

Research on the Assessment of Greenwashing in Corporate Environmental Information Disclosure Based on Large Language Models and the Dynamic Mechanism of Green Financing

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Abstract. This study is situated against the backdrop of global green economic transformation and examines the dynamic internal mechanisms linking greenwashing behavior in corporate environmental information disclosure with green financing policies. Drawing upon an interdisciplinary theoretical framework, the study constructs and empirically tests a model addressing the systematic discrepancy between the information conveyed in Environmental, Social, and Governance reports and actual green performance. The research gap lies in the quantitative identification of greenwashing phenomena and in the systematic analysis of the dynamic transmission mechanism by which green financing exerts both incentive and constraint effects over different time horizons. Employing large language models for in - depth semantic extraction and sentiment quantification of corporate environmental disclosures, and integrating a combined econometric model based on the Slack-Based Measure and the Malmquist index for precise measurement of actual green practices, a comprehensive greenwashing index is constructed. Subsequently, dynamic overlapping difference-in-differences and symbolic regression models are utilized to conduct a multidimensional, multi-period dynamic analysis of the short-term incentive and long-term constraint effects of green financing policies on corporate greenwashing behavior. The findings, underpinned by a methodological fusion of natural language processing techniques and econometric modeling, provide a novel empirical perspective on the dynamic mechanism linking green financing policies to corporate environmental governance and offer a data-driven theoretical basis for policymakers.

Keywords: Large Language Models; Greenwashing Index; Green Financing; Dynamic Difference-in-Differences; Symbolic Regression.

1. Introduction

In recent years, the global transition to a green economy has emerged as a central objective pursued by nations worldwide. As core participants in economic activity, corporations play an indispensable role in promoting green development and in facilitating the rational allocation of resources. Through the publication of Environmental, Social, and Governance (ESG) reports, corporations endeavor to demonstrate their commitments to green transformation [1]. Such disclosures serve not only to enhance corporate reputations but also to provide investors, consumers, and regulatory bodies with critical information for evaluating corporate sustainability [2].

Simultaneously, the rapid advancement of big data and artificial intelligence has introduced innovative approaches, such as text sentiment analysis and semantic mining based on large language models, for the quantitative evaluation of corporate environmental disclosures [3]. These emerging techniques enable precise comparisons across multiple channels and dimensions between corporate green communication and actual green practices, thereby facilitating the construction of a greenwashing index that reflects the discrepancy between communicated and realized actions. Such a framework provides robust theoretical and empirical support for dissecting the underlying drivers of corporate greenwashing behavior [4] [5]. Based on this background, the present study adopts a green financing perspective and leverages large language models and associated quantitative techniques to systematically assess the extent of greenwashing in corporate environmental disclosures and to investigate the dynamic impact mechanisms of green financing on corporate greenwashing

behavior [6]. The resulting greenwashing index is envisaged not only as an effective reference tool for regulators and financial institutions to enhance the identification of authentic corporate environmental performance but also as a basis for formulating and refining green financing policies, optimizing the allocation of green financial resources, and governing corporate greenwashing behavior, thereby contributing to the development of a well-regulated green financial market [7].

2. Theoretical Hypotheses and Analytical Framework

2.1. Formulation of Research Hypotheses

Based on extant theoretical foundations, the hypothesis positing a significant discrepancy between the level of corporate environmental information disclosure and actual green performance can be elucidated from multiple theoretical perspectives. Information asymmetries between management and shareholders incentivize managerial actors to employ selective disclosure strategies to enhance the firm's external image, as reflected in the propensity of management to engage in selective disclosure, rhetorical embellishment, and the exaggeration of environmental governance outcomes in order to mitigate external regulatory pressures or satisfy market expectations regarding green transformation. Concurrently, legitimacy theory posits that in pursuit of societal approval and legitimacy, firms may exhibit an overemphasis on the portrayal of their environmental performance, a practice that frequently results in a pronounced divergence between disclosed information and actual investments and improvements, thereby rendering the corporate green image a superficial representation rather than a genuine reflection of environmental governance capabilities.

With respect to the dynamic mechanism of green financing, its dual effects can be interpreted in terms of short-term incentives and long-term constraints. In the short term, firms, under the exigencies of immediate financing needs and external audit standards, are inclined to adopt greenwashing strategies to secure rapid access to financing. During this phase, the combined pressures of external financing demands and market expectations predispose firms to engender a spurious congruence between disclosed information and actual green practices, thereby garnering preferential treatment in competitive capital markets. Conversely, over the long term, the progressive refinement of green financing policies and the intensification of financial regulatory oversight foster a sustained incentive and constraint mechanism that compels firms to undertake substantive improvements in financing structure, investment orientation, and technological innovation in order to maintain market credibility and legitimacy. This process, characterized by the interplay of external financial support and internal governance enhancements, incrementally reduces the divergence between disclosed information and genuine performance, thereby mitigating greenwashing behavior and facilitating authentic green transformation. The research hypotheses are delineated in Table 1.

2.2. Analytical Framework

The analytical framework for assessing the degree of greenwashing based on large language models is predicated upon the construction of a comprehensive index that quantitatively captures the systematic discrepancy between corporate environmental disclosures and actual green performance. This framework integrates sentiment analysis and semantic mining algorithms to extract latent affective and semantic features from textual data, thereby identifying and quantifying the divergence between disclosed information and measured green performance. During the processing of textual information, the framework systematically assimilates techniques of sentiment polarity analysis and semantic extraction, with the model training phase meticulously capturing linguistic embellishments, rhetorical selections, and selective information presentation inherent in the corpus of environmental reports. Consequently, the large language model is able to effectively discern the linguistic patterns indicative of greenwashing phenomena within the corpus. Concurrently, the framework synergizes textual data with quantitative metrics by incorporating rigorously derived econometric indicators such as the Slack-Based Measure (SBM) combined with the Malmquist index, which affords a precise measurement of actual green practices. The resultant greenwashing index is constructed through a

methodical process of data comparison, indicator calibration, and weight allocation, thereby yielding an integrated, data-driven evaluative tool that serves as an objective metric for regulatory bodies. Figure 1 illustrates the comprehensive framework for assessing the degree of greenwashing based on large language models, wherein the flowchart delineates the sequential process—from data collection, preprocessing, and model fine-tuning to sentiment and semantic analysis, index construction, and result validation—with each phase interconnected through stringent data transfer protocols and methodological logic that ensures systemic coherence and endogenous integration.

Table 1. Research Hypothesis and Expected Outcomes

Research Hypothesis	Theoretical Basis	Expected Outcome
There is a significant gap between environmental disclosure and actual green performance.	Agency Theory: Information asymmetry incentivizes managers to embellish disclosure. Legitimacy Theory: Firms overstate environmental performance to gain social acceptance.	Firms may exaggerate green achievements, causing discrepancies between reported and actual performance.
Green financing increases greenwashing in the short term but reduces it in the long term.performance to gain social acceptance.	Short-term Incentives: Pressure for quick financing may drive superficial disclosure. Long-term Constraints: Improved policies and stricter oversight force genuine improvements.	In the short term, green financing may boost greenwashing behavior; in the long term, it encourages real green transformation.

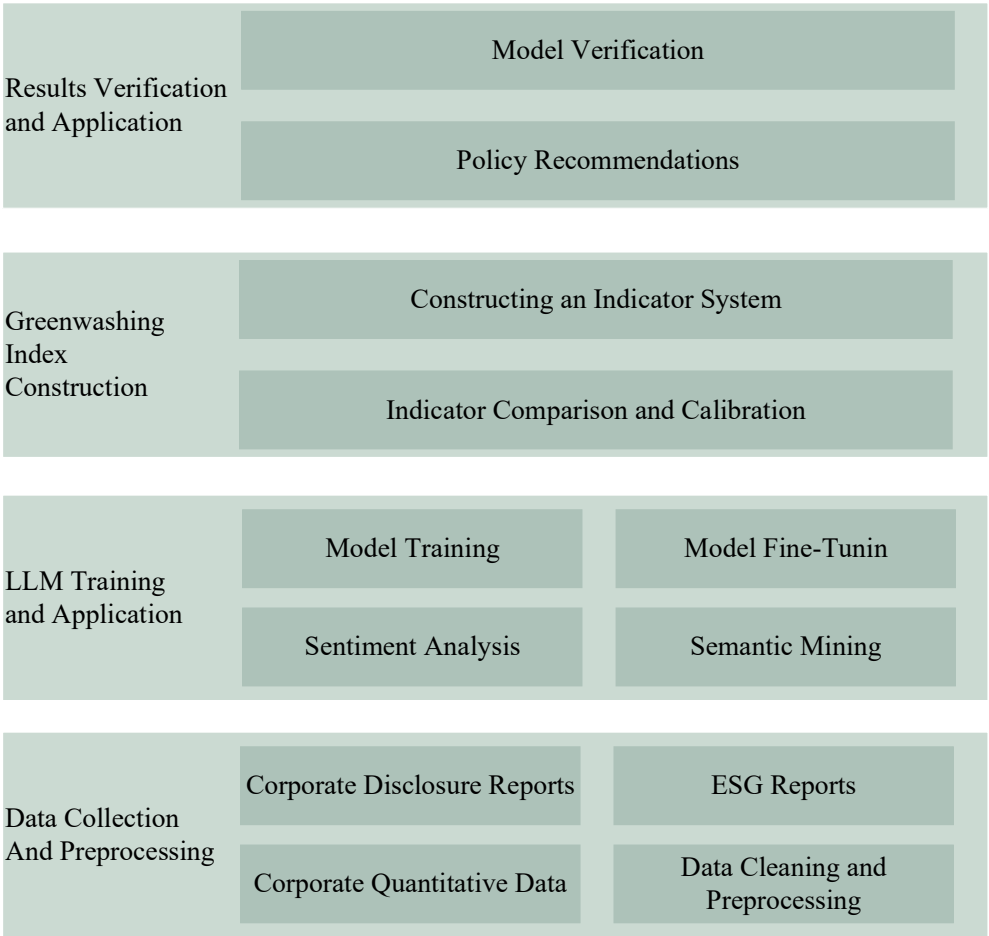


Figure 1. Framework for Assessing the Degree of Greenwashing Based on Large Language Models

The dynamic mechanism analytical framework is designed to elucidate the dual effects of green financing on corporate environmental disclosure behavior across different temporal dimensions, by constructing econometric models and employing causal inference techniques to capture the non-linear variations and interactive effects among endogenous variables under green financing policies. In this analytical process, data are collected on corporate environmental disclosures, financing time points, and quantitative indicators of green performance, with key control variables explicitly defined. The framework employs a dynamic overlapping difference-in-differences (DID) model to rigorously examine the differential impacts on greenwashing behavior before and after the implementation of green financing policies, while a symbolic regression model is further utilized to characterize the potential non-linear and interactive relationships among variables, thereby revealing the internal transmission mechanisms through which green financing exerts both incentive and constraint effects across different temporal dimensions. The overall evaluative process encompasses data preparation, variable definition, model construction, parameter estimation, robustness testing, and policy recommendation, forming a closed-loop system. Figure 2 presents the overall analytical framework in a flowchart format, with each process node—ranging from data collection and variable construction to model estimation, result feedback, and policy improvement—linked via rigorous causal logic and statistical verification, thus ensuring methodological consistency and dynamic progression.

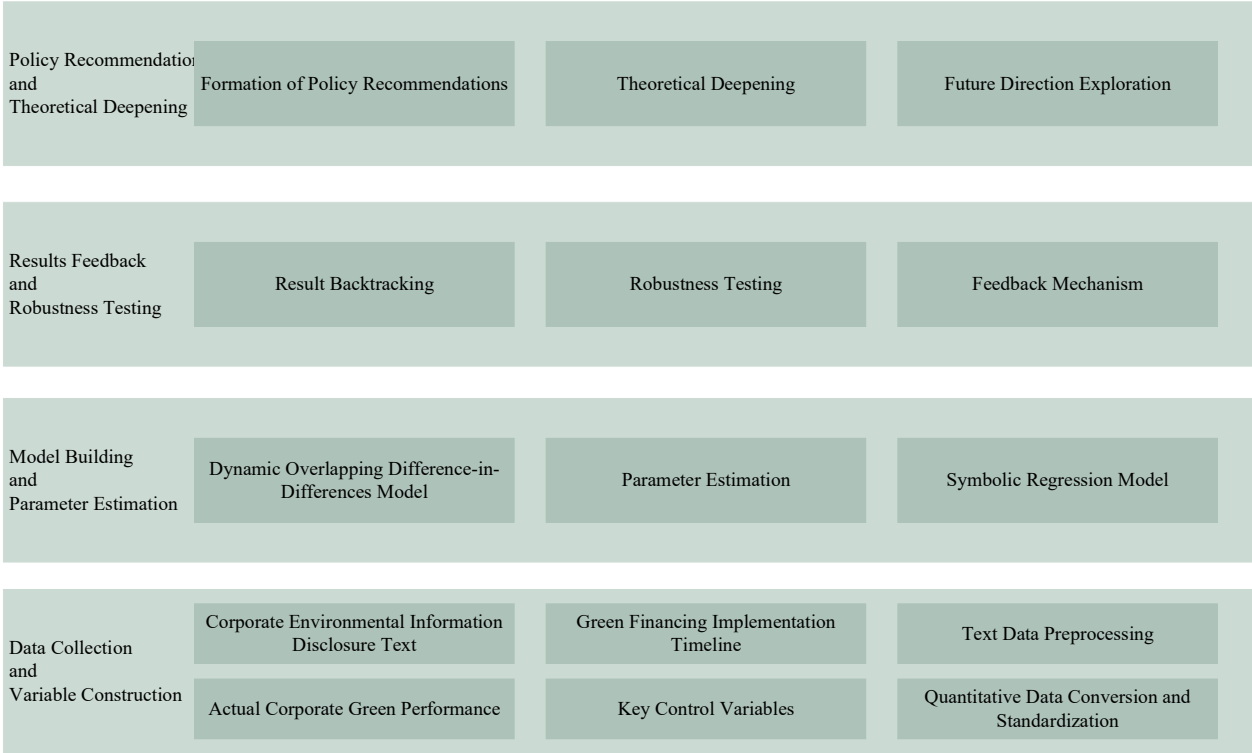


Figure 2. Dynamic Mechanism Analytical Framework

In summary, both analytical frameworks employ rigorous econometric methodologies and advanced natural language processing techniques to achieve an integrated, cross-disciplinary synthesis of data, thereby ensuring theoretical coherence and empirical consistency from data collection through model construction to result validation, and ultimately providing a scientific and systematic empirical foundation for the dynamic analysis of green financing policies and corporate environmental governance behavior.

3. Behavior Measurement and Empirical Analysis Methods

3.1. Measurement Method for Greenwashing Behavior

In order to quantitatively capture greenwashing behavior, the present study employs large language models to perform in-depth semantic extraction and sentiment quantification of corporate environmental disclosure texts. This process leverages a self-supervised learning framework based on a pretrained model that is fine-tuned on a vast corpus of domain-specific texts, thereby enabling the systematic extraction of linguistic modifications, rhetorical selections, and latent affective tendencies present in the disclosures. These extracted textual features are subsequently converted into numerical indicators, thereby providing a robust quantitative basis for the construction of a comprehensive index. During the model training phase, parameter estimation is achieved by optimizing an objective function that minimizes semantic error while accurately capturing the affective dimensions of the text. This optimization is mathematically expressed as:

$$\min_{\theta} L(\theta) = \min_{\theta} \sum_{i=1}^N \ell(f(T_i; \theta), y_i) \quad (1)$$

where T_i denotes the i th environmental disclosure text, $f(T_i; \theta)$ represents the sentiment prediction output of the large language model parameterized by θ , y_i corresponds to the true sentiment label of the text, and $\ell(\cdot)$ denotes the loss function. This optimization process ensures that the model output reliably reflects the latent modes of expression and affective dimensions inherent in the text, thereby enabling the precise quantification of greenwashing behavior.

For the quantitative assessment of actual green practices, the study integrates an econometric model that combines the Slack-Based Measure (SBM) with the Malmquist index, thereby facilitating an accurate evaluation of corporate green performance. Specifically, the SBM model addresses the slack in input and output variables to compute an efficiency score, as represented by:

$$\min_{\lambda, s^-, s^+} \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{ro}}} \quad (2)$$

where x_{io} denotes the i th input for decision-making unit o , y_{ro} represents the corresponding output, s_i^- and s_r^+ are the slack variables for inputs and outputs respectively, λ is the weight coefficient, and m and s represent the number of input and output variables, respectively. To depict efficiency changes over distinct time intervals, the Malmquist index is employed as follows:

$$M_0 = \sqrt{\frac{D_t(x_t, y_t)}{D_t(x_{t-1}, y_{t-1})} \times \frac{D_{t+1}(x_t, y_t)}{D_{t+1}(x_{t-1}, y_{t-1})}} \quad (3)$$

where $D_t(x, y)$ denotes the distance function at time t for a given set of inputs x and outputs y . The index provides a temporal dynamic reference for evaluating green performance. Definitions for all symbols adhere strictly to econometric standards, ensuring rigorous integration and dynamic comparability across multidimensional datasets.

The construction of the greenwashing index is achieved by employing a weighted synthesis of the sentiment score derived from the large language model and the quantitative green performance measure. This synthesis is mathematically formulated as:

$$GI = \alpha \cdot S_{text} + (1 - \alpha) \cdot P_{green} \quad (4)$$

where GI represents the constructed greenwashing index, S_{text} is the textual greenwashing score derived from sentiment analysis, P_{green} is the performance score computed using the combined SBM-Malmquist model, and α is an adjustment coefficient determined by the data characteristics and empirical requirements.

This weighted combination systematically reflects the discrepancy between disclosed information and actual green performance, thereby enabling precise quantification of greenwashing behavior. The construction method adheres to strict statistical inference procedures and optimization principles throughout data comparison, indicator calibration, and weight allocation, ensuring the internal logical consistency and econometric precision of the greenwashing index, which serves as an objective, data-driven evaluative tool for regulatory authorities and financial decision-makers.

3.2. Empirical Analysis Methods for the Dynamic Mechanism

To rigorously elucidate the dynamic effects of green financing on corporate greenwashing behavior, the study employs both a dynamic overlapping difference-in-differences model and a symbolic regression model, thereby establishing a closed-loop causal inference framework. This framework is predicated on the meticulous definition of key variables and control variables, and through the precise estimation of model parameters, it facilitates a quantitative investigation of the policy effects of green financing across multiple time dimensions. The dynamic overlapping DID model is specified as:

$$Y_{it} = \alpha + \sum_{k=-K}^K \beta_k I\{t = T_i + k\} + \gamma X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \quad (5)$$

where Y_{it} denotes the greenwashing behavior metric for firm i at time t , $I\{t = T_i + k\}$ is an indicator function that signifies the status of firm i relative to its financing time T_i at period k , β_k are the corresponding policy effect coefficients, X_{it} is the vector of control variables—including firm size, industry characteristics, and historical performance— λ_t represents time fixed effects, μ_i denotes firm-specific fixed effects, and ε_{it} is the stochastic error term. This model, estimated via ordinary least squares or maximum likelihood methods, incorporates robust standard errors to ensure statistical significance and econometric stability while addressing potential endogeneity issues through the inclusion of interaction terms and lagged effects.

Building upon the dynamic model, the symbolic regression approach is utilized to capture the non-linear and interactive relationships between the key independent variables and greenwashing behavior. This method eschews predetermined functional forms in favor of an evolutionary algorithm that iteratively generates mathematical expressions to optimally fit the observed data. The fundamental structure of the symbolic regression model is given by:

$$Y = f(X; \theta) + \varepsilon \quad (6)$$

where Y represents the greenwashing index, X is the vector of independent variables encompassing green financing indicators, corporate governance measures, innovation levels, and other controls, θ denotes the parameter set to be estimated, and $f(\cdot)$ is the function constructed by the symbolic regression algorithm. The process minimizes the prediction error iteratively by refining the structure and parameters of the expression, while ε represents the residual error term. This method effectively captures complex non-linear interactions among variables, thereby complementing traditional linear models in elucidating the inherent transmission mechanisms of green financing.

In constructing these models, precise definition and measurement of key and control variables are maintained in strict accordance with econometric standards. The greenwashing behavior metric, serving as the dependent variable, is derived from both the sentiment and semantic analysis of disclosure texts and quantitative performance indicators. Green financing, the policy variable, is

introduced as a binary indicator reflecting whether a firm has secured green financing at a specific time point. Control variables, including firm size, industry effects, historical environmental performance, and innovation capacity, are standardized to eliminate dimensional disparities and ensure consistency in parameter estimation. This is mathematically expressed by the following refined dynamic effect model:

$$Y_{it} = \alpha + \beta TREAT_i \times POST_t + \gamma Z_{it} + \lambda_t + \mu_i + \varepsilon_{it} \quad (7)$$

where $TREAT_i$ is a binary variable indicating whether firm i received green financing, $POST_t$ is an indicator for the post-policy period, and the interaction term $TREAT_i \times POST_t$ captures both the immediate and delayed effects of green financing on greenwashing behavior. The parameter β quantifies the policy effect, contingent upon the rigorous measurement and control of the variables in Z_{it} . This refined specification underpins both the symbolic regression and dynamic DID models, ensuring that the empirical investigation effectively addresses endogeneity concerns and yields precise estimates of the dynamic regulatory effects of green financing policies on corporate environmental disclosure behavior.

4. Conclusion

This study employs a methodologically rigorous approach by constructing a greenwashing index based on large language models and applying both dynamic overlapping difference-in-differences and symbolic regression models to empirically examine the dynamic effects of green financing policies on corporate environmental disclosure behavior. The findings systematically reveal the quantitative discrepancy between environmental disclosures and actual green performance, as well as the temporal evolution of this discrepancy under the influence of green financing policies. The empirical evidence provides a robust theoretical basis for the quantitative analysis of green financing effects, while also offering significant insights into the optimization of green financial resource allocation and the enhancement of corporate environmental governance systems. Moreover, the study delineates potential avenues for future research, including the refinement of variable selection, the deepening of mechanism analysis, and the extension of comparative studies across different jurisdictions, thereby contributing a scientifically grounded and systematically structured empirical support for the development of the field.

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