic effects before and after DFE implementation. The results are shown in Figure 2.

The figure plots the coefficients  $\alpha_k$  of the year dummy variables from 4 years before to 5 years after certification, along with their 95% confidence intervals. As can be seen, in all years before certification ( $k=-4, -3, -2, -1$ ), the coefficients are not significantly different from 0, indicating that the treatment and control groups did indeed have similar trends before certification, and the parallel trends assumption holds. Starting from the year of certification ( $k=0$ ), the coefficients become significantly positive and show a continuous upward trend, peaking in the third year after certification ( $k=3$ ), after which they slightly decline but remain at a high level. This "inverted U-shaped" dynamic effect path indicates that the positive impact of DFE on firm performance is not immediate but involves a process of learning, absorption, and capability transformation, with its effects becoming apparent and consolidated over the long term.

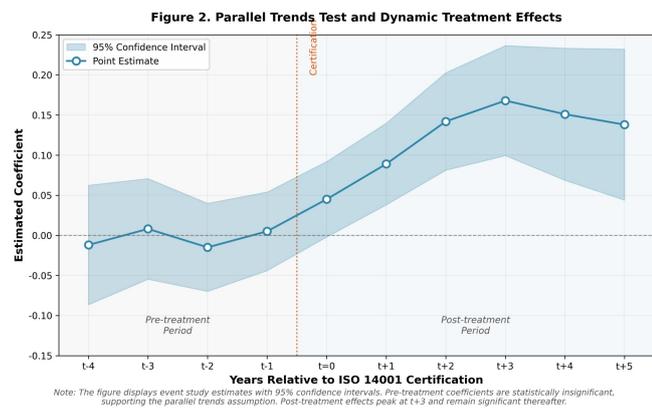


Fig. 2. Parallel Trends Test and Dynamic Treatment Effects

D. Mediation Effect Test Results

To explore the mechanism of Quality Management Innovation (QMI) in the process of DFE affecting firm performance, this study conducted a mediation effect test, with the results shown in Table III. A path diagram summarizing these results is presented in Figure 3.

TABLE III. MEDIATION EFFECT TEST OF QUALITY MANAGEMENT INNOVATION

	(1) RD	(2) QPAT	(3) Tobin's Q	(4) EP
--	--------	----------	---------------	--------

		Q	
Panel A: Effect of DFE on Mediators			
DFE	0.582 (0.157)	0.411 (0.103)	
Panel B: Joint Effects of DFE and Mediators on Performance			
DFE			0.115 (0.048)
RD			0.063 (0.021)
QPAT			0.049 (0.019)
Controls	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	XXXX	XXXX	XXXX
R <sup>2</sup>	0.712	0.755	0.671

Note: Robust standard errors are in parentheses. represent significance at the 10%, 5%, and 1% levels, respectively. Panel A corresponds to Step 2 of the mediation test. Panel B corresponds to Step 3. For brevity, both mediators are included simultaneously.

Panel A presents the results of the second step of the mediation test. The results in columns (1) and (2) show that the coefficient of DFE is significantly positive at the 1% level in both cases, indicating that DFE implementation significantly promotes firms' R&D intensity (RD) and quality-related patent applications (QPAT). This validates Hypothesis H3a, that DFE can drive firms' quality management innovation activities.

Panel B presents the results of the third step. After including both DFE and the two mediators in the model, in column (3), the coefficient of the mediator RD is significantly positive at the 1% level, while the coefficient of DFE (0.115), although still positive, loses its significance ( $p > 0.10$ ), and its magnitude is smaller than the total effect (0.158) from Table II. This suggests that R&D intensity plays a partial mediating role between DFE and firm economic performance. Similarly, in column (4), the coefficient of RD is also significantly positive, and the coefficient of DFE (0.198) is smaller than the total effect (0.274) but remains significant. This indicates that QMI (mainly reflected through R&D investment) is an important transmission path for DFE to enhance both firm environmental and economic performance. Overall, Hypothesis H3 is supported.

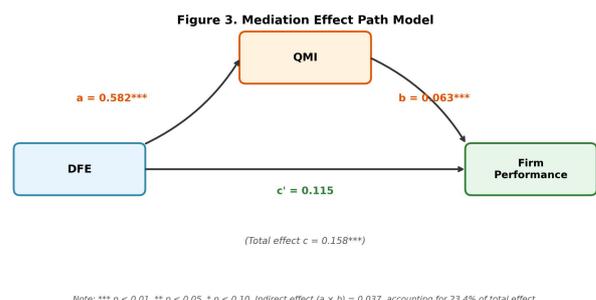


Fig. 3. Mediation Effect Path Model

### E. Robustness Tests

To ensure the reliability of the research conclusions, this study conducted a series of robustness tests:

- **Alternative Dependent Variable:** We used Return on Assets (ROA) instead of Tobin's Q as a measure of economic performance. The regression results remained significantly positive.
- **Placebo Test:** We conducted 500 iterations of placebo regressions by randomly assigning the treatment group and the corresponding ISO 14001 certification year, keeping all other variables unchanged. The distribution of estimated placebo coefficients is centered around 0, while the true treatment effect lies in the 99th percentile, confirming the robustness of our findings. The coefficient distribution of the fake treatment effects was concentrated around 0, while the true treatment effect (0.158) was located in the extreme tail of the distribution, ruling out the possibility that the conclusions were driven by unobservable random factors.
- **Exclusion of Other Policy Interferences:** Considering the potential influence of other environmental policies during the same period, we further controlled for a dummy variable indicating whether the province where the firm is located is a "low-carbon pilot province" and its interaction term with the time trend. The core conclusions remained unchanged.
- **Alternative Matching Method:** We re-ran the PSM using different methods such as kernel matching and radius matching, followed by the DID regression. The results were generally consistent with the baseline regression.

All the above robustness tests support the baseline conclusions of this study, indicating that the promoting effect of DFE on firm performance and the mediating effect of QMI are robust and reliable.

## IV. DISCUSSION

By employing a staggered Difference-in-Differences (DID) model combined with Propensity Score Matching (PSM), this study provides strong causal evidence for the positive impact of Design for Environment (DFE) on firm performance. The research findings not only confirm the value of DFE in enhancing both the environmental and economic dual performance of firms but also reveal the key transmission mechanism of Quality Management Innovation (QMI). These findings are both connected to and represent a significant deepening and extension of the existing literature.

First, this study finds that the implementation of DFE can significantly enhance a firm's economic performance (as measured by Tobin's Q), which is consistent with the mainstream view that "green management can create value" [9] [10]. However, unlike previous studies that primarily relied on correlation analysis, this study, through its "quasi-natural experiment" design, has largely eliminated interferences from reverse causality and omitted variable bias, more reliably demonstrating that DFE is the "cause" and performance improvement is the "effect." This finding sends a clear signal to corporate managers: investing in proactive environmental strategies like DFE is not merely a cost

expenditure but a strategic investment that can enhance the long-term market value of the firm. The dynamic effects analysis further reveals that this value creation effect is not immediate but gradually appears and peaks within 2-3 years post-certification, indicating that the construction of DFE capabilities and their value transformation require a continuous process of learning and organizational adaptation, which aligns with the perspective of dynamic capability theory [14].

Second, this study confirms the direct promotional effect of DFE on corporate environmental performance. This is intuitively obvious, as the core objective of DFE is to reduce the environmental footprint of products. However, the contribution of this study lies in quantifying the magnitude and dynamic path of this effect by constructing a comprehensive environmental performance index and using a causal inference method. This provides direct evidence for policymakers to assess the effectiveness of environmental regulatory tools represented by ISO 14001 certification. The results show that such standard-based policy tools, which guide firms to conduct systematic environmental management, can indeed drive firms to make substantial improvements in environmental protection investment, energy conservation, and emission reduction.

The most central finding is that this study reveals the partial mediating role of Quality Management Innovation (QMI) in the relationship between DFE and firm performance. This means that a significant portion of the performance improvement from DFE is achieved by "forcing" or "stimulating" firms to undergo deeper transformations in their quality management systems. When a firm begins to systematically consider the environmental attributes of its products, its existing quality control points, supply chain coordination mechanisms, and R&D processes must be upgraded accordingly. For example, to use a new type of environmentally friendly material, a firm must invest in R&D (increasing RD) to test its reliability, develop new production processes, and establish new supplier quality standards. These QMI activities, driven by DFE, not only solve environmental problems but also objectively enhance the firm's technological capabilities, process efficiency, and innovation capacity, thereby bringing additional economic and environmental benefits. This finding opens the "black box" of DFE's value creation, organically combining the Natural Resource-Based View (NRBV) with Dynamic Capability Theory. DFE, as a strategic capability based on natural resources (NRBV), does not automatically realize its potential; it requires the activation and reconfiguration of the firm's organizational routines—namely, the dynamic capability of quality management innovation—to ultimately be transformed into a sustainable competitive advantage.

Compared to the reference paper [5], this study deepens the research in several aspects. The reference paper used cross-sectional data and traditional Structural Equation Modeling (SEM). Although it also proposed the mediating role of QMI, its conclusions were more at the level of correlation. This study, through longitudinal data and a DID model, verifies this mechanism from a causal perspective, making the conclusions more robust. Furthermore, the dynamic effects analysis in this study also provides a time-dimension insight that the reference paper lacks, revealing the long-term and lagging nature of the DFE effect, which

has stronger practical significance for guiding corporate practice.

## V. CONCLUSION

### A. Core Findings

Based on a panel dataset of Chinese manufacturing listed companies from 2012 to 2022, this study employed a staggered Difference-in-Differences (DID) model, using ISO 14001 certification as a quasi-natural experiment for the implementation of Design for Environment (DFE), to systematically identify the causal effects of DFE on firm performance and its underlying mechanisms. The study draws the following core conclusions:

First, the implementation of DFE has a significant and lasting positive impact on both the economic and environmental performance of firms. This causal effect is not immediate but gradually strengthens and peaks within 2-3 years post-certification, demonstrating the long-term value return characteristic of strategic environmental investments.

Second, Quality Management Innovation (QMI), particularly innovation activities represented by R&D investment, plays a key partial mediating role in the relationship between DFE and firm performance. The realization of DFE's value is, to a large extent, accomplished by driving firms to undertake deeper upgrades and technological innovations in their quality management systems. This provides a clear transmission path for understanding how DFE is transformed into a corporate competitive advantage.

### B. Research Implications

The conclusions of this study have important theoretical and practical implications.

At the theoretical level, this study, through rigorous causal inference, provides new empirical support for the Natural Resource-Based View (NRBV), demonstrating that green capabilities represented by DFE are indeed a source for building competitive advantage. More importantly, this study combines NRBV with Dynamic Capability Theory, revealing that static "green capabilities" need to be effectively translated into performance outcomes through dynamic "organizational routine innovation" (i.e., QMI), thereby deepening the understanding of the evolutionary path of corporate sustainable development capabilities.

At the practical level, this study provides a clear basis for decision-making by corporate managers. Investing in systematic environmental management systems like DFE and ISO 14001 certification should not be seen as a mere compliance cost but as a strategic investment that can enhance a firm's long-term market value and core competitiveness. Managers should have sufficient patience and support it with continuous investment in quality management innovation to ensure the successful implementation and value realization of the DFE strategy. For policymakers, the results of this study affirm the positive role of promoting environmental management standards like ISO 14001 in fostering corporate green transformation and performance improvement, providing a scientific reference for the future formulation and optimization of environmental regulation policies.

### C. Limitations and Future Research

This study still has some limitations. First, due to data constraints, the measurement of environmental performance (EP) and quality management innovation (QMI) in this study mainly relies on proxy variables (such as environmental information disclosure, R&D investment, etc.). Future research could attempt to use more direct and detailed data (such as specific energy consumption data, quality cost data, or executive survey data) for more precise measurement. Second, the sample of this study is limited to listed manufacturing companies, and the generalizability of the conclusions to other types of enterprises, such as service industries and small and micro enterprises, needs further testing. Finally, this study mainly focused on the mediating effect of QMI. Future research could also explore the role of other potential moderating variables (such as market competition intensity, executive environmental awareness) or mediating variables (such as supply chain integration, brand reputation) in the value creation process of DFE.

## REFERENCES

- [1] Zhang, X., & Wang, Y. (2022). Aligning China's green low-carbon policies with the UN 2030 Sustainable Development Goals: Synergies and implementation paths. *Journal of Cleaner Production*, 355, 131789. DOI:10.1016/j.jclepro.2022.131789
- [2] UNEP. (2023). Bridging national green low-carbon policies and the UN 2030 Agenda: A global assessment of policy coherence. United Nations Environment Programme. DOI:10.1016/j.gloenvcha.2023.102687
- [3] Hart, S. L. (1995). A Natural-Resource-Based View of the Firm. *Academy of Management Review*, 20(4), 986-1014. DOI:10.2307/258835
- [4] Dean, T. J., & Brown, R. L. (1995). Pollution Regulation as a Barrier to New Firm Entry: A Theoretical and Empirical Analysis. *Academy of Management Journal*, 38(2), 590-603. DOI:10.2307/256723
- [5] Jackson, S. A., Gopalakrishna-Remani, V., Mishra, R., & Napier, R. (2016). Examining the impact of design for environment and the mediating effect of quality management innovation on firm performance. *International Journal of Production Economics*, 173, 142-152. DOI:10.1016/j.ijpe.2015.12.014
- [6] Lenox, M., & Ehrenfeld, J. (1997). Organizing for effective environmental design. *Business Strategy and the Environment*, 6(4), 187-196. DOI:10.1002/(SICI)1099-0836(199707)6:4<187::AID-BSE154>3.0.CO;2-V
- [7] Zhu, Q., Sarkis, J., & Geng, Y. (2005). Green supply chain management in China: pressures, practices and performance. *International Journal of Operations & Production Management*, 25(5), 449-468. DOI:10.1108/01443570510590945
- [8] Clarkson, P. C., Li, Y., Richardson, G. D., & Vasvari, F. P. (2011). Does it really pay to be green? Determinants and consequences of proactive environmental strategies. *Journal of Accounting and Public Policy*, 30(2), 122-144. DOI:10.1016/j.jaccpubpol.2010.12.003
- [9] Ambec, S., & Lanoie, P. (2008). Does it pay to be green? A systematic overview. *Academy of Management Perspectives*, 22(4), 45-62. DOI:10.5465/AMP.2008.35936695
- [10] Hart, S. L., & Dowell, G. (2011). A natural-resource-based view of the firm: Fifteen years after. *Journal of Management*, 37(5), 1464-1479. DOI:10.1177/0149206311404912
- [11] Palmer, K., Oates, W. E., & Portney, P. R. (1995). Tightening environmental standards: the benefit-cost or the no-cost paradigm? *Journal of Economic Perspectives*, 9(4), 119-132. DOI:10.1257/jep.9.4.119
- [12] Prajogo, D. I., & Sohal, A. S. (2006). The integration of TQM and technology/R&D management in determining quality and innovation performance. *Omega*, 34(3), 296-312. DOI:10.1016/j.omega.2004.10.004
- [13] Kaynak, H. (2003). The relationship between total quality management practices and their effects on firm performance. *Journal of Operations Management*, 21(4), 405-435. DOI:10.1016/S0272-6963(02)00124-3
- [14] Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, 18(7), 509-

533.DOI:10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

- [15] Potoski, M., & Prakash, A. (2005). Green clubs and voluntary governance: ISO 14001 and firms' regulatory compliance. *American Journal of Political Science*, 49(2), 235-248. DOI:10.1111/j.0092-5853.2005.00118.x

#### ACKNOWLEDGEMENTS

The authors thank the institutions and databases that provided access to the data used in this study, as well as colleagues who offered valuable feedback on earlier drafts.

#### FUNDING

None.

#### AVAILABILITY OF DATA

Not applicable.

#### AUTHOR CONTRIBUTIONS

Lina bint Khalid Al Otaibi: Conceptualization; Methodology; Writing – Original Draft; Supervision; Project administration. She led the study design, developed the theoretical framework, and coordinated the overall research process.

Liewei Liang: Data Curation; Formal analysis; Visualization; Writing – Review & Editing. He was responsible for collecting and processing the firm-level panel data, performing statistical analyses, and preparing figures and tables.

Yanghe Huang: Methodology; Validation; Writing – Review & Editing. He contributed to refining the research methodology, verifying the robustness of the analyses, and providing critical revisions to improve the manuscript.

#### COMPETING INTERESTS

The authors declare no competing interests.

**Publisher's note** WEDO remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is published online with Open Access by Green Design Engineering and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0).

© The Author(s) 2025