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Carbon emission indicators and short-run economic drivers: Evidence from financial development and industrialisation across income groups

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ABSTRACT

Anthropogenic carbon emissions remain closely linked to the structure and short-run adjustment of financial and industrial systems. Although much of the existing literature examines long-run relationships, short-run predictive dynamics are important because financial expansion, industrial fluctuations, and environmental pressures may respond rapidly to economic shocks and policy changes. This study examines Granger predictive relationships among financial development, industrialisation, and carbon emissions across 37 high-income and 13 low-income countries over the period 2000-2024. The analysis combines heterogeneous panel Granger non-causality testing with country-level VAR-based Granger tests. Cross-sectional dependence, second-generation panel unit-root tests, slope heterogeneity tests, and alternative lag specifications are used to strengthen the econometric assessment. The panel findings indicate weak evidence that financial development predicts changes in carbon emissions in high-income countries, whereas stronger financial development-emissions predictability is observed in low-income countries. Industrialisation predicts carbon emissions in both income groups, while the reversed relationship is not supported. Country-level findings reveal substantial heterogeneity, with predictive directions varying across national contexts and lag specifications. These results indicate that short-run finance-environment and industry-environment relationships are income- and country-specific. The findings support closer monitoring of financial expansion and targeted improvements in industrial energy efficiency, while remaining cautious about interpreting Granger predictability as structural causation.

1. Introduction

1.1. Background and policy relevance

Global warming has become a pressing worldwide concern in recent decades, with the World Meteorological Organisation (WMO) confirming the latest 11 years (2015-2025) as the warmest in the modern era (WMO, 2026). The elevated concentration of greenhouse gases in the atmosphere, stemming from destructive energy and land-use practices and human consumption and production behaviours, destabilises the global climate system through elevated sea levels, recurrent heat extremes, and worsening health risks (IPCC, 2023; Romero, 2023). Carbon dioxide solely accounts for 80% of the global warming effect from all anthropogenic greenhouse gases ever since 1990 (Lindsey, 2025). According to recent statistics, the highest global emissions peak of 37.8 gigatons occurred in the year 2024, highlighting the ongoing increase in human-caused greenhouse gas emissions (IEA, 2025). Several international initiatives, including the Paris Agreement and the SDGs, aim to reduce global emissions (UNFCCC, 2026; United Nations, 2025; UNDP, 2025). Nevertheless, despite these international endeavours, carbon emissions continue to rise, underscoring the need to investigate the critical role of financial development and industrialisation in shaping emission levels across both high- and low-income economies.

Accordingly, financial development and industrialisation are considered key contributors to global emissions. The financial development of a nation represents the expansion of the overall financial sector, including financial instruments, markets, and intermediaries, collectively facilitating a smooth flow of information and implementation with reduced cost, thereby enabling effective functioning of the financial sector of the economy (World Bank Group, 2026). Meanwhile,

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industrialisation reflects the transition of an economy from an agricultural basis to an industrial basis, which leads to significant changes in population trends, labour markets, income distributions, globalisation, and everyday lifestyle patterns (Catalina Espinosa, 2025). Both financial development and industrialisation immensely support economic advancement. Thus, understanding the role of financial development and industrialisation in shaping carbon emissions is crucial for facilitating well-structured policy guidance to achieve overall sustainable economic expansion while balancing financial and industrial development with environmental impacts.

From an environmental monitoring perspective, carbon emissions serve as a critical sustainability indicator used by policymakers and international organisations to track progress towards climate mitigation targets. Analysing the causal drivers of this indicator enables policymakers to better understand how financial systems and industrial expansion contribute to environmental pressures.

Further, countries' income levels significantly shape financial and industrial expansion and CO_2 emissions. Accordingly, amongst the income groups, High-income countries (HICs) often exhibit high resource consumption and energy demand, and carbon-intensive lifestyle patterns, contributing to a major share of global emissions (Dharmapriya et al., 2025). Although HICs comprise of 15% of the global population, these countries emit twice the share of the population with 34% of global emissions, while Low-income countries (LICs) contribute to less than 1% of global emissions, being home to 9% of the global population (Ritchie, 2024). Further, recent data indicate that an average person in HICs emits 30 times higher emissions than in LICs (Ritchie, 2023). However, LICs are a severely affected group from cascading climate hazards, including agricultural output loss, food shortages, health impacts, and income losses (Connolly-Boutin and Smit, 2016). In comparison with HICs, LICs experience 56% longer recovery periods after extreme climate events, hindering economic growth and financial and industrial development (UNDRR, 2026). Thus, given income disparities, conducting a comprehensive comparative analysis of HICs and LICs, is important in understanding the combined influence of financial development and industrialisation on carbon emissions, for designing effective country-specific policies to mitigate emissions while transitioning towards a sustainable future.

1.2. Financial development, industrialisation and environmental pressures

Financial development influences environmental pressures by shaping the allocation of financial resources across sectors and by regulating investment decisions toward either carbon-intensive or cleaner industries. This ultimately determines whether economic progress occurs in a sustainable or detrimental manner. Well-structured financial expansion could support economic sustainability by guiding financial flows towards renewable energy investments and green technologies (Horky and Fidrmuc, 2024; Doğan et al., 2025). However, financial development is often directed towards polluting industries due to promising predictable future returns from established energy sectors, and the absence of green financial instruments and incentives, leading to rising carbon emissions levels (Alnsour et al., 2024). Concurrently, industrialisation intensifies environmental pressures through increased energy production and consumption and pollution generated by mechanised manufacturing processes (Musa et al., 2025; Mentel et al., 2022). Particularly, emerging economies face serious challenges in tackling sharply rising emissions resulting from industrial growth, emphasising the environmental pressures associated with rapid economic development (Sadorsky, 2014). Furthermore, the influence of both financial and industrial development on carbon emissions is highly context-dependent, influenced by factors such as development stage, income level, regulatory policies, and financial system dynamics, which determine the extent to which environmental impacts are amplified or mitigated (Hao et al., 2016). Hence, a conceptual understanding of the causality linkages among financial development, industrialisation and carbon emissions across nations provides a robust foundation for examining how variations in economic and structural drivers affect emissions, thus enabling the formulation of evidence-based policies aligned with sustainable development.

These competing effects can be interpreted through several complementary environmental-economic perspectives. The scale effect associated with the STIRPAT/IPAT frameworks suggests that the expansion of production credit and industrial activity can increase energy use and environmental pressures. In contrast, ecological modernisation theory argues that more mature economic and financial systems may facilitate technological upgrading, cleaner production, and improved environmental regulation. The Environmental Kuznets Curve (EKC) perspective further suggests that the relationship between economic transmission and environmental pressure may differ across development stages as early industrialisation is often carbon-intensive, while advanced economies may possess greater technological and institutional capacity to reduce emissions intensity. These perspectives do not imply a uniform relationship, but rather support the expectation that financial development, industrialisation, and carbon emissions may display different short-run predictive patterns across HICs and LICs.

1.3. Research gap and motivation

Extensive research provides mixed evidence on the relationship between financial development, industrialisation, and carbon emissions. These differences partly reflect the use of alternative variables, country samples, institutional settings, and econometric designs. Long-run cointegration and ARDL in studies generally examine equilibrium relationships and adjustments processes, whereas panel causality studies test whether past changes in one variable contain predictive information about another. However, much of these evidence is based either on regional panels that impose relatively homogeneous relationships or on individual-country studies that cannot support systematic income group comparisons (Appiah et al., 2021; Emenekwe et al., 2022; Idowu et al., 2023; Khan et al., 2021; Lv and Li, 2021).

Therefore, three related gaps in the existing literature motivate this study. First, comparatively limited attention has been given to short-run Granger predictive relationships even though financial and industrial shocks may affect environmental indicators before long-run adjustment occurs. Second, conventional pooled panel approaches may obscure slope heterogeneity and overlook cross-country shocks, while single country models cannot identify broader income group patterns. Third, LICs remain less extensively examined than HICs and emerging economies despite their distinct financial depth, industrial structure, and climate vulnerability. Accordingly, this study compares high- and low-income groups using heterogeneous panel tests and supplements the panel evidence with country-level Granger causality results. The contribution lies in identifying whether short-run predictive patterns differ across income groups and countries, rather than introducing new visualisations or claiming structural causal relationships.

1.4. Research objectives

Accordingly, this study aims to achieve the following objectives across high-income and low-income countries.

1. To investigate the short-run causal relationship between financial development and carbon emissions in high-income countries and low-income countries.
2. To investigate the short-run causal direction between industrialisation and carbon emissions in high-income countries and low-income countries.
3. To compare the short-run causality among financial development, industrialisation, and carbon emissions at both the panel-level and individual country-level, across high-income countries and low-income countries.

1.5. Contributions of the study

This study makes three contributions: First, it provides a comparative assessment of short-run Granger predictive relationships among financial development, industrialisation, and carbon emissions across HICs and LICs over the period 2000 to 2024. Second, it addresses cross-country heterogeneity by combining income group panel evidence with country-level analysis, while explicitly testing cross-sectional dependence, slope heterogeneity, and stationarity using second-generation procedures. Third, it distinguishes robust income group patterns from country-specific and lag-sensitivity findings, thereby clarifying the limits of uniform policy interpretation. The graphical presentations are used solely to illustrate the findings and do not constitute methodological innovations.

1.6. Structure of the paper

The subsequent sections of the paper are structured as follows: beginning with a comprehensive critical literature review, followed by a description of the data and methodology. Next, the study's findings are presented, followed by results and discussion, culminating in policy recommendations and the conclusion.

2. Literature review

Environmental indicators have become an essential analytical tool for evaluating the sustainability implications of economic development. Indicators such as carbon emissions, energy intensity, and ecological footprint are widely used to assess environmental pressures associated with economic growth. Within this framework, examining the drivers of carbon emission indicators provides valuable insights into how financial and industrial dynamics influence environmental sustainability.

2.1. Financial development and carbon emissions

Financial development can influence carbon emissions through competitive channels. Through the scale and consumption channels, greater access to credit can expand industrial investment, household consumption, transport demand, and energy use, thereby increasing emissions. Conversely, through the technology and composition channels, financial development may support renewable energy, energy-efficient capital, and cleaner production, thereby reducing environmental pressure. Empirical findings therefore differ according to financial depth, the energy structure, regulatory quality, development stage, and the indicators and estimators employed. Positive relationships are reported in several national and panel studies, while other studies find negative, non-linear, or insignificant effects (Hao et al., 2016; Jiang and Ma, 2019; Lv and Li, 2021; Maji et al., 2017). These mixed findings indicate that financial development should not be assessed to have a uniform environmental effect across income groups.

Furthermore, a study of 25 OECD countries found that financial development negatively affects emissions and is statistically significant in 8 countries, including Austria, Denmark, Germany, Ireland, the Netherlands, Norway, Portugal, and the US (Lee et al., 2015). Further, a separate study on the top 10 emitters found that the panel PFMOLS test revealed a significant long-term positive relationship between FD and carbon emissions (Kayani et al., 2020), while another study on Greece identified a positive impact on carbon emissions in the long run (Işik et al., 2017). Conversely, previous research across 37 Sub–Saharan African countries found that FD negatively affects carbon emissions, indicating that a 1-unit increase in the FD index leads to a 2.867% reduction in CO_2 emissions in the long run (Emenekwe et al., 2022). Meanwhile, a separate discussion argues that higher carbon emissions damage the financial stability by reducing banks' solvency and capital buffer in non-crisis years (Ozili, 2025). However, the relationship between financial development and carbon emissions depends on environmental management risks, regulatory frameworks, green investments, and policy implications.

Moreover, few studies analysed the causal relationship between financial development and carbon emissions. Existing research on Denmark, France, Germany, Italy, and the United Kingdom found a one-way causal relationship from FD to carbon emissions (Apergis et al., 2023). In contrast, few other studies have contended that a unidirectional causal link exists from CO_2 to FDI in the top 10 carbon emitters (Kayani et al., 2020; Ajeigbe and Ganda, 2024). Additionally, a long-run bidirectional causality was found between financial development and carbon emissions in 23 developing countries and 44 Sub-Saharan African countries, respectively (Tinoco-Zermeño, 2022; Ganda, 2021). Conversely, another study no Granger-predictive relationship between financial development and carbon emissions across 65 economies (Ajeigbe and Ganda, 2024). Thus, financial development increases carbon emissions by making capital more readily available, thereby expanding industrial activity and driving higher production and consumption.

Overall, the evidence on the financial development-carbon emissions nexus remains uncertain, particularly across HICs and LICs, signalling the need for an in-depth investigation of the causality dynamics. Further, most studies are limited to the one-way impact of financial development on carbon emissions or vice versa, highlighting a short-term causality research gap. Moreover, most studies focused on a panel of nations, with very few on specific HICs and LICs, underscoring the need for further in-depth country-level analysis.

2.2. Industrialisation and carbon emissions

The industrialisation-emissions relationship similarly reflect the scale, composition, and technology effects. Early-stage industrialisation generally expands manufacturing output, construction fossil energy use, and infrastructure demand thereby increasing carbon emissions. At later stages, technological upgrading, cleaner production, industrial electrification, and stricter regulations may reduce emission intensity, although total emissions may remain substantial. Empirical differences therefore reflect industrial structure, energy dependence, urbanisation, technology capacity, and policy enforcement. Studies using ARDL and cointegration approaches typically distinguish long-run equilibrium relationships from short-run adjustments, while panel and time-series analyses examine predictive rather than structural causations (Appiah et al., 2021; Lv and Li, 2021; Khan et al., 2021; Mahmood et al., 2020).

Additionally, previous research across 20 African countries reported that a 1% increase in industrialisation is associated with a 0.3% increase in CO_2 emissions in the long run (Liu and Bae, 2018). In contrast, a separate study argued that industrialisation have negative impact on environmental degradation in eight selected ASEAN countries (Elfaki et al., 2022). However, from another perspective, it is documented that, in the long run, rising industrialisation reduces carbon emissions in Australia (Rahman and Alam, 2022). Further, previous research found positive results indicating that 1% rise in industrialisation will lead to an increase in carbon emissions by 1.64% in the long run (Asumadu-Sarkodie and Owusu, 2017). Similarly, industrialisation was identified as having a positive effect on per capita CO_2 emissions in the long term in Turkey (Pata, 2018). However, when considering the impact of industrialisation on carbon emissions, various factors, such as renewable energy plans, technological innovation, energy use patterns, and nations' industrial structures, are critical.

Moreover, some studies have analysed the causal relationship between industrialisation and carbon emissions. The extant literature found a unidirectional causal relationship from industrialisation to carbon emissions in Australia, Korea, and BRICS countries (Rahman et al., 2021; Song et al., 2023; Azam et al., 2022; Idowu et al., 2023). Conversely, a different study on Rwanda argued a one-way causal link from carbon emission to industrialisation (Asumadu-Sarkodie and Owusu, 2017). Additionally, a long-term bidirectional Granger

predictability between industrialisation and carbon emission was proved in OPEC countries (Idowu et al., 2023). However, another study found no Granger-predictive relationship between industrialisation and carbon emissions in Pakistan (Khan et al., 2021). Hence, the causality between industrialisation and carbon emission is mainly driven by high energy usage and productivity. Moreover, many studies have focused on a panel of countries, limiting their focus to HICs and LICs and encouraging cross-country-level analysis across both income groups.

Taken together, extant literature consistently shows an inconsistent relationship between industrialisation and carbon emissions across HICs and LICs. Additionally, most causality-based studies focus on long-run dynamics, rather than short-run patterns, establishing an underexplored gap for immediate changes. Moreover, existing studies are often limited by the sample period and the countries examined, indicating the need for a comprehensive comparative analysis of HICs and LICs.

2.3. Causality-focused studies: panel Vs. country evidence

This paper explains global trends in the relationships among financial development, industrialisation, and carbon emissions, highlighting cross-country research and publication trends from 2000 to 2025. The stacked bar chart in Fig. 1 shows the number of publications from 2000 to 2025, focusing on financial development, industrialisation, and carbon emissions. It is clear that the most articles were published in 2024, highlighting the growing literature in the field.

Further, the chord chart in Fig. 2 shows the number of research articles published between 2000 and 2025, covering the recent 26-year period. The lines represent the number of articles by country. The blue lines represent FD and CO_2, and the purple lines represent IND and CO_2. The inner circle shows the number of studies analysing financial development, industrialisation, and carbon emissions, while the outer circle shows the respective countries. Scopus database was utilised in creating the chord chart applying the following keywords such as: "CO_2 emissions" OR "Carbon emissions" OR "Carbon dioxide" OR "Carbon dioxide emissions" AND "Financial development" OR "Financial sector development" OR "Financial system development" OR "Domestic credit to private sector" OR "Private sector credit" OR "Credit to private sector" AND "Industrial value added" OR "Manufacturing value added" OR "Industrialisation" OR "Industrialisation". Consequently, compared with both nexus-related studies, most studies focus on IND and CO_2 emissions, totalling 1738 articles. Further, considerable attention is given to the FD and CO_2 emissions studies. Moreover, across countries, the most articles are published in China, followed by Pakistan and Turkey.

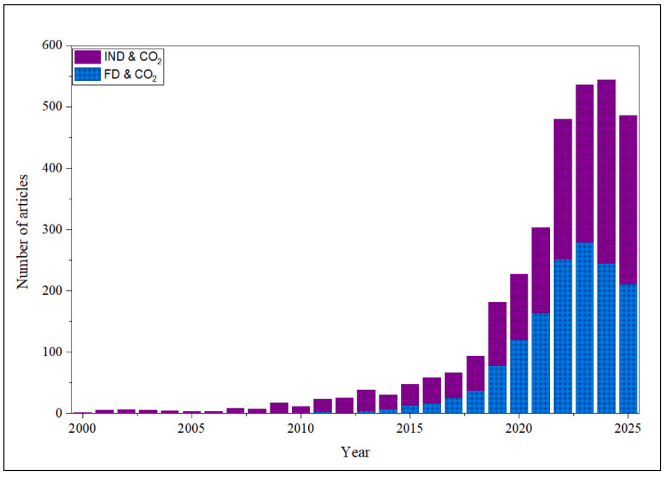


Fig. 1. Stacked bar chart representing the number of research articles published from 2000 to 2025. Note: Number of research publications by year. The bar represents the number of articles published each year. The blue bar represents articles about FD and CO_2, and the purple bar represents articles about industrialisation and CO_2.
Source: Authors' composition based on Scopus Database, created using OriginLab.

2.4. Methodological differences in existing evidence

Methodological design plays a central role in interpreting the mixed evidence. Long-run cointegration, FMOLS, DOLS, and ARDL studies examine equilibrium relationships or adjustments towards equilibrium. Error correction models can distinguish short-run responses from long-run effects, whereas Granger causality examines whether past observations of one variable improve the prediction of another. Panel-level tests provide average evidence across countries, but may conceal heterogeneous coefficients, and may be invalid when cross-sectional dependence is ignored. Country-specific VAR models allow greater heterogeneity but can be imprecise when annual time-series are short. Consequently, results obtained from long-run models, pooled panel coefficients, heterogeneous panel tests, and country-level VAR models should not be treated as directly equivalent.

2.5. Literature synthesis and research gap

The literature, therefore, suggests three conclusions. First, neither financial development nor industrialisation has a uniform relationship with carbon emissions because their effects depend on economic scale, energy composition, technological development, and institutional conditions. Second, conclusions about direction and timing depends on whether the analysis examines long-run equilibrium effects, short-run adjustment, average panel relationships, or country-specific predictive patterns. Third, pooled panel results may obscure structural heterogeneity and the influence of common cross-country shocks. These observations justify a methodology that first assesses cross-sectional dependence and slope heterogeneity, applies second-generation panel unit-root tests, and then estimates heterogeneous panel Granger predictive relationships. Country-level findings are retained as supplementary evidence because they can reveal national differences, but they are interpreted cautiously due to the relatively short annual time dimension.

3. Conceptual and analytical framework

3.1. Financial development and environmental nexus

Financial development significantly influences environmental sustainability by shaping investment patterns, industrial development, and the adoption of advanced technologies. Strong financial systems provide greater access to credit and capital, triggering industrial expansion, increased productivity, and energy use, often leading to rising emissions. Conversely, mature financial systems promote cleaner technology innovation, renewable energy use, green investment, and the adoption of advanced technologies, resulting in diverse effects on carbon emissions. Meanwhile, strong regulatory policies, investor preferences, and potential climate-related risks could influence financial expansion by driving investment in sustainable projects, including renewable energy and clean technologies. Therefore, the relationship between financial development and carbon emissions is dynamic and mutually reinforcing.

3.2. Industrialisation and the environmental nexus

Industrialisation plays an important role in environmental change, due to its influences on increased productivity, resource use and higher energy consumption, which often increase carbon emissions and environmental degradation. Further, with industrial transformations, carbon emissions could be reduced through technological innovation, the adoption of cleaner technologies, the use of renewable energy, and

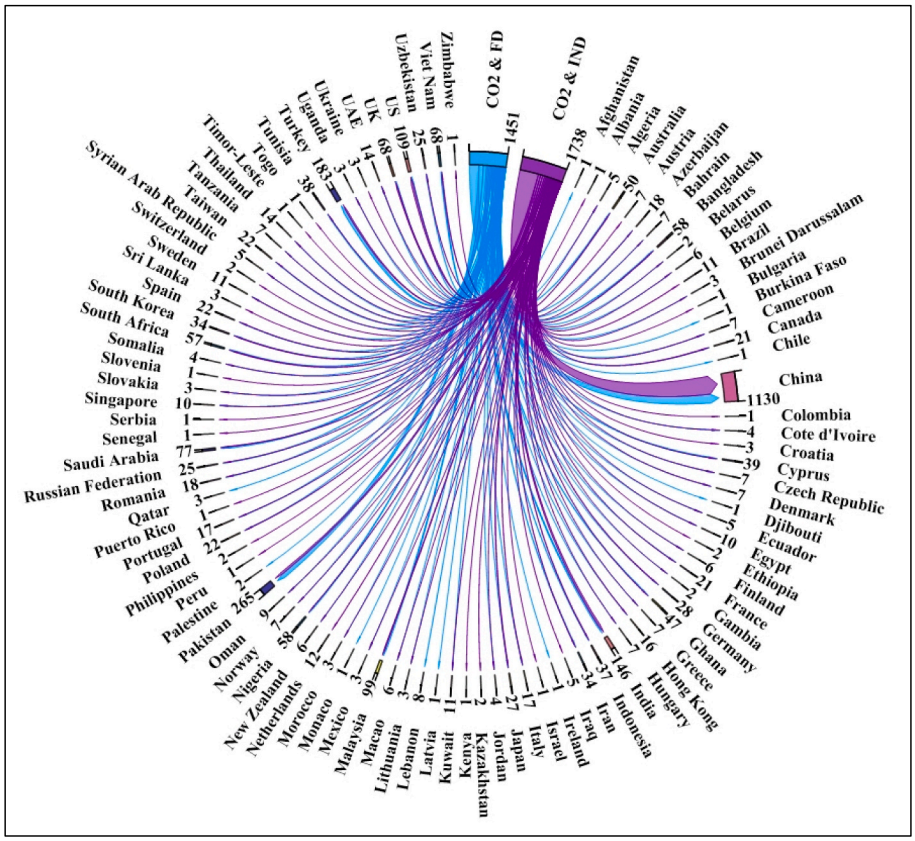


Fig. 2. Chord chart representing the number of research articles published between 2000 and 2025. Note: Number of research publications by country context. The lines represent the number of articles by country. The blue lines represent FD and CO_2, and the purple lines represent industrialisation and CO_2.
Source: Authors' composition based on Scopus Database, created using OriginLab.

sustainable production techniques and energy practices. At the same time, strict policies and regulations control the industrial activities and production decisions. Therefore, mutual linkage through feedback loops exists in the industrialisation-carbon emissions nexus.

3.3. Short-term causality perspective

The short-term Granger causality captures the immediate effects of financial development and industrialisation on carbon emissions, differing from long-term patterns. Short-term economic and environmental shocks could temporarily alter emissions and financial and industrial growth patterns. Examination of short-term causality patterns expands existing knowledge by interpreting transitional economic responses.

3.3.1. Granger causality conceptual suitability

Accordingly, this approach examines whether past values of financial development and industrialisation can help predict short-term changes in carbon emissions, and whether past values of carbon emissions are useful for predicting financial development and industrialisation. From a practical perspective, policy responses are often guided by past trends, such as financial expansion, industrial growth, and environmental degradation, particularly carbon emissions, which are gradually emerging over time. Thus, the Granger causality approach is conceptually suitable for the study, as it focuses on past values to investigate possible two-way effects.

3.3.2. Importance of short-run dynamics for policy timing

The short-run dynamics matter greatly for policy formulation because sudden financial, industrial, and environmental variations can depart from long-term outcomes. Policymakers must explicitly understand the short-run causal patterns among variables to plan timely strategies, policies, and regulatory interventions that achieve long-term sustainability through short-term adjustments.

3.4. Conceptual framework of the study

The conceptual framework outlined in Fig. 3 shows the relationship between financial development, industrialisation, and carbon emissions. Within this framework, carbon emissions function as an environmental sustainability indicator representing the environmental consequences of financial and industrial expansion. The framework represents the potential predictive relationships between financial development, industrialisation, and carbon emissions that are empirically examined in both directions.

4. Data and methodology

This section provides a detailed explanation of the variables, data sources, and the statistical methods used in the analysis.

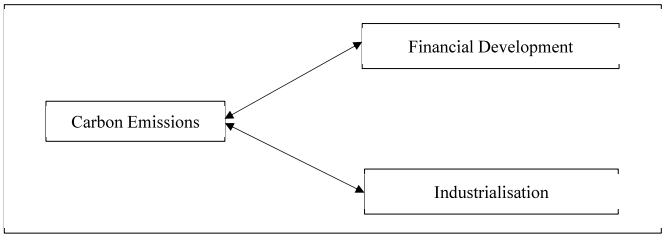


Fig. 3. Conceptual framework.
Source: Authors' composition.

4.1. Data sources and sample selection

The final strongly balanced data set comprised 50 countries, including 37 HICs and 13 LICs observed annually from 2000 to 2024. Countries with more than two missing annual observations for any core variables were excluded. For the retained countries, isolated internal missing observations were completed using linear interpolation, while extrapolation was limited to two endpoint observations. Appendix 1 provides the final dataset used in the analysis. Because interpolation and extrapolation may influence temporal relationships, the resulting Granger-predictive findings are interpreted cautiously. A complete-case non-imputed robustness analysis was not feasible because excluding observations with missing values would substantially reduce the useable sample. This issue is therefore acknowledged as a limitation.

4.2. Variable definition and measurement

This study applies a quantitative approach, using secondary data including metric tons per capita (Carbon emissions), Domestic credit to the private sector (Financial development), and Industry value added (Industrialisation). The data collected from reputable databases, including Our World in Data and the World Bank, are indicated in detail in Table 1.

All three variables were transformed into natural logarithms to reduce scale differences and improve the comparability of dynamic changes. The logged series are denoted as $\ln CO_2$, lnFD, and lnIND. Where the panel unit-root tests indicated non-stationarity, first differences of the logged variables were used. Accordingly, the HIC financial-development analysis uses $\Delta \ln CO_2$ and ΔlnFD, while lnIND is retained in level because it is stationary. All logged variables for LICs are stationary in level and are therefore entered in levels. Differenced logarithms represent short-run proportional changes, whereas level logarithms represent variation in the logged indicators.

4.3. Econometric strategy

The empirical strategy proceeds in five stages. First, cross-sectional dependence is tested using the Pesaran CD statistic because common financial conditions, energy price shocks, technology diffusion and international economic events may generate contemporary correlation across countries. Second, slope homogeneity is assessed using the Pesaran–Yamagata Delta test. Third, the Pesaran-CIPS second-generation panel unit root test is used to determine the stationarity of the logged variables while accounting for common cross-sectional factors. Fourth, the Dumitrescu–Hurlin heterogeneous panel Granger non-causality test is used to assess whether past values of financial development and industrialisation contain predictive information for carbon emissions and vice versa. The test permits country-specific coefficients and tests the null of homogeneous non-causality against the alternative that predictability exists for at least one country. Fifth, country-level VAR based Granger tests are used as supplementary explanatory evidence of national heterogeneity. Because these country models are based on only 25 annual observations, these are estimated parsimoniously and are not interpreted as structural causal estimates.

Table 1
Data and source of parameters.

Variable	Description	Measure	Transformation	Data Source
CO_2	Carbon emissions	Metric ton per capita	Natural logarithm: first difference where required	Our world in Data https://ourworldindata.org/grapher/co-emissions-per-capita
FD	Financial Development	Domestic credit to private sector (% of GDP)	Natural logarithm: first difference where required	World bank https://data.worldbank.org/indicator/FS.AST.PRVT.GD.ZS
IND	Industrialisation	Industry (including construction), value added (Current US$)	Natural logarithm: first difference where required	World bank https://data.worldbank.org/indicator/NV.IND.TOTL.CD?locations=US

Source: Authors' composition.

4.4. Stationarity testing and data transformation

Cross-sectional dependence was first assessed before selecting the panel unit root procedure. The Pesaran CD tests reject the null hypothesis of cross-sectional independence for both HICs and LICs, indicating significant cross-sectional dependence in both income groups. Therefore, the Pesaran CIPS test was used as the principal second-generation panel unit root test. For HICs, $\ln CO_2$ and lnFD are not stationary in levels but become stationary after first differencing, while lnIND is stationary in level. For LICs, $\ln CO_2$, lnFD, and lnIND are stationary in level. These results determine the transformation used in the heterogeneous panel test and reduce the risk of spurious predictive relationships. LIC and country-specific Pesaran tests are retained only as supplementary checks. The results of the panel unit root tests and the selected transformations are summarised in Table 2.

4.5. Cross-sectional dependence and slope heterogeneity

The Pesaran CD tests produce statistics of 45.857 for HICs and 6.1494 for LICs, rejecting cross-sectional independence at the 1% significance level in both groups. The Pesaran–Yamagata Delta and adjusted Delta statistics also reject slope homogeneity for both income groups. These findings indicate that common shocks and heterogeneous country responses and support the use of second-generation unit root procedures and heterogeneous panel analysis rather than imposing identical dynamic coefficients across countries. The detailed results of the cross-sectional dependence and slope homogeneity tests are presented in Table 3.

4.6. Granger causality model specification

Granger causality tests examine whether one variable can reveal predictive information about another in a time-series context. Granger non causality testing evaluates predictive temporal ordering rather than structural or experimental causation. The rejection of the non-causality null indicates that lag observations of one variable improve the prediction of another after accounting for its own lag observations. It does not establish that the first variable is an exogenous cause of the second. Therefore, the empirical findings are described throughout as Granger-predictive relationships, predictive directions, or temporal precedence.

Table 2
Pesaran CIPS panel unit root test results.

Income group	Variable	Level	First Difference	Integrated Decision
HIC	ln_CO_2	−1.616	−4.685***	I (1)
HIC	ln_FD	−1.216	−3.491***	I (1)
HIC	ln_IND	−2.248***	−3.943***	I (0)
LIC	ln_CO_2	−2.537***	−4.681***	I (0)
LIC	ln_FD	−2.494***	−4.690***	I (0)
LIC	ln_IND	−2.147*	−4.198***	I (0)

Source: Authors' composition.

Table 3
Cross-sectional dependence and slope heterogeneity test results.

Test	Income group	Variable/ Statistics	Test Value	p-value
CD Test	HIC	Joint model	45.857	0.0000
CD Test	LIC	Joint model	6.149	0.0000
Slope Heterogeneity	HIC	Delta	34.341	0.0000
Slope Heterogeneity	HIC	Adjusted Delta	37.469	0.0000
Slope Heterogeneity	LIC	Delta	19.019	0.0000
Slope Heterogeneity	LIC	Adjusted Delta	20.752	0.0000

Source: Authors' composition.

In this study, Stata 17 was used to analyse the data. Equation (1) was used in both panel- and country-level time-series Granger causality analyses. This equation was utilised to formulate the panel Granger equations to all the variables studied.

$$lnY_{i,t} = \sum_{k=1}^{p} \beta_i lnY_{i,t-k} + \sum_{k=0}^{p} \theta_k \, lnX_{i,t-k} + u_{i,t} \quad (1)$$

lnX and lnY in the equation indicate as the natural log forms of independent and dependent variables respectively, while i and t indicate the country and the time duration in years respectively, k is the frequency of the lags. β indicate the coefficient of regression and θ is the constant values of regression. $u_{i,t}$ donates the error term.

Because the time dimension is relatively short, inference is based primarily on the final-sample adjusted Z-bar tilde statistic rather than the standard Z-bar statistic. A one-lag specification is used to preserve degree of freedom and represent short-term annual predictability. Results at the 10% level are described as weak evidence and are distinguished from findings significant at the 5% and 1% levels.

4.7. Lag selection, robustness and diagnostics check

The internal stability test was examined by determining the optimal lag length for the Granger causality test. The lag length was determined using lag section criteria, including the Akaike Information Criterion (AIC), Schwarz Bayesian Information Criterion (SBIC), and Hannan-Quinn Information Criterion (HQIC). The minimum value among the information criteria is used to select the optimal lag length. A robustness test examined by estimating alternative lag lengths; core causality results were found to be qualitatively consistent across lag structures.

The principal models remain parsimonious because the study examined bivariate predictive directions and because the country-level annual series contain only 25 observations. Introducing a large set of controls into each country-specific VAR would substantially reduce degree of freedom and create over parametrised models. Nevertheless, GDP per capita, energy use, renewable energy composition, trade openness, urbanisation and institutional quality may jointly influence the observed relationships. The result should therefore be interpreted as conditional predictive associations rather than fully identify structural effects and omitted variable bias remain a limitation.

5. Empirical results

This section presents summaries of descriptive statistics, correlation analyses, and Granger causality results for HICs and LICs.

5.1. Descriptive statistics and preliminary analysis

The HICs and LICs' descriptive statistics for the variables FD, IND, and CO_2 emissions is presented below in Appendix 2. Based on that, the lowest mean of CO_2 metric ton capita value is obtained in the Democratic Republic of Congo, while the highest is observed in Trinidad and Tobago. Considering FD, the lowest mean value for Domestic credit to the private sector was recorded in Sierra Leone, while the highest was observed in Hong Kong. In the context of IND, the highest average Industry (including construction) value added was recorded in the United States, while the lowest was recorded in Guinea-Bissau.

Fig. 4 illustrates the distribution of the variables across HICs and LICs. Most of the HICs and LICs' metric tons per capita, Domestic credit to the private sector (% of GDP), and Industry value added (Current US $) data points are around the mean level.

5.2. Correlation analysis

The correlation matrix among HICs and LICs is presented in Fig. 5. The analysed coefficient for the HICs indicates a positive relationship between carbon emissions and Industrialisation, and Industrialisation and FD. Conversely, LICs indicate a positive relationship between carbon emissions and FD and between carbon emissions and Industrialisation. Further, Appendix 3 explains the detailed cross-country-level correlation coefficients.

The stationarity test for the study was conducted in both panel-wise and cross-country-wise. The Levin–Lin–Chu (LLC) test and Phillips-Perron test stationarity results for the HICs and LICs at both the panel and country levels are detailed in Appendix 4, respectively. After examining the stationarity test, the stability condition was verified by selecting the lag length. Additionally, Appendix 5 provides details on optimal lag length selection at the panel and country levels.

5.3. Panel-level granger causality results

5.3.1. Financial development and carbon emissions

Table 4 presents the heterogeneous panel Granger non-causality results. For HICs, the null hypothesis that financial development does not Granger predict changes in carbon emissions is rejected only at the 10% significance level using the final sample of estimation statistics. This constitutes weak evidence of short-run predictability, rather than a robust bidirectional Granger predictability. The reverse direction from changes in carbon emissions to financial development is not statistically supported. For LICs, financial development strongly Granger predicts carbon emissions at the 1% significance level. The asymmetric statistical strength of the two directions suggests that the dominant pattern in LICs runs from financial development to emissions with only limited evidence of feedback.

5.3.2. Industrialisation and carbon emissions

The industrialisation results are more consistent across income groups. For HICs, industrialisation strongly Granger predicts short-run changes in carbon emissions, while changes in carbon emissions do not predict industrialisation. For LICs, industrialisation also strongly Granger predicts carbon emissions, whereas the reverse direction is not supported. These findings indicate unidirectional industrialisation-to-emissions predictability in both groups, although the relevant economic mechanisms and emissions magnitudes may differ substantially between mature and early-stage industrial systems.

The Dumitrescu–Hurlin test identifies predictive direction but does not quantify the magnitude of emissions responses. Accordingly, the findings establish statistical predictability rather than economic magnitude. Claims about the size or practical scale of effects are avoided unless supported by coefficient-based dynamic estimates.

5.4. Country-level granger causality results

5.4.1. Granger causality results for HICs

The country-wise Granger causality results for HICs and LICs are presented in Fig. 6. The majority of the HICs revealed no Granger-predictive relationship between financial development and carbon

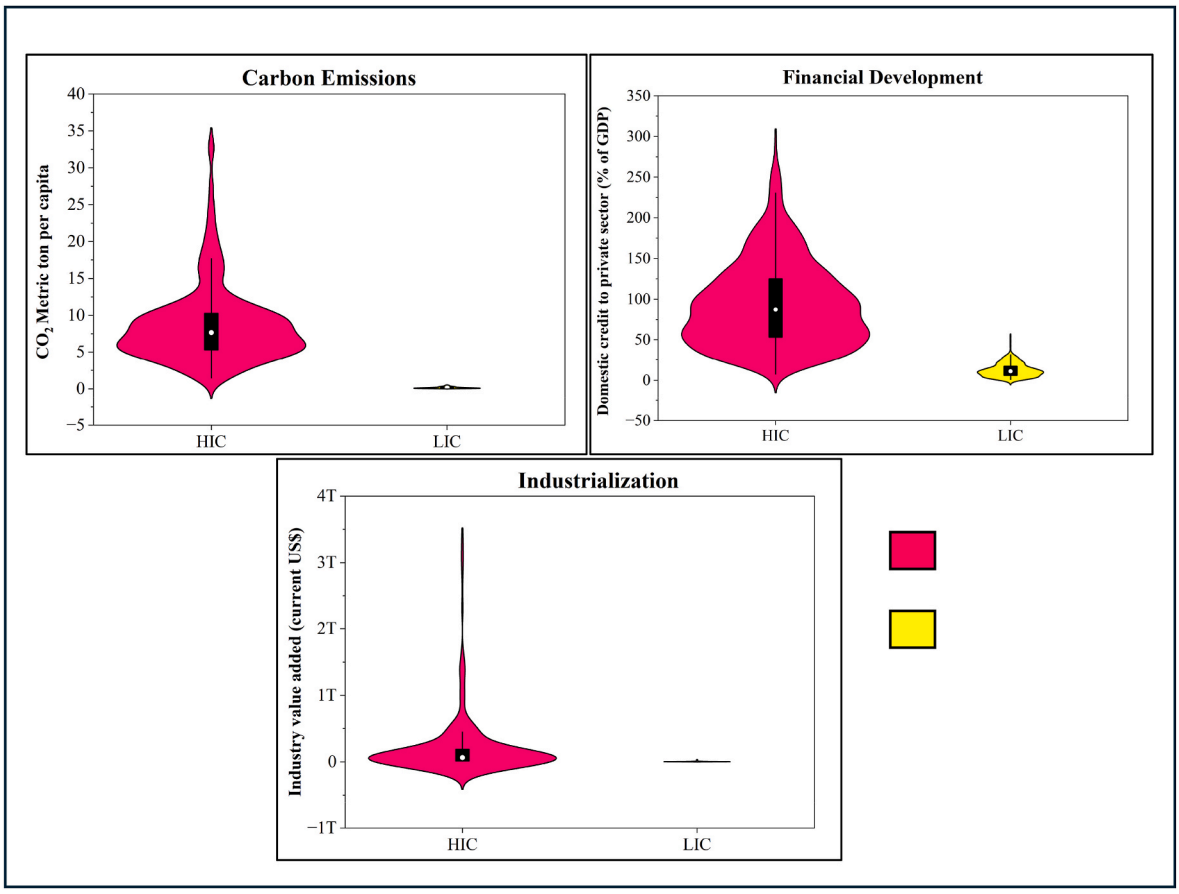


Fig. 4. Violin plots representing the distribution of CO_2 emissions, financial development and industrialisation between 2000 and 2024. Note: Violin plot for the data distribution of all three variables for HICs and LICs. The violin plots' widths indicate the density of the data at different values: wider sections represent higher data centralisation, and narrower sections represent lower centralisation. The white dot in the middle represents the median value.
Source: Authors' composition based on (Our World in Data, 2025; The World Bank, 2026a, b, c), created using OriginLab.

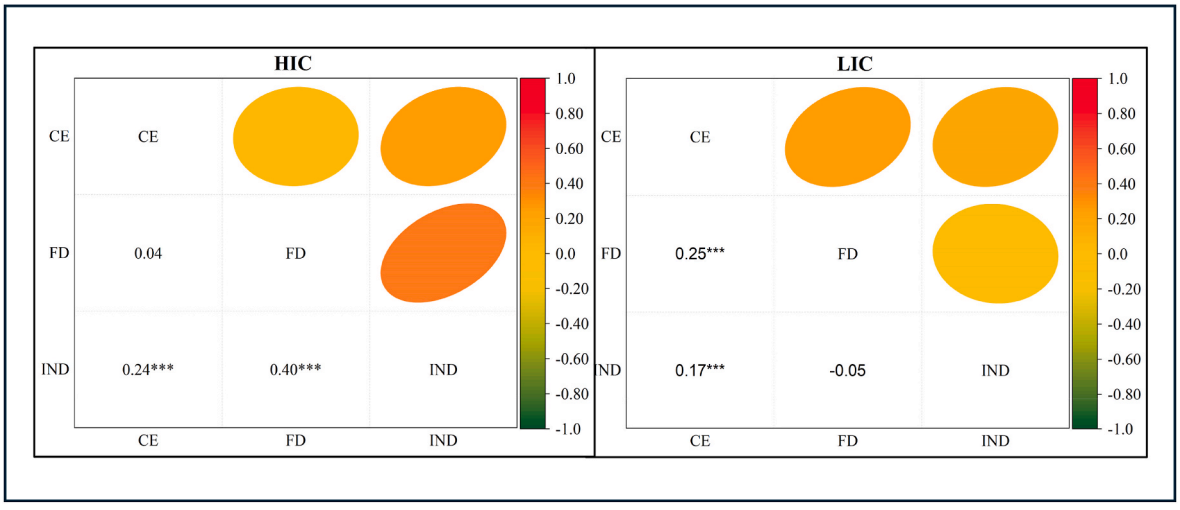


Fig. 5. Correlation Matrix of CO_2 Emissions, financial development and industrialisation for the period 2000 to 2024. Note: ***Significant at 1% level. The colour gradient in the correlation matrix, which ranges from green to red, depicts the negative-to-positive relationship between the variables.
Source: Authors' composition based on (Our World in Data, 2025; The World Bank, 2026a, b, c), created using OriginLab.

emissions. However, Chile, Guyana, the Netherlands, and Norway revealed a bidirectional relationship between financial development and carbon emissions. Furthermore, a few HICs indicated a unidirectional relationship from $dlnCO_2$ to lnFD in Bulgaria and Finland, while Belgium and Italy revealed a relationship from $dlnCO_2$ to dlnFD. In addition, Spain showed unidirectional Granger predictability from $dlnCO_2$ to ddlnFD. Conversely, Greece, Israel, Luxembourg, Macao, United States, and Uruguay revealed one-way causal link from dlnFD to $dlnCO_2$, along with Hungary and Ireland demonstrating unidirectional relationship from ddlnFD to $dlnCO_2$.

Table 4
Heterogeneous panel-granger results.

Income group	Null hypothesis	W-bar	Adjusted Z-bar	Adjusted p-value	Decision
HIC	Δ ln_CO_2 does not predict Δ ln_FD	1.5466	1.5470	0.1219	Do not reject
HIC	Δ ln_FD does not predict Δln_CO_2	1.5910	1.7048	0.0882	Weak rejection at 10%
HIC	Δ ln_CO_2 does not predict ln_IND	1.1527	0.1477	0.8826	Do not reject
HIC	ln_IND does not predict Δln_CO_2	3.6044	8.8571	0.0000	Reject
LIC	ln_CO_2 does not predict ln_FD	1.9285	1.7508	0.0800	Weak rejection at 10%
LIC	ln_FD does not predict ln_CO_2	3.9618	6.0749	0.0000	Reject
LIC	ln_CO_2 does not predict ln_IND	1.4871	0.8120	0.4168	Do not reject
LIC	ln_IND does not predict ln_CO_2	3.1536	4.3561	0.0000	Reject

Source: Authors' composition.

Further, in the short run, findings on industrialisation and carbon emissions indicate that most HICs lack a causal relationship between the two. Conversely, Denmark, Finland, Guyana, and Uruguay revealed a bidirectional relationship between Industrialisation and CO_2 emissions. Moreover, Antigua and Barbuda recorded unidirectional relationship from lnCO_2 to dlnIND, along with Czechia and Romania from dlnCO_2 to lnIND. Further, a unidirectional Granger predictability from dlnCO_2 to dlnIND was observed in Denmark, Greece, Ireland, Spain, and Sweden. In addition, Hong Kong revealed a one-way causal link from ddlnIND to dlnCO_2, while Austria, France, Iceland, Luxembourg, and South Korea demonstrated a unidirectional relationship from dlnIND to dlnCO_2. Overall, Appendix 6 presents the cross-country Granger causality results for HICs.

5.4.2. Granger causality results for LICs

In the context of LICs, such as Burkina Faso, Burundi, Democratic Republic of Congo, Liberia, Malawi, Mozambique, Niger, Rwanda, and Sierra Leone, no causal link was found between financial development and CO_2 emissions. Furthermore, Togo revealed unidirectional relationship from lnCO_2 to dlnFD, while Guinea-Bissau and Mali demonstrated one-way causal link from dlnCO_2 to dlnFD.

Meanwhile, in the context of the industrialisation-carbon emissions nexus, nations such as Burundi, Mali, Malawi, Niger, and Togo revealed no causal link between industrialisation and CO_2 emissions. In addition, Burkina Faso, Guinea-Bissau, and Rwanda demonstrated a one-way causal link from dlnCO_2 to dlnIND. Further, Liberia and Sudan showed a one-way link from dlnIND to lnCO_2, whereas the Democratic Republic of Congo, Mozambique, and Sierra Leone showed unidirectional flow from dlnIND to dlnCO_2. Furthermore, Appendix 7 presents detailed statistics of the cross-country Granger causality results for LICs.

Subsequently, a robustness check was conducted on the Wald Granger Causality findings for HICs and LICs. In this procedure, alternative lag lengths were checked along with the optimal lag lengths. The results provided in Appendix 8 and Appendix 9 represent most of the results that remained consistent, thereby ensuring the reliability of the findings across different criteria.

6. Discussion

6.1. Synthesis of key findings

The heterogeneous panel results reveal distinct short-run predictive patterns across the two income groups. In HICs, financial development provides only weak evidence of predicting changes in carbon emissions at the 10% significance level, while the reverse direction is not statistically supported. In LICs, financial development strongly predicts carbon emissions, while the reverse relationship is supported only weakly at the 10% level. The industrialisation results are more consistent across income groups: industrialisation strongly predicts carbon emissions in both HICs and LICs, whereas the reverse direction is not supported. These findings indicate that short-run financial development–emissions predictability differs by income group, while industrialisation-to-emissions predictability represents the more consistent panel-level pattern.

Further, at the country level, some nations showed similar panel-level trends, while others exhibited divergent causal patterns, challenging the universal applicability of overall income-group causality dynamics. In the context of financial development and carbon emissions, despite most nations revealing no causality patterns being consistent with the panel-level findings, HICs and LICs such as Belgium, Bulgaria, Chile, Finland, Greece, Guinea-Bissau, Guyana, Hungary, Ireland, Israel, Italy, Luxembourg, Macao, Mali, Netherlands, Norway, Spain, Togo, United States, and Uruguay evidenced combination of bidirectional and unidirectional flows. Further, across HICs, only a few nations, including Austria, Hong Kong, France, Iceland, Luxembourg, and South Korea, aligned with the panel's findings, exhibiting unidirectional flow from industrialisation to carbon emissions, whereas other nations showed divergent causality patterns. Meanwhile, across LICs, only Burundi, Mali, Malawi, Niger, and Togo confirmed panel-level patterns. These results indicate that country-level predictive patterns frequently differ from the panel-level findings, reinforcing the importance of country-specific analysis.

The comparison between HICs and LICs indicates that the strength of short-run predictive relationships differs across development contexts. Financial development exhibits only weak predictive evidence for carbon emissions in HICs but substantially stronger evidence in LICs. By contrast, industrialisation predicts carbon emissions in both income groups. These differences are consistent with the possibility that financial depth, industrial structure, energy systems, technological capacity, and regulatory conditions shape the observed relationships; however, these mechanisms are not directly tested in the present study and should therefore be regarded only as potential contextual explanations.

6.2. Comparison with existing literature

The short-run Granger causality analysis revealed heterogeneous findings across HICs and LICs within both nexuses, including both convergence and divergence. In the context of financial development and carbon emissions, amongst the HICs, 20 HICs showed no causality between financial development and carbon emissions, indicating both consistency and inconsistency with the existing literature. A similar causal pattern was documented in previous research on the European Union and Australia (Bayar et al., 2020; Rahman and Alam, 2022). However, counterarguments are also presented in the current literature, which mainly uphold the existence of causality, particularly in studies conducted in France, Germany, Japan, Portugal, and the United Kingdom (Abid et al., 2022; Shahbaz et al., 2016). The diverse methodological approaches employed and differences in time periods examined could potentially be the reasons for the varied findings.

Further, HIC's findings on Belgium, Bulgaria, Finland, Italy, and Spain conflict with the current literature focused on the European Union and G8 countries (Bayar et al., 2020; Abid et al., 2022). Further, in the context of the US, the finding aligns with previous research conducted

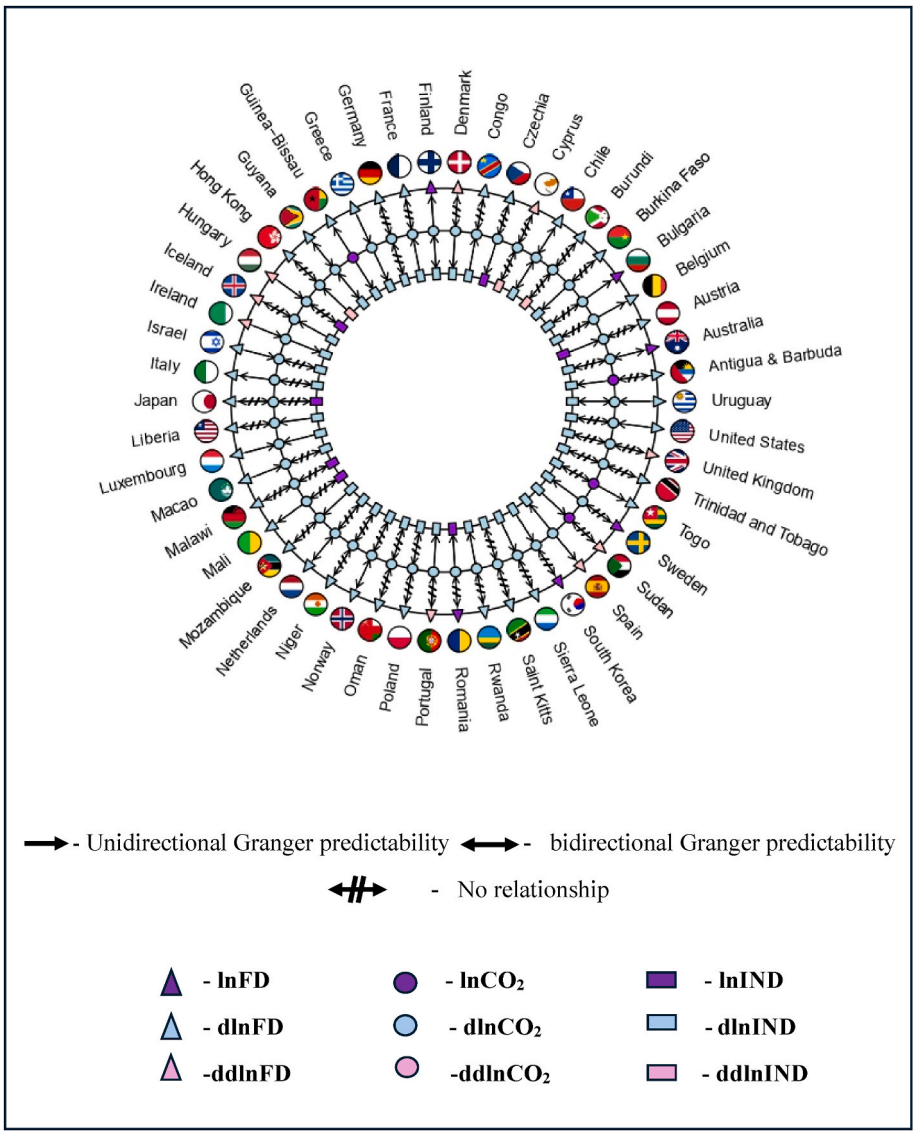


Fig. 6. Cross-country Granger causality results. Note: The relationship between two variables is represented with either "←" or "→" is unidirectional, "↔" is bidirectional, and "⇹" is no relationship.
Source: Authors' composition based on (Our World in Data, 2025; The World Bank, 2026a, b, c), created using RStudio.

on G8 countries (Abid et al., 2022), but another study conducted at the country-level specifically focusing on the US, contradicts the observed evidence proving the absence of causality between financial development and carbon emissions (Dogan and Turkekul, 2016). Furthermore, the observed finding in Greece is in line with a separate study that also revealed the same causal pattern (Atif, 2021). Additionally, a bidirectional relationship was evidenced between financial development and carbon emissions in the Netherlands, which diverges from the EU countries study, which revealed no causality (Bayar et al., 2020). The observed consistencies and inconsistencies with the existing literature may stem from differences in analytical approaches, variable definitions, the study's scope (panel or country-level), and other unobserved factors.

Similarly, among the LICs, only three nations showed causality patterns, while others documented the absence of causality between financial development and carbon emissions, highlighting that, even in less developed financial systems, environmental pressures are not significantly linked to carbon emissions. However, counterarguments in the literature suggest a two-way causal pattern in Sub-Saharan African countries, including the stated LICs (Emenekwe et al., 2022; Ganda, 2021). Further, the findings of LICs, including Guinea-Bissau, Mali, and Togo, which revealed a unidirectional flow from carbon emissions to financial development, contradict previous panel studies on SSA countries (Emenekwe et al., 2022; Ganda, 2021). Overall, the heterogeneous panel evidence indicates weak financial development-to-emissions predictability in HICs and substantially stronger predictability in LICs, while the country-level findings reveal considerable heterogeneity around these group-level patterns.

Moreover, in the context of the industrialisation-carbon emissions nexus, findings from Australia on the absence of causality between industrialisation and carbon emissions contradict an existing study showing causality (Rahman and Alam, 2022). Further, industrialisation was found to granger-cause carbon emissions in South Korea, consistent with a previous study that also captured short-run dynamics (Song et al., 2023). Additionally, Chile, Finland, Guyana, and Uruguay exhibited a two-way causal relationship between industrialisation and carbon emissions, consistent with prior scholarly discussion of 42 developing countries, including Chile and Uruguay (Yang et al., 2022). Thus, although HICs are highly developed economies with well-established financial systems, the influence of emissions varies across countries.

Meanwhile, considering LICs, the existing literature on Niger and Togo conflicts with the finding, proving the presence of two-way causality between industrialisation and carbon emissions (Yang et al., 2022). Additionally, the finding in Rwanda of a unidirectional link from carbon emissions to industrialisation is inconsistent with the existing literature, which revealed the absence of causality between industrialisation and carbon emissions (Asumadu-Sarkodie and Owusu, 2017). Further, unidirectional Granger predictability from industrialisation to carbon emissions was identified in the Democratic Republic of Congo and Mozambique, partially aligning with a prior study which revealed a bidirectional Granger predictability (Yang et al., 2022). At the panel level, industrialisation Granger-predicts carbon emissions in both HICs and LICs, while the reverse predictive direction is not supported in either income group. Hence, the panel and country-level insights suggest that the causality patterns are strongly influenced by country-specific factors. Accordingly, the subsequent section will provide an in-depth analysis of the underlying causes of the country-level causality patterns.

6.3. Interpretation of heterogeneous causality patterns

The heterogeneous country patterns should not be interpreted as direct evidence that particular institutional, energy or financial mechanisms produce the observed results. However, they are consistent with the broader literature showing that financial depth, industrial composition, energy systems, technological capacity, and regulatory institutions may condition finance-industry-environment relationships. Because these conditioning variables are not included directly in the present model, they are discussed only as potential contextual explanations requiring further testing. The panel evidence nevertheless identifies two dominant patterns. First, industrialisation contains predictive information for carbon emissions in both income groups. Second, financial development is more strongly linked to carbon emissions in the LIC panel, whereas HIC panel evidence is weaker. The country-level results reveal further heterogeneity, but several classifications are sensitive to lag selection. Accordingly, the discussion distinguishes robust country patterns from lag sensitivity for individual cases, rather than treating statistically significant country results as equally reliable.

7. Policy implications

The policy implications are restricted to the predictive relationships identified in the analysis. The strong industrialisation-to-emissions pattern in both income groups indicates that industrial expansion should be accompanied by closer monitoring of industrial carbon intensity. Relevant measures include sector-specific emissions reporting, industrial energy-efficiency standards, cleaner production processes, equipment upgrading, and the gradual electrification of industrial energy use. These measures are more directly connected to the observed industrialisation–emissions relationship than broad financial or climate-policy prescriptions.

For HICs, the industrialisation result suggests that advanced industrial capacity does not automatically eliminate short-run environmental pressure. Policies should therefore focus on emission-intensive sectors and monitor whether industrial output growth is accompanied by improvements in energy efficiency and carbon intensity. The weak HIC financial-development result does not justify treating financial expansion as a dominant emissions driver across all high-income countries.

For LICs, the stronger financial-development-to-emissions relationship suggests that the environmental implications of credit expansion should be monitored as financial access and productive investment grow. This finding does not demonstrate that particular financial instruments cause emissions. Rather, it supports the collection of sector-level credit and emissions data to determine whether new financing is concentrated in energy- and carbon-intensive activities. The industrialisation result also supports early adoption of energy-efficient infrastructure and production standards to reduce the risk of carbon-intensive technological lock-in.

Finally, country-level heterogeneity and lag sensitivity indicate that uniform policy prescriptions are inappropriate. National authorities should combine the panel findings with country-specific information on industrial structure, energy sources, financial allocation, and regulatory capacity before designing interventions. Non-significant Granger results should not be interpreted as evidence that financial or industrial activity is environmentally harmless.

8. Conclusion

8.1. Summary of key findings

This study examined short-run Granger-predictive relationships among financial development, industrialisation, and carbon emissions across 37 HICs and 13 LICs during 2000–2024. After accounting for cross-sectional dependence, heterogeneous slopes, and variable stationarity, the panel results indicate weak evidence that financial development predicts carbon-emission changes in HICs and stronger evidence that financial development predicts emissions in LICs. Industrialisation predicts carbon emissions in both income groups, while the reverse industrialisation relationship is not supported. Country-level findings are more heterogeneous and, in some cases, sensitive to lag choice. The evidence therefore supports income- and country-specific predictive patterns but does not establish structural causation.

8.2. Contributions to theory and policy

The study contributes by showing that average income-group findings coexist with substantial country heterogeneity and that short-run predictive patterns differ from the uniform relationships often implied by pooled models. The results are consistent with scale-effect and ecological-modernisation arguments that financial and industrial development may have different environmental implications across development stages. Methodologically, the study demonstrates the importance of testing common cross-country shocks, heterogeneous slopes, and stationarity before drawing conclusions from multi-country Granger analysis. Its contribution is therefore predictive and comparative rather than one of structural causal identification.

8.3. Limitations of the study

Several limitations should be recognised. First, Granger predictability does not establish structural causation and may reflect omitted common drivers. Second, the parsimonious specifications do not directly control for GDP per capita, energy consumption, renewable-energy use, trade openness, urbanisation, or institutional quality. Third, interpolation and limited extrapolation may affect temporal relationships. Fourth, country-level VAR tests rely on only 25 annual observations, reducing statistical power and increasing lag sensitivity. Fifth, the industrialisation indicator may capture changes in scale and price conditions in addition to structural industrial development. Finally, structural breaks associated with global financial shocks, commodity-price changes, the COVID-19 period, and major policy transitions may alter the estimated relationships.

8.4. Directions for further research

Future research should examine nonlinear and threshold relationships, test structural breaks, and incorporate renewable-energy transitions and institutional conditions directly. Dynamic heterogeneous panel estimators, common-correlated-effects models, and cross-sectionally augmented ARDL approaches could be used to distinguish short- and long-run responses while accounting for common factors. Longer time series or higher-frequency data would improve country-

level inference, while alternative industrialisation and financial-development indicators could test measurement sensitivity. Future studies should also evaluate whether energy structure, regulatory quality, and technological upgrading condition the predictive relationships identified here.

CRediT authorship contribution statement

Saina Nizar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Archana Natkunarasa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Ruwan Jayathilaka:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Suwani Hettiarachchi:** Writing – review & editing, Writing – original draft, Validation.

Declaration of use of AI

During the preparation of this work the authors used Grammarly for proof reading and spell checking. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2026.101592.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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