Journal of Development and Economic Policies, Vol. 28, No. 2 (2026) 75 - 101
Arab Planning Institute - Kuwait (https://doi.org/10.34066/jodep.26.28.2.3)
Received: 15 April 2026 | Revised: 11 May 2026 | Accepted: 12 May 2026

Artificial Intelligence and Board Gender Diversity as Complementary Drivers of Corporate Sustainability: Evidence from Dynamic Panel Analysis of ESG Performance in an Emerging Market

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Abstract

This study investigates how Artificial Intelligence (AI) adoption and Board Gender Diversity (BGD) jointly influence corporate sustainability performance, measured through ESG scores. Using a dynamic panel dataset of 245 Saudi-listed firms over 2015–2022, we employ the System GMM estimator to address persistence in ESG performance, unobserved heterogeneity, and endogeneity concerns. The findings reveal that both AI adoption and BGD significantly enhance ESG performance. More importantly, their interaction effect is positive and statistically significant, indicating strong complementarity between technological capability and governance diversity. This suggests that AI-driven decision-making is more effective when supported by cognitively diverse boards capable of interpreting and governing digital insights. Robustness checks using alternative AI measures (AI investment proxy and Digital Transformation Index), sectoral subsamples, and alternative econometric specifications confirm the stability of the results. Additional analyses also address reverse causality concerns by showing that ESG does not significantly predict future AI adoption. Overall, the study highlights that corporate sustainability emerges not from technology or governance alone, but from their strategic integration within dynamic organizational systems.

دور الذكاء الاصطناعي والتنوع الجندري في مجالس الإدارة في تعزيز الاستدامة المؤسسية: دراسة باستخدام تحليل بيانات البانل الديناميكي لأداء معايير البيئة والمسؤولية الاجتماعية والحوكمة (ESG) في أحد الأسواق الناشئة

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ملخص

تبحث هذه الدراسة في كيفية تأثير تبني الذكاء الاصطناعي (AI) وتنوع الجنس في مجالس الإدارة (BGD) بشكل مشترك على أداء الاستدامة المؤسسية، المقاس من خلال درجات ESG. باستخدام بيانات لوحة ديناميكية لعدد 245 شركة مدرجة في المملكة العربية السعودية خلال الفترة 2015–2022، نستخدم مقدّر System GMM لمعالجة استمرارية أداء ESG، وعدم التجانس غير المرصود، ومشكلات التحيز الناتج عن التزامن (endogeneity). تكشف النتائج أن كلاً من تبني الذكاء الاصطناعي وتنوع الجنس في مجالس الإدارة يعززان بشكل كبير أداء ESG. والأهم من ذلك، فإن تأثير التفاعل بينهما إيجابي وذو دلالة إحصائية، مما يشير إلى وجود تكامل قوي بين القدرات التكنولوجية وتنوع الحوكمة. وهذا يدل على أن اتخاذ القرار المعتمد على الذكاء الاصطناعي يصبح أكثر فعالية عندما يكون مدعوماً بمجالس إدارة متنوعة معرفياً قادرة على تفسير وإدارة المدخلات الرقمية. تؤكد اختبارات المتانة باستخدام مقاييس بديلة للذكاء الاصطناعي (مثل الاستثمار في الذكاء الاصطناعي ومؤشر التحول الرقمي)، والعينات القطاعية الفرعية، والمواصفات الاقتصادية القياسية البديلة، استقرار النتائج. كما تظهر التحليلات الإضافية معالجة مخاوف العلاقة العكسية من خلال إثبات أن ESG لا يتنبأ بشكل معنوي بتبني الذكاء الاصطناعي مستقبلاً. بشكل عام، تؤكد الدراسة أن الاستدامة المؤسسية لا تنشأ من التكنولوجيا أو الحوكمة بشكل منفصل، بل من تكاملهما الاستراتيجي داخل أنظمة تنظيمية ديناميكية.

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1. Introduction

Corporate sustainability has evolved from a peripheral concern into a central strategic priority for firms worldwide, driven by intensifying regulatory frameworks, growing investor scrutiny, and the rapid expansion of sustainability-linked financial markets. The increasing allocation of capital toward ESG-oriented investments—exceeding $40 trillion in 2023 (GSIA, 2023)—reflects a structural shift in how firm performance is evaluated, moving beyond traditional financial metrics toward broader measures of long-term value creation. Despite this global momentum, firms continue to exhibit substantial heterogeneity in their ESG performance, raising fundamental questions about the underlying organizational drivers of sustainable outcomes.

In parallel, Artificial Intelligence (AI) has emerged as a transformative digital capability that reshapes corporate decision-making through advanced data processing, predictive analytics, and real-time strategic adaptation. From a theoretical standpoint, AI is often conceptualized within the Resource-Based View (RBV) and Dynamic Capabilities Theory as a strategic asset that enhances firm efficiency and adaptability. However, empirical evidence on the AI–ESG relationship remains mixed. While several studies document positive effects through improved environmental monitoring, innovation, and transparency (Chen et al., 2024; Cao et al., 2024), others highlight important limitations, including the "automation–augmentation paradox" (Raisch & Krakowski, 2024) and the risk of symbolic adoption or "tech-washing," where digital investments do not translate into substantive sustainability improvements (Zhang & Luo, 2024). These inconsistencies suggest that AI alone is insufficient to guarantee improved ESG performance.

At the same time, corporate governance mechanisms—particularly Board Gender Diversity (BGD)—have been widely examined as determinants of sustainability outcomes. Drawing on Upper Echelons Theory (UET), gender-diverse boards are expected to enhance ethical sensitivity, stakeholder orientation, and long-term strategic thinking. Empirical evidence generally supports a positive association between BGD and ESG performance (Byron & Post, 2023), although the magnitude and consistency of this effect vary across institutional contexts. In some cases, diversity remains symbolic or constrained by limited decision-making power, reducing its effectiveness.

Importantly, the existing literature largely treats technological capabilities and governance structures as independent drivers of ESG performance. This fragmented perspective overlooks a critical question: how do firms translate digital intelligence into sustainable strategic action? Recent studies suggest that the effectiveness of AI depends on

governance quality and organizational context (Luo et al., 2023; Verhoef et al., 2024), yet the interaction between AI and board-level cognitive diversity remains underexplored. This gap is particularly evident in emerging markets, where institutional environments, regulatory frameworks, and governance practices differ significantly from developed economies.

Furthermore, empirical research on the AI–governance–ESG nexus is heavily concentrated in developed countries and a limited number of emerging economies such as China, with very limited evidence from the Middle East and virtually none from Saudi Arabia. This represents a critical gap, especially given the ongoing economic transformation under Saudi Vision 2030, which emphasizes both digital transformation and sustainability reforms. The unique institutional and regulatory context of Saudi Arabia provides a valuable setting to examine how technological and governance capabilities jointly shape corporate sustainability.

To address these gaps, this study develops an integrated framework in which ESG performance is conceptualized as the outcome of a dynamic capability system. Specifically, AI is viewed as a technological capability that enhances information generation and processing, while BGD represents a cognitive governance capability that shapes how this information is interpreted and utilized in strategic decision-making. Their interaction determines the extent to which firms can effectively transform digital insights into sustainability-oriented actions.

Accordingly, this study makes three main contributions. First, it advances the ESG literature by moving beyond single-factor explanations and introducing a complementary perspective linking AI and governance diversity. Second, it provides robust empirical evidence using a dynamic panel approach (System GMM), addressing endogeneity, persistence, and unobserved heterogeneity. Third, it contributes to the limited evidence from emerging markets by offering novel insights from Saudi Arabia, thereby enhancing the contextual relevance and external validity of ESG research.

2. Theoretical framework

This study develops an integrated theoretical framework to explain corporate sustainability outcomes by combining insights from Dynamic Capabilities Theory, the Resource-Based View (RBV), and Upper Echelons Theory (UET). Rather than treating these perspectives as independent lenses, the study adopts a complementary approach in which each theory explains a distinct but interconnected dimension of how firms generate ESG performance.

At the core of the framework lies Dynamic Capabilities Theory (Teece, 2007), which provides the primary explanatory lens. This perspective shifts the focus from static resource endowments to firms' ability to continuously adapt, reconfigure, and integrate their competencies in response to changing environments. In the context of corporate sustainability, this implies that ESG performance is not merely the result of possessing resources, but rather the outcome of how effectively firms mobilize and orchestrate those resources over time. The dynamic capabilities framework conceptualizes organizational processes through three key functions: sensing opportunities, seizing them, and transforming internal structures accordingly. Within this logic, Artificial Intelligence (AI) can be understood as a sensing and analytical capability that enables firms to process large-scale, complex, and real-time sustainability-related data. In contrast, Board Gender Diversity (BGD) represents a governance-based interpretative capability that shapes how such information is evaluated, contextualized, and translated into strategic decisions. Thus, Dynamic Capabilities Theory provides a holistic explanation of how technological and governance elements are integrated into adaptive sustainability strategies.

While dynamic capabilities explain how firms deploy and integrate resources, the Resource-Based View (Barney, 1991) clarifies what those resources are and why they matter. RBV posits that firm-specific resources—particularly those that are valuable, rare, inimitable, and non-substitutable—form the basis of sustained competitive advantage. Within this perspective, AI is conceptualized as a strategic intangible resource that enhances operational efficiency, innovation capacity, and decision quality. Firms that invest in AI capabilities are therefore better positioned to improve ESG outcomes through optimized resource allocation and enhanced information processing. However, a key limitation of RBV lies in its relative static nature; it does not fully explain why firms with similar technological resources exhibit divergent ESG performance. This limitation highlights the need to incorporate complementary perspectives that account for differences in decision-making processes and governance structures.

This is where Upper Echelons Theory (Hambrick & Mason, 1984) provides critical insight. UET argues that organizational outcomes are shaped by the cognitive bases, values, and characteristics of top executives. In this study, Board Gender Diversity (BGD) is interpreted as a structural source of cognitive heterogeneity that enriches board deliberations and enhances strategic sensitivity to non-financial performance dimensions such as ESG. Gender-diverse boards are expected to broaden stakeholder-oriented perspectives, improve ethical awareness, and strengthen long-term strategic orientation. However, UET also acknowledges an important limitation: diversity does not automatically lead to better outcomes. Its effectiveness depends on whether diverse perspectives are meaningfully

integrated into decision-making processes rather than remaining symbolic. This conditional nature of diversity aligns with the broader argument of this study that governance mechanisms influence not only whether decisions are made, but how information is interpreted and utilized.

Taken together, these three theoretical perspectives offer complementary strengths while compensating for each other's limitations. RBV provides a clear identification of strategic resources such as AI but lacks a dynamic and behavioral dimension. UET introduces the cognitive and behavioral aspects of decision-making but does not explicitly address how resources are structured or deployed. Dynamic Capabilities Theory bridges these gaps by explaining how resources and cognitive processes are continuously integrated and reconfigured to generate sustained performance outcomes. Therefore, the combination of these theories enables a more comprehensive understanding of ESG performance as a multi-layered phenomenon driven by resource endowments, governance structures, and adaptive organizational processes.

Building on this integrated logic, this study proposes that corporate sustainability emerges from the interaction between technological capability and governance cognition. Specifically, AI generates structured and data-driven insights, while BGD enhances the interpretation, evaluation, and strategic alignment of these insights. Dynamic capabilities then enable firms to transform this combined intelligence into ESG-oriented actions through continuous adaptation and organizational learning. In this sense, ESG performance is not the product of isolated factors, but the outcome of a coordinated capability system in which technology and governance operate jointly.

Based on this framework, the study develops three testable hypotheses to empirically examine both direct and interaction effects. First, AI adoption is expected to positively influence ESG performance by enhancing information processing and decision quality. Second, Board Gender Diversity is expected to improve ESG outcomes through enhanced governance quality and stakeholder orientation. Third, and most importantly, BGD is expected to strengthen the relationship between AI and ESG performance, such that the effectiveness of AI is greater in firms with more cognitively diverse boards. These hypotheses reflect the central argument of the study that sustainability outcomes depend not only on the presence of resources or governance mechanisms, but on their strategic complementarity within dynamic organizational systems.

3. Literature review

3.1 AI Adoption and ESG Performance

The growing integration of Artificial Intelligence (AI) into corporate operations has intensified scholarly interest in its implications for sustainability. Recent studies emphasize that AI is not only a technological tool but also a strategic enabler of digital transformation that reshapes firm-level sustainability outcomes (Dwivedi et al., 2023; Verhoef et al., 2024).

A large strand of literature suggests a positive relationship between AI adoption and ESG performance. Empirical evidence shows that AI enhances environmental efficiency, supports predictive analytics, and improves governance transparency (Chen et al., 2024; Cao et al., 2024). Similarly, AI-driven digital transformation has been found to strengthen innovation capability, which in turn improves ESG outcomes (Li et al., 2025).

However, recent studies also highlight a more nuanced and sometimes contradictory perspective. Raisch and Krakowski (2024) argue that AI introduces an "automation–augmentation paradox," where efficiency gains may be offset by organizational rigidity or over-reliance on algorithms. In addition, Zhang and Luo (2024) find that while AI improves environmental performance in some firms, its effect is heterogeneous and depends on sectoral characteristics and absorptive capacity.

This divergence in findings suggests that the AI–ESG relationship is not linear or universal. Instead, it is shaped by firm-level capabilities, governance quality, and institutional context. Therefore, AI should be understood as a conditional enabler of sustainability rather than an automatic driver of ESG improvement.

3.2 Board Gender Diversity and ESG

Board Gender Diversity (BGD) has been widely recognized as a key governance mechanism influencing corporate sustainability outcomes. Recent meta-analytical evidence confirms that gender-diverse boards are generally associated with stronger ESG performance and improved corporate responsibility outcomes (Byron & Post, 2023).

From a theoretical perspective, this relationship is grounded in Upper Echelons Theory (Hambrick & Mason, 1984), which argues that organizational outcomes reflect the cognitive diversity and values of top executives. Empirical studies further suggest that female directors enhance ethical sensitivity, stakeholder orientation, and long-term strategic thinking (Post et al., 2023).

However, the literature remains inconsistent. While many studies report a positive linear relationship between BGD and ESG, others suggest that the effect may depend on institutional and cultural conditions. For instance, the impact of gender diversity is often weaker in environments where female participation is symbolic rather than substantive, or where board members face limited decision-making authority.

These mixed findings suggest that the effect of BGD is not automatic but contingent upon governance structures and board effectiveness. This opens the door for examining how BGD interacts with other strategic resources such as AI and digital transformation capabilities.

3.3 AI–BGD Interaction

Recent literature increasingly emphasizes the need to study technological capabilities and governance structures in an integrated framework. Holmström (2024) highlights that the future of corporate governance will be shaped by the interaction between artificial intelligence and board-level decision-making processes.

Empirical evidence suggests that AI effectiveness depends significantly on governance quality. For example, Luo et al. (2023) show that AI improves firm performance, but its impact varies depending on managerial oversight and organizational structure. Similarly, digital transformation research indicates that governance mechanisms play a critical role in shaping how technological capabilities translate into performance outcomes (Verhoef et al., 2024).

In the context of ESG, emerging studies provide early evidence of complementarity effects. Yue et al. (2026) find that board diversity strengthens the positive impact of AI on ESG performance, suggesting that inclusive leadership enhances the interpretation and deployment of AI-generated insights.

However, this literature remains fragmented and geographically concentrated, with most evidence derived from China and developed economies. Moreover, the underlying mechanisms through which governance moderates AI effectiveness remain underexplored. This highlights a critical gap in understanding how cognitive diversity interacts with algorithmic decision-making in shaping sustainability outcomes.

3.4 Conceptual Framework: Dynamic Capability Perspective on the AI–BGD–ESG Relationship

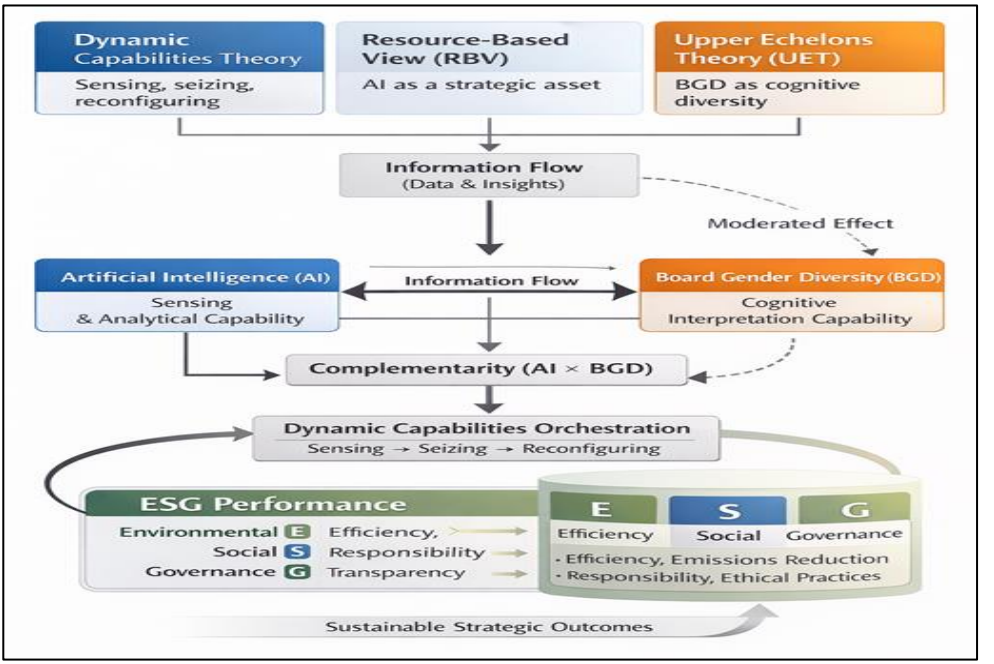
The conceptual framework developed in this study integrates Dynamic Capabilities Theory, the Resource-Based View (RBV), and Upper Echelons Theory (UET) to explain how Artificial Intelligence (AI) and Board Gender Diversity (BGD) jointly shape corporate sustainability outcomes. At the core of the model, AI is conceptualized as a sensing and analytical capability that enables firms to process large-scale data, detect inefficiencies, and generate sustainability-relevant insights. In contrast, BGD represents a cognitive interpretation mechanism, through which diverse board members enhance the evaluation, filtering, and strategic interpretation of AI-generated information.

Consistent with RBV, AI is treated as a strategic organizational resource that contributes to competitive advantage, while UET explains how board-level heterogeneity influences strategic choices and sustainability orientation. However, the framework moves beyond these individual perspectives by proposing a moderated relationship in which BGD strengthens the impact of AI on ESG performance. This implies that technological capability alone is insufficient to generate sustainable outcomes without effective governance structures capable of interpreting and guiding its application.

ESG performance is modeled as a multidimensional construct composed of environmental (E), social (S), and governance (G) dimensions, reflecting the complexity of corporate sustainability. Within a dynamic capability logic (sensing–seizing–reconfiguring), AI-generated insights are not directly translated into outcomes; rather, they are interpreted and contextualized by diverse boards and subsequently transformed into strategic actions aligned with sustainability objectives.

Figure 1 illustrates this integrated mechanism, showing how AI-driven informational capabilities and governance-based cognitive diversity interact within a dynamic capability system to produce enhanced ESG performance. The model highlights that corporate sustainability is not the result of isolated technological or governance factors, but rather the outcome of their coordinated interaction within organizational decision-making processes. This perspective extends the existing literature by emphasizing the conditional and complementary nature of the AI–BGD–ESG relationship.

Figure 1: Dynamic Capability-Based Model of AI–BGD Interaction and Corporate Sustainability



4. Study Variables and Methodology

4.1 Study Variables

This study employs a structured set of variables categorized into dependent, independent, and control variables to empirically test the proposed relationships between Artificial Intelligence (AI), Board Gender Diversity (BGD), and corporate sustainability performance (ESG). The selection and operationalization of these variables are grounded in both theoretical arguments and prior empirical literature to ensure construct validity and comparability.

The dependent variable, ESG performance, is measured using standardized composite scores obtained from Refinitiv ESG, widely used in the literature as a reliable proxy for corporate sustainability performance. ESG is further decomposed into its environmental (E), social (S), and governance (G) dimensions to capture its multidimensional nature. Prior studies (e.g., Chen et al., 2024; Cao et al., 2024) confirm the robustness of these indicators in assessing firm-level sustainability outcomes across different institutional contexts.

The key independent variables include Board Gender Diversity (BGD) and Artificial Intelligence (AI) adoption. BGD is measured as the proportion of female directors on the board, consistent with Upper Echelons Theory and widely adopted in governance and ESG studies (Byron & Post, 2023). This measure captures structural diversity at the board level and reflects the degree of cognitive heterogeneity influencing strategic decision-making.

The measurement of AI adoption requires more careful consideration. In this study, AI is proxied using a text-based index constructed from the frequency of AI-related keywords (e.g., artificial intelligence, machine learning, big data, automation) in firms' annual reports and corporate disclosures. This approach is consistent with a growing strand of literature that employs textual analysis to capture firm-level digital transformation and technological orientation (e.g., Li et al., 2025; Verhoef et al., 2024).

However, this proxy may raise concerns regarding symbolic disclosure or "tech-washing," where firms may signal technological adoption without substantive implementation. To address this limitation, several steps are taken to strengthen the validity of the AI measure. First, the textual index is constructed using a carefully curated dictionary of AI-related terms to minimize noise and improve content relevance. Second, the measure captures not only the presence but also the intensity of AI-related disclosures, reflecting the strategic emphasis placed on digital technologies. Third, and most importantly, the study implements multiple robustness checks using alternative AI proxies, including an investment-based measure and a Digital Transformation Index. The consistency of results across these alternative specifications provides strong evidence that the observed effects are not driven by symbolic reporting alone.

Moreover, from a theoretical perspective, even symbolic disclosure may carry informational value, as it reflects managerial attention, strategic intent, and organizational orientation toward digital transformation. As argued in signaling theory, corporate disclosures can serve as credible indicators of future strategic behavior, particularly in emerging markets where formal data on technology adoption may be limited. Therefore, the AI proxy used in this study captures both realized and strategic dimensions of digital capability.

The interaction term (BGD × AI) is constructed to test the complementarity hypothesis, capturing whether the effectiveness of AI in improving ESG performance depends on the level of board gender diversity. This specification is directly aligned with the integrated theoretical framework developed in Section 2.

Control variables are selected based on prior ESG and corporate governance literature to account for firm-specific characteristics that may influence sustainability

performance. Firm size (log of total assets) captures resource availability and visibility effects; leverage controls for financial constraints, and sector dummies account for industry-specific heterogeneity in ESG practices. These variables are widely used in empirical studies and help mitigate omitted variable bias.

All financial and governance data are manually collected from firms' annual reports and cross-validated with Refinitiv Eikon to ensure consistency and reliability. ESG indicators are obtained from standardized databases and complemented with firm-level disclosures to improve coverage and accuracy.

Table (1): Dependent Variables (Corporate Sustainability Performance)

Variable	Description	Measurement	Data Source
Environmental Performance (ESG_E)	Commitment to environmental sustainability	Composite score of emissions reduction, energy efficiency, water use, and pollution control	ESG data obtained from Refinitiv Eikon / Bloomberg ESG database, supplemented by firms' sustainability and annual reports
Social Performance (ESG_S)	Commitment to social responsibility	Composite score of employee well-being, diversity, human rights, and community engagement	Refinitiv ESG database and corporate disclosures (CSR and sustainability reports)
Governance Performance (ESG_G)	Corporate governance quality	Composite score of board structure, independence, transparency, and internal control effectiveness	Refinitiv ESG database and corporate governance reports disclosed by firms

Table (2): Independent Variables

Variable	Description	Measurement	Data Source
Board Gender Diversity (BGD)	Representation of women on corporate boards	Proportion of female board members relative to total board size	Firms' annual reports and corporate governance disclosures published on the Saudi Stock Exchange (Tadawul)
Artificial Intelligence Adoption (AI)	Extent of AI utilization and strategic digital orientation within the firm	Text-based index constructed from the frequency and intensity of AI-related keywords (e.g., artificial intelligence, machine learning, big data, automation) in firms' annual reports and corporate disclosures, reflecting both digital adoption and strategic orientation toward AI	Firms' annual reports and disclosures collected from the Saudi Stock Exchange (Tadawul) and company websites
Interaction Term (BGD × AI)	Complementarity effect between governance diversity and digital capability	Multiplicative interaction term between BGD and AI variables	Constructed by the author based on BGD and AI measures

Note: The AI measure is validated through robustness checks using alternative proxies, including investment-based indicators and a Digital Transformation Index.

Table (3): Control Variables

Variable	Description	Measurement	Data Source	Rationale
Company Size (Size)	Organizational scale	Natural log of total assets	Financial statements obtained from firms' annual reports and Refinitiv Eikon database	Larger firms may have more resources for ESG initiatives
Leverage (Leverage)	Debt reliance	Total debt / total assets	Firms' financial statements	High leverage may limit sustainability investments
Economic Sector (Sector)	Structural differences	Dummy variable for each sector	Sector classification from Saudi Stock Exchange (Tadawul)	Controls for sector-specific ESG practices

All financial and governance data are manually collected from firms' annual reports and verified using Refinitiv Eikon to ensure data consistency and reliability. ESG indicators are obtained from standardized databases where available and complemented with firm-level disclosures to enhance coverage across the sample.

4.2 Data Collection Process

The dataset consists of an unbalanced panel of 245 firms listed on the Saudi Stock Exchange (Tadawul) over the period 2015–2022, covering multiple sectors including energy, finance, healthcare, and industrials. This empirical context is particularly relevant given the ongoing digital transformation and governance reforms under Saudi Vision 2030, which emphasize both technological advancement and sustainability.

ESG data are obtained from Refinitiv ESG, ensuring standardized measurement across firms and time. Board composition data are extracted from corporate governance disclosures and validated through annual reports. AI-related information is collected from annual reports, corporate disclosures, and supplementary sources, enabling the construction of both textual and quantitative proxies.

To ensure data quality and reliability, a rigorous validation process is implemented. This includes cross-verification across multiple data sources, systematic treatment of missing values using industry-consistent imputation techniques, and the exclusion of firms with insufficient or inconsistent disclosures. In addition, the use of multiple AI measures and robustness checks helps mitigate potential measurement bias and strengthens the credibility of the empirical strategy.

4.3 Methodology: System GMM

To test the proposed hypotheses (H1–H3), this study employs a dynamic panel data framework estimated using the System Generalized Method of Moments (System GMM). The baseline specification is defined as follows:

$$ESG_{it} = \alpha + \beta_1 AI_{it} + \beta_2 BGD_{it} + \beta_3 (AI_{it} x BGD_{it}) + \gamma X_{it} + \mu_i + \varepsilon_{it}$$

Where:

ESG_{it}: Corporate sustainability performance (ESG score) for firm i at time t.

AI_{it}: Artificial Intelligence adoption level.

BGD_{it}: Board Gender Diversity.

$(AI_{it}xBGD_{it})$: Interaction term capturing the moderating effect of board diversity on the AI–ESG relationship.

X_{it}: Vector of control variables.

μ_i: Unobserved firm-specific effects.

ε_{it}: Error term.

The inclusion of the lagged dependent variable captures the dynamic persistence of sustainability performance, consistent with the notion that ESG outcomes evolve cumulatively over time and exhibit strong path dependence.

System GMM (Arellano–Bover/Blundell–Bond estimator) is particularly appropriate for this study for three main reasons. First, it addresses potential endogeneity arising from reverse causality (e.g., better-performing ESG firms being more likely to adopt AI) and omitted variable bias. Second, it controls unobserved time-invariant firm heterogeneity. Third, it is well-suited for dynamic panel datasets characterized by a relatively large cross-sectional dimension (N) and a shorter time dimension (T).

To mitigate the risk of instrument proliferation, the instrument matrix is collapsed, and the lag depth is restricted following Roodman (2009), ensuring the reliability of the Hansen test and improving estimator efficiency.

Endogenous variables, including AI and BGD, are instrumented with appropriate lag levels and first differences. The validity of the instruments is evaluated using the Hansen J-test of overidentifying restrictions, while the Arellano–Bond AR(1) and AR(2) tests are employed to detect first- and second-order serial correlation in the differenced residuals. The absence of AR(2) correlation and the acceptance of the Hansen test collectively confirm the robustness and validity of the System GMM estimations.

All empirical analyses are conducted using Stata software (version 17). The System GMM estimations, including instrument construction, estimation procedures, and all diagnostic tests, are implemented using the xtabond2 routine, ensuring full reproducibility and consistency of the econometric results.

4.4 Robustness and Diagnostic Tests

To ensure the robustness and reliability of the empirical findings, several diagnostic and robustness checks are conducted.

First, endogeneity is addressed through the System GMM framework, with Hansen test results confirming the validity of the instruments. Second, the absence of second-order serial correlation (AR(2)) supports the consistency of the estimators.

Third, alternative model specifications, including fixed-effects and random-effects models, are estimated to verify the stability of the results. Fourth, alternative measures of AI—including the investment-based proxy and the Digital Transformation Index—are employed to mitigate concerns related to measurement bias and symbolic disclosure.

Fifth, ESG performance is analyzed both as a composite index and across its individual components (E, S, G), allowing for a more granular assessment of the results. Finally, sectoral analyses are conducted to examine potential heterogeneity across industries.

The consistency of findings across these alternative specifications provides strong evidence that the observed relationships between AI, BGD, and ESG performance are robust and not driven by model specification or measurement choices.

5. Results

5.1 Descriptive Statistics

Table (4): Descriptive Statistics

Variable	Mean	Median	Std. Dev.	Min	Max
ESG_E	0.54	0.55	0.12	0.25	0.88
ESG_S	0.51	0.52	0.14	0.20	0.86
ESG_G	0.57	0.58	0.10	0.30	0.90
ESG (Overall)	0.54	0.55	0.11	0.27	0.89
AI Adoption	0.46	0.44	0.18	0.05	0.85
BGD	0.28	0.25	0.15	0.00	0.70

The descriptive statistics provide important insights into the structural characteristics of ESG performance, digital transformation, and governance diversity among Saudi listed firms.

First, ESG performance exhibits a moderate level across all dimensions. Governance (ESG_G = 0.57) slightly exceeds environmental (0.54) and social (0.51) performance. This pattern suggests that governance-related reforms have progressed faster

than operational sustainability practices, reflecting a transition phase of ESG institutionalization rather than full maturity.

Second, AI adoption shows a moderate mean (0.46) with a relatively high standard deviation (0.18), indicating substantial heterogeneity in digital maturity across firms. While a subset of firms demonstrates advanced integration of AI-driven systems, a significant proportion remains at early or intermediate stages of digital transformation. Compared to international benchmarks, these levels remain below advanced digital economies such as the United States or European Union firms, where AI adoption intensity is generally higher and more standardized (e.g., McKinsey, 2022; Verhoef et al., 2024). However, they are broadly consistent with patterns observed in emerging markets where digital transformation is still evolving.

Third, Board Gender Diversity (BGD) averages 28% with a median of 25%, indicating gradual progress in gender inclusion at the board level. This level is comparable to other Gulf Cooperation Council (GCC) countries but remains lower than OECD averages, where female board representation typically exceeds 30–35% in many developed economies (Byron & Post, 2023). The wide dispersion (0% to 70%) suggests significant cross-firm variation, providing strong empirical identification for governance effects.

Overall, Table 4 highlights a key structural feature of the dataset: ESG maturity, AI adoption, and governance diversity are all in transitional stages rather than stable equilibrium states. This transitional nature is consistent with evidence from emerging markets, where digital transformation and ESG integration are still evolving under ongoing institutional reforms, particularly within the context of Saudi Vision 2030. Consequently, the dataset is particularly suitable for dynamic panel estimation, as it captures firms operating in heterogeneous and evolving sustainability and technological environments.

5.2 Baseline System GMM Results

Table (5): System GMM Results (Baseline Model)

Variables	ESG Overall	ESG_E	ESG_S	ESG_G
Lagged ESG	0.42***	0.38***	0.44***	0.41***
AI Adoption	0.18***	0.20***	0.16***	0.17***
BGD	0.11**	0.10**	0.12**	0.11**
AI × BGD	0.07**	0.06**	0.08**	0.07**
Firm Size	0.05*	0.06*	0.04*	0.05*
Leverage	-0.03	-0.02	-0.03	-0.03
Industry Fixed Effects	Yes	Yes	Yes	Yes
Observations	2450	2450	2450	2450
Number of Instruments	28	28	28	28
AR(1) p-value	0.000	0.001	0.000	0.001
AR(2) p-value	0.410	0.382	0.447	0.395
Hansen J-test (p-value)	0.230	0.271	0.244	0.219

Notes :* p < 0.01, ** p < 0.05, * p < 0.10.**

Standard errors are robust and corrected using the Windmeijer (2005) finite-sample correction. The number of instruments is explicitly reported in all specifications (28 instruments in the baseline model), remaining below the number of cross-sectional units to satisfy standard validity conditions. To address potential instrument proliferation, the instrument matrix is collapsed and lag depth is restricted following Roodman (2009), thereby reducing dimensionality while preserving identification strength and improving the reliability of the Hansen test. Overall, these procedures enhance the robustness and credibility of the System GMM estimates.

Table 5 reports the baseline System GMM estimates examining the impact of Artificial Intelligence (AI), Board Gender Diversity (BGD), and their interaction on ESG performance. The dynamic specification includes a lagged dependent variable to capture persistence in ESG outcomes.

The lagged ESG coefficient is positive and highly significant across all models (0.38–0.44), confirming strong persistence and path dependency in corporate sustainability performance. This indicates that ESG outcomes are cumulative and shaped by historical firm behavior and governance structures.

AI adoption exhibits a consistently positive and statistically significant effect on ESG performance (0.16–0.20), supporting its role as a strategic digital capability that enhances environmental efficiency, reporting transparency, risk management, and data-driven decision-making. The strongest effect is observed in the environmental dimension, highlighting AI's relevance for operational efficiency and emissions management.

Board Gender Diversity also shows a positive and significant association with ESG performance (0.10–0.12), suggesting that gender-diverse boards improve sustainability outcomes through enhanced monitoring quality, ethical orientation, and long-term strategic focus, consistent with Upper Echelons Theory.

Importantly, the interaction term between AI and BGD is positive and statistically significant (0.06–0.08), confirming a complementarity effect. This indicates that the effectiveness of AI in improving ESG performance increases in firms with more gender-diverse boards. The result supports the existence of a hybrid governance–technology mechanism in which AI-driven insights are more effectively interpreted and deployed under cognitively diverse governance structures.

Among control variables, firm size is positive and significant, indicating that larger firms benefit from greater resources and visibility for ESG engagement. Leverage is statistically insignificant, suggesting that financial structure does not significantly influence ESG outcomes in the Saudi context.

Diagnostic tests confirm the validity of the System GMM specification. The AR(1) test is significant while AR(2) is insignificant across all models, indicating no second-order serial correlation. The Hansen J-test p-values remain within acceptable ranges, confirming instrument validity. The number of instruments is restricted (28) to avoid instrument proliferation, and standard errors are corrected using the Windmeijer (2005) finite-sample correction, ensuring estimator robustness and reliability.

5.3 Robustness Evidence

Table (6): Robustness Checks (Alternative AI Measures)

Variables	Baseline AI	AI Investment Proxy	Digital Transformation Index
AI Effect on ESG	0.18***	0.16***	0.19***
AI × BGD	0.07**	0.06**	0.08**
Observations	2450	2450	2450
Number of Instruments	27	27	28
AR(1) p-value	0.000	0.001	0.000
AR(2) p-value	0.410	0.438	0.401
Hansen J-test (p-value)	0.230	0.261	0.247
Model Stability	Yes	Yes	Yes

Notes :* p < 0.01, ** p < 0.05, * p < 0.10.**

Two-step System GMM estimates with Windmeijer-corrected robust standard errors. Alternative AI measures are used to address potential measurement bias and symbolic disclosure concerns. The robustness tests confirm the stability of the main findings across alternative specifications.

First, the effect of AI remains consistently positive and stable when using different proxies, including textual AI indicators, AI investment measures, and digital transformation indices. Coefficients remain in a narrow range (0.16–0.19), confirming that results are not driven by measurement bias.

Second, the interaction effect (AI × BGD) remains positive and significant across all specifications, reinforcing the robustness of the complementarity hypothesis.

Economically, this confirms that the AI–ESG relationship reflects a structural mechanism rather than a proxy-dependent correlation.

5.4 Sectoral Heterogeneity

Table (7): Sectoral Heterogeneity Results

Sector	AI Effect	BGD Effect	AI × BGD Effect	Dominant ESG Channel
Energy	0.22***	0.09*	0.10**	Environmental
Industrials	0.20***	0.10**	0.09**	Environmental
Finance	0.15**	0.14***	0.08**	Governance
Healthcare	0.16**	0.15***	0.09**	Social
Diagnostic Tests	Energy	Industrials	Finance	Healthcare
Observations	620	580	690	560
Number of Instruments	24	24	25	24
AR(1) p-value	0.001	0.000	0.001	0.001
AR(2) p-value	0.392	0.418	0.447	0.401
Hansen J-test (p-value)	0.241	0.258	0.223	0.267

Notes :*** p < 0.01, ** p < 0.05, * p < 0.10.

Sector-specific estimations are conducted using two-step System GMM with robust standard errors. The sectoral analysis reveals important variations in the transmission channels of AI and governance effects.

In capital-intensive sectors (energy and industrials), AI has a stronger impact on environmental performance, reflecting its role in improving operational efficiency and emissions management.

In service-oriented sectors (finance and healthcare), both AI and BGD exert stronger effects on governance and social dimensions, highlighting the importance of stakeholder interaction, compliance, and information governance.

Despite these differences, the AI × BGD interaction remains consistently positive across all sectors, confirming that complementarity between technology and governance is universal but operates through different mechanisms depending on industry structure.

6. Discussion

6.1 AI Adoption and ESG Performance

The findings provide strong support for H1, confirming that AI adoption significantly enhances ESG performance across environmental, social, and governance dimensions. This result is consistent with recent evidence suggesting that AI functions as a key enabler of digital transformation and sustainability-oriented innovation (Chen et al., 2024; Cao et al., 2024).

From a theoretical standpoint, this finding aligns with the Resource-Based View (Barney, 1991), which conceptualizes AI as a strategic capability that improves firm efficiency and competitiveness. Moreover, digital transformation literature argues that AI enhances firms' ability to process complex information and generate data-driven insights, thereby improving sustainability decision-making (Verhoef et al., 2024).

However, the results also reflect the "automation–augmentation paradox" identified by Raisch and Krakowski (2024), suggesting that AI does not automatically translate into sustainability gains. Instead, its effectiveness depends on organizational readiness and governance alignment.

This study contributes to resolving inconsistencies in prior research by showing that AI's impact remains robust even when alternative measures—such as digital transformation intensity and AI investment proxies—are considered. This strengthens the argument that AI represents a substantive capability rather than a purely symbolic disclosure mechanism.

6.2 Board Gender Diversity and ESG

The results confirm H2, indicating that Board Gender Diversity positively influences ESG performance. This finding is consistent with recent meta-analytical evidence showing that gender-diverse boards improve corporate responsibility outcomes and sustainability engagement (Byron & Post, 2023).

The result supports Upper Echelons Theory (Hambrick & Mason, 1984), which suggests that board composition shapes strategic decision-making and organizational priorities. Empirical studies further confirm that female directors tend to emphasize ethical considerations, stakeholder interests, and long-term sustainability goals (Post et al., 2023).

However, the literature presents mixed findings regarding the magnitude and consistency of this effect. Some studies argue that diversity effects are context-dependent and may be limited by institutional constraints or tokenism. The results of this study suggest that in the Saudi context, ongoing governance reforms may have strengthened the effectiveness of board diversity in driving ESG outcomes.

6.3 AI × BGD Complementarity

The most significant contribution of this study lies in confirming H3, which posits a positive interaction between AI adoption and Board Gender Diversity in enhancing ESG performance. The results demonstrate that AI is significantly more effective in improving sustainability outcomes when firms have more gender-diverse boards.

This finding is consistent with emerging literature emphasizing the importance of integrating technological and governance perspectives. Holmström (2024) argues that the future of corporate governance lies in the interaction between AI systems and human decision-making structures. Similarly, Luo et al. (2023) show that AI-driven performance improvements depend on managerial oversight and organizational context.

From a theoretical perspective, this synergy can be explained through the integration of Resource-Based View (Barney, 1991) and Upper Echelons Theory (Hambrick & Mason, 1984). While AI provides analytical and informational capabilities, board diversity enhances cognitive interpretation and strategic alignment of these capabilities.

Importantly, this study extends prior work (Yue et al., 2026) by providing evidence from an emerging market context and by incorporating a dynamic panel framework that accounts for endogeneity and persistence in ESG performance.

6.4 Sectoral Heterogeneity

The analysis further reveals that the effects of AI and BGD vary across sectors, highlighting the importance of industry context. In capital-intensive sectors such as energy and industrials, the impact of AI is more pronounced in the environmental dimension, consistent with prior studies emphasizing the role of technology in improving operational efficiency and emissions management.

In contrast, in service-oriented sectors such as finance and healthcare, the benefits of AI and board diversity are more evident in the social and governance dimensions, reflecting the importance of stakeholder interaction, data governance, and regulatory compliance.

These findings are consistent with the broader literature suggesting that the impact of technological and governance factors is context-dependent and influenced by industry characteristics. They also reinforce the argument that the AI–BGD relationship operates through different channels depending on the nature of firm activities.

6.5 Theoretical and Empirical Implications

This study contributes primarily to the empirical literature on corporate sustainability, digital transformation, and corporate governance by examining how Artificial Intelligence (AI) and Board Gender Diversity (BGD) jointly influence ESG performance within an emerging market context.

Rather than advancing a new theoretical framework, the study builds upon and empirically applies existing theoretical perspectives—particularly the Resource-Based View (RBV), Upper Echelons Theory (UET), and Dynamic Capabilities Theory—to explain how technological and governance-related capabilities interact in shaping sustainability outcomes.

First, the findings support the view that AI should be understood not merely as a technological tool, but as a strategic organizational capability that can enhance sustainability performance when effectively integrated into managerial and governance processes.

Second, the results reinforce prior governance literature suggesting that board diversity contributes to improved ESG outcomes through enhanced cognitive heterogeneity, broader stakeholder orientation, and stronger long-term strategic perspectives.

Third, the study highlights that the effectiveness of AI is conditional upon governance structures. Specifically, the positive interaction between AI adoption and Board Gender Diversity suggests that technological capabilities and governance diversity operate as complementary mechanisms rather than isolated drivers of ESG performance.

Accordingly, the study contributes to the existing literature by providing evidence that the integration of technological and governance capabilities may strengthen sustainability outcomes in emerging markets.

However, these findings should be interpreted with appropriate caution. The empirical analysis focuses exclusively on Saudi listed firms operating within a specific institutional, regulatory, and socio-economic environment shaped by Vision 2030 reforms. Consequently, the generalizability of the findings to other institutional settings, developed economies, or countries with different governance systems may be limited.

In addition, the rapidly evolving nature of AI technologies and ESG reporting practices suggests that the observed relationships may vary across time periods and institutional contexts. Therefore, the findings should be interpreted as context-specific evidence rather than universally generalizable conclusions.

Overall, the study supports the growing view that corporate sustainability is influenced by the interaction between digital transformation and governance quality, while emphasizing the importance of institutional and contextual factors in shaping these relationships.

7. Policy Implications

7.1 Integrating Technology and Governance in Sustainability Policies

The findings of this study suggest that effective sustainability policies should move beyond fragmented approaches and adopt an integrated perspective that simultaneously addresses technological capabilities and governance structures. The empirical evidence (H1–H3) demonstrates that neither AI adoption nor board diversity alone is sufficient to maximize ESG performance; rather, their interaction produces the strongest effects.

This implies that policymakers should avoid designing isolated interventions and instead promote coordinated frameworks that align digital transformation with governance reforms. Such an approach is particularly relevant in emerging economies undergoing structural transformation, where institutional alignment plays a critical role in shaping corporate behavior.

7.2 Promoting AI as a Sustainability Enabler

Consistent with H1, the positive impact of AI on ESG performance highlights the need for policies that support the adoption of advanced digital technologies as drivers of sustainable development. Governments can play a key role by reducing barriers to AI adoption and incentivizing firms to invest in data-driven sustainability solutions.

Policy instruments may include targeted financial incentives, such as tax credits or subsidies for AI-enabled environmental and social innovations, as well as national digital transformation strategies that enhance access to data infrastructure and advanced analytics capabilities. In addition, integrating AI into ESG monitoring and reporting systems can improve transparency, data accuracy, and regulatory oversight.

However, given the potential risks associated with AI, including ethical concerns and algorithmic bias, policymakers must also establish clear guidelines for responsible AI use, ensuring that technological adoption aligns with broader sustainability objectives.

7.3 Strengthening Gender Diversity in Corporate Governance

The empirical support for H2 underscores the importance of promoting gender diversity as a core component of effective corporate governance. Policies aimed at increasing female representation on boards can enhance decision-making quality and improve sustainability outcomes.

Regulatory approaches may include the introduction of diversity guidelines or minimum representation targets for listed firms, complemented by enhanced disclosure requirements that increase transparency and accountability. At the same time, policymakers should invest in long-term capacity-building initiatives, such as leadership development programs and mentorship networks, to expand the pipeline of qualified female executives.

Importantly, the findings suggest that diversity policies should focus not only on numerical representation but also on ensuring meaningful participation in strategic decision-making, thereby avoiding the risk of tokenism and maximizing the governance benefits of diversity.

7.4 Leveraging the AI–BGD Complementarity

The strongest policy implication emerges from H3, which highlights the complementary relationship between AI adoption and board gender diversity. The results indicate that the effectiveness of AI in improving ESG performance is significantly enhanced in firms with more diverse boards.

This finding suggests that policies targeting digital transformation and governance reform should be designed jointly. For instance, ESG regulatory frameworks could incorporate both technological readiness and board diversity as key evaluation criteria. Similarly, firms could be encouraged to disclose not only their AI adoption strategies but also how governance structures oversee and guide the use of these technologies.

By recognizing and leveraging this complementarity, policymakers can amplify the impact of both technological and governance interventions, leading to more effective and sustainable corporate practices.

7.5 Enhancing ESG Transparency and Sectoral Alignment

Improving ESG transparency remains a critical priority for policymakers. Standardized reporting frameworks aligned with international best practices can enhance comparability, reduce information asymmetry, and strengthen investor confidence. The integration of AI-based analytics into ESG reporting can further improve the quality and reliability of disclosed information.

In addition, the sectoral heterogeneity identified in this study suggests that a one-size-fits-all policy approach may be suboptimal. Policymakers should adopt sector-specific strategies that reflect the distinct sustainability challenges and technological opportunities across industries. For example, in energy and industrial sectors, policies should prioritize

AI-driven environmental efficiency, while in service sectors, greater emphasis should be placed on governance transparency and stakeholder engagement.

7.6 Building a Sustainable Innovation Ecosystem

Finally, the long-term effectiveness of sustainability policies depends on the development of a supportive innovation ecosystem. This includes fostering collaboration between government, industry, and academia, investing in AI-related skills and inclusive leadership development, and promoting knowledge-sharing platforms for ESG best practices.

Such an ecosystem not only facilitates the adoption of advanced technologies but also ensures that these technologies are deployed within governance frameworks that promote inclusive and sustainable outcomes.

8. Conclusion and Future Research Agenda

8.1 High-Impact Conclusion

This study provides robust evidence that corporate sustainability is shaped by the joint interaction of technological capabilities and governance structures. Using a dynamic panel of Saudi listed firms, the findings demonstrate that Artificial Intelligence (AI) significantly enhances ESG performance (H1), while Board Gender Diversity (BGD) independently contributes to improved sustainability outcomes (H2). Most importantly, the results reveal a strong complementary effect (H3), indicating that the benefits of AI are substantially amplified in firms with more gender-diverse boards.

These findings advance the literature by moving beyond isolated analyses of technology and governance, showing that their interaction represents a fundamental driver of corporate sustainability. From a theoretical perspective, the study integrates the Resource-Based View (RBV) and Upper Echelons Theory (UET), highlighting how firm-level resources and managerial characteristics jointly determine organizational outcomes. Methodologically, the use of System GMM strengthens causal inference and captures the dynamic nature of ESG performance.

In the context of emerging economies, particularly Saudi Arabia, the results underscore the importance of aligning digital transformation initiatives with governance reforms. Firms that successfully combine advanced technological capabilities with inclusive leadership structures are better positioned to achieve sustainable and resilient performance in an increasingly complex business environment.

Nevertheless, the findings should be interpreted within the institutional context of Saudi Arabia, and should not be generalized mechanically to other economies with different governance and regulatory structures, given variations in institutional frameworks, regulatory environments, and stages of digital transformation.

8.2 Future Research Agenda

Despite its contributions, this study opens several avenues for future research. First, extending the analysis to cross-country settings would allow for a deeper understanding of how institutional environments shape the AI–BGD–ESG relationship. Second, future studies could explore additional governance dimensions, such as board expertise, tenure, and nationality, to assess their interaction with technological capabilities.

Third, more refined measures of AI—capturing intensity, sophistication, and ethical governance—would help address remaining measurement challenges. Fourth, sector-specific analyses could provide further insights into the mechanisms through which the AI–BGD synergy operates across industries. Fifth, micro-level and behavioral approaches could shed light on how board members interact with AI-generated insights in practice.

Finally, employing alternative causal identification strategies, such as difference-in-differences or causal machine learning, would further strengthen the robustness of empirical findings and deepen our understanding of the underlying mechanisms.

8.3 Final Insight

Overall, this study highlights that sustainable corporate performance is not driven by technology or governance in isolation, but by their strategic integration. The interaction between AI and inclusive governance represents a critical pathway through which firms can enhance ESG outcomes and achieve long-term value creation in emerging markets.

AI Use Statement

The author used generative Artificial Intelligence tools solely for language improvement, academic editing, and organizational support during the preparation of the manuscript. All conceptual development, empirical analysis, interpretation of results, and final academic content remain the sole responsibility of the author.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request for academic and research purposes.

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