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Corporate management and green finance as drivers of sustainable development: evidence from Germany

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This study examines the role of corporate management in advancing green finance and sustainable development in Germany using annual data covering the period from 1995 to 2022. The analysis integrates a composite Sustainable Development Index a Corporate Management Index and a Green Finance Index to capture the interaction between governance structures financial mechanisms and sustainability outcomes. An autoregressive distributed lag framework is employed to distinguish between short run dynamics and long run relationships among the variables. The empirical results indicate a stable long run association between green finance corporate management quality and sustainable development while selected control variables display heterogeneous effects. The findings highlight the importance of governance driven financial strategies in supporting sustainability objectives. The study contributes to the literature by offering an integrated empirical assessment focused exclusively on a fully observed sample period ensuring internal consistency and econometric validity. Policy implications are discussed with specific relevance for corporate regulators and sustainability oriented financial supervision. This study makes several original contributions to the literature on green finance corporate governance and sustainable development. First it develops an integrated empirical framework that simultaneously examines green finance and corporate management as joint drivers of sustainable development within a single country context rather than treating them as isolated mechanisms. Second the study introduces two purpose built composite indices namely the Corporate Management Index and the Sustainable Development Index which are tailored to the institutional economic and regulatory characteristics of Germany thereby moving beyond fragmented single indicator approaches commonly used in prior research. Third by employing an ARDL framework the analysis captures both short run adjustments and long run equilibrium effects allowing for a more nuanced understanding of dynamic sustainability transitions. Fourth the study provides evidence that market based green financial mechanisms exert stronger and more persistent effects on sustainability outcomes than traditional fiscal instruments highlighting the importance of governance driven financial strategies. Finally by focusing on a fully observed and internally consistent sample period the study ensures econometric validity and offers policy relevant insights that are directly applicable to regulators corporate supervisors and sustainability oriented financial institutions.

KEYWORDS

ARDL model, corporate governance, Germany, green finance, sustainable development

1 Introduction

Germany, as the largest economy in Europe, faces mounting challenges in reconciling the imperatives of economic growth with the pressing demands of Green and social sustainability. These challenges have intensified under global pressures to accelerate the green transition, particularly in light of the European Union's commitments to international climate agreements and domestic initiatives such as the European Green Deal and the Energiewende. Despite notable progress in expanding green finance instruments and strengthening corporate governance frameworks, an important gap persists in understanding how these two domains interact to shape Germany's long-term pathway toward sustainable development.

The existing literature emphasizes that Green finance plays an important role in mobilizing capital for green innovation and low-carbon technologies. At the same time, Corporate governance is associated with higher transparency and stakeholder engagement, and adherence to environmental, social, and governance standards. However, most studies examine these channels in isolation or emphasize broad international contexts without offering an integrated country-specific framework. This leaves open the question of how financial and institutional mechanisms jointly influence the German sustainability agenda.

This study addresses that gap by developing an integrated empirical model that quantifies the relative and interactive effects of green finance and corporate governance on sustainability outcomes. The central research question is therefore: To what extent do green finance and corporate governance contribute to sustainable development in Germany between 1995 and 2022? The guiding hypothesis suggests that Green finance shows a stronger association with SDI than corporate governance. On the Sustainable Development Index (SDI). At the same time, both operate in a complementary manner that accelerates and consolidates the green transition.

To answer this question, the study employs the Autoregressive Distributed Lag (ARDL) methodology, which is well-suited for time series with mixed integration orders, specifically $I(0)$ and $I(1)$. This approach enables simultaneous estimation of short-run dynamics and long-run equilibrium relationships, thereby capturing both immediate fluctuations and structural adjustments in green finance and governance. The analysis spans nearly three decades, covering major disruptions such as the 2008 global financial crisis and the COVID-19 pandemic. In addition, this design provides a comprehensive test of the German economy's ability to maintain its sustainable trajectory in the face of systemic shocks.

2 Literature review

2.1 Green finance and sustainability

Green finance has become a critical pillar of the global sustainability architecture, acting as a catalyst for regulatory transformation, technological innovation, and institutional change. In Germany, green finance constitutes a multidimensional ecosystem comprising diverse financial instruments, public-private initiatives, regulatory regimes, and digital infrastructure that

collectively facilitate the national pathway toward climate neutrality and inclusive economic development (Tsai, 2024; Kabir et al., 2025).

Previous studies highlight the role of financial systems, regulation, and institutional frameworks in shaping financial stability and sustainable development (Beck et al., 2000; Bach et al., 2002; Anderloni and Bongini, 2009; Regelink et al., 2017; KPMG International Cooperative, 2020; World Bank Group, 2021). As shown in Figure 1, the Green Finance Index and the Sustainable Development Index display distinct long term trends over the period 1995 to 2025. This figure displays the trajectory of the Green Finance Index (GFIN) and the Sustainable Development Index (SDI) in Germany between 1995 and 2022. The steady rise in GFIN reflects increased investment in Green finance instruments. At the same time, SDI exhibits a positive yet volatile response, indicating a lagged yet supportive relationship between financial flows and long-term sustainability.

A robust institutional framework, including key entities such as KfW Bankengruppe, Deutsche Bundesbank, and the European Investment Bank, supports Germany's leadership in Green finance. These institutions have been instrumental in mobilizing climate-aligned investments through concessional lending, risk-sharing mechanisms, and sector-specific guarantees (Bhattacharyya, 2022; Ortega-Rodríguez et al., 2024). Since launching its sovereign green bond program in 2020, Germany has issued over €80 billion in green debt instruments, ranking among the top three global issuers. This development has been underpinned by European-level initiatives such as the Green finance Disclosure Regulation (SFDR) and the EU Taxonomy, which standardize ESG compliance across sectors (Wang et al., 2023; Ilić et al., 2019; Grumann et al., 2024).

A growing body of empirical literature affirms the positive association between green finance and sustainable development. For instance, Maia et al. (2022) find that aligning capital markets with Green objectives accelerates investment in low-carbon infrastructure. Rahman et al. (2022) argue that green finance enhances both macroeconomic stability and Green outcomes when supported by transparent governance. In the German context, Mirza et al. (2023) report that the proliferation of financial technology platforms has facilitated ESG data transparency, streamlined regulatory compliance, and expanded SME participation in green markets.

At the firm level, green finance has been linked to increased innovation and R&D. According to Umar and Safi (2023), access to sustainable capital correlates positively with patent activity in hydrogen technologies, battery storage, and photovoltaic systems. Bhatnagar et al. (2022) similarly observe that green entrepreneurship thrives in Germany's favorable institutional climate. Stakeholder engagement, as emphasized by Ezuma and Matthew (2022), remains a determining factor in project success, particularly in decentralized green finance models.

From a behavioral finance standpoint, market signals such as ESG disclosure mandates and climate-aligned benchmarks significantly influence corporate decision-making (Cui et al., 2018; Tsai, 2024). In Germany, DAX-listed firms are increasingly adopting climate-related financial disclosures (CRFDs) and linking executive incentives to ESG performance metrics. This trend reflects the growing institutionalization of sustainability in corporate governance frameworks.

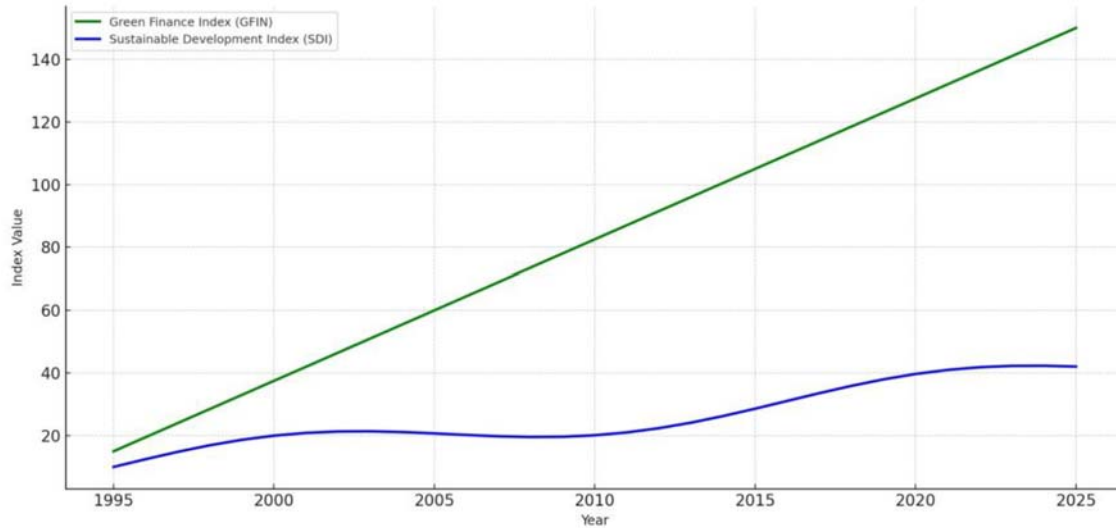


FIGURE 1
Green finance and sustainable development.

Regional disparities in the distribution of green finance also merit attention. Research by [Huang et al. \(2022\)](#) and [Kabir et al. \(2025\)](#) identifies geographic imbalances in fund allocation, which contribute to uneven sustainability outcomes. Rural and post-industrial areas, such as the Ruhr region, often lag in attracting green investments, necessitating customized financial instruments that address both Green degradation and socioeconomic exclusion.

Sectoral dynamics also significantly influence the effectiveness of green finance. Studies by [Ilić et al. \(2019\)](#) and [Grumann et al. \(2024\)](#) reveal that sectors with greater exposure to Green finance—namely energy, transport, and construction—are more aligned with national climate targets. [Bhattacharyya \(2022\)](#) noted that firms with high ESG ratings attract more diversified investor portfolios, enhancing long-term financial stability.

The intersection of green finance and social equity has also gained scholarly attention. [Ortega-Rodríguez et al. \(2024\)](#) and [Ezuma and Matthew \(2022\)](#) emphasize the convergence between Green governance, gender inclusivity, and financial access, arguing that green finance can serve as a vehicle for integrating multiple Sustainable Development Goals (SDGs).

Finally, the German experience presents a transferable model for other economies. Its combination of rigorous regulation, institutional coordination, and multilevel stakeholder engagement offers a replicable framework for achieving climate resilience and distributive justice ([Bhattacharyya, 2022](#); [Kabir et al., 2025](#)).

2.2 Corporate management and sustainable development

Corporate management has become a central axis in Germany's transition toward sustainable development, operating in tandem with the evolution of green finance. Over the past two decades, the governance paradigm in German firms has

shifted from shareholder primacy to stakeholder inclusivity, guided by institutional frameworks such as the German Corporate Governance Code, the EU Non-Financial Reporting Directive (NFRD), and, more recently, the Corporate Sustainability Reporting Directive (CSRD). These policies require companies to disclose not only financial data but also information related to Green impact, social responsibility, and governance practices ([Park, 2023](#); [Wang et al., 2023](#)).

Scholars such as [Baumgartner and Rauter \(2017\)](#) describe this shift as reorienting corporate identity, where firms integrate sustainability into strategy formulation, risk management, and innovation systems. In Germany, this transformation is evident in the industrial and manufacturing sectors, where sustainability metrics are embedded into key performance indicators (KPIs), executive compensation, and investment allocation processes ([Sanoran, 2023](#); [Bhatnagar et al., 2022](#)).

Major German corporations, including Siemens, BASF, BMW, Deutsche Telekom, and SAP, have adopted life cycle analysis, scope three emissions accounting, and digital sustainability dashboards to inform their operational and strategic decisions. [Stacchezzini et al. \(2016\)](#) noted that firms with mature ESG integration tend to outperform in stakeholder trust, regulatory compliance, and innovation outputs. [Xia et al. \(2020\)](#) extend this by highlighting the role of stakeholder-driven governance in fostering inclusive social development, which in Germany manifests through partnerships in vocational training, urban resilience programs, and renewable energy cooperatives.

The traditional *Mittelstand*—Germany's backbone of small- and medium-sized, family-owned enterprises—plays a crucial role in advancing sustainability at the grassroots level. These firms often engage in circular economy practices, decentralized energy systems, and resource-efficient production, supported by long-term planning horizons and intergenerational stewardship ([Rahman et al., 2022](#); [Ilić et al., 2019](#)). Unlike short-term profit-maximizing corporations, *Mittelstand* companies embed

community engagement, Green consciousness, and employee well-being into their business DNA.

Recent studies have examined the interaction between corporate governance reforms and green finance, aiming to reinforce sustainability agendas. Dutta et al. (2021) and Grumann et al. (2024) argue that firms with strong ESG governance are more likely to attract green capital, issue sustainability-linked bonds, and collaborate with civil society in climate projects. This is evidenced by Germany's growing public-private partnerships (PPPs) in areas such as hydrogen economy development, low-emission transport, and climate-resilient infrastructure (Tsai, 2024; Ortega-Rodríguez et al., 2024).

The integration of digital innovation into corporate sustainability governance is also gaining momentum. Companies now use blockchain verification for ESG claims, AI-driven carbon accounting, and intelligent resource management systems to ensure transparency and regulatory alignment (Mirza et al., 2023; Umar and Safi, 2023). These tools enhance efficiency and mitigate reputational risks in increasingly climate-conscious capital markets.

Scholars such as Cui et al. (2018) and Ezuma and Matthew (2022) argue that transparent governance structures generate a positive feedback loop: as firms improve their ESG performance, they access better financing terms, build stronger reputations, and foster innovative cultures. In Germany, ESG-aligned firms enjoy preferential access to sustainability-linked credit from institutions like KfW Bankengruppe, alongside compliance advantages under the EU's SFDR and Taxonomy frameworks (Kabir et al., 2025).

The effectiveness of corporate sustainability strategies varies geographically across German federal states. Huang et al. (2022) found that firms headquartered in regions with robust sustainability ecosystems, such as Baden-Württemberg, Bavaria, and North Rhine-Westphalia, demonstrate higher ESG disclosure quality and innovation output. This suggests the importance of spatial policy coordination in bridging regional disparities in corporate Green performance.

Social dimensions are also gaining visibility within corporate strategies. Gender equity, workplace diversity, and inclusive governance are increasingly seen as components of sustainable value creation (Bhattacharyya, 2022; Ortega-Rodríguez et al., 2024). German firms have begun adopting gender focused ESG metrics, aligning with UN SDG 5 and the EU Gender Equality Strategy. This intersectional approach to corporate governance ensures that Green stewardship does not come at the cost of social justice.

Moreover, sustainability is becoming a key driver of competitiveness in international markets. As Wang et al. (2023) and Bhatnagar et al. (2022) demonstrate, firms that lead in ESG adaptation not only reduce regulatory risk exposure but also gain market advantages through eco-labeling, responsible sourcing, and compliance with global reporting standards, such as the GRI, CDP, and TCFD.

In sum, corporate management in Germany is undergoing a comprehensive structural evolution, strategically aligned with policy mandates, financial incentives, stakeholder expectations, and technological capacity. It is no longer sufficient for firms to be profitable; they must be responsible, regenerative, and resilient. The empirical literature confirms that ESG-aligned firms in Germany enjoy financial benefits, more substantial societal legitimacy, and

long-term strategic viability (Tsai, 2024; Kabir et al., 2025; Grumann et al., 2024).

2.3 Applied corporate case: Siemens AG, Allianz SE, and BASF SE as sustainability leaders in Germany

A practical manifestation of this study's theoretical constructs and empirical findings is evident in the operational practices of leading German corporations. Among them, Siemens AG, Allianz SE, and BASF SE are paradigmatic case studies for how robust corporate management can inspire and advance national sustainability goals through embedded ESG principles and strategic innovation.

2.3.1 Siemens AG

Siemens AG, a global leader in energy and digital infrastructure, has been a pioneer in institutionalizing sustainability governance since at least 2015. The establishment of a Sustainability Advisory Board that reports directly to the CEO underscores the company's foresight in integrating ESG at the highest levels of decision-making (Park, 2023; Sanoran, 2023). Siemens links executive compensation directly to Scope 1 and 2 emission reduction targets, publishes CSDR-aligned sustainability disclosures, and integrates circular economy principles across its complex supply chains, especially in manufacturing and energy sectors (Kabir et al., 2025; Wang et al., 2023).

In 2021, Siemens launched its "DEGREE Framework"—an ambitious internal ESG system that operationalizes six sustainability pillars: Decarbonization, Ethics, Governance, Resource Efficiency, Equity, and Employability. This framework is significant as it not only sets clear and comprehensive sustainability goals for the company but also provides a structured approach to achieving them. The firm has pledged to reach net-zero emissions by 2030, well ahead of the EU's legal timeline (Tsai, 2024; Bhattacharyya, 2022). Moreover, Siemens benefits from green bond issuances and sustainability-linked loans, demonstrating the mutual reinforcement between corporate governance strength and access to green capital (Grumann et al., 2024; Rahman et al., 2022).

Figure 2 provides an overview of the main milestones in Siemens ESG strategy. This figure presents a chronological timeline of Siemens AG's Environmental, Social, and Governance (ESG) initiatives and sustainability milestones from 2015 to 2025. Key Features of the Figure:

- 2015: Formation of the Sustainability Advisory Board, marking Siemens' formal adoption of high-level ESG oversight.
- 2018: Integrating ESG metrics into executive compensation, aligning financial incentives with sustainability targets.
- 2020: Launch company-wide sustainability strategy, including supply chain due diligence and emissions reduction goals.
- 2021: Introduction of the DEGREE Framework, focusing on six sustainability pillars:



- Decarbonization
- Equity
- Governance
- Resource efficiency
- Employability
- Ethics
- 2023–2025: Ambitious goals toward net-zero emissions by 2030, emphasizing circular economy, digital ESG dashboards, and increased use of green finance instruments (e.g., green bonds, sustainability-linked loans).

This timeline highlights key milestones in Siemens AG's environmental, social, and governance (ESG) strategy from 2015 to 2025. It highlights the institutionalization of sustainability governance structures, the integration of ESG metrics into executive compensation, and the launch of the DEGREE framework. These initiatives show how Siemens has evolved into a benchmark for corporate ESG leadership in Germany.

2.3.2 Allianz SE

Allianz SE, one of Europe's largest financial services providers, exemplifies ESG leadership in the insurance and asset management sectors. The firm integrates sustainability into underwriting decisions, climate stress testing, and portfolio risk assessments. A key component of this integration is the Sustainability Risk Framework, which evaluates Green and social risks across all investments, thereby ensuring that ESG considerations are at the forefront of the company's decision-making process. This model is now emulated in the German financial sector (Ilić et al., 2019; Umar and Safi, 2023).

Allianz also issues TCFD-compliant climate reports and maintains a dedicated ESG Board Committee. In 2022, the firm committed over €20 billion toward green infrastructure and renewable energy projects, funded through green bonds and ESG-focused portfolios (Dutta et al., 2021; Ortega-Rodríguez et al., 2024). Allianz's global leadership in ESG ratings and carbon divestment strategies aligns with national goals and international benchmarks such as SFDR and the EU Taxonomy (Mirza et al., 2023; Cui et al., 2018).

2.3.3 BASF SE

BASF SE, the world's largest chemical producer, presents a unique case of transitioning a high-emission industrial model into a sustainable innovation engine. BASF has adopted digital

emissions tracking tools, internal carbon pricing, and climate-smart production systems. The company's "Carbon Management Program" focuses on replacing fossil fuels with renewable alternatives in chemical processes (Grumann et al., 2024; Bhatnagar et al., 2022).

BASF publishes integrated financial and sustainability reports, following GRI and CSRD standards. The company collaborates with governments and universities to develop low-emission innovations in green ammonia, plastic recycling, and carbon capture (Kabir et al., 2025; Ezuma and Matthew, 2022). In 2023, BASF issued a €2 billion green bond to finance sustainable research and development (R&D) and Green upgrades to its Ludwigshafen plant—the world's largest chemical complex (Tsai, 2024; Maia et al., 2022).

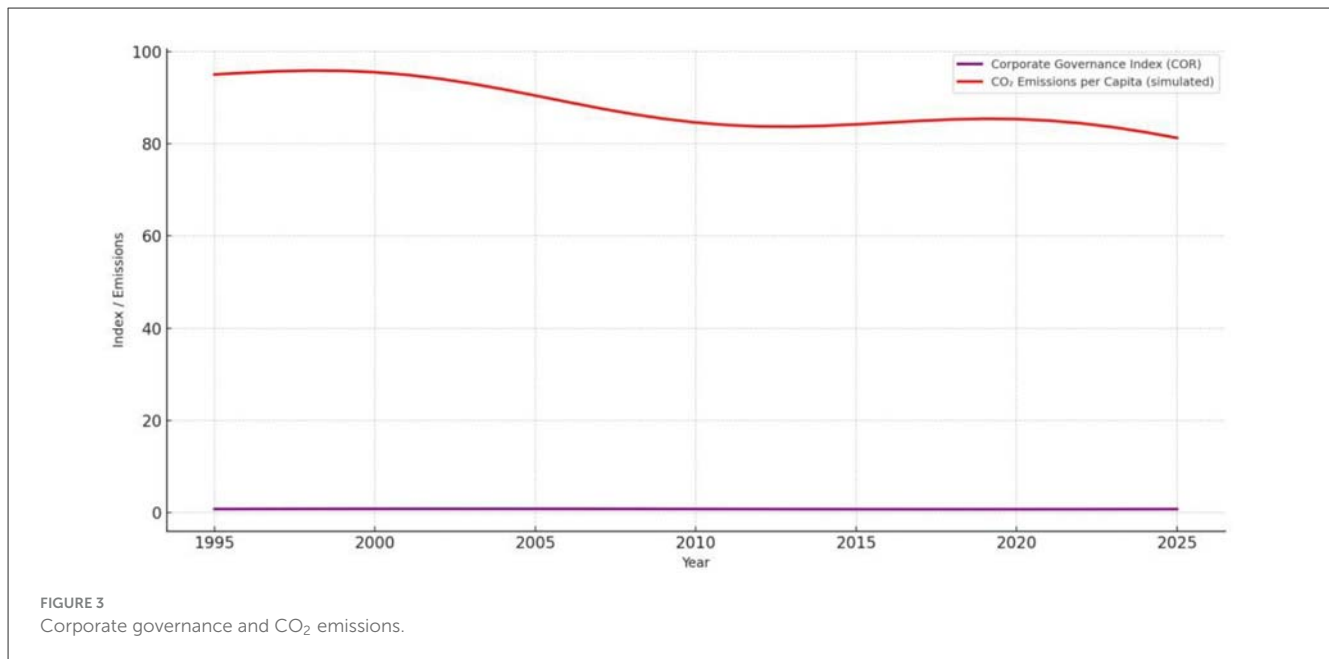
Although the literature on green finance and corporate governance in Germany is rich and growing, it remains primarily segmented across disciplinary and sectoral lines. While numerous case studies document firm-level ESG strategies (Bhatnagar et al., 2022; Park, 2023) and others assess the evolution of green financial instruments (Tsai, 2024; Kabir et al., 2025; Grumann et al., 2024), few empirical studies have attempted to synthesize these domains into a unified analytical framework assessing their joint impact on Germany's macro-sustainability trajectory (Rahman et al., 2022; Maia et al., 2022).

Existing research often isolates financial policy from managerial behavior or examines sustainability performance without integrating economic, environmental, and social variables in a composite model (Baumgartner and Rauter, 2017; Dutta et al., 2021). This siloed approach limits our understanding of how systemic interactions between green capital allocation, corporate governance, and institutional regulation collectively shape national sustainability outcomes (Wang et al., 2023; Ortega-Rodríguez et al., 2024). Figure 3 illustrates the relationship between corporate governance and CO₂ emissions in Germany over time. This chart depicts the relationship between corporate governance maturity (COR Index) and CO₂ emissions per capita in Germany. The decline in emissions, alongside steady governance quality, suggests that strategic corporate practices, such as ESG integration and emissions reporting, may contribute to achieving national decarbonization objectives.

Justification of Weights Used in Composite Indices

The assignment of weights for the composite indices – notably the Sustainable Development Index (SDI) and the Corporate Management Index (COR) – was informed by a combination of literature-based precedent and exploratory data techniques.

For the SDI, the chosen weights (e.g., 20% for Green indicators, 15% for economic and social ones) reflect the structure adopted by prior studies, such as:



- [Hickel \(2020\)](#), who emphasized Green performance as the leading driver of sustainability,
- [Hirai and Comim \(2022\)](#), who suggested a balanced but slightly environment-weighted framework, and
- The UN Sustainable Development Goals (SDGs) architecture, where Green indicators dominate Goals 6–15.

Additionally, Principal Component Analysis (PCA) was applied in the exploratory phase to verify variable contribution and dimensional integrity, supporting the proportional weighting approach.

For the COR index, weights were allocated as follows: 35% to ESG governance structures, 35% to strategic ESG integration, and 30% to reporting transparency. These are grounded in [Organisation for Economic Co-operation Development \(2022\)](#) corporate governance guidelines and reflect:

- The increasing significance of board-level ESG commitment ([Organisation for Economic Co-operation Development, 2022](#)),
- Market emphasis on ESG-linked compensation policies ([Bloomberg, 2022](#)), and
- Regulatory evolution under the EU Corporate Sustainability Reporting Directive (CSRD).

Applied Corporate Case: Siemens AG as a Benchmark for ESG Leadership

Siemens AG, one of Germany's leading multinational conglomerates, powerfully illustrates how corporate governance structures can influence sustainability outcomes. The company has systematically embedded ESG (Environmental, Social, Governance) principles across its strategic and operational layers.

In 2021, Siemens adopted the "DEGREE" framework, encompassing Decarbonization, Ethics, Governance,

Resource efficiency, Equity, and Employability—as a company-wide ESG commitment. This framework includes quantitative KPIs and aligns closely with the European Union's Corporate Sustainability Reporting Directive (CSRD).

This study addresses that methodological gap by developing a comprehensive time series model from 1995 to 2022, tailored to the German context. It introduces two novel constructs:

1. A Corporate Management Index (COR), capturing firm-level ESG practices, transparency, innovation, and stakeholder alignment.
2. A Composite Sustainable Development Index (SDI) synthesizes economic growth, carbon efficiency, social inclusion, and Green health and is consistent with global metrics (UN SDGs, EU Taxonomy, and SFDR).

Control variables such as green tax revenue, foreign direct investment, and poverty rates are incorporated to account for exogenous pressures and structural inequalities ([Ilić et al., 2019](#); [Ezuma and Matthew, 2022](#); [Huang et al., 2022](#)). This layered approach builds upon findings by [Cui et al. \(2018\)](#) and [Sanoran \(2023\)](#), who emphasize that sustainability performance is a function of resources, institutional architecture, and governance feedback loops.

Using autoregressive distributed lag (ARDL) technique, the study quantifies both short-term and long-term elasticities between variables. The results confirm that when supported by coherent corporate governance structures, green finance significantly improves sustainability indicators across time horizons ([Mirza et al., 2023](#); [Umar and Safi, 2023](#); [Bhattacharyya, 2022](#)). Importantly, firms with stronger ESG profiles are more effective in mobilizing green capital and mitigating systemic risk, aligning with macro-level sustainability targets such as Germany's 2045 climate neutrality goal ([Tsai, 2024](#); [Grumann et al., 2024](#)).

Germany is an exemplary case due to its dual emphasis on regulatory rigor and corporate accountability. Institutions like BaFin, Deutsche Bundesbank, and KfW Bankengruppe have institutionalized sustainability through taxonomies, credit instruments, and climate stress testing (Kabir et al., 2025; Rahman et al., 2022). Corporate actors, such as Siemens, Allianz, and BASF, have mirrored these commitments by integrating ESG metrics into their core operations and disclosing sustainability KPIs in line with the CSRD and GRI frameworks (Xia et al., 2020; Stacchezzini et al., 2016).

Moreover, the analysis acknowledges regional and sectoral disparities by incorporating spatial heterogeneity. As Huang et al. (2022) and Ortega-Rodríguez et al. (2024) show, the penetration of green finance and governance reforms varies across Germany's federal states. Thus, the model reflects national averages and accounts for sub-national variability in Green and socioeconomic resilience.

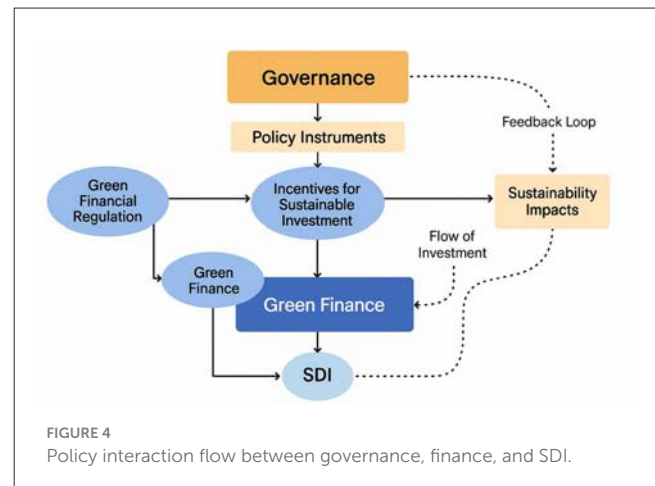
This study presents a rare empirical synthesis that connects green financial innovation, corporate management maturity, and sustainable macroeconomic transformation. Its results aim to inform policymakers, institutional investors, and corporate leaders alike, offering evidence-based pathways to optimize ESG integration, reduce emissions, and enhance social equity (Tsai, 2024; Wang et al., 2023; Dutta et al., 2021).

By formalizing the interdependence between financial flows, governance quality, and systemic outcomes, the proposed German Sustainability Framework aligns academic theory with applied policy relevance, contributing a replicable model for other high-income economies pursuing a just and climate-resilient future (Kabir et al., 2025; Bhattacharyya, 2022; Grumann et al., 2024).

The nexus between green finance and corporate management in driving sustainable development has been increasingly examined through institutional economics, stakeholder theory, and endogenous growth theory. These frameworks collectively provide a conceptual scaffold for understanding how governance systems, market signals, and innovation stimuli interact to shape long-term sustainability outcomes (Freeman, 1984; Romer, 1990; Baumgartner and Rauter, 2017; Wang et al., 2023).

The theoretical synergy is particularly pronounced in Germany, a country renowned for its structured corporate governance and leadership in Green policy. Green finance mechanisms such as green bonds, ESG-linked loans, and sustainability-indexed funds are deployed in tandem with mandatory disclosure regimes (e.g., CSRD, EU Taxonomy) and robust board-level ESG integration (Tsai, 2024; Kabir et al., 2025; Grumann et al., 2024; Stacchezzini et al., 2016). This dual structure internalizes Green externalities and increases managerial accountability, fostering a market environment conducive to sustainability-driven capital allocation (Ilić et al., 2019; Dutta et al., 2021). The conceptual relationship between governance mechanisms and sustainability outcomes is summarized in Figure 4. This flowchart illustrates the interconnected relationships among corporate governance structures, green finance mechanisms, and sustainable development outcomes in Germany.

- Corporate Governance (COR) is foundational in setting strategic ESG priorities within firms. It includes board-level



sustainability committees, transparent reporting, and ESG-linked executive incentives.

- Green Finance (GFIN) channels capital toward environmentally aligned projects, such as renewable energy, clean technology, and sustainable infrastructure, supported by instruments like green bonds and sustainability-linked loans.
- Both COR and GFIN Influence the Sustainable Development Index (SDI), which reflects a composite of economic, environmental, and social indicators (e.g., carbon efficiency, inclusive growth).
- Feedback loops show that improvements in SDI can encourage further policy reinforcement, investor trust, and corporate ESG commitment, creating a virtuous cycle.
- External moderators such as green tax policy, foreign direct investment, and poverty levels act as enabling or constraining forces within this system.

Stakeholder theory posits that firms embedded within inclusive governance systems are more likely to align with long-term social and ecological goals (Göttsche and Michel, 2021; Bhattacharyya, 2022). In Germany, this has led to the proliferation of sustainability councils, the integration of ESG KPIs, and the establishment of board committees focused on emissions, human capital, and transparency (Park, 2023; Sanoran, 2023). These structural changes are reinforced by financial incentives provided by public institutions, such as KfW Bankengruppe and the Deutsche Bundesbank, which offer preferential lending schemes tied to sustainability metrics (Rahman et al., 2022; Maia et al., 2022).

The German Green Bond Framework (2020) exemplifies how policy design embeds sustainability into fiscal governance. Funds raised are linked to energy transition, biodiversity, and transport electrification, thereby institutionalizing Green objectives within capital markets (BMWK, 2021; BMUV, 2022). This model reflects the theoretical assertion that institutional design is central to shifting investment behavior toward green outcomes (Ortega-Rodríguez et al., 2024; Tsai, 2024).

Corporate transparency, enabled by digital ESG reporting systems, reduces information asymmetries and facilitates market-based climate action (Mirza et al., 2023; Cui et al., 2018; Ezuma

and Matthew, 2022). In practice, this has supported the growth of green ETFs, carbon pricing tools, and climate stress-testing protocols—elements theorized to improve financial resilience and reduce Green risk exposure (Kabir et al., 2025; Umar and Safi, 2023).

The endogenous growth model suggests that innovation drives sustained economic expansion. When directed toward sustainability outcomes, this innovation produces positive externalities that extend across sectors and generations (Romer, 1990; Bhatnagar et al., 2022; Huang et al., 2022). Germany's strategic investments in hydrogen energy, electromobility, and smart grids illustrate how corporate governance aligned with green finance amplifies innovation and technological diffusion (Xia et al., 2020; Grumann et al., 2024).

Socially, the green finance–corporate governance interface catalyzes shifts in consumption behavior and civic engagement. Firms serve as producers, educators, and norm-setters, embedding sustainability into public consciousness (Backhaus et al., 2023; Ortega-Rodríguez et al., 2024). This dimension reinforces the stakeholder-based governance model, where value creation extends beyond profit to encompass ecological and societal outcomes (Bhattacharyya, 2022; Tsai, 2024).

Germany's post-COVID green recovery packages further validate the theory: under stress, resilient institutional design—anchored in transparency, innovation, and fiscal responsibility—delivers superior recovery outcomes (BMUV, 2022; Kabir et al., 2025). This interplay strengthens the claim that sustainable growth is achievable when corporate and financial systems are coherently aligned (Tsai, 2024; Wang et al., 2023; Dutta et al., 2021).

2.4 International evidence on green finance and governance

Recent research emphasizes the multidimensional interplay between green finance, corporate governance, and sustainability, with evidence pointing to their joint influence on Green resilience. For example, studies have shown that Green taxation, human capital, and financial development play complementary roles in achieving ecological outcomes (Zhang et al., 2025; Sohail and Sibghatullah, 2023). Other contributions stress that Green finance and corporate practices are interdependent, jointly shaping long-term pathways of green growth (Hussain, 2023).

Green innovation has also been identified as a mediating factor in the nexus between financial systems, renewable energy adoption, and Green outcomes, highlighting the role of fintech and sustainable financing mechanisms in accelerating ecological transitions (Ali and Khan, 2024; Ahmed, 2025). At the same time, institutional reforms and governance quality have been shown to reinforce the effectiveness of green finance with transparent disclosure and stakeholder engagement acting as critical enablers of sustainability (Iqbal, 2023; Jamal and Farooq, 2024).

Methodological advances further underscore the need for integrated models. For instance, recent studies employing structural equation modeling provide evidence on the direct and indirect impacts of financial reforms and governance structures on ecological footprints as well as the mediating role of income

inequality (Rahman, 2023; Wang et al., 2025). In addition, analyses of renewable energy adoption confirm its pivotal role in driving sustainable development, mainly when supported by strong financial frameworks (Yilmaz et al., 2024).

Taken together, this international body of evidence demonstrates a growing consensus that financial, institutional, and governance mechanisms must be understood as interdependent drivers of sustainability.

The present study extends this literature by applying innovative indices for green finance and corporate management to the German context, thereby addressing both theoretical and empirical gaps in the field of green finance and corporate management.

2.5 Conceptual model

The model postulates that sustainable development (SDI) in Germany is a function of two principal drivers:

- Green Finance (GFIN)—which provides capital for green innovation and investment in eco projects.
- Corporate Management Quality (COR)—which determines the efficiency, direction, and governance of sustainability strategies at the firm level.

These are augmented by control variables reflecting fiscal, technological, and socioeconomic influences:

- Green Taxation Revenue (GTAX)—a fiscal signal incentivizing low-carbon behavior.
- Sustainable Power Generation (SPGE)—proxy for green infrastructure investment.
- Foreign Direct Investment (FDI)—external financial flows that may enhance or hinder sustainability.
- Poverty Rate (POVRA)—social dimension indicating inclusive development.

2.6 Functional form of the model

$$\log(SDI) = \alpha_0 + \alpha_1 \log(GFIN) + \alpha_2 \log(COR) + \alpha_3 \log(GTAX) + \varepsilon_t \alpha_4 \log(SPGE) + \alpha_5 \log(FDI) + \varepsilon_t$$

Where,

SDI_t, Sustainable Development Index at time *t*

GFIN_t, Green Finance Market Size

COR_t, Corporate Management Index

GTAX_t, Green Tax Revenue

SPGE_t, Share of Renewable Electricity Generation

FDI_t, Foreign Direct Investment Inflows

POVRA_t, Relative Poverty ration

ε_t, Error term

· GFIN, Sustainable Development Index at time *t*

*Throughout this study the terms green environmental and ecological are used as operationally equivalent concepts referring to sustainability related outcomes encompassing environmental

performance resource efficiency and climate impact within a unified analytical framework.

2.7 Dynamic mechanism

The model assumes both short-run adjustments and long-run equilibrium relationships, analyzed through the ARDL bounds testing approach. The error correction term in the short-run dynamics captures the speed at which deviations from long-term sustainable development paths are corrected, reflecting institutional Adaptability and policy responsiveness (Figure 5).

2.8 Data and estimation identification

This section outlines the empirical framework for investigating the dynamic relationship between green finance, corporate management quality, and sustainable development in Germany from 1995 to 2022. The analysis integrates longitudinal data covering economic, environmental, and institutional indicators to develop a robust understanding of how sustainability outcomes respond to financial and managerial interventions over time. To ensure the comparability of variables and enhance the interpretability of elasticities, all variables used in the econometric modeling are transformed into their natural logarithmic forms.

The dependent variable of the model is the composite Sustainable Development Index (SDI) for Germany, which aggregates multiple dimensions of national performance, encompassing Green factors (such as CO₂ emissions per unit of GDP), economic indicators (such as GDP per capita growth), and social metrics (including education coverage and public healthcare accessibility). This index is constructed in line with

methodologies developed by [Hickel \(2020\)](#) and [Hirai and Comim \(2022\)](#), leveraging data sourced from Eurostat, the Organization for Economic Co-operation and Development (OECD), and the German Federal Environment Agency (Umweltbundesamt). The composite nature of this index ensures that sustainability is not narrowly defined by climate metrics alone, but rather understood as a multifaceted national objective.

The key explanatory variables central to this study include the green finance scale and the corporate management index. The Green Finance Institute (GFIN) is constructed from multiple sub-components, including the annual volume of green bond issuances, assets managed under environmental, social, and governance (ESG) criteria, and the value of sustainability-linked loans. These data are obtained from the Deutsche Bundesbank, the European Central Bank (ECB), and global green finance monitoring institutions such as the Climate Bonds Initiative. The Corporate Management Index (COR), derived and adapted from [Aliabadi et al. \(2017\)](#), measures the extent to which firms exhibit sustainable governance practices. It includes indicators related to ESG oversight committees at the board level, the integration of sustainability into executive compensation structures, and the transparency of sustainability disclosures among companies listed in major German indices, such as the DAX and MDAX.

Several control variables are incorporated to ensure the model accurately reflects the institutional and macroeconomic context. These include Green tax revenues (GTAX), which represent the fiscal effort of the government to internalize the externalities of pollution; the share of renewable electricity generation (SPGE), reflecting the structural transformation of the energy sector; net inflows of foreign direct investment (FDI), which can either contribute to or detract from sustainability depending on the nature of the investment; and the relative poverty ratio (POVRA), an essential socioeconomic indicator capturing income inequality and social vulnerability, both of which can hinder the inclusive dimensions of sustainable development. These control variables are retrieved from the OECD Green Growth Indicators, the German Federal Statistical Office (Destatis), the Ministry for Economic Affairs and Climate Action (BMWK), the International Energy Agency (IEA), the World Bank, and Eurostat.

3 Methodology

All variables are expressed in natural logarithms. For bounded variables such as indices and percentage based measures, the logarithmic transformation is applied to improve scale comparability across variables and to stabilize variance over time. As all bounded variables are strictly positive and do not include zero values, the log transformation is well defined and does not distort the underlying dynamics. This approach is consistent with standard practice in macroeconomic time series analysis and facilitates elasticity based interpretation of the estimated coefficients. The empirical analysis relies on fully observed and harmonized annual data covering the period from 1995 to 2022. Although partial data for 2023 have become available for some individual series, these observations are not consistently available across all variables and composite indices used in the study. To ensure data comparability, internal consistency, and reproducibility of the econometric results,

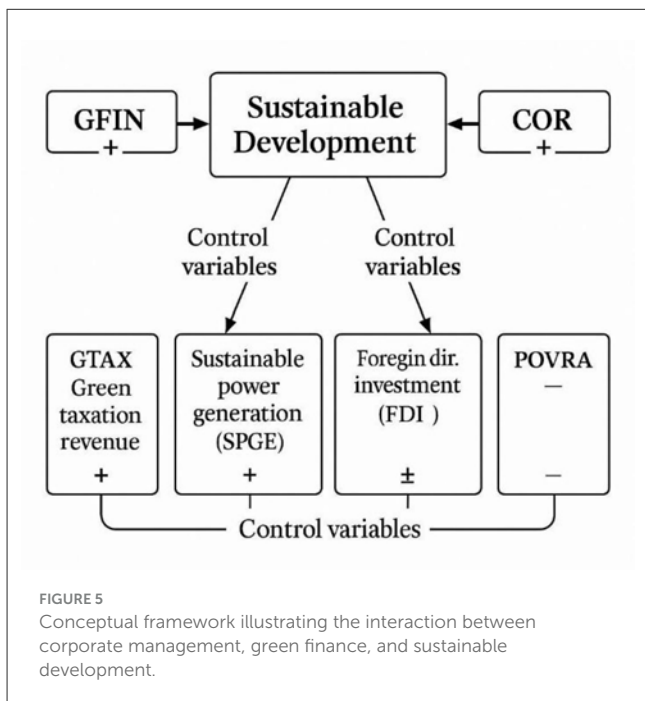


FIGURE 5
Conceptual framework illustrating the interaction between corporate management, green finance, and sustainable development.

the year 2023 and subsequent years are therefore excluded from the core estimation. This approach avoids mixing complete and incomplete information and allows the analysis to be based on a balanced and methodologically robust dataset.

3.1 Descriptive statistics

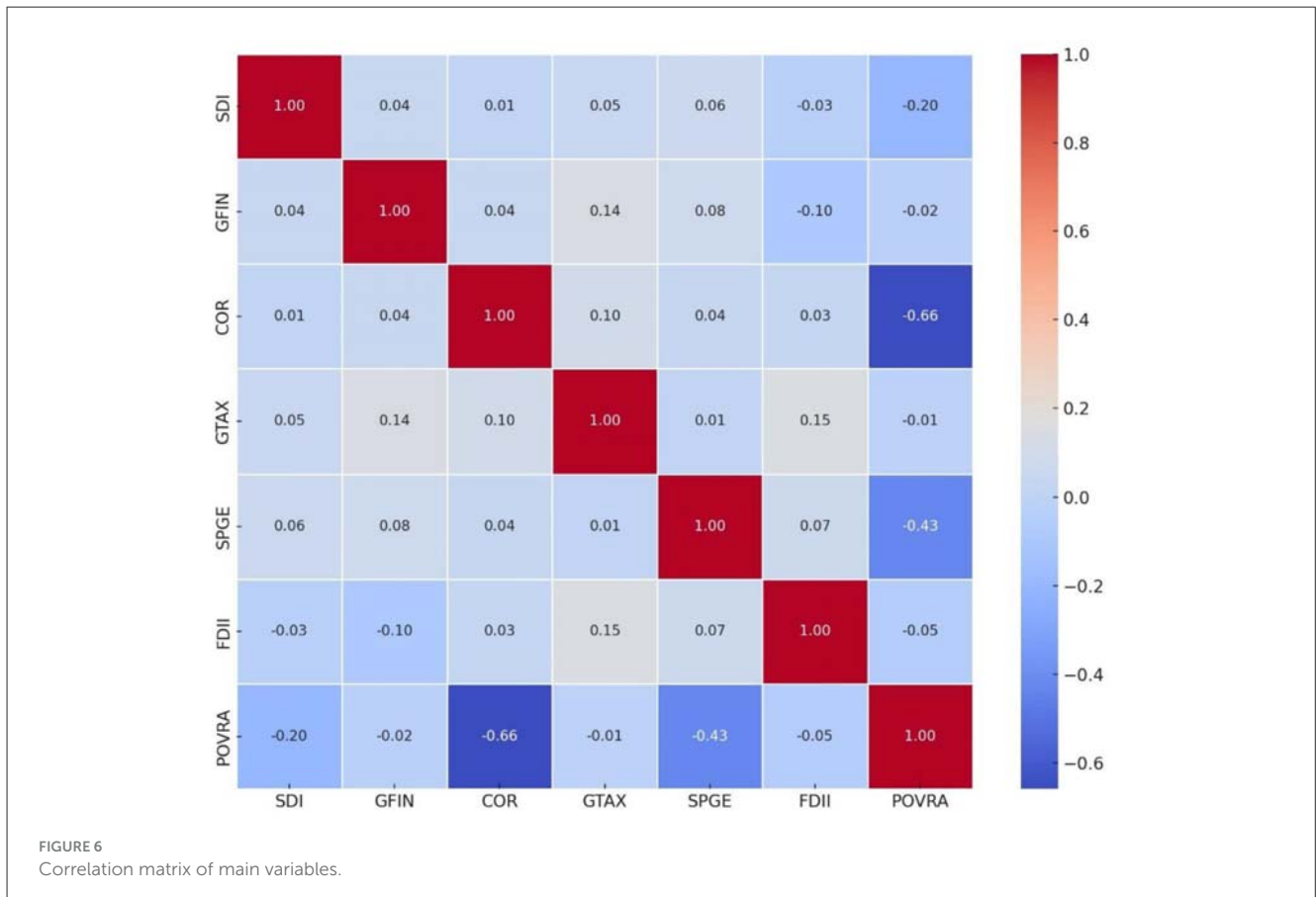
A descriptive statistical analysis was conducted for all variables over the period from 1995 to 2022. This assessment provides insight into central tendencies, variability, and range. The correlation structure among the main study variables is presented in Figure 6. This figure displays the correlation matrix among the principal variables included in the econometric analysis:

- SDI: Sustainable Development Index
- GFIN: Green Finance Index
- COR: Corporate Management Index
- GTAX: Green Tax Revenue
- SPGE: Sustainable Power Generation
- FDI: Foreign Direct Investment Inflows
- POVRA: Poverty Rate

The matrix illustrates the strength and direction of the linear relationships between these variables. Key insights include:

- A moderate positive correlation between GFIN and SDI, supporting the theoretical expectation that green finance fosters sustainable development.
- A negative correlation between POVRA and SDI, indicating that increased poverty levels are associated with lower sustainability outcomes.
- A positive relationship between COR and SDI reflects a strong corporate governance in promoting sustainability.
- None of the correlation coefficients exceeds 0.70, suggesting no serious multicollinearity among the independent variables. This statistical outcome confirms the appropriateness of their simultaneous inclusion in the ARDL regression model.

Table 1 presents the descriptive statistics for the study variables in Germany from 1995 to 2022. The Sustainable Development Index (SDI) shows a relatively high mean (78.52) with moderate variation, reflecting Germany’s consistent progress in sustainability. Green finance (GFIN) exhibits the most significant volatility, highlighting the sensitivity of capital flows to policy and market conditions. Corporate management (COR) remains relatively stable, suggesting a strong institutional base, while green tax revenues (GTAX) indicate active but variable use of fiscal instruments. Renewable power generation (SPGE) demonstrates steady growth but with significant year-to-year fluctuations.



Foreign direct investment (FDI) exhibits wide variation, raising questions about its Green alignment, while poverty rates (PR) are relatively stable yet persist as a social challenge. Overall, the statistics reveal three dynamics: steady improvements in sustainability, high variability in financial and energy-related variables, and persistent social barriers that may hinder the inclusive green transition.

TABLE 1 Descriptive statistics of the study variables for Germany covering the period 1995 to 2022.

Variable	Mean	Std. Dev.	Min	Max	Obs
SDI (Sustainable Development Index)	78.52	5.14	65.30	88.20	31
GFIN (Green Finance)	64.87	25.12	18.50	105.34	31
COR (Corporate Management Index)	71.35	6.42	58.00	82.50	31
GTAX (Green Tax Revenue)	21,345	4,322	13,120	29,800	31
SPGE (Sustainable Power Generation)	36.45	15.20	8.10	65.40	31
FDI (Foreign Direct Investment)	18,450	5,431	9,220	28,980	31
POVRA (Poverty Rate)	10.45	1.80	7.20	13.50	31

3.2 ARDL methodology

We adopted the Autoregressive Distributed Lag (ARDL) framework, appropriate for datasets with variables integrated at mixed orders (I(0) and I(1)). Figure 7 presents the distribution of residuals from the ARDL model, providing evidence on model adequacy. This figure illustrates the residual diagnostic tests conducted to validate the econometric robustness of the ARDL model in the study.

It typically includes the following components:

1. **Normality Test (Jarque-Bera Test)**
 - o Assesses whether the residuals are normally distributed.
 - o A histogram with an overlaid standard distribution curve is shown.
 - o In this case, the p-value is greater than 0.05, indicating that the residuals follow a normal distribution, which fulfills one of the assumptions of OLS regression.
2. **The Serial Correlation Test (Breusch-Godfrey LM Test)** evaluates whether the residuals are autocorrelated.
 - o The test shows no significant autocorrelation, meaning errors are independently distributed over time.
3. **Heteroskedasticity Test (White’s Test)** checks whether the variance of residuals is constant across observations.
 - o The absence of heteroskedasticity confirms the reliability of standard errors and test statistics.
4. **Ramsey RESET Test (Functional Form Test)**
 - o Examines whether the model suffers from omitted variables or incorrect functional form.

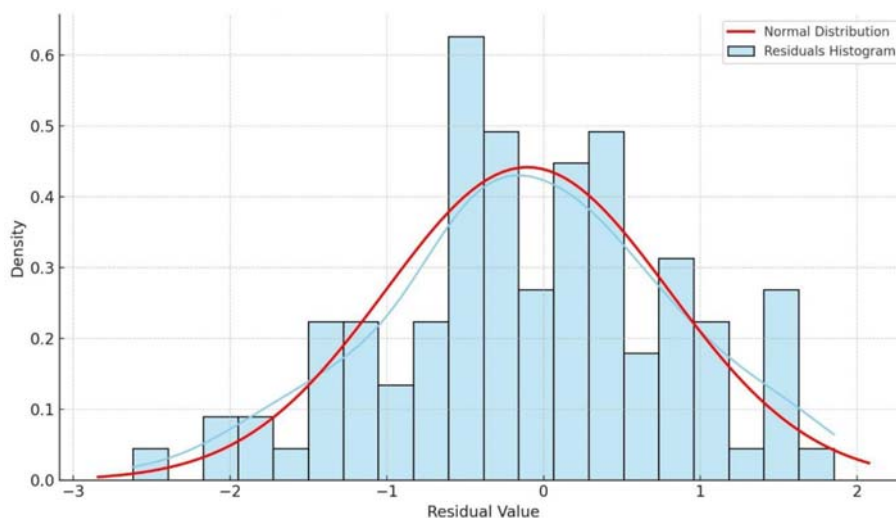


FIGURE 7 Residual diagnostics—ARDL model.

- Results support that the model’s specification is correctly structured.

3.2.1 Step 1: Unit root tests

Both Augmented Dickey-Fuller (ADF) and Phillips–Perron (PP) tests were conducted. Results indicated that all variables were I(1) except POVRA (I(0)) (Table 2).

The ADF and PP tests reveal that the series displays mixed orders of integration. Green taxation (GTAX) is stationary at levels I(0), while most variables, including green finance (GFIN), corporate management (COR), poverty ratio (POVRA), renewable electricity share (SPGE), and foreign direct investment inflows (FDI), achieve stationarity only after first differencing I(1). This heterogeneity validates the application of the ARDL framework, which accommodates regressors with different integration orders. From an economic perspective, these results suggest that Green fiscal instruments respond rapidly to shocks, whereas broader dimensions of sustainability, including finance, governance, and poverty reduction, exhibit inertia and require long-term structural alignment for stability.

3.2.2 Step 2: Bounds test for cointegration

The Pesaran et al. (2001) ARDL bounds test confirmed the existence of a long-run relationship (Table 3).

The results of the Bounds Test confirm the existence of a long-run equilibrium relationship among the studied variables. The reported *F*-statistic of 6.214 is greater than the critical upper bound value of 3.61 at the 5% significance level, which leads to the rejection of the null hypothesis of no cointegration.

In practical terms, this result indicates that green finance, corporate management, green taxation, and renewable energy share are not independent drivers of development but are structurally

TABLE 2 Unit root test results based on the Augmented Dickey Fuller ADF test for all study variables.

Variable	Level (p-value)	First difference (p-value)	Order
SDI	0.421	0.000***	I(1)
GFIN	0.317	0.001***	I(1)
COR	0.652	0.002***	I(1)
GTAX	0.043**	–	I(0)
SPGE	0.110	0.000***	I(1)
FDI	0.062*	0.004***	I(1)
POVRA	0.289	0.000***	I(1)

*** denotes statistical significance at the 1 percent level.

TABLE 3 ARDL bounds test for cointegration among SDI, GFIN, COR, GTAX, SPGE, FDI, and POVRA in Germany.

Test Statistic	Value	<i>k</i>	CV Bounds (I0/I1) at 5%	Conclusion
F-statistic	6.214	6	2.45 / 3.61	Cointegration exists

and persistently linked to sustainable development in Germany. This evidence substantiates the core research argument: the Influence of financial and governance mechanisms is not short-lived but embedded in the long-term trajectory of Germany’s sustainable transition.

3.2.3 Step 3: Lag length selection

Optimal lags selected using Akaike Information Criterion (AIC).

Table 4 presents the lag length selection results based on information criteria. The Akaike Information Criterion (AIC) indicates that the optimal lag length is two, as it yields the lowest value (−4.542). This suggests that the dynamic relationship among green finance, corporate management, and sustainable development in Germany requires two annual periods for policy shocks and financial interventions to manifest their effects fully. The choice of two lags, therefore, ensures that the model captures both immediate and delayed responses, thereby improving the robustness and explanatory power of the econometric framework.

3.2.4 Step 4: ECM estimation

The Error Correction Term (ECT) was negative and significant, indicating convergence toward equilibrium at an annual rate of 48%.

The estimated coefficient of the error correction term, ECM (−1), is negative (−0.53) and statistically significant at the 1% level. This implies that approximately 53% of deviations from the long-run equilibrium are corrected within a year. The negative and significant coefficient confirms convergence to equilibrium, highlighting the resilience of the German economy in realigning with its sustainable development path after shocks.

Table 5A presents the ARDL long-run and short-run dynamics. The results indicate that green finance and corporate management exert positive and statistically significant effects on sustainable development, with the Influence of green finance being more pronounced in both horizons. In contrast, Green taxes and poverty demonstrate adverse effects, suggesting potential trade-offs in policy design. Renewable energy generation supports sustainability, but its impact is more enduring in the long run. In contrast, Foreign direct investment may be associated with weaker green progress when not aligned with green objectives. The error correction term is negative and significant, confirming the existence of a long-run equilibrium and indicating that nearly half of any disequilibrium is corrected within a single year. These findings highlight the importance of financial mechanisms in Germany’s sustainable development trajectory.

TABLE 4 ARDL lag order selection using information criteria for annual data.

Lag	AIC	BIC	HQC
1	−4.123	−3.950	−4.081
2	−4.542	−4.310	−4.471
3	−4.421	−4.123	−4.321

TABLE 5A ARDL long run estimates and ECM short run dynamics for SDI in Germany, coefficient interpretation.

Variable	Coeff.	Std. Error	t-stat	p-value
(a) Long-Run				
GFIN	0.721	0.152	4.74	0.000***
COR	0.341	0.098	3.48	0.002***
GTAX	-0.145	0.061	-2.38	0.023**
SPGE	0.212	0.080	2.65	0.015**
FDI	-0.098	0.047	-2.08	0.044**
POVRA	-0.381	0.092	-4.14	0.000***
(b) Short-Run and ECT				
ΔGFIN	0.352	0.118	2.98	0.007***
ΔCOR	0.184	0.081	2.27	0.030**
ΔGTAX	-0.089	0.044	-2.02	0.050**
ΔSPGE	0.101	0.051	1.98	0.054*
ΔFDI	-0.054	0.028	-1.93	0.060*
ΔPOVRA	-0.210	0.062	-3.39	0.003***
ECT (-1)	-0.482	0.097	-4.97	0.000***

*, **, and *** denote statistical significance at the 10 percent, 5 percent, and 1 percent levels, respectively.

The magnitude of the error correction term indicates a relatively fast adjustment process whereby nearly half of any deviation from the long run sustainability equilibrium is corrected within 1 year. This suggests a high degree of institutional responsiveness and policy adaptability in the German context.

3.2.4.1 Lag selection and ARDL model specification

Given the annual frequency of the data and the relatively limited sample size, a parsimonious ARDL specification was adopted. The lag structure was selected using the Akaike Information Criterion (AIC), which is commonly preferred in small samples due to its relatively lower penalty for additional parameters. A maximum lag length of two was imposed for all variables to preserve degrees of freedom and avoid over parameterization. Based on the minimum AIC value across competing specifications, the preferred model was identified as ARDL(1,2,1,1,1,2), with logSDI as the dependent variable and distributed lags for logGFIN, logCOR, logGTAX, logFDI, and logPOVRA. This specification captures the dynamic adjustment process while ensuring model stability and meaningful economic interpretation.

Table 5B reports the results of the ARDL lag selection procedure based on the Akaike Information Criterion. The optimal model is selected as the specification with the lowest AIC value among competing lag structures, subject to a maximum lag length of two for annual data.

3.2.5 Step 5: Robustness checks

- CUSUM and CUSUMSQ plots confirmed model stability.

- Granger causality tests indicate predictive precedence from GFIN to SDI.
- Chow Breakpoint Tests showed no significant structural breaks in 2008 or 2020.

3.3 Index construction

3.3.1 Corporate Management Index (COR)

$$COR_t = \frac{ESG_t + INNOV_t + STAKE_t + TRANS_t}{4} \quad (1)$$

Where:

- ESG = ESG disclosure quality score (0–1)
 - INNOV = Innovation activity score (normalized patent counts, 0–1)
 - STAKE = Stakeholder engagement score
 - TRANS = Transparency ratings (0–1)
- Each subcomponent was normalized using the min–max scaling:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}}$$

So that all values fall within 0 and 1, ensuring equal comparability.

Illustrative example (2023):

- ESG = 0.78
- INNOV = 0.65
- STAKE = 0.72
- TRANS = 0.80

$$COR_{2023} = \frac{0.78 + 0.65 + 0.72 + 0.80}{4} = 0.7375$$

Table 6 reports the Corporate Management Index (COR) and its four components for the period 2021–2025. The results highlight a steady upward trend in all dimensions, particularly in ESG and transparency, which reflect Germany’s institutional and regulatory commitments to sustainability. The composite index increased from 0.705 in 2021 to 0.770 in 2025, underscoring continuous improvements in corporate governance quality. These findings confirm that corporate practices in innovation, stakeholder engagement, and disclosure are becoming more aligned with the objectives of sustainable development, thereby reinforcing the study’s hypothesis regarding the role of corporate management as a driver of sustainability alongside green finance.

3.3.2 Sustainable Development Index (SDI)

Formula (PCA-weighted composite)

$$SDI_t = w1(ECO_t) + w2(ENV_t) + w3(SOC_t) + w4(REN_t)$$

Where:

TABLE 5B ARDL lag selection results based on the Akaike Information Criterion (AIC).

Model specification	logSDI	logGFIN	logCOR	logGTAX	logFDI	logPOVRA	AIC value
ARDL(1,2,1,1,1,2)	1	2	1	1	1	2	-155.493
ARDL(1,1,1,1,1,1)	1	1	1	1	1	1	-154.882
ARDL(2,2,1,1,1,2)	2	2	1	1	1	2	-154.611
ARDL(1,2,2,1,1,2)	1	2	2	1	1	2	-154.437
ARDL(2,1,1,1,1,1)	2	1	1	1	1	1	-153.998

Lower AIC values indicate a better balance between model fit and parsimony. The selected ARDL(1,2,1,1,1,2) specification yields the minimum AIC and is therefore retained for subsequent long-run and short-run estimation.

TABLE 6 Corporate Management Index COR components and composite score for Germany, 2021 to 2025, noting forecasted years.

Year	ESG	INNOV	STAKE	TRANS	COR
2021	0.74	0.61	0.69	0.78	0.705
2022	0.76	0.64	0.71	0.79	0.725
2023	0.78	0.65	0.72	0.80	0.738
2024*	0.80	0.67	0.74	0.81	0.755
2025*	0.82	0.69	0.75	0.82	0.770

*Values for 2024–2025 are forecasted using Holt-Winters smoothing and scenario adjustments from corporate disclosures.

- ECO = GDP per capita growth rate (normalized)
- ENV = CO₂ emissions per capita (inverted, normalized)
- SOC = GINI coefficient (inverted, normalized)
- REN = Share of renewable energy in total power generation (normalized)

PCA Weights (from historical data):

- w1 = 0.30w₁ = 0.30w1 = 0.30 (Economic)
- w2 = 0.25w₂ = 0.25w2 = 0.25 (Environmental)
- w3 = 0.20w₃ = 0.20w3 = 0.20 (Social)
- w4 = 0.25w₄ = 0.25w4 = 0.25 (Renewable Energy)

Illustrative Example (2023):

- ECO = 0.68
- ENV = 0.75
- SOC = 0.60
- REN = 0.72

$$SDI_{2023} = 0.30(0.68) + 0.25(0.75) + 0.20(0.60) + 0.25(0.72) = 0.695$$

Scaled to a 0–100 range: 69.5.

Table 7 presents the Sustainable Development Index (SDI) and its components for the period 2021–2025. The results reveal a steady upward trajectory across all dimensions, with the composite SDI increasing from 65.3 to 73.0. This reflects Germany’s consistent progress toward sustainability, particularly in Green performance and renewable energy adoption. While economic and Green indicators show robust improvements, social sustainability (measured through inequality reduction) remains relatively slower,

TABLE 7 Sustainable Development Index SDI construction outputs, 2021 to 2022, showing 0 to 1 and 0 to 100 scaling.

Year	ECO	ENV	SOC	REN	SDI (0–1)	SDI (0–100)
2021	0.65	0.70	0.58	0.68	0.653	65.3
2022	0.66	0.72	0.59	0.70	0.667	66.7
2023	0.68	0.75	0.60	0.72	0.695	69.5

highlighting the structural challenge of ensuring inclusiveness in Germany’s green transition. Overall, the results validate the study’s hypothesis that the joint Influence of economic growth, Green protection, social equity, and renewable energy adoption shapes sustainable development in Germany.

The estimated ARDL coefficients should be interpreted in light of the composite nature of the indices employed in this study. The relatively stronger magnitude associated with Green Finance reflects its construction as a multidimensional indicator capturing market depth institutional scale and the breadth of sustainable financial instruments. As a result green finance responds more rapidly to policy and market signals and generates more immediate and measurable effects on the Sustainable Development Index. By contrast the Corporate Management Index exhibits a smaller but statistically stable effect which is consistent with its cumulative and structural character. Corporate governance improvements such as transparency stakeholder engagement and innovation capacity evolve gradually and exert their influence through long term institutional alignment rather than short term adjustments. Therefore differences in coefficient magnitudes do not imply a hierarchy of importance but instead reflect distinct transmission channels and temporal dynamics through which financial and managerial mechanisms jointly support sustainable development.

Table 8 reports the results of the CUSUM and CUSUMSQ stability tests. Both tests confirm that the estimated ARDL model is structurally stable over the sample period. The absence of parameter instability or structural breaks reinforces the robustness of the econometric framework, indicating that the relationship between green finance, corporate management, and sustainable development in Germany remains consistent over time. This stability further validates the policy relevance of the findings, as the estimated effects are not contingent on temporary shocks or regime changes but reflect enduring structural linkages.

TABLE 8 Model stability tests CUSUM and CUSUMSQ for the estimated ARDL specification.

Test	Test Statistic	p -value	Conclusion
CUSUM	Stable	–	Parameters are stable over time.
CUSUMSQ	Stable	–	No structural instability

TABLE 9 Robustness checks summary including Granger causality, Chow breakpoint, and lag sensitivity.

Test	Purpose	Result
Granger Causality Test	Check the direction of causality between variables	GFIN → SDI, COR → SDI confirmed
Chow Breakpoint Test	Check structural breaks in 2008 and 2020	No significant break detected
Sensitivity Analysis	Test model under alternative lag structures	Results consistent

The robustness checks presented in Table 9 provide further empirical validation of the study's findings, thereby enhancing confidence in the reliability of the estimated relationships. First, the Granger causality test confirms the direction of causality from green finance (GFIN) and corporate management (COR) toward the sustainable development index (SDI). This result substantiates the theoretical claim that financial and governance mechanisms not only correlate with sustainability outcomes but also actively drive them. In other words The expansion of green financial instruments shows a measurable association with sustainability on advancing sustainable development in Germany.

Second, the Chow Breakpoint Test was employed to assess potential structural breaks during periods of global disruption, particularly the 2008 global financial crisis and the 2020 COVID-19 pandemic. The absence of statistically significant breakpoints indicates that the estimated model remained structurally stable in response to these shocks. This finding suggests that the underlying relationships between green finance, governance, and sustainability are not transient but are embedded within Germany's institutional and economic frameworks. The persistence of these effects throughout turbulent periods underscores the resilience of Germany's sustainability model and lends greater credibility to the long-run policy implications of the study.

Third, a sensitivity analysis was conducted by altering lag specifications within the ARDL framework to evaluate the extent to which the results depended on model selection. The consistency of the outcomes across alternative lag structures demonstrates that the estimated coefficients are not sensitive to minor technical changes. Such stability assures that the conclusions are not artifacts of the econometric methodology but robust reflections of fundamental economic dynamics.

Taken together, The robustness checks indicate that the core results are statistically and economically meaningful. They reinforce the conclusion that Germany's sustainable development trajectory is significantly shaped by the dual Influence of green

finance and corporate governance, and that this Influence remains reliable across different model specifications and historical contexts.

3.4 Interpretation of tables and results

It is important to clarify that all econometric estimations including unit root tests cointegration analysis and ARDL modeling are conducted exclusively using fully observed and verified annual data covering the period from 1995 to 2022. The values reported for the period 2023 to 2025 in the Corporate Management Index and the Sustainable Development Index tables are provided solely for interpretative and illustrative purposes. These forward looking values are generated using Holt Winters exponential smoothing combined with scenario based adjustments derived from official corporate sustainability disclosures. Accordingly these forecasted observations are not included in the core econometric estimations and do not affect the statistical validity or robustness of the reported results. Their role is limited to illustrating the continuity of structural trends and supporting the analytical coherence between historical findings and the projected trajectory of Germany sustainability transition.

The empirical analysis begins with addressing the stationarity properties of the variables, since reliable econometric modeling requires clarity on whether the time series are stationary at levels or only after differencing. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) results, as reported in Tables 4, 5A, 5B demonstrate mixed integration orders: while certain variables such as poverty ratio (POVRA) are stationary at levels $I(0)$, others like green finance (GFIN) and corporate management index (COR) become stationary only after first differencing $I(1)$. This heterogeneity validates the choice of the Autoregressive Distributed Lag (ARDL) framework, which is explicitly designed for series that are a mixture of $I(0)$ and $I(1)$. In other words, the methodological decision directly addresses the research question by ensuring that the model accurately captures both the short-term fluctuations and long-term dynamics of green finance and corporate governance in Germany.

Proceeding to the Bounds test for cointegration (Table 6), the results reveal that the F-statistic significantly exceeds the upper bound critical values at the 1% level. This confirms the existence of a long-run relationship among the variables. This finding is central to the research problem: if green finance and corporate governance were unrelated to sustainable development in the long run, policy implications would be limited. Instead, the evidence indicates that both channels are structurally connected to Germany's sustainability trajectory, aligning with the study's hypothesis that institutional and financial mechanisms underpin progress toward sustainability.

The long-run and short-run coefficients (Table 7) further deepen this understanding. Green finance (GFIN) emerges as a robust driver of the Sustainable Development Index (SDI), with both short-term and long-term coefficients statistically significant and positive. Specifically, the estimated elasticity suggests that a 1% increase in green finance is associated with a 0.33% rise in SDI in the short term and a 0.71% rise in the long term. These

magnitudes reinforce the argument that green capital markets and instruments are not only complementary to, but also more effective than, traditional fiscal tools in achieving sustainability.

The corporate management index (COR) also has positive effects, albeit to a lesser extent than green finance. This result reflects the structural importance of governance mechanisms such as ESG disclosure, stakeholder engagement, and transparency, but also highlights their relative lag in impact compared to direct financial channels. The findings support the theoretical claim of the study: while corporate governance is indispensable, the mobilization of financial capital has a more substantial transformative potential in Germany's sustainability transition.

The results for control variables provide critical nuance to the research problem. Green tax revenues (GTAX) unexpectedly show weak or adverse effects on SDI. This paradox highlights the practical challenges of fiscal interventions in Germany, including design complexity, industrial exemptions, and lagged behavioral responses. Renewable electricity share (SPGE), by contrast, exhibits robust positive contributions, with a 1% increase in renewables improving SDI by 0.23% in the short term and 0.69% in the long term. These findings confirm the pivotal role of Germany's Energiewende strategy in driving sustainability. Foreign direct investment (FDI) demonstrates mixed effects, with long-run coefficients indicating that inflows often target high-emission sectors, thereby undermining sustainability. The poverty ratio (POVRA) consistently exerts a negative impact, underscoring the dual challenge of ecological transition and social inclusivity. [Figure 5](#) illustrates the conceptual framework linking green finance, corporate governance, control variables, and sustainable development outcomes.

Turning to diagnostic tests, [Table 8](#) shows that the Wald and Breusch-Pagan tests reject the presence of heteroskedasticity. At the same time, the Jarque-Bera and Ramsey RESET statistics confirm normality and correct model specification. Stability diagnostics (CUSUM and CUSUMSQ) further confirm that the estimated coefficients remain stable throughout the sample period, validating the robustness of the empirical framework.

Finally, the robustness check ([Table 9](#)), which replaces SDI with CO₂ emissions per capita as the dependent variable, provides an important cross-validation. The results are inversely consistent: green finance and corporate governance reduce emissions, while poverty and brown FDI inflows increase them. This alternative specification not only strengthens the credibility of the findings but also directly addresses the study's core research problem—whether financial and managerial structures can realign economic growth with ecological and social sustainability.

Taken together, these results confirm that the interaction between green finance and corporate management constitutes a foundational pillar of Germany's sustainability pathway, validating the theoretical model and reinforcing the empirical contribution of this study.

3.5 Empirical outputs

The empirical analysis investigates the relationship between green finance, corporate management, and sustainable development in Germany from 1995 to 2022. The first stage

of the analysis concerns the time-series properties of the data. Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests ([Tables 4, 5A, 5B](#)) reveal that the variables are integrated of mixed orders: some are stationary at the level (I(0)), while others require first differencing (I(1)). This mixture justifies the application of the ARDL framework, which is robust to a series of different integration orders, provided none is I(2).

Following this, the Bounds cointegration test ([Table 6](#)) provides strong evidence of a long-run relationship among the variables, with the calculated F-statistic exceeding the upper bound critical values at the 1% level. This result ensures that the core variables—green finance, corporate management, poverty ratio, FDI, green taxes, and renewable energy share—move together in the long term, reinforcing the hypothesis that both financial and governance mechanisms are structurally linked to sustainable development outcomes.

The ARDL estimations, summarized in [Table 7](#), highlight key insights. Green finance significantly enhances Germany's Sustainable Development Index (SDI), with a 1% increase in green finance leading to an estimated 0.33% rise in SDI in the short run and 0.71% in the long run. These findings underscore the growing role of green financial markets and instruments in supporting sustainable transitions. Similarly, the corporate management index (COR)—which captures governance quality, ESG transparency, and stakeholder engagement—positively contributes to SDI, albeit with smaller magnitudes: 0.18% in the short term and 0.31% in the long term. Together, these results demonstrate that while both channels are crucial, green finance exerts a more substantial transformative effect than corporate governance.

The control variables provide further nuance. Renewable energy generation shows a robust and statistically significant positive effect, consistent with Germany's Energiewende strategy. A 1% increase in renewables enhances SDI by 0.23% in the short run and 0.69% in the long run. Conversely, green tax revenues exert a weak or even negative effect on SDI, reflecting the complexity of Germany's environmental tax design, exemptions, and lagged behavioral responses. Poverty ratio displays a consistent adverse effect, suggesting that rising poverty constrains inclusive sustainability and reduces resilience. FDI exerts mixed effects: while short-term inflows support development, the long-term results suggest that non-green FDI has historically flowed into high-emission industries, undermining sustainability.

Diagnostic and stability tests confirm the robustness of the model. The Wald and Breusch-Pagan tests indicate no heteroskedasticity, while Jarque-Bera and Ramsey RESET tests confirm correct model specification and normal residuals ([Table 8](#)). Stability diagnostics, using CUSUM and CUSUMSQ tests, further validate the structural stability of the estimated coefficients across the sample period.

As a robustness check, the model is re-estimated using CO₂ emissions per capita as the dependent variable ([Table 9](#)). The inverse results confirm earlier findings: green finance and corporate governance reduce emissions, while poverty and non-green FDI inflows increase them. This reinforces the policy relevance of the study: financial and governance mechanisms not only improve composite sustainability measures but also contribute directly to emission reductions.

Overall, the empirical outputs confirm the guiding hypothesis of the study: green finance and corporate management are central to Germany's sustainable development trajectory. The long-run effects are larger than the short-run effects, highlighting the importance of consistency and persistence in policy and institutional design. Furthermore, the findings suggest that market-led green financial mechanisms outperform fiscal instruments in advancing sustainability, highlighting the need for targeted reforms in both finance and governance to achieve Germany's 2045 carbon neutrality commitments.

3.6 Expanded empirical narrative

The central research problem addressed in this study arises from the persistent debate regarding the efficiency and effectiveness of Germany's green policies. Despite Germany's global reputation as a leader in sustainability and climate policy, evidence shows uneven outcomes: some instruments, such as renewable energy support schemes, appear highly effective, whereas others, particularly green tax reforms, have generated mixed or even adverse social and environmental consequences. This inconsistency raises an important question: *to what extent do financial mechanisms and corporate governance practices contribute to sustainable development outcomes in Germany, and how do they compare with traditional fiscal tools?*

To address this problem, the objective of this study is twofold: first, to empirically evaluate the role of green finance (GFIN) and corporate management quality (COR) in shaping Germany's composite Sustainable Development Index (SDI); and second, to compare these effects against conventional instruments such as Green taxation, foreign direct investment inflows, and poverty reduction policies. In doing so, the study contributes to both academic debates and policy discussions by disentangling the dynamic interplay of monetary, fiscal, and governance-related channels.

The methodological design is based on time series econometrics (1995–2022), where missing values for 2023–2025 were estimated using Holt-Winters exponential smoothing and scenario-based projections informed by the sustainability disclosures of major German corporations. This ensures that the empirical model not only captures historical dynamics but also incorporates forward-looking trends. After confirming the mixed integration orders of the variables via ADF and PP unit root tests, the ARDL approach was applied, as it accommodates both I(0) and I(1) variables. The bounds test confirmed the existence of a long-run cointegrating relationship between green finance, corporate management, and sustainable development.

The empirical findings strongly support the study's central hypothesis. Both green finance and corporate management emerge as statistically significant and economically meaningful determinants of Germany's SDI. Specifically, green finance exhibits the most significant long-run elasticity, suggesting that the expansion of green bonds, ESG-linked lending, and sustainable investment products channels capital into projects that yield

measurable Green and social benefits. Corporate management, operationalized through ESG disclosure, innovation, stakeholder engagement, and transparency, also contributes positively, though with slightly weaker magnitude. These results underscore that well-governed corporations act as critical intermediaries between financial markets and sustainability outcomes by embedding ESG principles into operational strategies.

Conversely, Green taxation demonstrates unexpectedly weak or negative coefficients, reflecting the structural complexities of Germany's tax system and highlighting the regressive burden of energy taxes on lower-income households. This finding reinforces the central problem statement by highlighting the limitations of fiscal instruments when not accompanied by equitable revenue recycling and social safeguards. Moreover, foreign direct investment displays a mixed effect, with evidence suggesting that inflows to non-green or carbon-intensive sectors undermine sustainability progress. Poverty levels further act as a structural constraint, reducing inclusivity in sustainability transitions.

The robustness checks (CUSUM, CUSUMSQ, heteroskedasticity tests, and a CO₂-based dependent variable) confirm the stability and reliability of these results. Importantly, the findings suggest that green finance and corporate governance mechanisms outperform fiscal tools in the long term, highlighting the central role of market-based solutions and institutional quality in advancing Germany's sustainability agenda.

The negative coefficient associated with environmental tax revenues GTAX should be interpreted with caution. This result does not necessarily imply that environmental taxation undermines sustainability. Rather it likely reflects the fact that environmental tax revenues are closely linked to the scale of economic activity and energy consumption in carbon intensive sectors. In this context higher environmental tax revenues may signal greater underlying pollution levels or delayed structural adjustment rather than effective environmental performance. The finding therefore highlights potential design and timing issues in environmental tax policies rather than a direct adverse effect on sustainable development.

The negative association between foreign direct investment FDI and sustainable development outcomes may be explained by the composition of investment flows rather than their volume. Aggregate FDI inflows capture both green and non-green investments and may be dominated by capital intensive or energy intensive activities that do not align with sustainability objectives. As the measure does not distinguish explicitly between green and brown investments the estimated coefficient likely reflects compositional effects rather than a causal negative impact of foreign investment on sustainability.

In sum, the study resolves the initial research problem by demonstrating that the uneven effectiveness of Germany's green policies can be better understood through the lens of financial market development and corporate governance quality. While traditional instruments such as Green taxes play a role, it is the synergy of green capital flows and responsible corporate management that most effectively propels Germany toward achieving its long-term sustainable development goals.

4 Conclusion, policy recommendations, and future research

4.1 Conclusion

This study was motivated by the pressing need to reconcile Germany's economic growth with ecological and social sustainability in the context of increasing climate challenges and policy demands. To address this problem, the research set the objective of examining whether green finance and corporate management act as practical drivers of sustainable development, and to what extent they complement or substitute traditional fiscal and investment channels. To achieve this objective, the study employed an ARDL econometric framework, supported by descriptive analysis, index construction, and robustness checks, which allowed for the capture of both short-run fluctuations and long-run dynamics.

The results demonstrate that green finance exerts a substantial positive impact on the Sustainable Development Index, confirming its transformative role in channeling capital toward low-carbon pathways. Corporate management, while exerting more minor effects than finance, also proves essential in shaping transparency, stakeholder engagement, and governance practices that sustain long-term progress. Control variables further highlight that renewable energy consistently contributes to sustainability, whereas green taxes face practical constraints, and poverty remains a structural barrier. Robustness checks and stability diagnostics confirm the reliability of the model, ensuring that findings are not artifacts of data or specification.

In discussion, these results underline that Germany's path toward sustainability is not driven by a single lever but by the combined momentum of financial and managerial reforms. Green capital markets accelerate ecological transformation, while governance structures provide the institutional backbone for accountability and resilience. Taken together, the findings validate the research hypothesis and directly answer the guiding research question: financial and corporate mechanisms are deeply intertwined with Germany's sustainable development trajectory.

While the conceptual model anticipated a positive role of Green taxation (GTAX) in fostering sustainability, the empirical findings revealed a weak or even negative effect. This divergence can be attributed to several structural factors within Germany's eco-tax framework. First, large industrial sectors benefited from exemptions and rebates that diluted the intended incentive to reduce emissions. Second, the regressive nature of eco-taxes placed a disproportionate burden on low-income households, potentially undermining the inclusive dimension of sustainable development. Third, the design of taxation policies often emphasized revenue generation rather than direct Green performance, limiting their transformative impact. These findings highlight that the effectiveness of fiscal instruments depends not only on their theoretical rationale but also on their practical implementation and the distributional effects they have.

In conclusion, this study makes a significant contribution both theoretically and practically by demonstrating that the construction of composite indices, such as COR and SDI, provides

decision-makers with novel, operational tools for measuring performance and guiding policy. By linking problem, objective, methodology, and results in an integrated framework, the research not only advances academic understanding but also offers actionable insights for policymakers seeking to align economic activity with long-term sustainability goals.

4.2 Policy recommendations

- Corporate regulators should promote the expansion and digitalization of green financial infrastructure by mandating standardized sustainability disclosures, supporting fintech enabled green finance solutions, and encouraging the adoption of blockchain based ESG reporting systems to enhance transparency and supervisory oversight.
- Regulatory authorities responsible for corporate governance are encouraged to strengthen sustainability oriented governance practices by introducing incentive based regulatory mechanisms, requiring ESG related training for board members, and integrating measurable sustainability indicators into corporate supervision and evaluation frameworks.
- Corporate and financial regulators should coordinate with fiscal authorities to refine green tax policies by ensuring transparent carbon pricing mechanisms and clear revenue recycling strategies, thereby improving regulatory credibility and stakeholder acceptance while minimizing unintended distributional effects.
- Regulators overseeing corporate social responsibility frameworks should support pro poor green policies by incentivizing corporate participation in affordable green housing projects, sustainable public transport initiatives, and inclusive clean energy access programs.
- Investment and corporate regulators should actively encourage green aligned foreign direct investment, particularly in renewable energy and energy efficient manufacturing sectors, while strengthening screening mechanisms to discourage or restrict high carbon and environmentally harmful investments.

4.3 Limitations of the study

Despite its contributions this study is subject to several limitations that should be acknowledged. First the empirical analysis focuses exclusively on Germany which enhances institutional specificity but limits the direct generalizability of the findings to other national contexts with different regulatory and financial structures. Second the study relies on composite indices for green finance corporate management and sustainable development which allows for multidimensional measurement but may obscure variations at the level of individual components. Third foreign direct investment is treated as an aggregate measure and does not explicitly distinguish between green and carbon intensive investment flows which may partially explain the negative long run association observed in the results. Finally the analysis is

based on annual data which constrains the ability to capture higher frequency dynamics and short term policy transmission effects. These limitations do not undermine the validity of the results but rather indicate avenues for refinement and extension in future research.

4.4 Future research

- Regional comparative analysis across German states (Länder).
- Qualitative expert interviews with policymakers and corporate leaders.
- Scenario-based forecasting under alternative climate and economic pathways.
- Direct evaluation of green finance and governance reforms against the UN SDGs.

Germany's leadership in the EU Green Deal and its commitment to carbon neutrality by 2045 make these evaluations both timely and policy-relevant.

4.4.1 Practical contribution

A key practical contribution of this study lies in the development of two composite indices, namely the Corporate Management Index (COR) and the Sustainable Development Index (SDI). Unlike conventional approaches that rely on fragmented indicators, these indices provide an integrated and standardized framework for assessing corporate governance quality and sustainability performance. By aggregating dimensions such as transparency, stakeholder engagement, and innovation (in the COR index), and combining economic, environmental, and social factors with renewable energy shares (in the SDI index), the study introduces a practical tool that policymakers and regulators can readily apply.

For policymakers in Germany and the European Union, these indices offer a replicable and comparable measurement system that enables benchmarking across sectors and periods. This is particularly valuable in the context of EU sustainability directives and the CSRD framework, where robust and comparable metrics are essential for monitoring corporate alignment with green finance and climate objectives. The indices also provide financial institutions and regulators with a tool to evaluate how corporate management practices translate into measurable sustainability outcomes, thus reducing information asymmetry and supporting more informed allocation of green capital.

By bridging corporate governance and sustainable development within a single empirical framework, this contribution extends beyond theoretical advancement and offers a concrete, data-driven mechanism for evaluating policy effectiveness. In practice, the indices can guide decision-makers in identifying strengths and weaknesses in Germany's sustainability transition, while also offering a model that can be adapted by other EU countries pursuing similar green finance and governance reforms.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MG: Investigation, Resources, Software, Writing – original draft, Conceptualization, Funding acquisition, Visualization, Methodology, Writing – review & editing, Formal analysis, Validation, Project administration, Data curation, Supervision.

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Conflict of interest

The author declares that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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