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Research Paper

Drivers of atmospheric greenhouse gas emissions: Evidence from high-income countries

Gimhani Samarakoon, Sinelya Silva, Dinuri Wijesinghe, Mehul Gunasekara, Ruwan Jayathilaka [1,*], Chamathka Punchihewa

SLIIT Business School, Sri Lanka Institute of Information Technology, New Kandy Road, Malabe, Sri Lanka

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ABSTRACT

Environmental sustainability remains a critical challenge in high-income economies, where economic activity, energy use, and structural transformation continue to influence greenhouse gas (GHG) emissions. This study examines the drivers of GHG emissions growth across 51 high-income countries over the period 2000–2024. Unlike prior studies focusing on emission levels, this research emphasises emissions growth dynamics, providing a more responsive perspective on environmental change. The analysis employs panel regression with fixed-effects and Driscoll–Kraay standard errors, complemented by country-level multiple linear regressions to capture cross-country heterogeneity. The results indicate that economic growth, energy consumption, and fertiliser use are associated with increases in emission growth, while trade openness and digitalisation are linked to reductions, albeit with relatively small marginal effects. Foreign direct investment and urbanisation do not exhibit statistically significant effects. The findings reflect emission source dynamics in high-income economies and highlight the importance of energy structure, technological progress, and policy frameworks in shaping emissions trajectories. The study contributes to the literature by focusing on emission growth rather than emission levels, distinguishing between statistical and economic significance, and combining aggregate and country-specific analyses to inform targeted environmental policy.

1. Introduction

Environmental sustainability challenges in high-income countries are largely driven by unsustainable human activities such as burning fossil fuel, inefficient energy use, uncontrolled urban population expansion, and agricultural activities, which emit Carbon dioxide (CO_2), Methane (CH_4), and Nitrous oxide (N_2O), which play a major role in increasing Greenhouse Gas (GHG) emissions around the world [1]. As a result, climate change is becoming more intense, leading to rising global temperatures, rising sea levels, more frequent droughts, more intense heat waves, and stronger hurricanes worldwide [2]. Reducing and controlling emissions is essential for improving atmospheric composition, air quality, and climate stability. In addition to climate impacts, these emissions play a critical role in atmospheric chemistry by influencing the concentration of air pollutants such as $PM_{2.5}$, ozone precursors, and nitrogen oxides, thereby affecting both outdoor and indoor air quality.

High-income countries contribute highly to global warming. Evidence suggests that 10% of the richest countries account for a large share of global warming since 1990 [3]. During the past two decades, more than half a million deaths have occurred due to extreme weather events around the world, and >12,000 climate-related disasters have been reported globally. Furthermore, countries such as Japan and Germany have experienced environmental disasters, indicating that the impact is not limited to a single region [4]. The findings from the World Health Organisation (WHO) demonstrate that climate change-related deaths will number nearly 250,000 each year from 2030 to 2050, and that the estimated health damage is nearly US$ 4 billion [5]. Therefore, countries should prioritise environmental policies to lower emissions through sustainable strategies to limit future health risks and economic burdens.

Economic growth plays a key role in a country's development, but its hidden environmental harm is often overlooked. As the economy

* Corresponding author.
E-mail addresses: gimhanisamarakoon4@gmail.com (G. Samarakoon), anne.sinelya@gmail.com (S. Silva), dinuriwijesinghe@gmail.com (D. Wijesinghe), mehulgunasekara12@gmail.com (M. Gunasekara), ruwan.j@sliit.lk (R. Jayathilaka), chamathka.p@sliit.lk (C. Punchihewa).
[1] Web: https://www.sliit.lk/academic/academic-staff/ruwan.j.

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expands, it significantly increases energy consumption, industrialisation, and transportation [6,7]. Similarly, countries rely on foreign investment to stabilise their economy through technological transformations. On the other hand, Foreign Direct Investments (FDI) increase the country's emissions through fossil fuel utilisation and energy-intensive industries [8]. Furthermore, energy consumption is a crucial factor in human life, facilitating everyday activities such as electricity generation, transportation, and cooking [9]. Combustion-based energy systems are also a major source of atmospheric pollutants, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, which have direct implications for air quality and human health. Further, on average, a person in developed economies such as Iceland, the United States, Oman, and Qatar consumes energy up to 100 times more than in poor economies [10]. The atmospheric and health impacts of GHG and associated pollutant emissions can be mitigated through targeted emission control and energy transition strategies.

On the other hand, fertiliser consumption contributes to the higher emissions, especially synthetic nitrogen fertiliser. Furthermore, the agricultural sector is the second-largest contributor to global emissions [11]. In atmospheric terms, fertiliser use is a significant source of nitrous oxide (N_2O) and ammonia (NH_3), which contribute to secondary aerosol formation and degrade air quality. Through fertiliser consumption, crops absorb only half of the fertiliser, while the remainder increases global emissions [12]. Conversely, TO has a mixed impact on GHG emissions. It contributes to higher emissions through the expansion of energy-intensive industries and weak environmental policies, but with cleaner technology and strong policy implementation, emissions can be reduced [13]. Furthermore, global trade and transportation by air, sea, and land create environmental challenges such as air pollution [14]. The impact of digitalisation primarily reduces global emissions, but it depends on how it is used and on a country's regulations. Further, by 2050, digital technologies will contribute to 20% reduction in GHG emissions globally in sectors such as energy and transportation [15]. In recent years, urbanisation has accelerated worldwide. In high-income countries such as Australia, Japan, and Western European countries, >80% of people live in urban areas [16], and unplanned urbanisation leads to high GHG emissions [17,18]. Fig. 1 proves that high-income countries emit more GHG. Therefore, it is necessary to mitigate GHG emissions to manage global climate change and environmental degradation to secure a future for humanity. To attain this goal, the study provides evidence-based insights into critical policy implications for enhancing sustainability and environmental quality.

Importantly, this study is not directly focused on model atmospheric chemical processes, pollutant transport, or concentration dynamics. Instead, it focuses on macro-level drivers of emissions that are closely associated with common sources of both GHG emissions and air pollution. Therefore, the findings should be interpreted as indirect implications of atmospheric conditions through shared emission pathways, rather than the direct causal effect of air quality.

Despite existing research on the key drivers of GHG emissions, significant gaps remain, motivating the present study. The present study addresses the following empirical and interpretative gaps. First, in the existing literature, most studies examine GHG emissions as the dependent variable, while the key drivers of GHG emissions growth remain comparatively underexplored. Moreover, limited studies explicitly connect macroeconomic drivers of GHG emissions with atmospheric emission pathways and air quality implications, particularly in high-income countries.

Second, from a methodological standpoint, relatively few studies apply both Panel Regression and Multiple Linear Regression (MLR) approaches to examine cross-country differences alongside changes over time within a single analysis. In addition, country-level heterogeneity is frequently overlooked, even though nations differ widely in terms of economic development, energy systems, and environmental regulatory frameworks.

Third, the 3Ps framework is used as an organising theoretical lens to connect the economic, environmental, and social dimensions of GHG emission growth. It is not treated as a methodological contribution, but as a framework for interpreting the sustainability implications of the empirical findings. Moreover, the study aligns with the Sustainable Development Goals (SDGs) that are related to climate action and environmental sustainability.

The study aims to assess the impact of per capita GDP growth, Fertiliser Consumption, Energy Consumption, Trade Openness (TO), Digitalisation, Foreign Direct Investment (FDI), and Urbanisation in high-income countries. Importantly, this study contributes to the literature by reframing the analysis from emission levels to GHG emission growth dynamics in high-income countries. Rather than claiming novelty solely from updated data or standard econometric techniques, the study provides a growth-rate interpretation of how macroeconomic, energy, agricultural, trade, digital, investment-related, and demographic factors are associated with annual changes in emissions. The study also distinguishes between statistical significance and economic magnitude, which

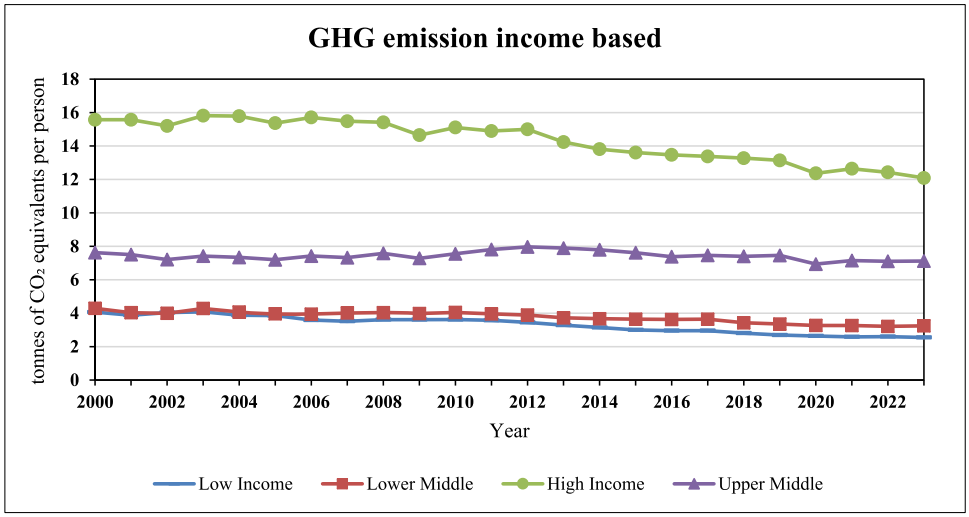


Fig. 1. Trendline for greenhouse gas emissions for income groups. Note: The green line with circles shows the high-income group, the purple line with triangles illustrates the upper-middle income group, the maroon line with squares indicates the lower-middle income, blue line represents the low-income group. Source: Authors' illustration based on Our World in Data.

is important because the dependent variable is measured as an annual growth rate. In addition, the study combines aggregate panel-level evidence with country-level estimates and grouped policy patterns to provide more practical policy guidance for high-income economies. The subsequent sections are organised as follows. The assessment begins with the literature review findings, theoretical framework, data, and methodology, followed by results and discussion, and concludes with policy recommendations, limitations, and suggestions for further research.

2. Literature review

2.1. Economic growth and GHG emissions

As high-income economies grow while addressing climate targets, it's questionable whether economic growth still leads to higher GHG emissions. Several studies highlight that economic growth increases GHG emissions in high-income countries, as these countries aim to sustain economic expansion while meeting climate targets. Early studies generally suggest that, as they become wealthier, decoupling is often temporary, and no country has yet achieved human well-being while remaining within environmental limits. Therefore, it indicates that GDP growth does not eventually lead to long-term reductions in emissions [19,20]. Additionally, rising income levels and economic output can increase emissions due to greater production despite sustainability commitments [21–23], highlighting the "scale effect," where emissions persist despite technological advances and energy efficiency. However, more recent studies suggest that economic growth does not necessarily lead to higher emissions when supported by technological innovation, structural transformation, and effective environmental policies [24]. Nonetheless, such decoupling is possible with strong environmental governance and integrated policy frameworks [25]. Without such integrated systems, economic growth tends to harm the climate, underscoring the need for measures that decouple economic growth from emissions in developed economies. In some countries, sustainable practices are crucial in shaping the relationship between growth and GHG emissions [26]. Empirical evidence from countries like the USA and Japan also suggests that strong decoupling between economic growth and CO_2 emissions had no effect over the period [27]. A study in Saudi Arabia examines the asymmetric link between economic activity and air pollution and finds it nonlinear and varies with the direction of change, stating that impacts of growth and industrial conditions differ not only by magnitude but also by the sign depending on whether the shock is positive or negative [28]. Similarly, findings in New Zealand reveal both positive and negative relationships between key variables, highlighting the complexity of sustainable development [29]. Results indicate that energy intensity has a positive effect on sustainable economic growth, while energy use exerts a negative impact. These mixed findings also reflect the sustainability concern highlighted in the 3Ps model, where economic expansion (profit) and improved living standards (people) often generate environmental issues (planet) unless balanced through effective policies and sustainable development strategies. However, the overall and country-specific dynamics of the growth–emissions relationship in high-income countries remain underexplored, leaving a gap for investigation. Economic growth plays a crucial role in driving GHG emissions in high-income countries due to rapid expansion and industrialisation. It may generate environmental challenges when growth remains structurally unbalanced.

2.2. Energy consumption and GHG emissions

Energy consumption is recognised as a key driver of GHG emissions, particularly in high-income countries. Expansion of the energy-intensive production sector, transport networks, higher living standards, and other related activities requires high energy production, and most high-income countries still rely on fossil fuels such as coal, oil, and natural gas. The amount and type of energy used to support economic and social activities play an important role in shaping global patterns of GHG emissions. Moreover, fossil fuel energy consumption is known to worsen environmental quality in high-income countries, as it increases CO_2 emissions [30]. Existing findings highlighted mixed evidence regarding the impact of energy consumption on emissions [31,32]. In the past decade, overall emissions have decreased by 17%, even though countries like Germany, the UK, and Poland remain the largest CO_2 emitters in the world [33]. However, renewable energy can contribute to emissions reduction, but the impact can differ in the short run and long run, and contrasting findings exist regarding its impact on emissions. Empirical findings suggest that, while renewable energy consumption decreases emissions in the short run by 18.8%, it eventually increases emissions by 28% in the long run [30]. In contrast, renewable energy reduces emissions in both the short run and the long run, highlighting strong technological advancement and energy efficiency [34–36]. Moreover, in most EU countries, there's a decrease in gross inland energy consumption [37,38], but in countries like Poland and Estonia, emissions still rise, accounting for nearly 80% of GHG emissions. Furthermore, existing studies have discussed the impact of energy consumption on emissions, aligning with the 3Ps theory. From the "people" perspective, energy consumption enhances living standards, supports the economy, and provides access to essential services such as healthcare and education. Further, energy contributes to increased GHG emissions and air pollution through the use of fossil fuels for energy generation, but using renewable energy can mitigate this environmental harm. From a "Profit" perspective, energy consumption involved in economic growth and the use of energy efficiency reduce production costs. Nevertheless, based on prior findings, the results regarding the effect of energy consumption on emissions are inconclusive, leaving a gap for further analysis. The effect of energy use on GHG emissions is exacerbated by continued dependence on fossil fuels, inefficient consumption patterns, and higher-level industrial and transportation activities, which sustain high emissions. From an atmospheric science perspective, fossil fuel-based energy consumption is a dominant contributor to air pollutant emissions, linking energy systems directly with ambient air quality deterioration.

2.3. Fertiliser use and GHG emissions

In past decades in high-income countries, the rapid expansion of agriculture has become a major global concern, and fertiliser use is a key driver that not only boosts crop yields but also significantly releases nitrous oxide, a potent GHG. In crop production systems, synthetic nitrogen fertilisers lead directly to N_2O emissions, while conventional tillage practices further intensify emissions by accelerating soil organic matter decomposition [39–41]. Furthermore, farming management practices play a key role in determining GHG emissions through biological factors such as soil moisture and organic matter dynamics [42,43]. Countries like China, India, the USA, and the EU-28 were responsible for 62% of total emissions [40] and also nitrification inhibitors that can reduce N_2O emissions without affecting crop yield [44]. In contrast, shifting from chemical to organic fertiliser reduces emissions because organic fertiliser does not require energy-intensive industrial production and enhances soil health [45]. Moreover, contrasting findings in the existing literature have discussed the impact of fertiliser consumption on GHG emissions using the 3Ps theory. From a planet perspective, higher fertiliser consumption contributes to ecological damage and higher emissions. Similarly, from the people's perspective, fertiliser consumption enhances food security and human well-being. Further, the profit perspective emphasises the farm productivity and economic growth through fertiliser management. Overall, the impact of fertiliser on GHG emissions depends on the type, quality, and management of fertiliser. Based on existing studies, there is a methodological gap in the study of the impact of fertiliser consumption on GHG emissions, and few studies have provided policy implications for mitigating agriculture-related

emissions. Although fertiliser consumption is mainly linked to higher GHG emissions, particularly in high-income countries due to excessive use of chemical fertilisers in agricultural practices, the impact depends on how well fertiliser is managed, soil conditions, and the adoption of sustainable measures. These emissions also contribute to atmospheric nitrogen cycles, influencing particulate matter formation and regional air pollution dynamics.

2.4. Trade openness and GHG emissions

TO is widely recognised as a key driver of environmental sustainability, as expanding international trade can directly affect production, energy use, and, consequently, GHG emissions. Empirical evidence on the relationship between TO and GHG emissions confirms that international trade significantly contributes to both increases and decreases in emissions. High-income countries are well integrated into global trade, stimulating economic growth and technological progress. A growing body of empirical evidence suggests that TO contributes negatively to CO_2 emissions through technology transfer and efficiency improvements, as well as through the promotion of renewable energy [46–48]. On the other hand, TO initially increases CO_2 emissions due to the industrial movement of goods and highly depends on fossil fuel for energy generation, but as income level rises, emissions decline as countries adopt cleaner technology and enforce environmental regulations [34,49,50]. Moreover, developed countries that have strict environmental policies shift their pollution-intensive industries to countries with weaker environmental regulations [51], thereby reducing emissions in developed countries; this supports the pollution haven hypothesis. Theoretically, the relationship between trade and emissions can be interpreted through the 3Ps theory [52]. TO contributes to economic growth (profit), while affecting environmental (planet) and, on the other hand, influencing social welfare (people). However, in high-income countries, most existing studies have examined the impact of TO on CO_2 emissions, while few have focused on GHG emissions. Moreover, a limited number of studies investigate the impact of trade on the growth of GHG emissions using the 3Ps theoretical framework.

2.5. Digitalisation and emissions

The association between digitalisation and GHG emissions has increasingly gained scholarly attention, particularly in high-income countries where advanced digital infrastructure is widely adopted. Despite technological advancements, these economies continue to emit, sparking debates over whether digital transformation improves or worsens environmental outcomes. Existing studies provide mixed evidence. Some research suggests that digitalisation increases emissions due to rising electricity consumption, the expansion of digital infrastructure, and higher energy demand associated with digital technologies [53–55]. Conversely, other studies find that digitalisation can contribute to emission reductions by improving carbon productivity through technological innovation and efficiency gains [56,57]. Evidence also highlights that digital technologies can reduce emissions by lowering energy demand, improving efficiency, and facilitating environmentally friendly practices such as electronic transactions and reduced paperwork [58,59]. The adoption of advanced and less emission-intensive technologies enabled by digitalisation has been shown to enhance resource efficiency and reduce carbon emissions [55]. Previous studies rely on general digitalisation indicators, which may overlook the varied impact of digital transformation on emissions. However, these divergent findings can be interpreted through the 3Ps theory, in which digital transformation simultaneously supports economic productivity while creating an environmental burden that can affect societal well-being. Consequently, the adaptive sustainability implications of digitalisation for GHG emissions in high-income countries have been less examined, particularly regarding how efficiency gains interact with digital infrastructure expansion. This highlights the need for further investigation into the dynamic and heterogeneous effects of digitalisation on GHG emissions in high-income economies. However, digitalisation might remain inconclusive on the impact of GHG emissions for high-income countries. While digital technologies can improve efficiency and reduce emissions, they can also increase energy demand and electronic waste, potentially offsetting environmental gains.

2.6. FDI and emissions

The relationship between FDI and GHG emissions has attracted considerable attention in numerous academic studies across the environmental and economic literature. FDI can significantly shape environmental outcomes as global investment flows rise. Empirical findings remain mixed across countries and sectors. Even though FDI plays a major role in economic growth in developed countries, globalisation and FDI flows could lead to pollution-intensive activities. However, in some cases, firms may choose to pay pollution taxes rather than invest in cleaner technologies [60], which helps explain why pollution remains high. A study focuses on how FDI associated with CO_2 emissions is time-varying, showing a decline in emissions that eventually gave way to increased GHG emissions in the period 2000–2015 [61], concluding that the environmental impact is not consistent over time. Much of the existing literature highlights this interrelation through the Pollution Halo Hypothesis. It shows how industries that transfer to host countries can harm the environment, especially in sectors with lower technological levels and environmental awareness. They accept dirty FDI to promote growth and employment [62,63]. Air pollution variables in high-income countries, such as TO, urbanisation, and energy consumption, were shown to worsen GHG emissions, making it challenging to achieve the SDGs. Considering the consequences of FDI on climate change, countries like Austria, Bulgaria, and Bahrain harm the environment by attracting polluting industries that rely heavily on fossil fuels, thereby producing more waste and unclean energy [8,64,65]. This causes environmental damage, making it unsustainable. These findings reflect the sustainability challenge proven in the 3Ps framework, where foreign investment simultaneously drives economic expansion while causing environmental pressure that can ultimately affect societal welfare. . The sustainability implications of FDI for emissions in high-income countries remain insufficiently explored. Several approaches often fail to address the FDI–emissions relationship using country-wise analysis, creating a noticeable gap in existing literature. However, the literature suggests that the impact of FDI on GHG emissions is not stable but highly depends on a country's regulatory strength and technological capacity. While FDI can support higher returns and economic stability, it is also associated with challenges and can be directed towards pollution-intensive activities.

2.7. Urbanisation and emissions

Urbanisation has emerged as a key driver of GHG emissions as expanding cities intensify energy demand, transportation, and industrial activities, leaving a gap in the literature regarding its relationship in high-income countries. Rapid urbanisation, particularly in emerging economies, is often associated with industrial expansion, improved access to education and healthcare, increased employment opportunities, and expanding transport networks [66], all of which contribute to rising emissions. Population agglomeration and changing lifestyles in urban areas also increase demand for infrastructure, industry, and transportation services [67,68], thereby further intensifying energy consumption and emissions. Studies indicate that rapid urban population growth can worsen environmental conditions by increasing consumption patterns and the use of consumer products that release harmful chemicals into the atmosphere (Chien et al., 2022). In contrast, some studies highlight that sustainable or "green urbanisation" can promote environmentally friendly industrial development and improved urban

efficiency [69]. Well-planned urbanisation in developed economies can contribute to emission reductions through improved infrastructure, efficient transport systems, and even optimised regional food distribution networks [70]. Similarly, evidence from high-income countries found that a 1% increase in urbanisation can reduce CO_2 emissions when supported by strong environmental policies and effective governance [71,72]. However, the impact of urbanisation on emission levels can be uncertain. These findings reflect the 3P's perspective, where even though urbanisation promotes economic growth, there can be other threats, such as pressure on housing and public services, leading to poor environmental conditions. Despite these insights, many existing studies focus on individual countries and may overlook the varied effects of urbanisation across countries and the influence of different policies on emissions. Therefore, the evolving impact of urbanisation on GHG emissions is such that urban growth leads to environmental degradation. However, the impact of urbanisation on emission levels can be uncertain. Even though urbanisation is often driven by better opportunities, infrastructure, and living standards, there can be other threats associated with rapid urban growth, particularly pressure on housing and public services, leading to poor environmental conditions. Urbanisation further intensifies atmospheric pollution through increased transport emissions, industrial activities, and energy demand, making cities critical hotspots for air quality management.

2.8. Summary of literature and conceptual framework

The 58 studies reviewed in this literature survey were published between 2007 and 2026. Fig. 2 illustrates the total number of studies examining the individual effects of these determinants on GHG emissions. Existing studies have extensively examined individual drivers of emissions, particularly economic growth, energy consumption, and trade openness. However, relatively few studies integrate these determinants within a unified framework, while focusing on emissions growth rather than levels. Moreover, cross-country heterogeneity in high-income economies remains underexploited. This study contributes to the literature by combining panel and country-level analysis using updated data through 2024 and focusing on emission growth dynamics to provide a more comprehensive and policy-relevant understanding of environmental sustainability.

The conceptual framework of the study illustrates a unidirectional relationship in nature, as represented in Fig. 3, with hypothesised independent and dependent variables that are assumed to affect the dependent variable.

2.9. Hypothesis & theoretical framework

This analysis uses seven independent variables, each examined for its individual impact on the dependent variable. Thus, there are seven hypotheses.

H_1: Per capita GDP growth positively affects GHG emission growth.
H_2: Energy consumption positively affects GHG emission growth.
H_3: Fertiliser Consumption positively affects GHG emission growth.
H_4: Trade openness negatively affects GHG emission growth.
H_5: Digitalisation negatively affects GHG emission growth.
H_6: FDI has an ambiguous (non-linear) effect on GHG emissions growth.
H_7: Urbanisation has an uncertain but context-dependent effect on GHG emissions growth.

The 3P's framework (People–Planet–Profit), also known as the Triple Bottom Line, emphasises that sustainable development must balance economic growth (profit), environmental protection (planet), and social well-being (people) [73]. Within this perspective, economic drivers such as GDP growth, TO, FDI, digitalisation, and urbanisation represent the profit dimension, reflecting the expansion of economic activities that can increase production and technological progress. The theoretical framework integrates the growth environmental nexus, which suggests that economic expansion increases environmental pressure through scale effects; the energy emission relationships, which highlight fossil fuel dependency as a key driver of emissions; and the pollution haven/halo hypothesis, which explains how trade and foreign investment influence environmental outcomes. Based on these theoretical foundations, the study develops a directional hypothesis linking each variable to emission growth.

3. Data and methodology

3.1. Sample selection and justification

This study estimates the impact on GHG emissions growth from per capita GDP growth rate, Energy Consumption, Fertiliser Consumption,

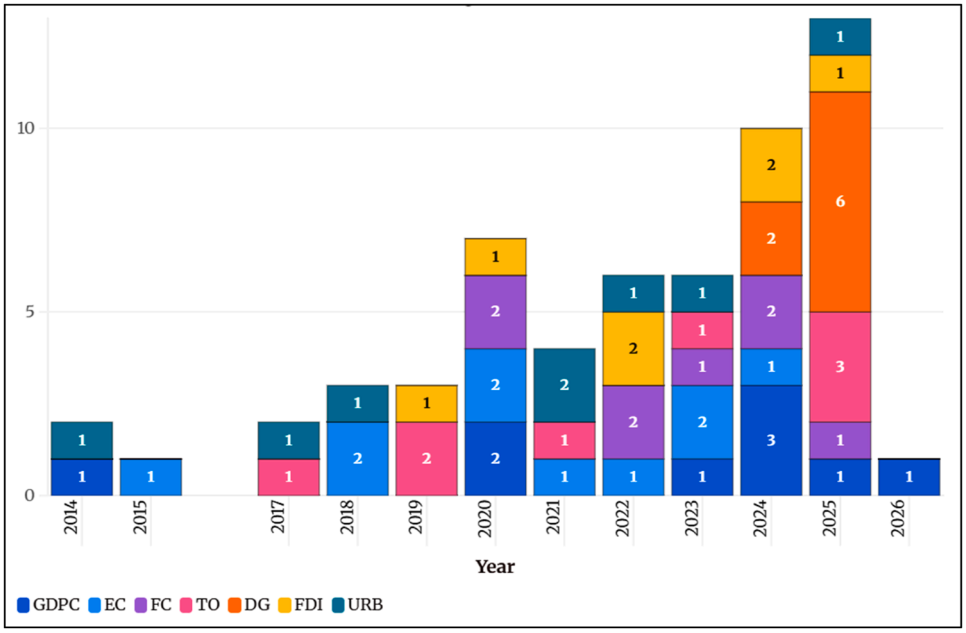


Fig. 2. Distribution of research articles based on variables from 2007 to 2026. Source: Authors' illustration.

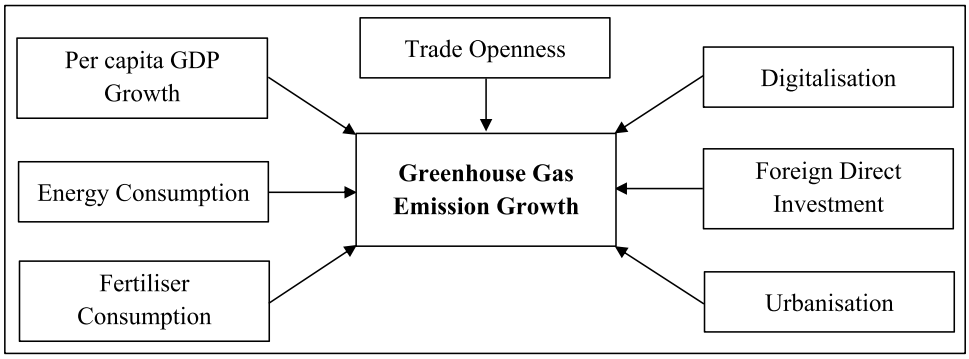


Fig. 3. Conceptual framework. Source: Authors' illustration.

Trade Openness, digitalisation representing Internet Usage, Foreign Direct Investment, and Urbanisation across 51 countries in the high-income group over the period of 2000 – 2024. Panel data are widely used in the literature to examine environmental and economic factors affecting GHG emissions [74].

For the analysis, data are collected from Our World in Data and the World Bank, as shown in Table 1, which lists the data sources for GHG emissions growth and the independent variables. However, some countries have been omitted, such as Andorra, Liechtenstein, Macao, Nauru, and Taiwan, due to insufficient data availability. To handle minor missing values, linear interpolation, linear extrapolation, and backwards extrapolation techniques have been employed. In this study, the dependent variable represents the growth rate of emissions; thus, the estimated coefficient captures the marginal change in emission growth dynamics rather than absolute emission level scalability. The GHG emission growth rate was calculated as the growth rate of GHG emissions, expressed as a decimal (the proportion of the previous year's value). GHG emissions are used as a proxy for broader atmospheric emission intensity, as they are closely associated with co-emitted air pollutants that affect atmospheric composition. Additionally, fertiliser consumption and FDI are divided by 100 to improve the comparability of coefficients. Based on a comprehensive review of the relevant literature, this study has adopted thousands of kilowatt-hours per person as the unit of energy consumption to reduce decimal complexity in the analysis. The dataset used for this analysis is provided in Appendix 1.

The dependent variable is measured as the annual growth rate of per capita GHG emissions rather than the absolute emission level; therefore, the estimated coefficients should be interpreted as marginal associations with emission growth dynamics, not as changes in absolute tonnes of emissions. The explanatory variables are retained in their standard level, percentage or share forms because the study examines whether existing economic structure, energy use, trade exposure, digitalisation, investment dependency and urbanisation conditions are associated with changes in emission growth. Accordingly, the interpretation focuses on direction, statistical significance, and relative magnitude. This approach also helps distinguish whether a factor accelerates or slows annual emission growth even when absolute emission levels differ substantially across countries.

Table 1
Data source selection.

Variable	Definition	Measurement	Source
GHGGR	Greenhouse Gas Emissions Growth rate	Growth of tonnes of CO_2 equivalents per person	Our World in Data https://ourworldindata.org/grapher/per-capita-ghg-emissions
PGDP	Per capita GDP growth	GDP per capita growth (annual %)	World Bank https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG
EC	Energy Consumption	Kilowatt-hours per 1000 people	Our World in Data https://ourworldindata.org/grapher/per-capita-energy-use
FC	Fertiliser Consumption	Kilograms per 100 hectares of arable land	World Bank https://data.worldbank.org/indicator/AG.CON.FERT.ZS
TO	Trade Openness	Trade as a share of GDP	Our World in Data https://ourworldindata.org/grapher/trade-as-share-of-gdp
DG	Digitalisation	Internet usage (% of population)	World Bank https://data.worldbank.org/indicator/IT.NET.USER.ZS
FDI	Foreign Direct Investment	Net inflows as a share of GDP (in hundreds)	World Bank https://data.worldbank.org/indicator/BX.KLT.DINV.WD.GD.ZS
URB	Urbanisation	% of total population	World Bank https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

Source: Authors' compilation.

3.2. Econometric model specification

To examine the impact of per capita GDP growth, energy consumption, fertiliser consumption, TO, digitalisation, FDI, and urbanisation on GHG emissions growth, the study employs Panel Regression and Multiple Linear Regression (MLR). Eq. (1) presents the panel regression model employed in this study to examine the overall impact of key factors on GHG emissions growth in the high-income group. This analytical technique combines cross-sectional and time-series data to illustrate how variables evolve over time [75]. Additionally, panel regression accounts for unobserved heterogeneity, ensuring the reliability of the analysis's findings. Potential endogeneity may arise due to reverse causality, simultaneity, and omitted variables, particularly between emission growth and economic growth, energy consumption, trade openness, and FDI. Although the fixed-effects model controls for time-invariant country-specific heterogeneity, it may not fully address dynamic persistence and simultaneity. Therefore, this study uses a two-step system GMM estimator as an additional robustness check

$$\mathrm{GHGGR}_{it} = \beta_0 + \beta_1 \mathrm{PGDP}_{it} + \beta_2 \mathrm{D_EC}_{it} + \beta_3 \mathrm{FC}_{it} + \beta_4 \mathrm{TO}_{it} + \beta_5 \mathrm{INT}_{it} + \beta_6 \mathrm{FDI}_{it} + \beta_7 \mathrm{FDI}^2{}_{it} + \beta_8 \mathrm{URB}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In the following multiple linear regression equation, as shown in Eq. (2), energy consumption was converted to a first difference to achieve stationarity. Further, digitalisation is represented by internet usage (INT), and foreign direct investment is represented by the squared term FDI^2. The term i represents the countries of the study and t indicates the year, while β_0 represents the intercept, μ_i indicates the individual-specific heterogeneity and time-invariant. λ_t captures time-specific

effect and individual-invariant, and the error term is depicted by ε_{it} .

$$\mathrm{GHGGR}_t = \beta_0 + \beta_1\ \mathrm{PGDP}_t + \beta_2\ \mathrm{D_EC}_t + \beta_3\ \mathrm{FC}_t + \beta_4\ \mathrm{TO}_t + \beta_5\ \mathrm{INT}_t + \beta_6\ \mathrm{FDI}_t + \beta_7\ \mathrm{FDI}^2{}_t + \beta_8\ \mathrm{URB}_t + \varepsilon_t \quad (2)$$

Importantly, the inclusion of country-level multiple linear regression allows for the identification of heterogeneity in the determinants of emissions, thereby offering more nuanced policy insight. The analysis provides broader insight into the influence of key determinants on GHG emissions and supports policymakers in formulating country-level strategies.

3.3. Pre-estimation diagnostic

This analysis was conducted using Stata (version 17.0) to generate the results, and the visualisations were created using Flourish Studio, Microsoft Excel, and PowerPoint. A unit root test was conducted using the Im-Pesaran-Shin (IPS) test to assess the stationarity of the data series, as shown in Appendix 2: Table A1. Results demonstrated that all variables were stationary except energy consumption, as the p-values did not exceed the 5% significance level. To address this issue, the first difference transformation was applied to energy consumption, which passed the stationarity test. The multicollinearity test was conducted using the Variance Inflation Factor (VIF) to assess multicollinearity among the independent variables. Further, if multicollinearity exists, the

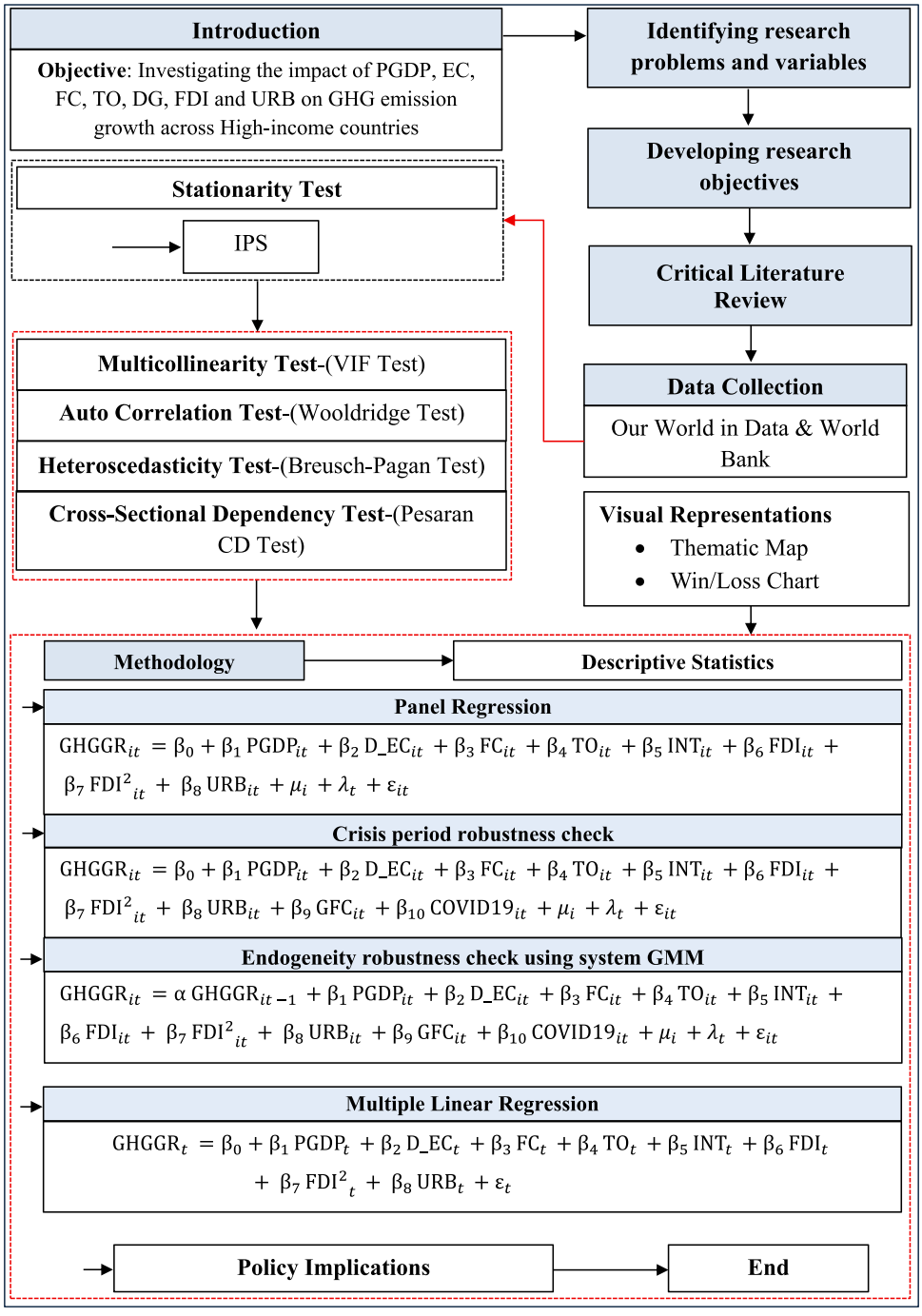


Fig. 4. Research overview workflow diagram. Source: Authors' illustration.

VIF will be greater than 10 [76]; no multicollinearity was detected in the study, as shown in Appendix 2: Table A2. Moreover, an autocorrelation test was conducted to ensure there is no correlation among the model's residuals, as shown in Appendix 2: Table A3. Additionally, heteroscedasticity was tested to check whether the variance of the error terms is constant across observations; as shown in Appendix 2: Table A4. The heteroskedasticity tests indicate significant variance heteroskedasticity ($Chi^2 = 925.77$, P-value = P < 0.01). The presence of heteroscedasticity can lead to biased standard errors and unreliable results; therefore, robust standard errors were used in the regression models. The cross-sectional dependence among countries was assessed using the Pesaran CD test, as shown in Appendix 2: Table A5. Accordingly, the test confirms strong cross-sectional dependency (CD-test 31.54, P-value -P < 0.01), justifying the use of Driscoll-Kraay standard errors. Fig. 4 illustrates the process from data collection and model estimation to policy implications, providing an overview of this research through a workflow diagram.

3.4. Estimation strategy

The findings of the panel data specification test relating the Fixed Effect (FE) model and the Random Effect (RE) model based on Eq. (1) are presented in Appendix 2: Table A6. The F-test was conducted to select between the Pooled Ordinary Least Squares (POLS) and FE models, and the Lagrange Multiplier (LM) test was employed to compare POLS with the RE model. After conducting both the F-test and LM test, the null hypothesis was rejected, implying that the POLS model is unsuitable for this analysis. Finally, the Hausman test was conducted to determine whether the RE or FE model was appropriate. Based on the outcome of the Hausman test, the FE model was identified as the preferred model for the study.

4. Results

4.1. Descriptive statistics and trends

For a better understanding, the summary of descriptive statistics for high-income countries is demonstrated in Appendix 2: Table A7. The complete data set contains 1275 observations covering GHG growth, per capita GDP growth, energy consumption, fertiliser consumption, TO, digitalisation, FDI, and urbanisation. The results of descriptive statistics show clear differences across the variables. The GHG growth recorded a negative mean of −0.008, and TO had the highest average of 114.342, measured as a share of GDP. Compared to other variables, per capita GDP recorded the second-lowest average value of 1.737, but values vary widely, ranging from −20.33 to 23.46. Among the variables, urbanisation recorded the second-highest average, at 78.027.

4.2. Baseline panel regression results

A panel regression model was estimated to investigate the overall impact of the variables on GHG emissions growth. Findings related to Driscoll-Kraay standard errors with FE are included in Table 2. Considering per capita GDP growth, while holding other variables constant, time invariant unobserved heterogeneity controlled by FE, a one-unit increase in per capita GDP growth leads to an increase in the growth rate of GHG emissions by 0.0053 tonnes of CO_2 equivalents per person (P = 0.000), suggesting that GDP largely contributes to GHG emissions in high-income countries. The positive relationship between economic growth and emissions growth reflects the scale effect, where increased production and consumption intensify energy use and emissions.

Turning to energy consumption during the period 2000–2024, a 1 unit increase in the change of energy consumption leads to an increase in the growth rate of GHG emissions by 0.0030 tonnes of CO_2 equivalents per person (P = 0.004) while holding other factors constant, assuming individual-specific effects are correlated with independent variables, while controlling for unobserved heterogeneity, suggesting a shift to energy efficiency sources. Since energy consumption is included in the first difference, the estimated coefficient reflects short- run changes in energy use and their impact on emissions growth, rather than long- term level effects. Energy consumption remains the dominant driver of emissions, reflecting continued reliance on fossil fuels in high-income economies. This also implies an increase in atmospheric pollutant emissions due to fossil fuel combustion, reinforcing the link between energy use and degraded air quality. Moreover, in fertiliser consumption, the findings indicate that GHG emissions growth would increase by 0.0032 tonnes of CO_2 equivalents per person at 1% significance level, suggesting that higher fertiliser consumption is associated with a rise in GHG emissions growth. TO would contribute to a decrease of 0.0005 tonnes of CO_2 equivalents per person at the 1% significance level, reflecting that the adoption of cleaner technology in trade in high-income countries would affect environmental degradation. Lastly, a one-unit increase in digitalisation leads to a decrease in the growth rate of GHG emissions by 0.0005 tonnes of CO_2 equivalents per person (P = 0.044), suggesting that adoption of digital technology contributes to reducing emissions. Although TO and digitalisation are statistically significant, their estimated coefficients are relatively small in magnitude, indicating modest marginal effects on emission growth. This suggests that while these factors contribute to emission mitigation, their economic impact is limited compared to dominant drivers such as energy consumption and economic growth. The negative effects suggest the efficiency gains and technology transfer, although they are of a relatively small magnitude, indicate limited economic impact compared to the primary drivers. Fig. 5:A &:B visualise the thematic map of GHG emissions growth for the year 2024 of 51 countries of the high-income group.

Since the study covers the period 2000 to 2024, additional robustness checks were conducted to examine whether the baseline findings are sensitive to major global shocks and potential endogeneity concerns.

Table 2
Driscoll-Kraay standard errors with random-effect and fixed-effect model estimates for high-income countries.

Variable	High-Income group	
	RE	FE
PGDP	0.0052***	0.0053***
	(0.0010)	(0.0009)
D_EC	0.0031***	0.0030***
	(0.0007)	(0.0007)
FC	0.0007	0.0032***
	(0.0008)	(0.0010)
TO	−0.0001***	−0.0005**
	(0.00003)	(0.0001)
INT	−0.0004**	−0.0005**
	(0.0002)	(0.0002)
FDI	0.0042	0.0041
	(0.0035)	(0.0043)
FDI^2	−0.0008	0.0004
	(0.0009)	(0.0012)
URB	0.00004	0.0028
	(0.0003)	(0.0017)
Constant	0.0187	−0.1535
	(0.0250)	(0.1153)
No. of Countries	51	51
No of years	25	25
R^2 Within	-	0.1156
R^2 Overall	0.1111	-

Note: *significant at 10%, **significant at 5%, ***significant at 1% significance level. Standard errors are represented in parentheses.

4.3. Crisis period robustness check

To address possible heterogeneity in the emission growth rates over

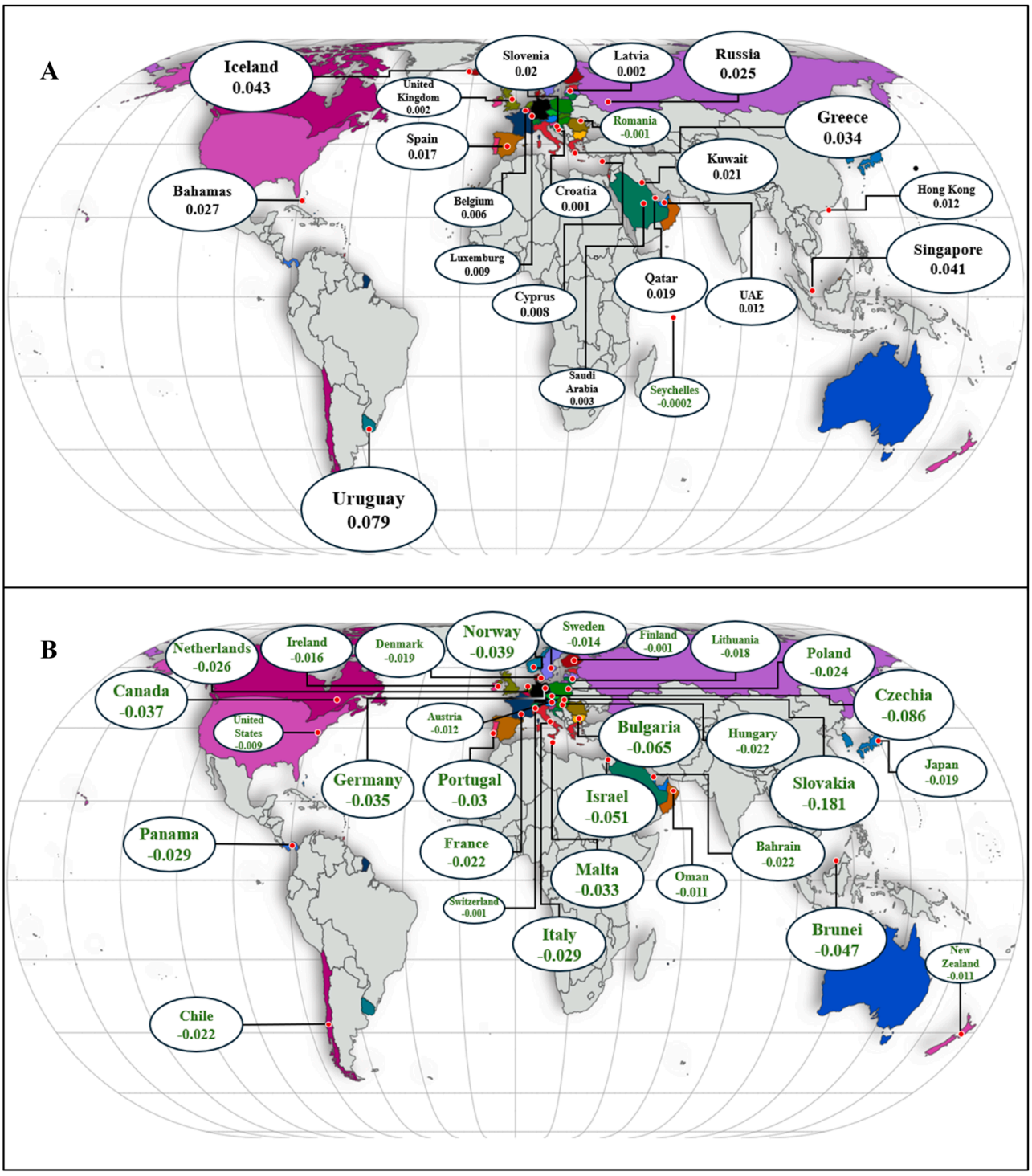


Fig. 5. Greenhouse gas emissions growth for the year 2024 for high-income countries. Note: The oval shape showing the GHG growth sizes changes based on the GHG emissions growth values for 2024. Values in black represent GHG emission growth, and green values represent GHG emission decline for the year 2024. Source: Authors' illustration based on Our World in Data.

the 2000 to 2024 period, an additional fixed-effect model with Driscoll-Kraay standard errors was estimated by including crisis-period dummy variables for the global financial crisis and the COVID-19 period. The global financial crisis dummy captures the 2008 to 2009 period, while the COVID-19 dummy captures the 2020 to 2021 period. This specification allows the analysis to examine whether the baseline relationships are driven by exceptional macroeconomic or pandemic-related shocks (Tables 3 and 4).

The crisis-period robustness results remain broadly consistent with the baseline fixed-effect estimates. Per capita GDP growth, changes in energy consumption and fertiliser consumption continue to have a positive and statistically significant effect on GHG emission growth. In contrast, trade openness and digitalisation remain negative and statistically significant. The GFC and COVID-19 dummy variables are statistically insignificant, indicating the main results are not driven solely by these exceptional crisis periods. Therefore, the baseline findings are robust after controlling for major time-period shocks.

Table 3
Crisis period robustness check using fixed-effects with Driscoll-Kraay standard errors.

Variable	High-income group FE
PGDP	0.0053***
	(0.0010)
D_EC	0.0030***
	(0.0007)
FC	0.0031***
	(0.0010)
TO	−0.0005**
	(0.0002)
INT	−0.0005**
	(0.0002)
FDI	0.0042
	(0.0043)
FDI^2	0.0003
	(0.0013)
URB	0.0027
	(0.0017)
GFC	−0.0005
	(0.0048)
COVID-19	0.0027
	(0.0071)
Constant	−0.1498
	(0.1143)
No. of Countries	51
No of years	25
R^2 Within	0.1157

Note: *significant at 10%, **significant at 5%, ***significant at 1% significance level. Standard errors are represented in parentheses. GFC represents the 2008 to 2009 global financial crisis dummy, and COVID-19 represents the 2020 to 2021 pandemic period dummy.

4.4. Endogeneity robustness check using system GMM

Potential endogeneity may arise from simultaneity, omitted variables and reverse causality between GHG emission growth and key explanatory variables such as economic growth, energy consumption, trade openness and FDI. Although the fixed-effects model controls for time-invariant country-specific heterogeneity, it may not fully address dynamic persistence and simultaneity. Therefore, a two-step system GMM estimator was employed as an additional robustness check. The lagged dependent variable and the main explanatory variables were treated as potentially endogenous, while the instrument count was restricted using the collapse option to reduce instrument proliferation.

The system GMM results provide additional support for the baseline findings. Per capita GDP growth remains positive and statistically significant, indicating that economic expansion continues to increase GHG emission growth after accounting for potential dynamic endogeneity. Changes in energy consumption also remain positive and marginally significant, further confirming the role of energy use in emission-growth-dynamics. Urbanisation becomes negative and marginally significant in the dynamic specification, suggesting that urbanisation may reduce emission growth in some high-income economies when supported by efficient infrastructure and environmental regulations. The AR (1) test is significant, as expected in first-differenced GMM models, while the AR (2) test is insignificant, indicating no evidence of second-order serial correlation. The Hansen test does not reject the validity of the instruments, and the number of instruments remains below the number of country groups. Therefore, the system GMM results reduce endogeneity concerns and support the robustness of the main conclusions.

4.5. Country-level multiple linear regression

After examining the aggregate panel-level relationships and robustness checks, country-level multiple linear regression was conducted to identify heterogeneity in the determinants of GHG emissions growth across 51 high-income countries. This country-level analysis complements the panel estimates by showing whether the direction and significance of each determinant vary across national contexts. The findings of MLR for the high-income countries are presented in Appendix 2: Table A8. Per capita GDP growth has a significant positive impact on GHG emissions growth in countries such as Austria, the Bahamas, Qatar, and Singapore, suggesting that economic growth affects environmental pressures. Countries such as Bahrain, Finland, New Zealand, and others show an insignificant impact, implying that per capita GDP growth doesn't affect the growth of emissions. Changes in energy consumption have a positive and significant impact on the growth of GHG emissions across countries such as Bahrain, Belgium, and Israel, which are high due to dependence on fossil fuels, natural gas, and coal for energy generation. Norway and New Zealand demonstrate a negative impact on the growth of GHG emissions. Fewer countries fall into the insignificant cluster, indicating that energy use is a key driver of emissions in high-income countries. Turning to fertiliser consumption, the results show that most countries experience a positive impact of fertiliser consumption on growth of GHG emissions, indicating that the use of synthetic fertilisers largely contributes to increased GHG emissions.

A mixed impact of TO on the growth of GHG emissions can be demonstrated across high-income countries. New Zealand and Portugal demonstrate a positive impact, while the Bahamas, Italy, and Japan represent a negative impact on the growth of GHG emissions. This indicates that some countries have implemented trade policies and barriers to control trade, while others have not, which varies the consequences for the environment. Digitalisation has a negative impact on the growth of GHG emissions in countries such as Finland and Japan, suggesting adaptation to new technologies and advancements. While a

Table 4
Endogeneity robustness check using two-step system GMM.

Variables	High-income group Coefficient
GHGGR $_{it-1}$	−0.1069
	(0.0889)
PGDP	0.006**
	(0.0025)
D_EC	0.0128*
	(0.0069)
FC	0.0012
	(0.0068)
TO	0.0001
	(0.0002)
INT	−0.0002
	(0.0004)
FDI	0.0414
	(0.0421)
FDI^2	−0.0045
	(0.0095)
URB	−0.0046*
	(0.0025)
GFC	0.0192
	(0.0217)
COVID-19	0.0156
	(0.0110)
Constant	0.3386*
	(0.1789)
No of observations	1224
No of countries	51
Wald χ^2	108.98***
Instruments	21
AR(1) p-value	0.006
AR(2) p-value	0.211
Hansen p-value	0.429
Sargan p-value	0.026

Note: *significant at 10%, **significant at 5%, ***significant at 1% significance level. Standard errors are represented in parentheses. The Hansen test is reported as the preferred instrument validity test under the robust two-step GMM specification.

significant negative impact is evident in Bahrain and Portugal, these countries contribute to environmental degradation due to inefficient use of technology. Fig. 6 illustrates a win/loss chart for 51 countries in the high-income group from 2000 to 2024. This presents whether GHG emissions have grown or shrunk over the years.

When it comes to FDI, it represents a nonlinear relationship (FDI^2) in some countries. During the initial stage in Belgium, a negative impact is observed on GHG emissions growth, but after the threshold, FDI^2 shows a positive impact, whereas Singapore demonstrates the opposite. Lastly, in urbanisation, a positive and significant impact is represented in Japan on GHG emissions growth, while several countries such as Bahrain, Bulgaria, Portugal, and Kuwait demonstrate a negative and significant impact on GHG emissions Growth due to effective urban planning.

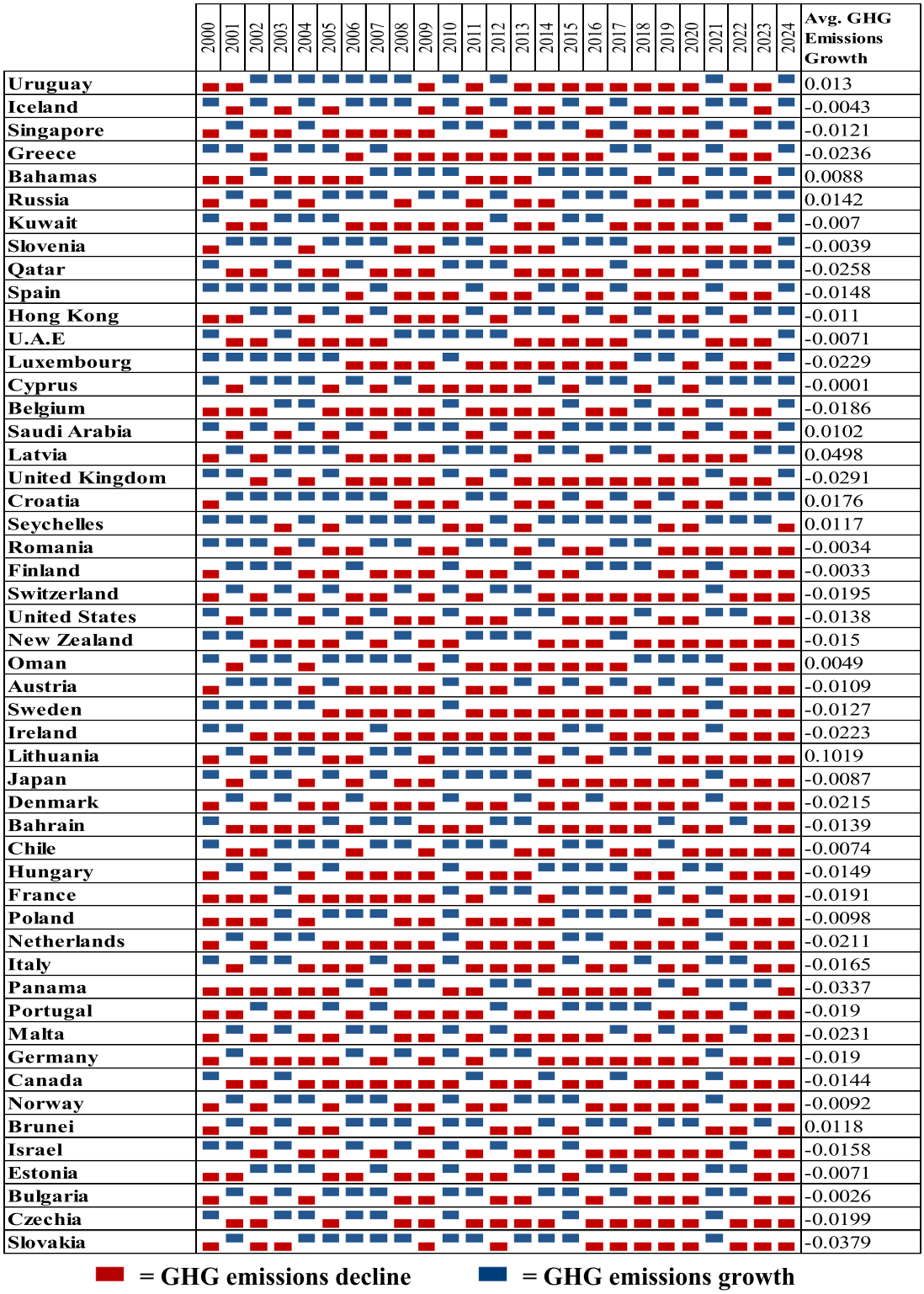


Fig. 6. Win / Loss chart identifying GHG emissions growth or decline for high-income countries from 2000 to 2024. Note: The colour scale ranges from maroon (GHG emissions growth (+)) to dark blue (GHG emissions decline (-)). Source: Authors' illustration based on Our World in Data.

5. Discussion

Overall, the findings demonstrate that economic expansion, fertiliser use, and energy use are major factors influencing GHG emissions growth among high-income countries. However, TO contributes to reducing emissions. The evidence supports the three pillars of the 3Ps theory in different ways.

The magnitude of the estimated coefficients should be interpreted in relation to the growth-rate form of the dependent variable. Since GHG emission growth is measured as an annual proportional change, the coefficients are expected to be numerically small. For example, the coefficient of per capita GDP growth indicates that a one-unit increase in GDP per capita growth is associated with a modest increase in annual GHG emission growth, rather than a large change in absolute tonnes of emissions. Similarly, the negative coefficients of trade openness and digitalisation indicate that these factors are associated with reductions in emission growth, but their marginal effects are relatively small. Therefore, the findings should be interpreted by considering both statistical significance and economic magnitude. In this regard, economic growth, energy consumption, and fertiliser consumption emerge as stronger practical drivers of emission growth, while trade openness and digitalisation provide statistically significant but economically modest mitigation effects. Importantly, while the results indicate a positive association between economic growth and emission growth, this relationship is not universal. In some high-income economies, decoupling has been observed where economic growth occurs alongside declining emissions due to technological advancement and environmental policies. Further, across high-income countries, economic expansion contributes to higher emissions through industrial activities and a consumption-intensive lifestyle. Even though these countries are economically advanced, they depend heavily on fossil fuels for industry, thereby contributing directly to CO_2 emissions [52,77]. Moreover, high-income individuals should prioritise transitioning to clean energy sources, adopting fuel-efficient transportation, and changing unnecessary consumption habits. The findings contribute to the 3Ps theory. Under the "People" pillar, increasing economic expansion enhances high living standards and well-being. On the other hand, it significantly increases GHG emissions and climate-related health risks. The pillar of "Profit" highlights that economic expansion reflects industrial expansion and enhances profitability, but these activities contribute to high emissions. Further, the third "Planet" dimension of economic expansion contributes to environmental unsustainability and higher emissions.

The positive impact of energy consumption on emission growth reflects the continued reliance on fossil fuels in many high-income economies. However, this relationship may weaken or reverse in countries with a high share of renewable energy, highlighting the importance of energy structure in shaping emission outcomes. Energy demand is high in developed economies due to industrial activity. Countries continue to use fossil fuels for energy generation, which directly impacts GHG emissions. Further, growth in urbanisation and high living standards contributes to high energy use in households. However, the environmental damage depends on the energy generation structure and policies used. Existing past studies also confirm that EC is the main driver of emissions in high-income countries [78,79]. Even though EC contributes to human well-being, it increases the country's emissions under the "People" dimension of the 3Ps theory. Further, EC enhances the county's "Profit" pillar through higher industrialisation, exports, and energy-driven innovation and production, but it contributes to higher emissions. Within the "Planet" dimension, EC contributes to environmental degradation and leads to climate change, including air pollution and ecosystem damage. However, high-income countries need to shift to renewable energy sources such as solar, wind, and hydropower, as well as to efficient energy use and smart energy management, to achieve sustainable goals [80].

The positive impact on GHG emissions growth from fertiliser consumption results from the excess use of synthetic fertiliser to maximise crop yields, which releases N_2O. Furthermore, the rise in emissions is due to high-energy fertiliser production and transport, which use fossil fuels [44,81]. Under the pillar of "People", FC contributes to agricultural growth, but it also poses risks to human health. Similarly, in the "Profit" dimension, fertiliser use enhances agricultural profitability, but it also increases emissions. On the other hand, under "Planet", FC is essential for agricultural productivity, but it contributes to higher emissions. These countries should adopt nitrification-inhibitor-enhanced fertiliser or biofertilisers, along with strict environmental policies.

Observed outcomes signify that the impact of TO on GHG emission growth is negative in high-income countries. They use modern energy-efficient machines in trade and strictly follow environmental rules and regulations. Furthermore, countries have adopted cleaner production methods to minimise emissions. These countries import cement and chemicals from low-income countries, which could reduce CO_2 emissions since high-income countries have limited access due to strict environmental policies. Within the 3Ps framework, TO contributes to environmental sustainability. From the "People" perspective, improved employment quality, reduction in pollution from TO, to enhance the human well-being. The "Profit" pillar is sustained through export competitiveness and productivity gains. Further, under the "Planet" dimension, TO enhance environmental sustainability. But if high-income countries heavily depend on oil and diesel for long-distance transportation in international trade, this can enhance GHG emissions growth [52,82].

Similarly, the mitigating impact of digitalisation on GHG emissions growth in high-income countries can arise from enhanced operational efficiency and the adoption of advanced technologies, such as smart systems and artificial intelligence, which reduce energy consumption and resource waste. Moreover, strong environmental regulation in high-income countries encourage to adopt cleaner and more sustainable technologies. In addition, digitalisation enhances carbon productivity through technological innovation, accelerating progress in renewable energy technologies and low-carbon solutions that increase emissions mitigation and energy efficiency [83]. The 3Ps sustainability framework provides a comprehensive approach to understanding how digitalisation influences environmental factors, economic, and social development simultaneously. From the "People" perspective, digitalisation has enhanced education, sustainable consumption behaviour, social inclusion, and employment opportunities, thereby enhancing human well-being. At the same time, from a "Profit" perspective, digitalisation enhances the economy by improving productivity, promoting technological innovation, and improving energy and resource efficiency. This facilitates reducing production costs, minimising waste, and adopting cleaner technologies, thereby enabling companies to achieve higher profitability by reducing environmental harm. From the "Planet" dimension, digitalisation contributes to mitigating emissions and enhancing environmental sustainability.

However, the non-linear term of FDI shows an insignificant impact on GHG emissions growth. This is due to strict environmental policies, and most foreign investments are focused on the service and technology sectors, which generate less pollution than other activities. Urbanisation also does not have a statistically significant impact on the growth of GHG emissions. In high-income countries, they already exhibit a high level of urban development and management. Further, efficient urban infrastructure, urban density, and strong urban environmental policies contribute to low emissions in these countries. This may reflect the structural characteristics of high-income economies where foreign investments are concentrated in less emission-intensive sectors and urban systems are relatively efficient and well-regulated. However, the findings reflect emission source dynamics that influence both greenhouse gas emission and air pollution, such as particulate matter and nitrogen oxides. Although the study does not explicitly model atmospheric concentrations.

6. Policy implications

From an atmospheric management perspective, the identified drivers highlight the need for integrated emission control strategies that simultaneously target greenhouse gases and co-emitted air pollutants. Policies addressing energy systems, agriculture, and urban development can therefore yield co-benefits for both climate mitigation and air quality improvement.

6.1. Short-term policy implications

The study's findings indicate that several countries experience frequent periods of emissions growth, underscoring the need for immediate policy action. For countries such as the United States, Canada, Germany, Japan, and other industrialised economies, short-term policies should focus on rapidly reducing emissions without disrupting economic performance. Given the strong positive impact of energy consumption on emissions growth, policies promoting non-renewable energy adoption and energy efficiency improvements are essential to mitigate emissions in high-income economies. And strengthening energy efficiency standards in the industrial and transportation sectors can help reduce energy use and emissions in the short run. Policies that promote electric vehicles, improved public transport systems, and cleaner fuel standards are also essential to lower emissions from the transport sector, which remains a major contributor in many high-income countries. Furthermore, strengthening carbon pricing mechanisms such as carbon taxes or emissions trading schemes can encourage firms to adopt cleaner production technologies. Collectively, these short-term measures can help high-income countries with persistently high emissions move towards sustainability while maintaining economic stability.

6.2. Long-term policy implications

This study is mainly linked with United Nations SDGs, SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Aligning SDG-oriented policies helps governments design integrated climate strategies, promote sustainable consumption and production patterns. High-income countries can achieve long-term reductions in GHG emissions while maintaining economic performance and resilience, ensuring a sustainable pathway toward achieving global climate targets.

The country-level results can be translated into policy-relevant patterns rather than interpreted only as individual country outcomes. First, growth and energy-driven countries require strong renewable energy substitution, industrial energy efficiency standards and cleaner production technologies. Second, fertiliser-driven countries require precision agriculture, improved nitrogen management, nutrification inhibitors and gradual movements towards organic or bio-fertiliser alternatives. Third, countries where trade openness and digitalisation reduce emission growth should strengthen green trade channels, low-carbon logistics, digital energy-management systems, and technology diffusion. Fourth, countries with significant FDI or FDI^2 effects require an investment scanning mechanism that prioritises green FDI and discourages pollution-intensive capital inflows. Finally, urbanisation-sensitive countries require compact urban planning, low-emission public transport and energy-efficient building systems. This grouped interpretation provides more actionable policy guidance than a general statement that each country requires a specific decarbonisation strategy.

7. Conclusion

This study explores the impact between key socioeconomic factors on GHG emissions by employing panel regression and multiple regression models for high income countries over the period of 2000–2024, The key findings exhibit a significant positive impact from economic growth, energy consumption, and fertiliser consumption on GHG emission growth, suggesting that industrial production, energy intensive activities from fossil fuel use and agricultural inputs continues to generate significant impact on emissions even in the advanced economies. Conversely, TO supports global efforts to reduce GHG emissions through technology diffusion and efficiency improvements, and digitalisation similarly negatively affects emissions. These findings confirm that these factors remain central drivers of emissions in high-income economies while highlighting the need for strong environmental frameworks that align with the 3Ps, or the triple bottom line theory.

This study contributes to the literature by reframing the analysis from emission levels to GHG emission growth dynamics in high-income countries. Rather than claiming novelty solely from updated data or standard econometric techniques, the study provides a growth-rate interpretation of how macroeconomic, structural, technological, investment-related and demographic factors are associated with annual changes in emissions. The findings also distinguish between statistically significant effects and economically modest marginal effects, which is important when the dependent variable is measured as an annual growth rate. In addition, the study contributes by combining aggregate panel-level evidence with country-level estimates and grouped policy patterns. This approach helps identify dominant emission-growth channels, such as energy-driven, fertiliser-driven, trade/digital mitigation, FDI-sensitivity, and urbanisation-sensitive patterns among high-income countries.

However, the study addresses several limitations despite the valuable insights. The study covered 25 years of data and was limited to 51 high-income countries due to insufficient data for several others. Second, using country-level data may overlook important emission trends across sectors and regions, which weaken the effectiveness of policy recommendations. The relatively low explanatory power of the model may reflect the inherent volatility of growth rate variables, as well as omitted factors such as renewable energy adoption, environmental policy stringency, technological innovation, and climate-related shocks. These factors may explain additional variations in emission dynamics across countries.

Further research should focus on combining sectoral and regional data sets using measures such as intensity-based indicators and alternative approaches, and on machine learning methods to address endogeneity and nonlinear relationships, thereby improving actionable evidence and enhancing the reliability of environmental policymakers.

Ethics approval

Not applicable.

Declaration of generative AI and AI-assisted technologies in the writing process

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CRediT authorship contribution statement

Gimhani Samarakoon: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sinelya Silva:** Writing – review & editing, Writing – original draft, Visualization, Validation,

Software, Methodology, Formal analysis, Data curation. **Dinuri Wijesinghe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Mehul Gunasekara:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis. **Ruwan Jayathilaka:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Chamathka Punchihewa:** Writing – review & editing, Writing – original draft.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexres.2026.102152.

Data availability statement

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

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