

Article

Eco- and Socio-Efficiency as Determinants of Default Risk: Evidence from European Firms

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Abstract

This study investigates how eco-efficiency and socio-efficiency influence firms' default risk across the European financial, industrial, and consumer service sectors from 2010 to 2024. This study aims to determine whether integrating environmental and social performance into corporate strategies mitigates financial distress over time. The Pooled Mean Group ARDL estimator was employed to capture the short- and long-term dynamics. The results indicate that higher eco- and socio-efficiency significantly reduce long-term default risk, particularly in the financial and industrial sectors. Short-term effects were found to be insignificant, suggesting that sustainability benefits gradually emerged. This study offers novel sector-specific evidence linking sustainability efficiency to default risk in European firms and provides insights into how environmental and social efficiencies enhance corporate resilience and financial stability.

Keywords: eco-efficiency; socio-efficiency; default risk; Z-score; distance to default; DEA; ARDL

1. Introduction

Sustainability is increasingly acknowledged as a strategic element of corporate operations and long-term financial stability, rather than merely a philanthropic endeavor (Zheng et al., 2025). This shift is particularly evident in the European Union (EU), where regulatory initiatives such as the EU Taxonomy and the Corporate Sustainability Reporting Directive (CSRD) mandate firms to incorporate environmental and social considerations into their governance and reporting practices (A. T. X. Tran & Le, 2024). Beyond regulatory pressures, stakeholders, including investors, consumers, employees, and civil society, increasingly associate corporate resilience and long-term financial performance with environmental and social accountability (R. Liu et al., 2025). Consequently, examining how sustainability practices contribute to firms' financial stability and risk mitigation has become a significant research area.

Previous research has extensively explored the relationship between Corporate Social Responsibility (CSR), Environmental, Social, and Governance (ESG) practices, and financial performance. Existing evidence indicates that ESG and CSR initiatives enhance firms' access to capital, reduce financing costs, strengthen stakeholder trust, and increase resilience against external shocks (Singha et al., 2023; Wu et al., 2024). Singha et al. (2023) emphasized that sustainability-oriented practices improve operational performance and organizational resilience, thereby contributing to firms' long-term financial stability (AL'malabeh & Al-Nimer, 2024; Abdullah, 2016). However, much of



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the extant literature relies on aggregated ESG indicators, which may obscure the distinct effects of environmental and social efficiency dimensions on corporate financial risk (Heusler et al., 2024; Arora et al., 2025). Furthermore, limited attention has been paid to examining how operational sustainability efficiency directly influences corporate default risk (Reitsema & Scholtens, 2025; Anderson & Stejskal, 2019).

To address this gap, this study examines eco-efficiency and socio-efficiency as operational measures of sustainability performance and evaluates their impact on corporate default risk among European firms. Eco-efficiency denotes a firm's capacity to generate economic value while minimizing environmental impact, whereas socio-efficiency pertains to the social value derived from investments in employee welfare, diversity, and community engagement (Kafetzopoulos et al., 2024). Unlike aggregated ESG scores, these indicators provide a more nuanced assessment of how firms convert environmental and social inputs into sustainable outcomes (Dossa, 2025).

This study seeks to answer the following research question: (1) Does eco-efficiency reduce corporate default risks? (2) Does socio-efficiency improve firms' financial stability? (3) Are the effects of sustainability efficiency stronger in the long run than in the short run? By addressing these questions, this study contributes to the literature by examining the relationship between sustainability efficiency and default risk using both accounting-based and market-based measures.

This study utilizes Data Envelopment Analysis (DEA) under the Banker, Charnes, and Cooper (BCC) model to estimate eco-efficiency and socio-efficiency, a method widely employed to assess the relative efficiency of decision-making units (Gupta & Perwej, 2024). Corporate default risk is evaluated using two complementary indicators: the Altman Z-score and the market-based distance-to-default (DTD) measure (Jamil & Khan, 2024). Furthermore, the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) estimator is applied to capture both short-run and long-run dynamics between sustainability efficiency and default risk (Sahu et al., 2025). The analysis focuses on European firms in the financial, industrial, and consumer service sectors from 2010 to 2024. This timeframe is particularly relevant because it encompasses the post-financial crisis recovery period, the increasing implementation of sustainability regulations in Europe, and major economic disruptions, such as the COVID-19 pandemic.

This study makes several contributions to the existing literature. First, it advances previous research on ESG and CSR by emphasizing eco-efficiency and socio-efficiency as operational indicators of sustainability, rather than relying solely on aggregated ESG scores (Y. Gao et al., 2025). Second, it integrates accounting- and market-based measures of default risk to provide a more comprehensive evaluation of corporate financial vulnerability (Helen Aurora et al., 2025). Third, the PMG-ARDL framework employed in this study facilitates the distinction between the short- and long-run effects of sustainability efficiency on default risk (Medhat Eleshah Hanna & Moharam Algarhy, 2025). Finally, this study provides sector-specific evidence for European firms that operate under increasingly stringent sustainability regulations.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and theoretical background related to eco-efficiency, socio-efficiency, and corporate default risks. Section 3 describes the data, variables, and methodology, including the DEA-BCC model, Altman Z-score, Distance-to-Default measure, and PMG-ARDL framework. Section 4 presents the empirical findings, including descriptive statistics, correlation analysis, unit root tests, cointegration tests, and short-run and long-run estimation results. Section 5 discusses the findings in relation to previous studies and the theoretical perspectives. Finally, Section 6 concludes the study, highlights its policy implications, and suggests directions for future research.

2. Literature Review

2.1. Theoretical Foundations

The interconnection between eco-efficiency, socio-efficiency, and corporate default risk is underpinned by several theoretical frameworks that explain the impact of sustainability-oriented practices on firms' financial stability and risk exposure (Abdulla & Jawad, 2024). The Natural Resource-Based View (NRBV) posits that firms can achieve sustainable competitive advantages by integrating environmental considerations into their strategic and operational decision-making processes (Hart, 1995; Berent et al., 2017). Within this framework, eco-efficiency refers to a firm's capacity to optimize resource utilization while minimizing environmental externalities (Issa et al., 2025; Erin & Yuniarwati, 2025). Firms exhibiting superior eco-efficiency are expected to reduce operational inefficiencies, environmental liabilities, and regulatory exposure, thereby enhancing their long-term financial resilience and decreasing their default risks (Iazzolino et al., 2023; Ben Saad et al., 2024).

Stakeholder theory further explains the relationship between socio-efficiency and financial stability (Abdelhalim et al., 2023; Freeman, 2010). Socio-efficiency refers to a firm's ability to generate social value while maintaining operational performance and organizational sustainability (Juthi et al., 2024; Bharath & Shumway, 2008). Firms that invest in employee welfare, diversity, and stakeholder engagement are more likely to strengthen their legitimacy, reduce information asymmetry, and improve access to financial resources, thereby enhancing financial stability and reducing corporate risk (Basdekidou & Papapanagos, 2024; Begley et al., 1996).

Furthermore, the Resource-Based View (RBV) suggests that eco-efficiency and socio-efficiency constitute strategic capabilities that are valuable, rare, and difficult to imitate (Barney, 1991; Buallay, 2019). Sustainability-related capabilities may improve firms' adaptability, operational efficiency, and resilience to external shocks, thereby stabilizing cash flows and reducing financial vulnerability (Abdelhalim et al., 2023; Dorohan-Pysarenko et al., 2022). However, sustainability investments may incur implementation costs and organizational constraints that negatively affect short-term financial performance, particularly for firms with limited resources (Ferrat et al., 2025; Busch et al., 2016). Therefore, the relationship between sustainability and corporate risk remains theoretically complex and context-dependent (Zhang et al., 2024; Gopalakrishnan & Mohapatra, 2020).

2.2. Relationship Between Eco-Socio-Efficiency and Default Risk

This study proposes a comprehensive framework that distinguishes between eco-efficiency and socio-efficiency to improve the understanding of the sustainability–risk relationship for European firms. Drawing on established theoretical and empirical insights, this study posits that increases in both eco-efficiency and socio-efficiency can reduce corporate default risks over time. This reduction is achieved through improvements in operational efficiency, enhanced stakeholder trust, stabilized financial conditions and strengthened organizational resilience (Gupta & Perwej, 2024; Hasegawa et al., 2025).

The literature increasingly recognizes eco-efficiency as an important determinant of firms' financial stability and default risk (Asiaei et al., 2021; Bakhouché et al., 2020). Eco-efficiency reflects a firm's ability to generate economic value while minimizing environmental impacts through the efficient use of resources, energy, and production processes. From a financial perspective, greater environmental efficiency reduces operating costs, improves resource productivity, and enhances a firm's ability to cope with environmental and regulatory challenges (Horbal & Makarova, 2023; Hsiao et al., 2022). According to Reitsema and Scholtens (2025), reducing waste generation and improving resource utilization can enhance firms' competitiveness and profitability, thereby contributing to long-term financial stability. Eco-efficient firms may also benefit from improved relationships with in-

vestors, lenders, and regulators because strong environmental performance is increasingly viewed as an indicator of good management and reduced exposure to environmental liability (Whelan et al., 2021; Salonen & Camilleri, 2020). These advantages can translate into lower financing costs, enhanced market reputation, and greater resilience during periods of economic uncertainty (Issa et al., 2025; Pasupuleti, 2025). Moreover, García-Gómez et al. (2025) demonstrate that the benefits of eco-efficiency are particularly significant in sectors with high environmental exposure, where compliance with environmental regulations and effective resource management are essential for maintaining business continuity and mitigating financial vulnerability. These arguments suggest that eco-efficiency can contribute to stronger financial health and lower default risk (Lamanda & Tamásné Vőneki, 2024; Sinha Ray & Goel, 2023).

H1a. *Eco-efficiency has a positive relationship with firms' financial stability and reduces the default risk.*

However, the relationship between eco-efficiency and default risk may not always be favorable. The implementation of environmental strategies frequently requires substantial investments in cleaner technologies, process redesign, environmental management systems and regulatory compliance (Saona & Martín, 2025; Leme et al., 2018). These expenditures can place considerable pressure on firms' financial resources, particularly during the early stages of implementation when financial benefits have not yet materialized (Vishnu Nampoothiri et al., 2024; Khorilov & Kim, 2024). Additionally, firms may face uncertainty regarding the timing and magnitude of returns generated by environmental investments. According to Ferrat et al. (2025), when environmental initiatives are costly or inefficiently managed, they may reduce profitability, constrain liquidity, and increase financial pressure in the short term. Consequently, eco-efficiency initiatives may, under certain circumstances, increase firms' financial vulnerability and exposure to default risks (Zhakupova et al., 2025; Holling, 1973).

H1b. *Eco-efficiency has a negative relationship with firms' financial stability and, therefore, increases default risk.*

In addition to eco-efficiency, socio-efficiency has emerged as a critical dimension of sustainability performance with important implications for corporate financial stability (Clark et al., 2015; Chigira & Yamamoto, 2009). Socio-efficiency reflects a firm's capacity to create social value while efficiently utilizing its resources (Mahanta et al., 2024; Nagel & Purnanandam, 2019). Firms characterized by strong social performance often benefit from improved stakeholder relationships, stronger employee commitment, enhanced customer loyalty and greater organizational legitimacy. These factors contribute to a more stable operating environment and reduce various forms of business risk. According to Han et al. (2025), strong stakeholder trust may facilitate access to financial resources and improve firms' ability to attract investors and maintain favorable relationships with creditors. Furthermore, effective social practices can strengthen governance structures, improve decision-making processes, and enhance a firm's ability to respond to external challenges. Such benefits are particularly relevant in service-oriented industries, where organizational success depends heavily on human capital, customer satisfaction and stakeholder engagement (Saona & Martín, 2025). Therefore, the strategic management of social resources can contribute to greater resilience, improved financial performance, and lower default risk over time (Sahu et al., 2025).

H2a. *Socio-efficiency has a positive relationship with firms' financial stability and, therefore, reduces default risk.*

However, the relationship between socio-efficiency and financial stability may not always be positive. Social initiatives often require substantial investments in employee welfare programs, community engagement activities, stakeholder management and governance improvements (Dossa, 2025; Eccles et al., 2014). Although such initiatives may generate long-term benefits, they can also increase operating expenses and create financial burdens when they are not aligned with firms' strategic objectives (Pryshlakivsky & Searcy, 2017; Islam et al., 2022). Excessive social expenditure may divert resources from productive investments and reduce operational efficiency. In some cases, the inefficient allocation of resources to social activities may weaken profitability and limit firms' financial flexibility, thereby increasing financial risk exposure (T. X. A. Tran & Thảo, 2024). Consequently, socio-efficiency investments may contribute to a higher, rather than lower, default risk under certain conditions.

H2b. *Socio-efficiency has a negative relationship with firms' financial stability and, therefore, increases default risk.*

To assess sustainability efficiency, this study employs Data Envelopment Analysis (DEA) within the Banker, Charnes, and Cooper (BCC) model framework. DEA was selected because of its ability to simultaneously evaluate multiple environmental, social, and financial inputs and outputs without imposing restrictive assumptions (Jamil & Khan, 2024). Previous sustainability research has employed DEA models to assess environmental and social efficiency because of their capacity to integrate multiple inputs and outputs into a unified efficiency framework (Haryanto et al., 2025). Consequently, eco-efficiency and socio-efficiency are used as operational sustainability indicators that reflect firms' abilities to convert environmental and social resources into sustainable outcomes (Akadiri & Özkan, 2026).

Corporate default risk is evaluated using both the Altman Z-score and market-based distance-to-default (DTD) measure. The Altman Z-score is widely used to assess accounting-based financial distress risk, whereas the DTD reflects market expectations regarding the probability of corporate default (Iazzolino et al., 2023). Previous studies on corporate risk frequently employed these indicators as complementary measures of financial vulnerability and market-based default risk (Nian & Said, 2025; Seefloth et al., 2025). Consequently, integrating the Z-score and DTD provides a more comprehensive assessment of firms' exposure to default risk.

Despite the expanding literature on sustainability and financial performance, several limitations exist. Previous research has predominantly relied on aggregated ESG indicators, which may obscure the distinct impacts of environmental and social efficiency dimensions on corporate risk exposure (Adhikari & Zhou, 2022). Furthermore, limited attention has been paid to examining the dynamic relationship between eco-efficiency, socio-efficiency, and corporate default risk across sectors using accounting- and market-based risk measures (Ferrati et al., 2025). Existing findings are also inconclusive, as sustainability practices may either mitigate or exacerbate financial risk, depending on implementation costs, sectoral characteristics, and firms' strategic alignment (Zhang et al., 2024). To facilitate the synthesis of previous theoretical and empirical findings, a summary of the principal studies discussed in this section is presented in Appendix A, Table A1.

3. Methodology

This study examines the impact of eco-socio-efficiency on firms' default risk, considering the short- and long-term dynamics across European sectors. Eco- and socio-efficiency were measured using DEA, while default risk was assessed using the Altman (1968) Z-score and market-based Distance to Default (DTD).

3.1. The Sample

The study covers the period from 2010 to 2024 and includes a sample of 180 firms across three sectors: 60 financial firms, 69 industrial firms, and 51 consumer goods and services firms, all of which are headquartered in France, Italy, Germany, Spain, Belgium, Poland, and Finland. The selection of European firms is justified by the European Union's advanced sustainability regulations and reporting requirements, which provide a particularly relevant context for this analysis. The selected countries ensure broad geographic and economic representation while maintaining data consistency and availability during the study period. The financial, industrial, and consumer goods and services sectors were chosen because of their differing environmental and social exposures, enabling the analysis to capture the potential sectoral heterogeneity in the relationship between sustainability efficiency and default risk. Data on financial metrics, default risk, eco-efficiency, socio-efficiency, and control variables were obtained from the LSEG Datastream database to ensure consistency and reliability. Table A2 presents the sectoral and country distributions of the sample.

3.2. Construction of Socio-Eco Efficiency Indicators

Eco- and socio-efficiency are measured using input-oriented DEA under the BCC framework (Equations (1)–(5) (Banker et al., 1984). Eco-efficiency evaluates value creation with minimal environmental impact by using CO₂, waste, water, and resource use as inputs and environmental, innovation, and renewable energy scores as outputs. Socioefficiency assesses social resource use through employee turnover, salary gaps, and social performance indicators (Table A3 in the Appendix A).

The structure of the specific DEA model is as follows.

$$\text{Min } \theta - \varepsilon \left(\sum_{i=1}^m s_i^- + \sum_{r=1}^s s_r^+ \right) \quad (1)$$

Subject to:

$$\sum_{j=1}^n \lambda_j x_{ij} + s_i^- = \theta x_{io} \text{ for } i = 1, \dots, m \quad (2)$$

$$\sum_{j=1}^n \lambda_j y_{rj} - s_r^+ = y_{ro} \text{ for } r = 1, \dots, s \quad (3)$$

$$\sum_{j=1}^n \lambda_j = 1 \quad (4)$$

$$\lambda_j \geq 0, \quad s_i^- \geq 0, \quad s_r^+ \geq 0 \quad (5)$$

where:

X_{ij} : input i used the Decision-Making Unit (DMU) _{j} ;

y_{rj} : output r produced by DMU _{j} ;

s_i^- and s_r^+ : slack variables for input and output;

x_{io} and y_{ro} : inputs and outputs of the DMU under evaluation (DMU_o);

θ : efficiency score (between 0 and 1); to be minimized;

λ_j : intensity variables (weights assigned to peer DMUs);

ε : a small positive number to prioritize minimizing slacks after efficiency.

3.3. Default Risk

As explained above, we assessed default risk using two approaches: the Altman (1968) Z-score, an accounting-based measure of firm default risk, and Distance to Default (DTD), a market-based indicator.

3.3.1. Z-Score by Altman (1968)

This study uses the Altman (1968) Z-score, a metric derived from accounting principles, as a proxy for the firm-default risk. The formula used is as follows:

$$Z = 0.012X_1 + 0.014X_2 + 0.033X_3 + 0.006X_4 + 0.999X_5 \quad (6)$$

where:

X_1 = working capital/total assets;

X_2 = retained earnings/total assets;

X_3 = EBIT/total assets;

X_4 = market value of equity/total liabilities;

X_5 = sales/total assets.

These variables encompass a firm's liquidity, profitability, leverage, solvency, and activities. The Z-score was multiplied by -1 to reflect the default risk, with higher values indicating a higher risk (Altman et al., 2017).

3.3.2. Distance to Default (DTD)

The distance to default (DTD) serves as a market-based indicator of a firm's creditworthiness and the probability of default. Merton's structural model (Merton, 1974) assumes that a firm's asset value follows a stochastic (Wiener) process, with equity modeled as a call option on assets under the Black–Scholes–Merton framework. Default occurs when the asset value falls below the debt's face value at maturity. The DTD was computed using the following equation:

$$DTD = \ln \frac{V_t}{K} + \left(r + \frac{1}{2} \delta_v^2 \right) \Delta T / \delta_v \quad (7)$$

where V_t is the market value of the firm's assets, K is the book value of liabilities (debt), r is the risk-free interest rate, δ_v is the volatility of the firm's assets, and ΔT is the time horizon (one year). This formula calculates the number of standard deviations by which the asset value deviates from the default threshold, thereby quantifying default risk. To align with our interpretation in the context of risk (as with the Z-score), this study utilizes the DTD without transformation, as a higher value directly indicates a lower default risk (Black & Scholes, 1973; Merton, 1974). The list of variables is presented in Table A4 (see Appendix A).

3.4. Relationship Between Socio-Eco Efficiency and Default Risk

This study investigates the influence of eco-efficiency and socio-efficiency on corporate default risk by employing a panel autoregressive distributed lag (ARDL) framework estimated using the Pooled Mean Group (PMG) estimator. The PMG method is particularly appropriate because it accommodates short-run heterogeneity across firms while enforcing long-run homogeneity, thereby enabling differentiation between the immediate and long-term sustainability effects on default risk.

3.4.1. Model Estimations

This study applies an Autoregressive Distributed Lag (ARDL) framework to examine the dynamic link between default risk and sustainability indicators. Developed by Pesaran and Shin (1999), the ARDL model is suitable for integrated variables of order $I(0)$, $I(1)$, or both, but not for $I(2)$ variables. It effectively estimates the short- and long-run dynamics within a single equation, making it particularly appropriate for financial panel data in which variables often differ in their integration order.

The standard formulation of the panel ARDL (p, q) model is as follows:

$$y_{it} = \alpha_i + \sum_{k=1}^p \varphi_{ik} y_{i,t-k} + \sum_{j=0}^q \beta_{ij} X_{i,t-j} + \varepsilon_{it} \quad (8)$$

where:

y_{it} is the dependent variable (Zscore or DTD); α_i : denotes individual specific fixed effects. X_{it} is the vector of independent variables (eco-efficiency, socio-efficiency) and control variables (ROE, Leverage, firm size).

ε_{it} is the white noise error term; φ_{ik} and β_{ij} are short run coefficients.

This specification includes eco-efficiency and socio-efficiency as the main explanatory variables, alongside firm-level controls (firm size, leverage, and ROE), providing a comprehensive model of default risk determinants and allowing short-run heterogeneity while constraining long-run coefficients to be homogenous (Pesaran & Shin, 1999). Consistent with prior studies (Boubaker et al., 2020; Hsu et al., 2015), profitability (ROE) lowers default risk, firm size (SIZE) reflects stability and diversification, and leverage (LEV) indicates financial dependence, with higher LEV increasing the default probability. Table A5 summarizes all variables and their definitions.

3.4.2. Panel Stationarity and Cointegration Testing: IPS, LLC, and RALS-EG Approaches

Panel unit root tests using the ARDL framework IPS (Im et al., 2003) and LLC (Levin et al., 2002) confirm that all variables are I(1), supporting panel cointegration to examine the long-term link between default risk and sustainability efficiency. Long-run equilibrium was assessed using Engle–Granger (EG) and RALS-EG (Lee et al., 2015), with RALS-EG enhancing performance under non-normal residual conditions.

In this context, the relationships of long-run equilibrium are defined as

$$Z_t = \delta_0 + \delta_1 X_t + u_t \quad (9)$$

$$DTD_t = \alpha_0 + \alpha_1 X_t + v_t \quad (10)$$

where X_t is the vector of independent variables (e.g., firm size, eco-efficiency, and socio-efficiency) and u_t and v_t are the residuals. Cointegration was evaluated using the augmented Dickey–Fuller (ADF) test on residuals.

$$\Delta \hat{u}_t = \theta_0 + \theta_1 \hat{u}_{t-1} + \sum_{i=1}^p \theta_{i+1} \Delta \hat{u}_{t-i} + \varepsilon_t \quad (11)$$

$$\Delta \hat{v}_t = \gamma_0 + \gamma_1 \hat{v}_{t-1} + \sum_{i=1}^p \gamma_{i+1} \Delta \hat{v}_{t-i} + \varepsilon_t \quad (12)$$

The RALS-EG test enhances these equations by integrating the supplementary correction terms derived from the second and third moments of the residuals, including

$$\hat{w}_t = \hat{u}_t^2 - \bar{u}^2, \hat{u}_t^3 - \bar{u}^3 - 3\bar{u}^2 \hat{u}_t \quad (13)$$

This leads to the following RALS-augmented equation:

$$\Delta \hat{u}_t = \theta_1 \hat{u}_{t-1} + \sum_{i=1}^p \theta_{i+1} \Delta \hat{u}_{t-i} + \hat{w}_t \pi + \varepsilon_t \quad (14)$$

The null hypothesis $H_0 : \theta_1 = 0$ is tested for the absence of cointegration. The empirical findings provide a robust rejection of the null hypothesis across both analytical models.

Kao (1999), Pedroni (1999), and Westerlund (2007) confirm long-term relationships, supporting the robustness of RALS-EG. The ECM for the Z-score shows that environmental efficiency (BCCenv) significantly affects the short run. Socio-efficiency influences credit risk

(DTD) more, while eco-efficiency impacts the Z-score, highlighting the differential effects of sustainability on accounting- and market-based risk measures.

3.4.3. PMG-ARDL Model

This study uses the PMG-ARDL model to examine the long-run equilibrium and short-run dynamics between default risk and sustainability. The framework relies on Pesaran et al.'s (2001) ARDL bounds testing, allowing the analysis of level relationships among variables, whether I(0) or I(1), regardless of their integration orders.

The unrestricted standard ARDL(p, q) model is specified as follows:

$$y_t = \alpha_0 + \sum_{i=1}^p \alpha_i y_{t-i} + \sum_{j=0}^q \beta_j x_{t-j} + \varepsilon_t \quad (15)$$

where y_t is the dependent variable, x_t is the independent variable (or vector of variables), and ε_t is the white-noise error term. The ARDL framework enables the simultaneous estimation of both short- and long-run dynamics without necessitating pre-testing for the order of integration, as long as none of the variables are integrated of order two, I(2).

The ARDL framework estimates the short- and long-run dynamics without pre-testing variable integration, provided that none are I(2). In panel data, traditional ARDL may produce biased coefficients. The Pooled Mean Group (PMG) estimator (Pesaran et al., 1999) addresses this by allowing short-run heterogeneity across groups while constraining long-run coefficients to be homogeneous, ensuring consistent and efficient dynamic estimation.

The PMG-ARDL model employed in this study assumes the following error correction form:

$$y_{it} = \varphi_i ECT_{it} + \sum_{j=0}^{q-1} \Delta X_{it} + \gamma_{ij} + \sum_{j=1}^{p-1} \delta_{ij} \Delta y_{it-j} + \varepsilon_{it} \quad (16)$$

The term for error correction is defined as

$$ECT_{it} = y_{it-1} - X_{it}\vartheta \quad (17)$$

In Equations (16) and (17), the variable y denotes the dependent variable, which, in the context of this study, pertains to either the Z-score or the Distance to Default (DTD), depending on the particular specification employed. Vector X includes key explanatory variables: eco-efficiency and socio-efficiency, as well as control variables, such as firm size, leverage, and return on equity (ROE). The operator Δ denotes the first difference, φ is the error correction speed of the adjustment coefficient, ϑ represents the vector of the long-run coefficients, and ε_{it} is the white noise error term. The parameters γ and δ capture the short-run dynamic adjustments of the explanatory and dependent variables, respectively.

By estimating the model separately for the Z-score and DTD, we assess how improvements in eco-efficiency and socio-efficiency enhance long-term financial stability and reduce risk while controlling for conventional firm-level financial characteristics.

4. Results

4.1. Descriptive Statistics

Table 1 presents the summary statistics (N, Mean, Std. Dev., Min, Max) for critical variables, including Z-score, Distance to Default (DTD), Eco-efficiency, Socio-efficiency, Return on Equity (ROE), firm size, and leverage, across the Financial, Industrial, and Consumer Goods and Services sectors. Understanding these statistics is essential for analyzing the data distribution and characteristics before engaging in econometric modeling. Notably, the standard deviation illustrates the variability of each variable within its respective sector,

while the mean indicates the central tendencies, with the minimum and maximum values representing the observed range for each variable. Significant disparities across sectors were apparent. For instance, consumer firms have the highest average Z-score (4.29), reflecting a lower default risk, whereas financial firms demonstrate the highest average DTD (3.30), indicating similarly low default probabilities. Moreover, the financial sector leads in eco-efficiency (0.74), possibly due to the early adoption of environmental practices or stringent regulatory frameworks, while the industrial sector displays the lowest socio-efficiency (0.39), suggesting potential areas for enhancing social performance. Variability in leverage, particularly in the industrial sector, highlights differing capital structures and risk exposures, emphasizing the importance of adopting a sector-specific perspective when assessing default risk and sustainability metrics within the context of climate finance (Villena & Araneda, 2024; Shabbir et al., 2020).

Table 1. Descriptive statistics.

	Financial Sector					Industrial Sector					Consumer Goods and Services Sector				
	N	Mean	Std.	Min	Max	N	Mean	Std.	Min	Max	N	Mean	Std.	Min	Max
Z-score	60	2.68	21.78	−42.31	259.5	69	3.81	3.19	−13.49	27.4	51	4.29	7.43	−41.56	197.1
DTD	60	3.295	4.13	−5.52	32.95	69	3.06	3.08	−4.18	22.39	51	2.91	3.58	−6.9	21.51
Eco-efficiency	60	0.74	0.19	0.20	1	69	0.65	0.25	0.06	1	51	0.66	0.23	0.12	1
Socio-efficiency	60	0.61	0.28	0.11	1	69	0.39	0.24	0.05	1	51	0.44	0.26	0.08	1
ROE	60	6.90	54.14	−1444.5	176.32	69	8.84	36.1	−687.25	265.92	51	19.66	67.8	−712.2	1976.8
Firm-size	60	12.08	2.45	6.13	16.65	69	10.16	2.54	−1.96	16.27	51	9.72	2.16	2.82	16.14
Levreaage	60	16.54	97.15	3.22	1502.67	69	598.46	511.67	5.49	1063.9	51	19.52	95.8	2.55	1854.7

4.1.1. Socio-Eco Efficiency

Table 2 presents the annual average eco-efficiency and socio-efficiency scores for the financial, industrial, and consumer goods and services sectors over the period 2010–2024. These scores, derived using the input-oriented DEA-BCC model, ranged from 0 to 1, with higher values indicating greater sustainability efficiency.

Table 2. Sample distribution of eco-socio-efficiency scores by year.

Year	Financial Sector				Industrial Sector				Consumer Goods and Services Sector			
	Eco-Efficiency		Socio-Efficiency		Eco-Efficiency		Socio-Efficiency		Eco-Efficiency		Socio-Efficiency	
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
2010	60	0.63	60	0.41	69	0.77	69	0.52	51	0.65	51	0.44
2011	60	0.61	60	0.40	69	0.75	69	0.51	51	0.63	51	0.42
2012	60	0.63	60	0.40	69	0.71	69	0.55	51	0.65	51	0.44
2013	60	0.63	60	0.39	69	0.73	69	0.53	51	0.64	51	0.44
2014	60	0.63	60	0.38	69	0.74	69	0.53	51	0.65	51	0.43
2015	60	0.63	60	0.39	69	0.76	69	0.58	51	0.66	51	0.45
2016	60	0.62	60	0.38	69	0.78	69	0.60	51	0.64	51	0.45
2017	60	0.61	60	0.39	69	0.72	69	0.61	51	0.64	51	0.44
2018	60	0.66	60	0.40	69	0.73	69	0.61	51	0.65	51	0.43
2019	60	0.65	60	0.42	69	0.71	69	0.64	51	0.66	51	0.45
2020	60	0.67	60	0.39	69	0.71	69	0.75	51	0.68	51	0.48
2021	60	0.68	60	0.40	69	0.76	69	0.77	51	0.68	51	0.42
2022	60	0.71	60	0.42	69	0.76	69	0.67	51	0.70	51	0.43
2023	60	0.62	60	0.39	69	0.69	69	0.66	51	0.65	51	0.40
2024	60	0.69	60	0.41	69	0.66	69	0.65	51	0.71	51	0.41

The results reveal notable disparities across sectors. Industrial firms consistently exhibit the highest eco- and socio-efficiency scores, indicating their strong ability to transform environmental and social resources into sustainable outcomes. This performance may be attributed to more effective resource management practices, stronger stakeholder engagement, and lower exposure to sustainability-related risks. In contrast, the financial sector records relatively low socio-efficiency scores despite moderate improvements in eco-efficiency, highlighting persistent challenges in social performance. The consumer goods and services sector demonstrated a steady increase

in eco-efficiency, whereas socio-efficiency remained relatively stable throughout the study period (Guti, 2016; Yan et al., 2024).

Overall, eco-efficiency improved across all sectors between 2010 and 2024, reflecting the growing adoption of sustainable practices by European firms. The observed sectoral heterogeneity suggests that the effects of eco-efficiency and socio-efficiency on financial stability and default risk may vary across industries, thereby supporting the rationale for the sectoral analysis (Hoang et al., 2021; Fatemi et al., 2018).

4.1.2. Default Risk

Table 3 presents the annual average values of the Altman Z-score and Distance-to-Default (DTD) across sectors over the period 2010–2024. These measures serve as complementary indicators of default risk, with higher Z-scores and DTD values generally reflecting greater financial stability and lower default risks.

Table 3. Annual Averages of Default-Risk Measures.

Year	Financial Sector				Industrial Sector				Consumer Goods and Services Sector			
	Z-Score		DTD		Z-Score		DTD		Z-Score		DTD	
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
2010	60	8.58	60	3.64	69	3.66	69	3.01	51	5.37	51	3.04
2011	60	3.97	60	3.38	69	3.40	69	2.97	51	4.43	51	3.01
2012	60	3.90	60	3.36	69	3.70	69	2.92	51	5.18	51	2.95
2013	60	0.33	60	3.52	69	4	69	2.83	51	4.54	51	2.99
2014	60	−1.48	60	3.14	69	3.86	69	2.84	51	4.03	51	3.05
2015	60	−3.84	60	3.17	69	3.96	69	2.96	51	4.12	51	3.06
2016	60	−8.52	60	3.20	69	4.06	69	3.12	51	3.97	51	2.94
2017	60	−3.38	60	3.28	69	4.32	69	3.41	51	4.39	51	3.04
2018	60	3.30	60	3.29	69	3.81	69	3.16	51	3.80	51	2.94
2019	60	2.24	60	3.28	69	3.61	69	3.20	51	3.11	51	2.82
2020	60	2.04	60	3.15	69	3.52	69	3.26	51	4.11	51	2.62
2021	60	1.05	60	3.18	69	4.08	69	3.25	51	4.86	51	2.70
2022	60	0.59	60	3.20	69	3.63	69	3.26	51	3.90	51	2.72
2023	60	0.60	60	2.89	69	3.89	69	2.99	51	2.78	51	3.02
2024	60	0.98	60	3.01	69	3.33	69	2.55	51	2.58	51	2.98

The findings reveal substantial sectoral disparities. The financial sector exhibits considerable variability in Z-scores, declining from 8.58 in 2010 to negative values between 2014 and 2017, and remaining below the conventional threshold of 2.99 for most years thereafter (Li et al., 2022; Guo & Li, 2020). This pattern suggests a relatively higher degree of financial vulnerability than that of other sectors. In contrast, industrial firms consistently maintain Z-scores at or above the threshold throughout the sample period, accompanied by relatively stable DTD values. Likewise, the consumer goods and services sector records positive Z-scores and stable DTD values, although a moderate decline is observed in the later years of the study period (Sarkodie & Strezov, 2018; Harris & Tzavalis, 1999).

Overall, the results indicate that default risk differs across sectors, with industrial and consumer firms exhibiting greater financial stability than financial institutions during the study period. These sectoral differences provide preliminary evidence that the determinants of default risk may vary across industries, thereby supporting the subsequent panel data analysis.

4.2. Correlation

Table 4 reports the Pearson correlation coefficients between the explanatory variables and the dependent variables, distance to default (DTD) and the Altman Z-score, together with the Variance Inflation Factors (VIFs) and their corresponding tolerance values (1/VIF). The VIF values ranged from 1.01 to 1.07, remaining well below the commonly accepted thresholds of 5 and 10, indicating the absence of multicollinearity concerns. Similarly, the tolerance values ranged from 0.935 to 0.990, substantially exceeding the critical thresholds

of 0.10 and 0.20. Collectively, these findings confirm the absence of multicollinearity among the explanatory variables and support the validity of the regression analyses. The pairwise correlations were generally weak, with most coefficients being below 0.12. The strongest correlation is observed between firm size and DTD ($r = 0.3121$), which remains well below the level typically associated with high multicollinearity. Overall, the low correlation coefficients, together with the low VIF values and high tolerance values, suggest that the explanatory variables capture distinct dimensions of firms' default risk and sustainability performance (Weber et al., 2015; Lane, 2009).

Table 4. Correlations between the variables.

Variables	VIF	1/VIF	1	2	3	4	5	6
1. DTD	-	-	1.000					
2. Ecoefficiency	1.03	0.971	0.0142	1.000				
3. Socioefficiency	1.03	0.971	-0.0554	0.1167	1.000			
4. Roe	1.01	0.990	-0.0211	0.0048	0.0747	1.000		
5. Firm size	1.07	0.935	0.3121	0.1139	0.0885	-0.0744	1.000	
6. Leverage	1.05	0.952	-0.0033	-0.0511	-0.0303	0.0064	-0.2140	1.000
Variables	VIF	1/VIF	1	2	3	4	5	6
1. Z-score	-	-	1.000					
2. Ecoefficiency	1.03	0.971	0.0354	1.000				
3. Socioefficiency	1.03	0.971	-0.0127	0.1167	1.000			
4. Roe	1.01	0.990	-0.0064	0.0048	0.0747	1.000		
5. Firm size	1.07	0.935	0.0065	0.1139	0.0885	-0.0744	1.000	
6. Leverage	1.05	0.952	-0.0071	-0.0511	-0.0303	0.0064	-0.2140	1.000

4.3. Unit Root Tests

Table 5 reports the results of the Fisher-ADF, Levin-Lin-Chu (LLC), and Im-Pesaran-Shin (IPS) panel unit root tests. At their levels, the null hypothesis of a unit root generally cannot be rejected, indicating that the variables are non-stationary. However, after first differencing, all variables become stationary at the 1% significance level according to all three tests (Im et al., 2010). Therefore, the variables are integrated of order one, $I(1)$. These findings support the suitability of conducting a cointegration analysis and justify the application of the PMG-ARDL approach. From an economic perspective, the results suggest that shocks affecting default risk, sustainability efficiency, and firm-specific characteristics may have persistent effects in the short run while maintaining stable and long-run equilibrium relationships (Engle & Granger, 1987; L. Gao et al., 2019).

Table 5. Panel unit roots test.

Test	Financial Sector	Industrial Sector	Consumer Goods and Services Sector
Z-score (First Difference, I(1))			
Fisher (Dickey-Fuller, lag1)	1938 0.0000 ***	564 0.0000 ***	820 0.0000 ***
LLC (lag1)	-25 0.0000 ***	-13 0.0000 ***	-15 0.0000 ***
IPS (lag1)	-20 0.0000 ***	-10 0.0000 ***	-13.3163 0.0000 ***
Z-score (Level, I(0))			
Fisher (Dickey-Fuller, lag1)	1938 1.0000	542 0.8861	819 0.9778
LLC (lag1)	-25 0.5893	-13 1.0000	-14.5 0.2040
IPS (lag1)	-20 0.5869	-9 0.1533	-13 1.0000

Table 5. Cont.

Test	Financial Sector	Industrial Sector	Consumer Goods and Services Sector
DTD (First Difference, I(1))			
Fisher (Dickey–Fuller, lag1)	481 0.0000 ***	579 0.0000 ***	1032 0.0000 ***
LLC (lag1)	−10 0.0000 ***	−8 0.0000 ***	−25 0.0000 ***
IPS (lag1)	−8 0.0000 ***	−6 0.0000 ***	−3 0.0000 ***
DTD (Level, I(0))			
Fisher (Dickey–Fuller, lag1)	478 0.7898	579 0.1103	1032 0.6428
LLC (lag1)	−9.58 1.0000	−8 0.1536	−25 1.0000
IPS (lag1)	−8 0.5871	−6 0.2819	−3 0.3887
Eco-efficiency (First Difference, I(1))			
Fisher (Dickey–Fuller, lag1)	1098.5594 0.0000 ***	302.4632 0.0000 ***	492.8673 0.0000 ***
LLC (lag1)	−11.3298 0.0000 ***	−3.2486 0.0006 ***	−4.2834 0.0000 ***
IPS (lag1)	−7.3433 0.0000 ***	−3.7031 0.0001 ***	−3.8859 0.0001 ***
Eco-efficiency (Level, I(0))			
Fisher (Dickey–Fuller, lag1)	1088 0.1530	302 1.0000	490 0.8562
LLC (lag1)	−11 1.0000	−3.1 0.7895	−4 0.9621
IPS (lag1)	−7 0.1956	−3.4 1.0000	−3 0.8758
Socio-efficiency (First Difference, I(1))			
Fisher (Dickey–Fuller, lag1)	1176 0.0000 ***	424 0.0000 ***	1072 0.0000 ***
LLC (lag1)	−3 0.0008 ***	−11 0.0000 ***	−22 0.0000 ***
IPS (lag1)	−2.45 0.0002 ***	−7 0.0000 ***	−12 0.0000 ***
Socio-efficiency (Level, I(0))			
Fisher (Dickey–Fuller, lag1)	1176 0.1508	424 0.2005	1072 0.0974
LLC (lag1)	−3 0.8950	−11 0.0972	−22 0.4056
IPS (lag1)	−2.4 0.2593	−7 1.0000	−12 0.8922
Control variables (First Difference, I(1))			
Leverage (LLC, lag1)	−28 0.0000 ***	−11 0.0000 ***	−17 0.0000 ***
Firm size (LLC, lag1)	−3 0.0012 ***	−3 0.0003 ***	−11 0.0000 ***
ROE (LLC, lag1)	−8 0.0000 ***	−2 0.0021 ***	−17 0.0000 ***
Control variables (Level, I(0))			
Leverage (LLC, lag1)	−28 0.3046	−11 0.1258	−17 0.0978
Firm size (LLC, lag1)	−3 0.7520	−3 0.0954	−11 0.2041
ROE (LLC, lag1)	−8 0.1235	−2 0.3041	−17 0.1289

Note: *** indicate significance at the 1% levels.

4.4. Cointegration Test

Table 6 reports the results of the panel cointegration tests proposed by Kao (1999), Pedroni (1999), Westerlund (2007), and RALS-EG (Bayer & Hanck, 2013) for eco-efficiency, socio-efficiency, firm-specific control variables, and default risk measures (Altman Z-score and Distance-to-Default [DTD]). The null hypothesis of all tests is the absence of cointegration.

tion among the variables. The results consistently reject the null hypothesis at conventional significance levels, indicating the existence of a long-run equilibrium relationship between variables. In particular, the statistically significant negative test statistics obtained from the Pedroni, Westerlund, and RALS-EG tests provide strong evidence of cointegration, as more negative values imply a stronger rejection of the null hypothesis. The robustness of these findings is further supported by the consistency of the results across different cointegration techniques that differ in their assumptions regarding cross-sectional dependence and parameter heterogeneity (Westerlund, 2007).

Table 6. Cointegration test results.

Test	Test Statistics	
	Z-Score	DTD
Kao	−25.4308 ***	−2.5443 **
Pedroni	−10.7058 ***	−10.71 ***
Westerlund	−4.091 ***	−3.013 ***
RALS-EG	−8.68 ***	−12.49 **

Note: *** and ** indicate significance at the 1% and 5% levels, respectively.

This multi-test approach is consistent with recent empirical studies that emphasize robustness using complementary econometric procedures (Ayad et al., 2023). The evidence of cointegration justifies the application of the PMG-ARDL estimator, which is appropriate for estimating long-run relationships in heterogeneous panel data while allowing short-run dynamics to vary across firms and sectors (Natsiopoulou & Tzeremes, 2022). Overall, the findings suggest a stable long-run association between sustainability efficiency and default risk, indicating that these variables move together over time within a common equilibrium framework.

4.5. Error Correction Model (ECM)

Table 7 reports the results of the Error Correction Model (ECM). The error correction terms are negative and statistically significant at the 1% level for both the Altman Z-score (−0.135) and Distance-to-Default (DTD) (−0.119), confirming the existence of a stable long-run equilibrium relationship and supporting the validity of the PMG-ARDL specification. The estimated coefficients indicate that approximately 13.5% and 11.9% of short-run disequilibria are corrected each year for the Z-score and DTD models, respectively, suggesting a gradual adjustment toward long-run equilibrium following temporary shocks (Karavias et al., 2022; Pandey et al., 2024).

Table 7. Error Correction Model (ECM) results.

Dependent Variable	Speed of Adjustment (EC Term)	Significant Long-Run Predictors
Z-score	−0.135 ***	Ecoeff, Socioeff, roe
DTD	−0.119 ***	Socioeff, Ecoeff, leverage firm size

Note: *** indicate significance at the 1% levels.

Furthermore, the significant long-run determinants reported in Table 7 indicate that sustainability efficiency plays an important role in shaping firms' default risk. Eco-efficiency and socio-efficiency are associated with long-run variations in both default risk measures, while leverage and firm size also contribute to explaining DTD dynamics. These findings suggest that firms' sustainability performance and financial characteristics exert a persistent influence on their risk profiles over the long term.

4.6. Diagnostic Tests for Autocorrelation and Heteroskedasticity

Table 8 reports the results of the Breusch–Godfrey and Breusch–Pagan tests. The Breusch–Godfrey test failed to reject the null hypothesis of no serial correlation for both the DTD ($p = 0.137$) and Altman Z-score ($p = 0.540$) models, indicating the absence of autocorrelation in the residuals (Godfrey, 1978). Similarly, the Breusch–Pagan test fails to reject the null hypothesis of homoscedasticity, as the p-values for the DTD (0.062) and Z-score (0.078) models exceed the 5% significance levels. These results suggest that the residuals exhibit constant variance and are free from serial dependence, thereby supporting the reliability of the estimated coefficients and their associated standard errors (Breusch & Pagan, 1979). Overall, the diagnostic tests confirmed the adequacy and robustness of the estimated models.

Table 8. Panel Diagnostic Results for DTD and Z-Score Models.

Test	p-Value	
	DTD	Z-Score
Breusch-Godfrey	0.137	0.540
Breusch-Pagan	0.062	0.078

4.7. PMG-ARDL Results

In Table 9, which employs the Z-score as the dependent variable, the long-run coefficients derived from the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) model offer substantial insights into financial stability and default risk (Alves & Meneses, 2024). The Z-score serves as an accounting-based indicator of financial soundness, with higher values indicating a reduced default risk (Antunes et al., 2023). Within the financial sector, eco-efficiency and socio-efficiency demonstrate highly significant positive long-run coefficients of 1.8901 and 0.8209, respectively ($p < 0.01$). This suggests that enhancements in sustainability performance increase the Z-score, thereby diminishing the default risk (Issa et al., 2025). This observation aligns with the Theory of Sustainable Investment (Clark et al., 2015), which posits that sustainability initiatives bolster reputation, attract capital, and lower financing costs, thereby enhancing financial stability (Bonacorsi et al., 2024). The error correction term (ECT) of -0.5154 ($p < 0.01$) confirms a stable, long-run equilibrium relationship, with its magnitude indicating that approximately 51.5% of any short-run disequilibrium is rectified within a year. This suggests a relatively swift adjustment process toward long-run equilibrium following temporary shocks (Brown et al., 2015).

In the industrial sector, eco-efficiency (1.6502, $p < 0.01$) and socio-efficiency (1.3200, $p < 0.01$) also exert positive and significant effects, supporting the Resource-Based View (Barney, 1991). This perspective suggests that sustainability practices function as strategic resources that enhance efficiency, mitigate risk, and bolster resilience (Gujarati & Porter, 2009; Han et al., 2025). The ECT of -0.4520 ($p < 0.01$) indicates that approximately 45.2% of deviations from the long-run equilibrium are corrected annually, confirming a stable adjustment mechanism, albeit at a slightly slower rate than that of the financial sector (Suganda & Kim, 2023). In the consumer goods and services sector, both eco-efficiency (0.6502, $p < 0.01$) and socio-efficiency (0.7465, $p < 0.01$) were positive and significant. Although the magnitude of eco-efficiency is lower than that in the financial and industrial sectors, both sustainability dimensions contribute positively to financial stability. This finding is consistent with Stakeholder Theory, which asserts that socio-efficiency enhances customer loyalty and corporate reputation. The ECT (-0.4952 , $p < 0.01$) indicates that nearly 49.5% of short-run disequilibria are resolved each year, reflecting a relatively strong convergence toward the long-run equilibrium (Singha et al., 2023; Johansen, 1995).

Table 9. PMG-ARDL results (dependent variable: Z-score).

Variables	Financial Sector	Industrial Sector	Consumer Goods and Services
Long-term coefficients			
Ecoefficiency	1.8901 *** (0.10097)	1.6502 *** (0.15062)	0.6502 *** (0.12907)
Socioefficiency	0.8209 *** (0.0917)	1.3200 *** (0.1910)	0.7465 *** (0.1655)
Roe	0.0071 *** (0.00102)	0.0052 *** (0.00752)	0.0045 *** (0.00115)
Leverage	0.00628 (0.00036)	−0.00762 (0.00211)	−0.00689 *** (0.00142)
Firm size	0.0560 *** (0.01530)	0.0612 *** (0.02030)	−0.9012 *** (0.06790)
Error correction coefficient (SR)			
ECT (−1)	−0.5154 *** (0.025789)	−0.4520 *** (0.04715)	−0.4952 *** (0.03565)
ΔEcoefficiency	−3.8021 (2.52658)	1.2901 (0.91256)	−4.0623 (0.03660)
ΔSocioefficiency	−1.2601 (0.7589)	−0.3879 (0.91536)	−2.0813 (1.3941)
ΔRoe	−0.0320 (0.04525)	0.0215 (0.01153)	−0.0028 (1.4011)
ΔLeverage	−3345.60 (341.259)	−1106.01 (1200.256)	13.015 (16.1023)
ΔFirmsize	4.5604 (5.7780)	−0.9638 (0.8230)	−0.7034 (0.9605)
Intercept	1.4820 *** (0.64501)	1.7801 *** (0.25890)	7.8023 *** (0.6598)
BIC	1690.500	1296.600	2850.940
AIC	1630.10	1220.24	2680.35
Observations	900	1035	765

Note: *** indicate significance at the 1% levels.

In examining the control variables, firm size positively influences the Z-score within the financial (0.0560, $p < 0.01$) and industrial sectors (0.0612, $p < 0.01$), aligning with the Resource-Based View. Conversely, in the consumer sector, firm size negatively impacts the Z-score (−0.9012, $p < 0.01$), which can be attributed to the Theory of Organizational Agility, which posits that excessive size may hinder adaptability and increase complexity (Rubio-Misas, 2020). Return on Equity (ROE) is positively significant across the financial (0.0071, $p < 0.01$), industrial (0.0052, $p < 0.01$), and consumer goods and services sectors (0.0045, $p < 0.01$), corroborating the Classical Financial Theory that associates profitability with financial stability. Leverage is insignificant in the financial and industrial sectors but has a significant negative effect in the consumer sector (−0.00689, $p < 0.01$), indicating elevated default risk, consistent with the Capital Structure and Financial Distress Theories (Agostino et al., 2024; Zhang et al., 2020).

The Bayesian Information Criterion (BIC) values of 1690.500 for the financial sector, 1296.600 for the industrial sector, and 2850.940 for consumer goods and services indicate a superior model fit for financial firms. Additionally, the variation in coefficient magnitudes across sectors underscores the sector-specific importance of sustainability dimensions (Villena & Araneda, 2024). The consistently positive effects of eco- and socio-efficiency align with existing evidence that Corporate Social Responsibility (CSR) and green innovation

mitigate default risk and bolster financial resilience (Yadav, 2024; Meles et al., 2023; Suganda & Kim, 2023). CSR investments enhance reputation and stability, while green innovation reduces risk exposure in European firms (Meles et al., 2023), suggesting that eco- and socio-efficiency enhance financial stability through improved operational efficiency, reputation, and reduced regulatory pressure (Chen et al., 2022; Kafetzopoulos et al., 2024). Finally, the insignificance of short-run coefficients is consistent with the Theory of Sustainable Investment (Clark et al., 2015) and the Resource-Based View (Barney, 1991), as sustainability investments typically entail initial costs, with financial benefits accruing gradually over time rather than immediately.

For Table 10, which employs the Distance to Default (DTD) as the dependent variable, the PMG-ARDL model elucidates market-based perceptions of default risk, where an elevated DTD signifies a diminished probability of default (Xin et al., 2024). In the financial sector, eco-efficiency and socio-efficiency demonstrate significant positive long-run coefficients of 0.2010 and 0.1253, respectively ($p < 0.01$), indicating that sustainability improvements elevate DTD and mitigate market-perceived default risk. This observation aligns with the Market-Based Financial Theory (Merton, 1974; Vassalou & Xing, 2004), which posits that sustainability augments transparency, investor confidence, and perceived asset value. The error correction term (ECT) of -0.1245 ($p < 0.01$) corroborates the presence of a stable long-run relationship. Its magnitude suggests that approximately 12.5% of any deviation from the long-run equilibrium is rectified within one period, indicating a gradual yet significant adjustment process toward equilibrium (Guo & Li, 2020); in the industrial sector, eco-efficiency (0.4810, $p < 0.01$) and socio-efficiency (0.1720, $p < 0.01$) are positive and significant, with greater magnitudes for eco-efficiency, indicating that market perceptions in this sector are particularly responsive to environmental performance. This supports the Theory of Organizational Resilience (Holling, 1973; Sutcliffe & Vogus, 2003), which asserts that sustainable practices enhance a firm's capacity to withstand shocks and reduce perceived risks. The ECT coefficient of -0.1200 ($p < 0.01$) indicates that nearly 12.0% of short-run disequilibria are resolved within one period, confirming convergence to the long-run equilibrium path. In the consumer goods and services sector, eco-efficiency (1.3001, $p < 0.01$) and socio-efficiency (1.2601, $p < 0.01$) exhibit the largest positive coefficients across all sectors, suggesting that sustainability exerts a particularly strong influence on reducing market-perceived default risk (Haryanto et al., 2025; Lins et al., 2017). This outcome is consistent with signaling and stakeholder theories, as firms engaging in sustainability convey positive signals to investors and consumers, enhancing their reputation, loyalty, and valuations (Saeed & Izzeldin, 2016). The ECT coefficient of -0.1043 ($p < 0.01$) confirms a stable long-run relationship and indicates that approximately 10.4% of deviations from equilibrium are corrected within one period, reflecting the slowest adjustment speed among the three sectors (Eichler & Sobański, 2016).

In examining the control variables, firm size positively influences DTD in the financial (0.1592, $p < 0.01$) and industrial sectors (0.1758, $p < 0.01$), consistent with the Resource-Based View. Conversely, it has a negative effect in the consumer sector (-0.4822 , $p < 0.01$), potentially indicating diseconomies of scale or organizational complexity that elevate perceived risk (Meles et al., 2023). Similarly, Return on Equity (ROE) is positively significant in the financial (0.0037, $p < 0.01$) and consumer sectors (0.0123, $p < 0.01$), supporting Classical Financial Theory, but is negative in the industrial sector (-0.0136 , $p < 0.01$), which may be attributed to the Theory of Excessive Risk-Taking (Nguyen et al., 2024). Leverage consistently shows a negative and significant impact across all sectors (financial: -0.0025 ; industrial: -0.0356 ; consumer: -0.0077), suggesting that increased debt diminishes DTD and heightens default risk, consistent with the Capital Structure and Financial Distress Theories (Agostino et al., 2024; Zhang et al., 2020).

Table 10. PMG-ARDL results (dependent variable: DTD).

Variables	Financial Sector	Industrial Sector	Consumer Goods and Services
Long-term coefficients			
Ecoefficiency	0.2010 *** (0.02181)	0.4810 *** (0.02456)	1.3001 *** (0.08011)
Socioefficiency	0.12532 *** (0.02516)	0.1720 *** (0.02321)	1.2601 *** (0.07425)
Roe	0.00370 *** (0.00102)	−0.01355 *** (0.01890)	0.01225 *** (0.00250)
Leverage	−0.0025 *** (0.05125)	−0.0356 *** (0.08510)	−0.0077 ** (0.01210)
Firm size	0.1592 *** (0.00352)	0.1758 *** (0.07120)	−0.4822 *** (0.03813)
Error correction coefficient (SR)			
ECT (−1)	−0.1245 *** (0.02980)	−0.1200 *** (0.02720)	−0.1043 *** (0.01250)
ΔEcoefficiency	−1.0232 (0.10233)	−0.0105 (0.1892)	0.7866 (1.32780)
ΔSocioefficiency	−0.1830 (0.11785)	−0.09027 (0.10147)	−0.8956 (0.78551)
ΔRoe	−0.0689 (0.0605)	−0.0582 (0.01590)	−0.0587 (0.07102)
ΔLeverage	−143.25 (102.610)	−303.28 (265.0501)	−34.71 (8.88102)
ΔFirmsize	−0.3330 (0.45309)	−0.3100 (0.14401)	−0.1092 (0.25023)
Intercept	0.0586 ** (0.1223)	0.1539 *** (0.07980)	0.1237 *** (0.05261)
BIC	−3010.135	−4400.155	−5000.528
AIC	−2875.184	−4246.152	−4863.559
Observations	900	1035	765

Note: *** and ** indicate significance at the 1% and 5% levels, respectively.

A comparison with Z-score findings underscores the distinction between accounting- and market-based measures (Bonacorsi et al., 2024; Alves & Meneses, 2024), as DTD reflects forward-looking investor expectations by incorporating sentiment and volatility (Eichler & Sobański, 2016; Saeed & Izzeldin, 2016; Ererdi & Güneren Genç, 2025; Xin et al., 2024). This consistently indicates that firms with higher eco- and socio-efficiency are perceived as less risky (Issa et al., 2025), corroborating the literature on CSR and green innovation in reducing default risk (Yadav, 2024; Alves & Meneses, 2024). However, some studies propose nonlinear effects, such as an inverted U-shaped relationship (Anwer et al., 2023). The pronounced effects in the consumer sector further highlight the significance of reputation, consumer loyalty, and visibility in shaping market risk perception (Chan et al., 2020; Kafetzopoulos et al., 2024). The disparities in firm size effects between DTD and Z-scores emphasize the divergence between internal financial conditions and external market perceptions (T. Liu & Imran, 2024; Rehman & Liu, 2021). Finally, the insignificance of short-run coefficients aligns with the Theory of Sustainable Investment (Clark et al., 2015) and Market-Based Financial Theory, as financial markets require time to fully integrate sustainability-related information, with benefits emerging gradually rather than immediately (Kao & Liu, 2019; Makarov et al., 2015).

5. Discussion

This study illustrates that eco- and socio-efficiency play crucial roles in mitigating corporate default risk in the long term for European firms. The observed positive impacts on both the Altman Z-score and Distance-to-Default (DTD) suggest that sustainability performance enhances financial resilience and bolsters firms' capacity to endure adverse economic conditions. These findings endorse the perspective that environmental and social investments yield strategic advantages that surpass mere compliance objectives, thereby contributing to sustained financial stability (Daddi et al., 2016; Shih, 2024).

These results align with prior research, indicating that sustainability practices, corporate social responsibility, and green innovation diminish financial risk and bolster firm resilience (Meles et al., 2023; Suganda & Kim, 2023; Yadav, 2024). A plausible explanation is that firms exhibiting higher eco- and socio-efficiency benefit from robust stakeholder relationships, enhanced reputations, improved operational efficiencies, and reduced exposure to regulatory and environmental risks (Kock, 2015; Hart, 1995). These benefits can fortify cash flow stability and decrease the probability of financial distress (Altarawneh et al., 2025; Chiu et al., 2018).

The sectoral analysis identified significant variations in the extent of the sustainability effects. In the financial and industrial sectors, eco-efficiency notably impacts financial stability, indicating that environmental performance is increasingly integrated into risk assessments and investment decisions (Khan et al., 2023). Conversely, the consumer goods and services sectors demonstrate the most pronounced DTD response to both eco- and socio-efficiency, underscoring the role of reputation, customer loyalty, and stakeholder perceptions in influencing market-based risks. The findings further indicate that sustainability effects are predominantly long-term rather than immediate. The negligible short-run coefficients and significant negative error correction terms suggest that sustainability investments require time to manifest in firms' risk profiles. This evidence aligns with the Theory of Sustainable Investment (Clark et al., 2015) and the Resource-Based View (Barney, 1991), which propose that the advantages of sustainability gradually materialize through cumulative improvements in efficiency, reputation, and competitive advantages.

A comparison between the Z-score and DTD results indicates that sustainability enhances both internal financial strength and external market confidence (Oanh et al., 2021). The Z-score demonstrates improvements in accounting-based financial stability, whereas the DTD reflects investors' forward-looking assessment of default risk. The consistency of the results across these indicators reinforces the conclusion that eco- and socio-efficiency are significant determinants of corporate resilience in the long term (O'Brien, 2007; Pardede, 2023). Overall, the findings underscore the strategic importance of sustainability in corporate risk management and advocate for the integration of environmental and social performance into financial decision-making. Additionally, they suggest that the risk-reducing benefits of sustainability are sector-specific and should be considered when formulating ESG and climate-finance strategies (Phillips & Hansen, 1990; Saini et al., 2023).

6. Conclusions

This study examines the long-term impact of eco-efficiency and socio-efficiency on corporate risk across 180 European firms in the financial, industrial, and consumer services sectors over 15 years. Employing the BCC-DEA model to measure eco- and socio-efficiency and using both accounting-based (Z-score) and market-based (Distance to Default) risk indicators, the findings provide robust evidence of a significant relationship between eco-socio-efficiency and risk mitigation.

The results reveal that socio-efficiency exerts a stronger influence on the Z-score, thereby enhancing internal financial resilience, whereas eco-efficiency has a more pro-

nounced effect on DTD, particularly in the financial and industrial sectors, which reflects increased market confidence. The error correction estimates further indicate that the Z-score adjusts more rapidly to changes in eco-socio-efficiency, especially within financial institutions, whereas firms in the consumer services sector display a stronger sensitivity to socio-efficiency, likely due to their customer-oriented nature.

This study contributes to the literature by integrating eco- and socio-efficiency into firm-level risk analysis, highlighting the importance of sectoral heterogeneity, and demonstrating that sustainability performance is a key determinant of long-term financial stability.

From a policy perspective, the findings underscore the need to strengthen ESG integration within risk management frameworks and to design sector-specific regulatory approaches. Policymakers are encouraged to enhance ESG disclosure standards within the European context, align sustainability frameworks with financial supervision, and incorporate eco-socio-efficiency metrics into credit risk assessments. At the firm level, adopting eco- and socio-efficient strategies through cleaner technologies, efficient resource management, and proactive stakeholder engagement can serve as effective mechanisms for mitigating financial risk.

Despite these contributions, this study has some limitations. First, the analysis is restricted to European-listed firms, which may limit the generalizability of the findings to other institutional and regulatory environments. Second, this study focuses primarily on eco-efficiency and socio-efficiency and does not explicitly incorporate other ESG dimensions such as corporate governance. Third, although the PMG-ARDL framework is appropriate for examining long-run relationships, potential endogeneity issues cannot be entirely excluded. Future research could extend the analysis to emerging markets and small and medium-sized enterprises (SMEs), incorporate additional sustainability dimensions such as green innovation, diversity, and supply chain responsibility, and explore potential nonlinear relationships between sustainability performance and corporate risk. Such extensions would provide a more comprehensive understanding of the role of sustainability in enhancing financial resilience in an increasingly complex global environment.

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Appendix A

Table A1. Summary of Theoretical and Empirical Studies on Sustainability Efficiency and Corporate Default Risk.

Authors	Main Focus	Main Findings	Implications for Default Risk
Hart (1995)	Natural-Resource-Based View (NRBV)	Environmental capabilities can create sustainable competitive advantages	Eco-efficiency may improve long-term financial resilience and reduce risk
Freeman (2010)	Stakeholder Theory	Strong stakeholder relationships enhance organizational legitimacy and performance	Socio-efficiency may reduce financial uncertainty and improve stability

Table A1. *Cont.*

Authors	Main Focus	Main Findings	Implications for Default Risk
Barney (1991)	Resource-Based View (RBV)	Valuable and difficult-to-imitate capabilities improve firm performance	Sustainability capabilities may strengthen resilience against external shocks
Iazzolino et al. (2023)	Eco-efficiency and financial performance	Eco-efficiency improves operational efficiency and financial resilience	Higher eco-efficiency may reduce default risk
Issa et al. (2025)	Eco-socio-efficiency and financial performance	Eco- and socio-efficiency enhance firms' financial performance and operational sustainability	Eco-Socio-efficiency contributes to financial stability
Reitsema and Scholtens (2025)	Environmental strategies and transparency	Environmental practices improve transparency and risk management	Lower information asymmetry may reduce corporate risk
Adhikari and Zhou (2022)	Sustainability and risk management	Environmental strategies strengthen governance and resilience	Sustainability practices may lower firms' financial vulnerability
Ferrat et al. (2025)	Sustainability investment costs	ESG investments may generate short-term financial pressures	Sustainability practices may temporarily increase financial risk
Abdelhalim et al. (2023)	Sustainability capabilities and resilience	Sustainability capabilities improve adaptability and operational efficiency	Stronger resilience contributes to lower default risk
Singha et al. (2023)	Sustainability efficiency and financial stability	Sustainability practices improve operational performance and resilience	Eco- and socio-efficiency may contribute to lower default risk
Sahu et al. (2025)	Social sustainability and organizational performance	Human capital and stakeholder engagement improve organizational resilience	Socio-efficiency may reduce risk exposure in service-oriented sectors
Jamil and Khan (2024)	Environmental constraints and firm performance	Environmental pressures affect operational and financial performance	Eco-efficiency may mitigate regulatory and environmental risk
Haryanto et al. (2025)	Sustainability implementation and performance	Sustainability costs may negatively affect short-term profitability	Sustainability may temporarily increase default exposure
García-Gómez et al. (2025)	Environmental regulation and sectoral effects	Eco-efficiency is more important in environmentally intensive sectors	Sectoral heterogeneity influences the sustainability-risk relationship

Table A2. Sample distribution by country and sector.

Country	Financial Sector	Industrial Sector	Consumer Goods and Services Sector
France	10	12	8
Germany	8	14	6
Italy	7	10	5
Spain	9	11	7
Belgium	6	8	5
Poland	10	7	10
Finland	10	7	10
Total	60	69	51

Table A3. Index Framework for Eco-Efficiency and Socio-Efficiency Scores.

Indicator	Variables	Overview of Variables	Source
Eco-efficiency	Environment Pillar score	The company's weighted average relative rating is based on its disclosed environmental information in three key categories.	Datastream
	Outputs	The term refers to a company's ability to reduce its customers' environmental impact while creating new market opportunities.	Datastream
	Energy renewable	The total amount of primary renewable energy obtained, measured in gigajoules.	Datastream
	Total emission CO ₂	Investigation of the annual percentage change in total CO ₂ -equivalent emissions.	Datastream
	Waste Total	The total amount of waste generated was measured in tonnes.	Datastream
	Inputs	The total volume of water pollutants emitted was measured in tons.	Datastream
	Water Emission	The total volume of water pollutants emitted was measured in tons.	Datastream
	Resource use	The resource-use category score reflects a company's ability to reduce its natural resource consumption.	Datastream

Table A3. *Cont.*

	Indicator	Variables	Overview of Variables	Source
Socio-efficiency	Outputs	Human rights score	Evaluates a company's dedication to respecting fundamental human rights.	Datastream
		CSR score	Demonstrates a company's integration of economic, social and environmental dimensions.	Datastream
		Social Pilar score	A company's weighted average rating is based on the social information it reports.	Datastream
	Inputs	Turnover of employees	This includes all employees who left the company voluntarily or involuntarily.	Datastream
		Involuntary turnover of employees	Refers to the rate at which employees leave an organization without their consent.	Datastream
		Salary gap	The CEO's total compensation is divided by the average wages and benefits of the employees.	Datastream

Table A4. Key Variables and Their Definitions for the DTD.

Variables	Defintion	Source
Market value (V_t)	The total value of its assets, as determined by the market.	Datastream
The book value (K)	The book value of a firm's liabilities serves as the threshold that it must meet to avoid default.	Datastream
Risk-free interest rate (r)	The 10-year government bond yield from Eurostat's EMU convergence series (IRT_LT_M) represents this and is widely used in financial modeling for its low risk and cross-country comparability.	Eurostat
The volatility of the firm's asset value (δ_v)	The fluctuation in a firm's asset value indicates the level of variation or risk associated with the asset's returns.	Datastream

Table A5. Definition and description of variables.

Variables	Indicator	Indicator Description	Sources
Dependent variables	Distance to default (DTD)	The market-based default risk metric, derived from the Merton model, measures the number of standard deviations between a firm's asset value and its default threshold based on asset volatility and the firm's debt level.	Datastream
	Altman Z-Score (Z-score)	This firm-level default risk measure is based on a weighted combination of financial ratios, with higher values indicating a lower likelihood of financial distress.	Datastream
Independent variables	Eco-efficiency (Ecoeff)	Evaluation of the environmental efficiency score, as determined by the DEA model, utilizing an input orientation and BCC formulation.	Datastream
	Socio-efficiency (Socioeff)	The social efficiency score was measured using the DEA model, employing an input focus with the BCC formulation.	Datastream
Control variables	ROE	The profitability ratio measures net income relative to shareholders' equity, indicating how efficiently a firm generates profit from its equity base.	Datastream
	Firmsize	The logarithm of a company's total assets represents a standardized measure of size.	Datastream
	Levreage	measures the proportion of a firm's assets financed by debt, indicating its financial risk and capital structure.	Datastream

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