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Research paper

Drivers of carbon emissions in G7 economies: Evidence on energy use, globalisation, urbanisation, industrialisation and innovation

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ABSTRACT

Rising CO_2 emissions remain a major sustainability challenge, particularly in advanced economies that account for a considerable share of historical emissions. This study examines the key determinants of CO_2 emissions in G7 countries by jointly considering globalisation, energy consumption, urbanisation, industrialisation, and technological innovation. Using a balanced panel dataset for Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States over the period 1997–2023, the analysis applies panel regression techniques and country-specific multiple linear regressions to capture both common effects and heterogeneity across economies. The results indicate that energy consumption is a robust driver of CO_2 emissions across the G7. Technological innovation contributes to emission reduction at the panel level; however, its effect becomes statistically insignificant in country-specific estimations, reflecting cross-country differences in innovation structures and policy environments. Globalisation significantly increases emissions in Canada, while its influence is negligible elsewhere. Urbanisation shows a mitigating effect only in the United States, and industrialisation increases emissions in Canada and Italy but reduces emissions in Japan. Overall, the findings highlight that decarbonisation strategies in advanced economies should prioritise the transition to clean energy while strengthening innovation-oriented climate policies tailored to country-specific contexts.

1. Introduction

Carbon dioxide (CO_2) emissions have become a primary global concern because of their dominant role in climate change (Hannah Ritchie and Max Roser, 2025). Among greenhouse gas emissions, the largest share is attributed to carbon emissions (World Bank, 2025). Globally, CO_2 emissions generated through energy rose by 0.8% in 2024. This rise contributed to a 422.5 ppm increase in atmospheric carbon emissions (IEA, 2025a). Even though most of the advanced economies are already expanding strategies for green transition, these countries still find themselves fighting with CO_2 emissions (Chen et al., 2025) which accounts for considerable ecological damage.

Due to their advanced technology, financial capabilities, and influence on environmental policy frameworks, advanced economies, which also include G7 countries, play a crucial role in global decarbonisation strategies.

Studies show that in advanced countries, technological advancements could critically influence decarbonisation. For instance, prior studies show that in G7 countries, investments in research and development could reduce higher carbon levels and achieve sustainable development goals (Cao et al., 2025). Advanced economies can lead the way to achieve decarbonisation by adopting zero-emission strategies (IEA, 2025b), indicating that their influence on the world's policy frameworks guides global sustainability.

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The group of seven (G7), which includes Canada, France, Germany, Italy, Japan, the United Kingdom (UK) and the United States (USA), is responsible for a significant share of historic as well as current CO_2 emissions, which caused substantial environmental harm (Hannah Ritchie and Max Roser, 2025). Together, the G7 countries contributed 25% of the carbon emissions generated through energy (IEA, 2025b), which is a considerable share given the small percentage of the world's population represented by the G7. This highlights their significant contribution to sustainability concerns, even with the presence of advanced technology, financial capabilities and ecological policy frameworks. Furthermore, six G7 countries are ranked among the global top 20 emitters, suggesting their influence on environmental pressure (Hannah Ritchie and Max Roser, 2025). G7 countries play a significant role in the global economy and climate discussions because they are among the world's most developed and highly industrialised countries. Altogether, they contribute to a considerable amount of (nearly 45%) global GDP (Zhang et al., 2024). Since it plays a significant role in the world economy, it is a major contributor to energy, global trade, and technology, making it a major contributor to CO_2 emissions.

Globalisation (GLO) is identified as the major factor of economic development which supports enhance economies (Jahanger et al., 2024). Most studies have found that energy consumption (EC) is positively linked to emissions (Huang and Ren, 2024). In consideration of urbanisation (URB), it is found to be a significant component of emission-driven degradation (Zeb et al., 2025). Some studies report that industrialisation (IND) and technological innovation (TI) also shape emissions (Khan et al., 2024b; Sahu et al., 2024), as indicated by panel studies.

Therefore, the background of the study motivates to examine the dynamics on carbon emissions in G7 countries with the aim of providing valuable insights for achieving a sustainability through mitigating emissions.

Even though the existing studies have examined the drivers of CO_2 emissions, most of them focus on global or broad country contexts (Adeleye et al., 2023; Chen and Lee, 2020; Hassan et al., 2025), with the advanced economies that have considerable importance in the global economy and environmental discussions, have received narrow adoption. Previous studies often examine these variables in isolation, ignoring the collective impact of GLO, EC, URB, IND and TI (Khan et al., 2024a; Zeb et al., 2025). Moreover, existing literature often shows conflicting results while examining the drivers of emissions. Findings from previous studies indicate that until a specific period, GLO is positive, and afterwards it declines (Ivanovski and Hailemariam, 2022). However, another study suggests that GLO clearly has a positive impact on CO_2 (Chen et al., 2025). Similarly, findings on TI have been mixed results (Adebayo and Kirikkaleli, 2021; Fatima et al., 2024). These contradictory findings may arise from differences in time periods and the econometric methodologies used. Therefore, there remains limited consensus regarding the impact of GLO, EC, URB, IND and TI on CO_2 in G7 economies.

This study aims to fill these gaps by assessing the impact of GLO, EC, URB, IND and TI on CO_2 emissions in G7 economies, employing panel regression and multiple linear regression (MLR), delivering valuable insights for designing strategies to mitigate emissions.

The current study aims to examine the impact of GLO, EC, URB, IND and TI on CO_2 emissions in G7 countries from 1997 to 2023. This study also seeks to explore the heterogeneity across G7 countries.

The research questions of this study are: how do GLO, EC, URB, IND and TI influence CO_2 emissions in G7 countries? and how do these effects vary across G7?

Although the extensive literature often examines the determinants of CO_2 emissions, the analytical evidence remains unsettled in the G7 economies. This research captures a few main gaps.

First, a conceptual gap emerges since prior studies often examine socioeconomic drivers of CO_2 emissions, which are GLO, EC, URB, IND, and TI in isolation, ignoring their combined effect in the G7 context. Second, methodological gaps arise because most literature often ignores country-wise comparisons to capture the heterogeneity across G7 countries. Third, regional gaps arise from the lack of extended, long-term studies that assess multiple emission drivers in combination across the G7. Finally, it provides insights for policymakers in developing strategies to reduce CO_2 emissions and promote sustainable development at the country-specific level. This study focuses on identifying the direct and heterogeneous effects of key socio-economic drivers- GLO, EC, URB, IND and TI- on CO_2 emissions in G7 economies.

By addressing these crucial gaps in prior literature, this analysis contributes to current knowledge on CO_2 emission dynamics and socioeconomic factors by employing panel regression and country-specific analyses from 1997 to 2023, and in the context, offers updated insights from cross-country analysis.

The structure of this study is as follows: the theoretical framework and literature review; section three includes the data and methodology; section four presents the results; and the following sections present discussion, policy implications and conclusion.

2. Literature Review

This section reviews the framework and past literature in assessing the impact of GLO, EC, URB, IND and TI on CO_2 emissions in global, continental, and country-specific studies. Fig. 1 shows the number of research publications from 2010 to 2026 which focus on the key independent variables of the study.

2.1. Globalisation and environmental quality

The relationship between globalisation and CO_2 emissions has been a topic of numerous studies, which have reported complex findings particularly in G7 countries. Global studies often argue that globalisation possesses a favourable influence on ecological balance (Fatima et al., 2022; He et al., 2021; Zaidi et al., 2019) possibly due to facilitating technological diffusion. Conversely, another study indicates that globalisation was favourable to ecological degradation by increasing CO_2 emissions until 2000, but switches sides afterwards by decreasing carbon emissions (Ivanovski and Hailemariam, 2022) as technique effect became more dominant suggests that association of globalisation and emissions could be non-linear. In contrast, some studies highlight that overall globalisation serves as a tool that decreases damage to the nature, while economic globalisation is found to be enhance the pollution and political globalisation improves the natural systems (Farooq et al., 2022). These suggest the heterogenous nature of relationships of globalisation and emissions. Furthermore, a global study reports that higher globalisation tends to decrease emissions in net energy exporters while promote environmental burden in energy importers (Chiu and Zhang, 2025) suggesting context dependence of effects of globalisation.

Consideration of G7 countries, in Canada and the USA, globalisation has become a significant influence on atmospheric harm (Jahanger et al., 2024) may result from energy-intensive trade. Prior studies focused on G7 context observed that globalisation was the key influencer of worsening environmental quality (Chen et al., 2025; Shahbaz et al., 2018; Yang and umar, 2022) indicating that through the scale effect, whereby economic expansion leads to higher emissions. Despite the above findings, literature employing semi-parametric panel data analysis discovered that globalisation presents an inverted U-shaped relationship (Liu et al., 2020) indicating that in G7 countries, globalisation supports the EKC theory. This suggests that globalisation initially increased emissions but eventually reduced them.

Taken together, these reveal that the role of globalisation on CO_2 emissions can provide mixed findings. Furthermore, trade, economic development and international agreements could impact globalisation, indicating the importance of a G7-specific analysis.

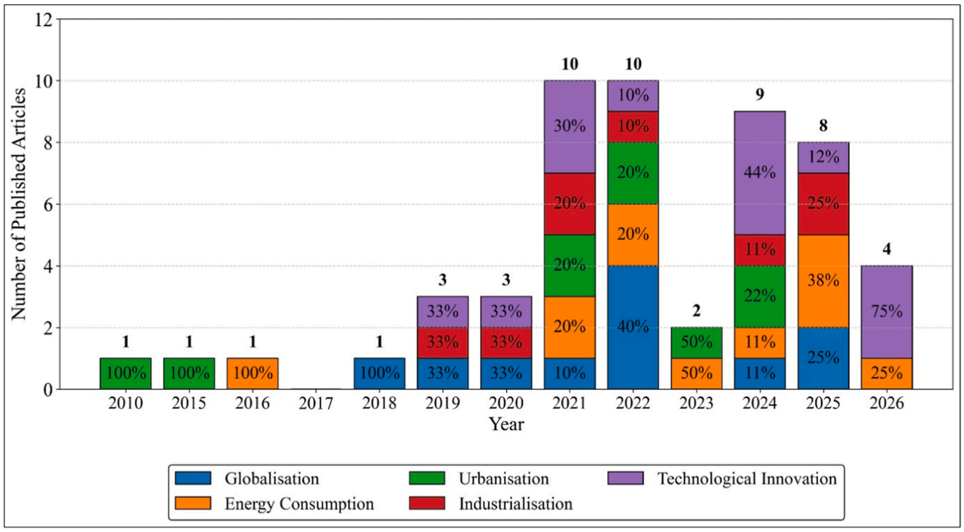

Fig. 1. Number of publications by year for each variable. Note: This bar chart illustrates the number of publications per year for each variable. Each colour represents the specific variable in the study. The percentages shown inside each bar represent how much each variable contributes to the total number of publications in that particular year. Source: Authors' illustration.

2.2. Energy consumption and carbon emissions

In previous literature, energy consumption has been identified as one of the most significant determinants of climate change and environmental degradation. Energy consumption is considered one of the main determinants of carbon emissions (Dharmapriya et al., 2025a, 2025b) potentially due to the energy-intensive economic activities. A global analysis revealed that renewable energy declines emissions, whereas non-renewable energy expands emissions (Dissanayake et al., 2023), highlighting the necessity of transition towards cleaner energy. Recent evidence identified that artificial intelligence promote green energy integrations and boost energy efficiency through smart energy management strategies (Sun et al., 2025; Wang et al., 2026b) demonstrating the importance of artificial intelligence in terms of expanding sustainability.

Regarding the G7 context, studies indicate that energy consumption worsens environmental quality in those economies (Gyamfi et al., 2021; Nasrullah et al., 2021; Ruza and Caro-Carretero, 2022; Zhang et al., 2024) highlighting that their heavy reliance on fossil fuel energy sources. Additionally, a study focused on developed countries observed that in the USA, energy demand and CO_2 mutually influence each other (Dogan and Turkekul, 2016), posing difficulties for achieving sustainability in advanced economies. On the other hand, clean energy consumption improves ecological quality in G7 economies. For instance, a G7 study employed the method to determine clean energy consumption tends to reduce emissions and support sustainability (Li and Haneklaus, 2022), potentially due to the shift towards renewable sources including wind and solar power.

Given the varying impacts of energy consumption and emissions, the results vary depending on the considered period, selected methodologies and country preference; instead, it is essential to assess the effects of energy consumption on CO_2 emissions across G7 countries.

2.3. Urbanisation and structural transformation

Urbanisation is often considered a process that represents social and economic transformation, which can trigger CO_2 emissions. According to a cross-country analysis, urbanisation plays a crucial role in undermining sustainability by increasing emissions (Li and Lin, 2015; Poumanyvong and Kaneko, 2010) due to the energy-intensive urban infrastructures. However, other global studies reported a different pattern, in which urbanisation contributed heavily to emission mitigation (Purwono et al., 2024; Wang et al., 2021), this suggest that well planned urban areas promote sustainability conditions. A panel data analysis suggests that in non-OECD countries, urban growth reduces emissions. In contrast, in OECD countries, it has no significant impact (Ma and Ogata, 2024). This indicates a different outcome, namely that urbanisation has an asymmetric relationship depending on the context due to the different economic structures. A study of OECD countries discovered an inverted U-shaped relationship between urbanisation and CO_2 emissions, highlighting urbanisation shift from positive to negative effect on emissions (Chen et al., 2022) reflecting that higher urbanisation may support the environment in later stages.

Focusing on G7 economies, a study focused on the USA, implies that there has been an increase in atmospheric quality at the state level (Tawfeeq, 2023) as a result of the transition towards service-based economies. Different outcomes were observed in another study, implying that urban growth enhance the environmental burden (Li and Haneklaus, 2022) may be attributed to energy-intensive life style in advanced economies. A separate analysis notes urbanisation contributes to rising CO_2 emissions except France and Italy (Katircioglu, 2021) which reflects the heterogeneous effect of urbanisation due to the different stages of development.

Overall, the impact of urbanisation on CO_2 emissions shows mixed results. Further urban policies and economic structures could affect ecological impact of urbanisation. Therefore, assessing the impact of urbanisation on CO_2 emissions is crucial for the current G7 countries.

2.4. Industrialisation and environmental degradation

Recent literature vastly identified industrialisation as a key driver of CO_2 emissions. For instance, prior literature found that industrial growth expands CO_2 emissions and disrupts natural setting (Dehdar et al., 2022; Keser et al., 2025; Onwe et al., 2024; Wang et al., 2020), reflecting the dominance of scale effect in advanced economies. In addition, a study focused on developed countries confirmed the unidirectional association between industry and CO_2 emissions (Wu et al., 2021) due to carbon-intensive manufacturing activities. However, research notes that the interaction of industrialisation and emissions can differ across income levels (Dong et al., 2019). The same analysis reveals that industrialisation has an increasing effect on CO_2 emissions in high-income countries, may be attributed to large scale industrial productions.

From the G7 perspective, an analysis reveals, industrial growth harmed environmental quality due to rising emissions in France (Kahia and Ben Jebli, 2021), suggesting that France continued carbon-intensive activities. A separate study indicate, industrialisation amplifies pollution which may be driven by the dominance of scale effect, while in the long run industry growth improve emission efficiency (Zeb et al., 2025) which could be a result of the presence of technique effect.

Prior literature depicted that industrialisation frequently expands emissions. However, technological capabilities and industrial structures could vary the results demonstrating the importance to assess the impact of industrialisation on CO_2 emission in this study.

2.5. Technological innovation on decarbonisation

As in the previous literature, technological innovation is recognised as the major contributor to reducing CO_2 emissions. In high-income countries, technological advancement leads to emission abatements (Apanasovich and Apanasovich, 2025; Chen and Lee, 2020; Cheng et al., 2021; Erdiaw-Kwasie et al., 2024) primarily through improvements of energy-efficiency technologies. Conversely, a study suggested that the development of innovation mitigates emissions due to the cleaner technologies, while adverse shocks in innovation raise CO_2 emissions (Rahman et al., 2022) due to the inefficient technologies. However findings from the analysis employing quantile regressions indicate that the impact of technology on environment performance varies across context (Alvarado et al., 2024) suggest that the relationship of innovation and emissions could be influenced by level of development and policy frameworks of nations.

Despite these advancements, global literature emphasised the influence of modern innovations, specifically artificial intelligence on environment. Recent research found that artificial intelligence and sustainability show a U-shaped relationship (Zhang et al., 2026a) demonstrating that early stages of artificial intelligence support sustainability through efficiency gains while advanced artificial intelligence expand emissions through higher energy demand. Conversely, a study indicated emerging artificial intelligence enhance pollution whereas sophisticated artificial intelligence improves ecological balance (Wang et al., 2026a) through optimising energy use. A separate analysis revealed that artificial intelligence supports low carbon efficiency (Zhang et al., 2026b) through energy efficiency improvements.

In the context of G7 countries, studies reveal that innovation supports decarbonisation (Fatima et al., 2024; Khan et al., 2024a) driven by the structural transformations in the economies. In contrast, Japanese study revealed that innovation expand higher carbon emission levels (Adebayo and Kirikkaleli, 2021), highlighting that innovation could link to the carbon-intensive manufacturing in advanced economies. Alternatively, G7 analysis shows the relationship of innovation and CO_2 emission is time dependent (Awaworyi Churchill et al., 2019). This demonstrate that the role of innovation change across time. Another analysis demonstrates innovation improves low carbon efficiency in G7 excluding for Japan (Huang et al., 2021), demonstrating the heterogeneous impact of the innovation. Overall, the environmental impact of innovation could be varied due to the policy frameworks and economic capacities emphasising the importance of investigating the impact of innovation on emissions in G7.

Overall, combining these essential drivers of CO_2 emissions, this study aims to assess the effects of globalisation, energy consumption, urbanisation, and industrialisation on CO_2 emissions in G7 countries to provide insights for policymakers to achieve sustainability.

2.6. Synthesis of literature and research gap

Numerous prior studies showed that EC emerge as the main driver of environmental degradation in advanced economies (Dharmapriya et al., 2025b) possibly due to heavy use of non-renewable energy. TI is mostly identified as a long-term mitigating factor (Khan et al., 2024a), may be caused by advanced energy efficiency technologies. However, evidence of GLO, URB and IND demonstrated inconclusive findings (Ivanovski and Hailemariam, 2022; Li and Haneklaus, 2022; Liu et al., 2020; Zeb et al., 2025). These inconclusive results may be explained by methodological preferences, policy framework heterogeneity and varied economic structures in G7 economies. To further synthesise the literature, Table 1 summarises selected prior studies according to their variables, regional focus, methodological approach, and key findings. The table highlights that previous studies commonly examine these determinants separately or within broader regional samples, while limited attention has been given to the joint effects of globalisation, energy consumption, urbanisation, industrialisation and innovation in G7 economies.

Taken together, the literature highlights few key gaps. Firstly, there is a lack of studies analysing GLO, EC, URB, IND and TI together within a single comprehensive framework. Secondly, the literature on G7 is uneven, with limited studies that combine both panel and country-level heterogeneity analyses. To address these gaps, it is crucial to examine the impact of socioeconomic drivers on emissions across G7 economies.

3. Hypothesis development

3.1. Globalisation and CO_2 emissions hypothesis

Globalisation enforces a complex influence on environmental degradation, together supporting technology transfer and cleaner production during growing economic activity, and trade. Higher globalisation is connected with larger emission levels, demonstrating that global interconnectedness can strengthen pollution whereas advanced economies adapt sustainable practices (Cai et al., 2025). On the other hand there is an inverted U-shaped association between globalisation and emissions demonstrating globalisation may raise degradation of natural systems but may help reduce them beyond a certain point (Liu et al., 2020). Even with these contrasting pathways, the impact of globalisation on environmental degradation in G7 economies remains an empirical issue.

H_1. : Globalisation significantly influence CO_2 emissions in G7 economies.

3.2. Energy consumption hypothesis

Energy Consumption is a key determinant of CO_2 emissions, especially in advanced economies where energy demand remains high even as cleaner energy sources are slowly adopted. On one hand, reliance on fossil fuels raises production and transportation activities, harm low carbon intensity (Zhang et al., 2024). On the other hand, advances in energy efficiency and cleaner energy technologies can reduce environmental degradation (Li and Haneklaus, 2022). Despite these opposing effects, the impact of energy consumption on sustainability is still a matter in G7 economies.

H_2. : Energy consumption increases CO_2 emissions in G7 economies.

3.3. Urbanisation and CO_2 dynamics hypothesis

Prior literature often argued that urbanisation enhanced environmental burden in G7 economies (Li and Haneklaus, 2022) through the influence of energy demand, economic structure. Conversely, urbanisation has mixed effects on CO_2 emissions with impacts varying from urban policies and economic structures (Katircioglu, 2021). These divergent effects of urbanisation on CO_2 emissions remain an empirical issue in G7 nations.

H_3. : Urbanisation has a significant impact on CO_2 emissions.

This hypothesis is stated in non-directional form because prior evidence suggests that urbanisation may either increase emissions through infrastructure expansion and higher energy demand or reduce emissions through urban density, public transport, and energy-efficient urban systems.

Table 1
Literature Summary Table.

Author(s) & Year	Country/ Region	Variables	Methods	Key Findings	Gap addressed by current study
(Dharmapriya et al., 2025b)	High Income Countries	CO_2, Energy Use	Panel Regression and MLR	Energy use is the main emission driver of all the income groups.	Did not specifically analyse the G7 countries.
(Khan et al., 2024a)	G7 Economies	CO_2, technological innovation	CS-ARDL model	Technology innovation and R&D reduce emissions.	Globalisation, energy consumption, urbanisation, industrialisation are not included.
(Ivanovski and Hailemariam, 2022)	21 OECD Countries	CO_2, Globalisation	Extended STIRPAT model, Panel econometric analysis (DCCEMG) and Dummy Variable Estimator (LLDVE)	Globalisation enhances emissions till certain period, after that it reduce CO_2.	Focus only on OECD countries. Did not consider energy consumption, urbanisation, industrialisation and innovation. Not specifically analyse G7 countries raising a research gap.
(Li and Haneklaus, 2022)	G7 Economies	CO_2, Urbanisation	Panel ARDL Method	Urbanisation decreases CO_2 emissions	Not focus on Globalisation, energy consumption, industrialisation and innovation which raise a significant gap in literature.
(Liu et al., 2020)	G7 Economies	CO_2, Globalisation	Semi-Parametric Panel Fixed Effects Model	Globalisation and CO_2 form an inverted U-shaped relationship.	Did not consider energy consumption, urbanisation, industrialisation and innovation which raise a research gap.
(Zeb et al., 2025)	G7 Economies	CO_2, Urbanisation, Industrialisation	Panel ARDL Method	In long-run Industrialisation support emission mitigation and in short-run enhance emissions. Urbanisation found to increase emissions in both long and short run.	Inconclusive findings regarding the urbanisation and industrialisation, omitted important variables such as globalisation, energy consumption, industrialisation and innovation raising a significant gap.

Source: Compiled by authors.

3.4. Industrialisation and emissions hypothesis

Industrialisation is commonly associated with high energy consumption and higher CO_2 emissions. Industrial growth raise emissions due to the development of energy-intensive production methods in G7 economies (Khan et al., 2024a). Conversely, industrialisation found to have reduction effect on environmental harm in G7 economies (Zeb et al., 2025). According to these, the effects of industrialisation on CO_2 emissions remain inconclusive in these advanced economies.

H_4. : Industrialisation affects CO_2 emissions heterogeneously across the G7.

3.5. Technological innovation and emission mitigation hypothesis

Evidence from G7 nations demonstrates that innovation, effectively reduces CO_2 emissions (Fatima et al., 2024) through carbon-efficient technologies. In contrast, the impact of technological innovation on environmental degradation could be varied depend on the context (Huang et al., 2021), suggesting the heterogenous impact of innovations. Thus, the effect of technological innovation on CO_2 emissions is empirically unclear in advanced economies.

H_5. : Technological innovation mitigates CO_2 emissions in the long run.

By analysing these hypotheses, this study aims to extend the current knowledge of determinants of CO_2 emissions.

4. Data and methodology

4.1. Data sources and variables description

For this study, a panel data set for Canada, France, Germany, Italy, Japan, the UK, and the USA from 1997 to 2023 is obtained. Further, Supplementary Material 1 provide the data set that was utilised in this analysis. The statistical analysis procedure (Stata code framework) is included in Supplementary Material 2. The source of the data and variables is included Table 2.

Table 2
Data sources and variables.

Variables	Definition Measure	Source
CO_2	Carbon Dioxide Emission (Metric Ton Per Capita)	Our World in Data https://ourworldindata.org/grapher/co-emissions-per-capita
GLO	Globalisation (KOF Globalisation Index)	KOF Globalisation Index https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html
EC	Energy Consumption (MWh per person)	Our World in Data https://ourworldindata.org/grapher/per-capita-energy-use
URB	Urbanisation (Urban population growth as a % of annual)	WDI https://data.worldbank.org/indicator/SP.URB.GROW
IND	Industrialisation Industry (including construction), value added (% of GDP)	WDI https://data.worldbank.org/indicator/NV.IND.TOTL.ZS
TI	Technological Innovation (Research and dev. expenditure (% of GDP))	WDI https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS

Source: Compiled by authors.

4.2. Measurement of variables

The current study measures CO_2 emissions in metric tons per capita. The KOF Globalisation Index is used to estimate GLO. Kilowatt-hours per person is employed to estimate EC, which represents the energy demand. URB is measured as an annual percentage growth of the urban population to capture short term structural changes. However, robustness check using the levels of urban population (% of the population) were also conducted. IND is represented through the industry (including construction) valued as a percentage of GDP. Research and development expenditure as a percentage of GDP represented the technological innovation of the countries. To ensure a meaningful comparison and analysis, the current study adapted the EC unit of measurement to megawatt-hours per capita.

4.3. Model specification

To explore the impact of GLO, EC, URB, IND and TI on CO_2 emissions in G7 economies, this study applies the panel regression technique. This technique is extensively accepted to capture the factors of CO_2 emissions in prior literature (Kalayci and Hayaloglu, 2018). As presented in Eq. (1), CO_2 emissions are treated as the dependent variable, whereas GLO, EC, URB, IND and TI are treated as the independent variables. To ensure stationarity and avoid spurious estimations the dependent variable CO_2 emission is used in first-difference form. Energy use, urbanisation, and technological innovation are also entered in first-difference form, whereas globalisation and industrialisation are retained in levels because they are stationary at level according to the panel unit root tests. Appendix 1 reported the order of integration of variables for each country. Accordingly, the panel model specified as follows:

$$\Delta CO_{2it} = \beta_0 + \beta_1 GLO_{it} + \beta_2 \Delta EC_{it} + \beta_3 \Delta URB_{it} + \beta_4 IND_{it} + \beta_5 \Delta TI_{it} + \mu_t + \omega_t + \varepsilon_{it} \quad (1)$$

In equation (1), i represents the country, t represents the year, μ_t captures common fixed effects shocks, ω_t captures random unobserved time-varying influences and (ε_{it}) is considered as the error term.

4.4. Panel estimation strategy

Accounts for the unobserved heterogeneity across countries and ensures the stability of the outcomes, this analysis applied Pooled Ordinary Least Square (POLS), Fixed Effect (FE) and Random Effect (RE) estimations and identified the most appropriate estimation for the analysis. The FE model was used to handle for time- invariant unobserved heterogeneity in each country, whereas both country - specific and cross-country variations are addressed through the RE model, which effectively captures the complex nature of environmental degradation in G7 economies.

4.5. Country - specific multiple linear regression approach

To address the country - specific variations between independent and dependent variables in each country and provide a deep assessment of the CO_2 emission dynamics, this study employs the MLR. General model employed as below,

$$CO_{2t} = \alpha_0 + \alpha_1 GLO_t + \alpha_2 EC_t + \alpha_3 URB_t + \alpha_4 IND_t + \alpha_5 TI_t + \varepsilon_t \quad (2)$$

In equation (2), t represents the year and (ε_{it}) considered as the error term. Given the relatively small-time dimension (T = 27), the country-specific regressions are interpreted cautiously as exploratory analysis to capture heterogeneity rather than definitive causal estimates. To mitigate overfitting concern, model diagnostics including adjusting R^2, AIC and BIC are reported.

4.6. Diagnostic and robustness test

Panel unit root tests (Levin Lin Chu and IPS) were conducted for both level and first difference variables. The results indicate that CO_2, EC, URB and TI exhibit non stationarity in levels, but become stationary after first differencing while GLO and IND were found to be stationary in levels. Therefore, a mixed transformation approach was adopted to ensure stationarity while preserving long run information were appropriate.

Multicollinearity and autocorrelation tests are conducted to further clarify the reliability and validity of the model (Gujarati and Porter, 2009; Wooldridge, 2013). In addition, to verify the stability over time in the regression model, Vector Autoregression (VAR) is conducted (Holtz-Eakin et al., 1988).

Potential endogeneity may arise due to reverse causality (e.g., emissions influencing energy policy) and omitted variables. While the current study employs panel estimators to mitigate unobserved heterogeneity, future research could extend the analysis using instrumental variables or dynamic panel approaches (e.g., System GMM).

5. Empirical results

This section provides a clear overview of the findings of the analysis, highlighting valuable insights into how GLO, EC, URB, IND and TI interact with CO_2 emissions.

5.1. Descriptive statistics

The descriptive statistics, including the number of observations, mean values, standard deviations, and the minimum and maximum values of CO_2, GLO, EC, URB, IND and TI are presented in this section. Further, to support understanding of the data set employed in this study, Supplementary Material 3 presents the descriptive statistics and correlation matrix. The USA records the highest average of CO_2 emissions, at 18.125 metric tons per capita, followed by Canada, Germany, Japan, the UK, and Italy with values of 16.373, 9.920, 9.482, 7.667 and 7.033 metric tons per capita. In contrast, France reveals a considerably lower average emission of 5.815 metric tons per capita.

In terms of globalisation, the UK has the highest globalisation index, which is 85.679, followed by Japan, which has the lowest value at 70.461 among the seven countries. EC is highest in Canada, where the mean value shows 111.564 megawatt hours per person, which is followed by Italy, where it records a substantially lower average emission of 33.783 megawatt hours per person. Urbanisation, measured by the annual percentage growth in the urban population, is highest in Canada, at 1.303%. Germany, at 0.266%, shows the lowest urbanisation. Industrialisation, measured by industry value added as a percentage of GDP, is highest in Japan, with a mean of 29.372%, and lowest in France, with a mean of 18.467%. Japan shows the highest value for technological innovation, measured by research and development expenditure as a percentage of GDP, with a mean of 3.141%, followed by Italy, with a mean of 1.215%.

Furthermore, the correlation matrix demonstrates positive correlations between EC and CO_2, URB and CO_2, IND and CO_2, TI and CO_2 and a negative correlation between GLO and CO_2.

5.2. Trend analysis of key variable

Trend analysis of key variables of this study is presented in Fig. 2 for the G7 countries. The USA continuously leads the CO_2, and France maintains the lowest emissions in the G7 context. Canada holds high energy levels with minor fluctuations. GLO shows a continuous rise in all the G7 countries. URB shows positive trends, with noticeable fluctuations, across most G7 countries. Japan leads the IND in the G7 with noticeable fluctuations. However, Canada recently experienced a sharp increase in industrialisation. Japan has consistently led in innovation among the G7 economies, yet recently the USA surpassed Japan.

5.3. Model selection and specification test

The results from the FE model and RE model provide valuable insights to understand the relationship between the dependent variable CO_2 emissions and independent variables. The present study used three specification tests, as presented in Table 3, to identify the most appropriate model for the analysis among the POLS, FE, and RE models.

According to the results of the F test (χ^2=64.78, p = 0.00), the null hypothesis is POLS, and the alternative hypothesis is FE. The P value is less than the significance level, the null hypothesis is rejected. In the case of LM test results (χ^2=0.25, p = 0.31), the null hypothesis is POLS, and the alternative hypothesis is the RE model and accept the null hypothesis. In the Hausman test, where the null hypothesis is RE model and the and the alternative hypothesis is FE model. The Hausman test (χ^2=3.45, p = 0.63) suggests that the null hypothesis of no systematic difference cannot be rejected. However, given the structural heterogeneity across G7 countries, both fixed and random effect results are reported for robustness. After considering all the three specification tests, this

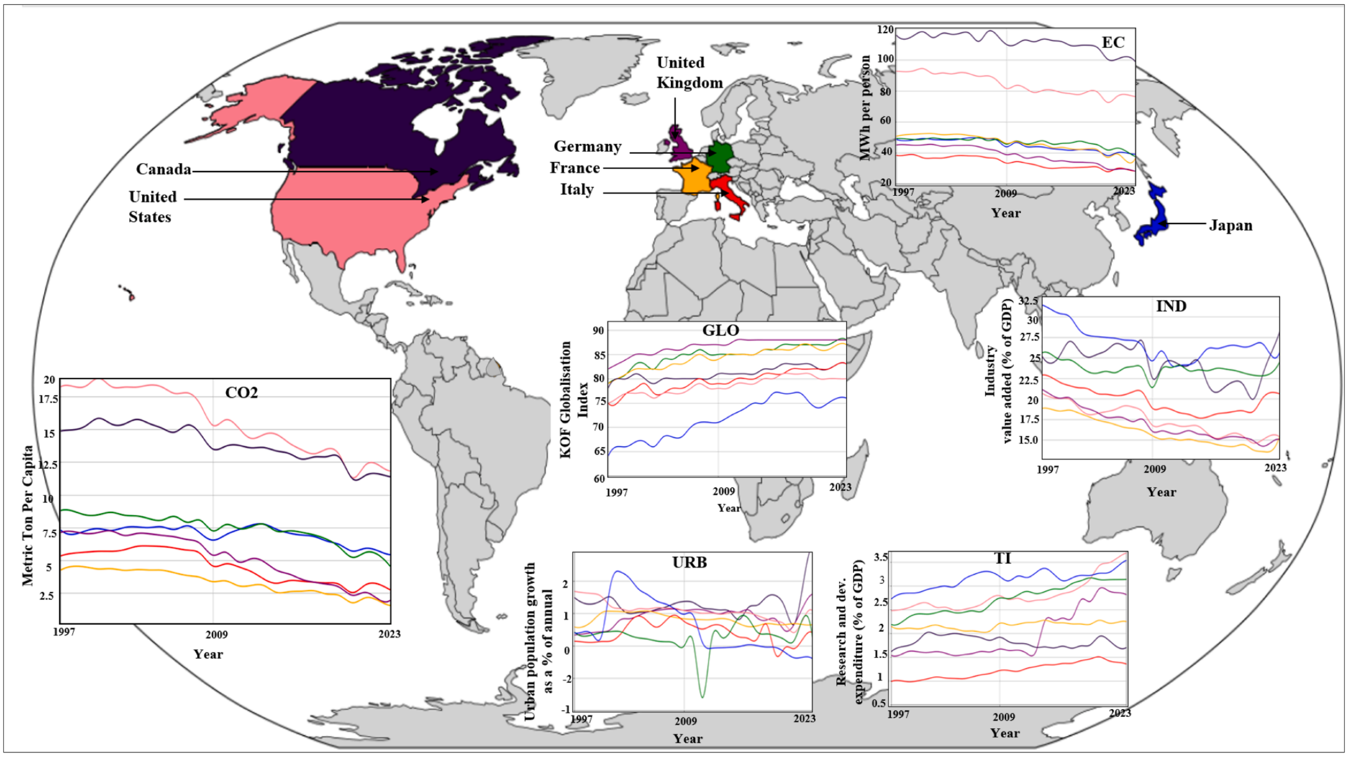

Fig. 2. Trends of variables in G7 countries (1997–2023). Note: This map illustrates the G7 countries. Line graphs show the variations of key variables across the G7 countries from 1997 to 2023. Source: Authors' illustration.

Table 3
Specification tests for the panel regression model.

F Test	LM Test	Hausman Test
H_0: POLS	H_0: POLS	H_0: Random Effect
H_1: Fixed Effect	H_1: Random Effect	H_1: Fixed Effect
64.78***	0.25	3.45

Note: ***significant at 1% significance level.
Source: Compiled by authors.

analysis accepts the RE as the most appropriate model.

5.4. Panel regression analysis

The results of panel regression are represented by Table 4 and Fig. 3 with FE and RE model coefficient values.

According to the Random effect, unobserved heterogeneity is random and not correlated with independent variables, while holding all other variables constant, the results suggest that a one-unit increase in EC MWh per person is associated with a 0.166-unit increase in CO_2 emissions per capita, suggesting EC largely determines emission levels in the G7 countries. Panel regression results are presented in Supplementary Material 4. However, in the RE model, unobserved heterogeneity is random and not correlated with independent variables while holding all other variables constant, the results demonstrate that with 1% increase in research and development expenditure as a percentage of GDP leads to decrease in CO_2 emissions per capita by 0.359 units, implying that innovation driven advancements can play a crucial role in emission reduction. In contrast, GLO, URB and IND indicate a statistically insignificant impact at the panel level.

5.5. Robustness and diagnostic results

The mean VIF denotes a value of 1.229 where it confirms that multicollinearity is not a concern in this model. The Wooldridge test was conducted to check for first-order serial autocorrelation. Since the p-value exceeds the significance level, the null hypothesis is not rejected, implying no autocorrelation. A VAR stability test was conducted to check stability over time. The results of the VAR model ensures that all the eigenvalues lie within the unit circle, suggesting the VAR model fulfils the stability requirement of the model. As an additional robustness check, the model was re-estimated using the conventional urbanisation level measure, namely urban population as a percentage of total

Table 4
FE and RE models results for G7 countries.

	FEM	REM
Intercept	0.433 (1.825)	0.01 (0.609)
p-value	0.820	0.987
t-value	0.24	0.02
GLO	−0.008 (0.017)	−0.002 (0.006)
p-value	0.635	0.714
t-value	−0.50	−0.37
D_EC	0.165*** (0.033)	0.166*** (0.032)
p-value	0.002	0.000
t-value	5.05	5.13
D_URB	−0.008 (0.055)	−0.004 (0.057)
p-value	0.883	0.947
t-value	−0.15	−0.07
IND	0.008 (0.021)	0.005 (0.007)
p-value	0.698	0.536
t-value	0.41	0.62
D_TI	−0.3*** (0.073)	−0.359*** (0.093)
p-value	0.006	0.000
t-value	−4.11	−3.87
R^2 Within	0.6524	0.6506
R^2 Between	0.3633	0.5261
R^2 Overall	0.6340	0.6479
F Significant	56.52	147.84

Note: *, **, *** represent 10%, 5% and 1% significance level, respectively. Coefficients are reported with robust standard errors in parentheses.
Source: Authors' compilation.

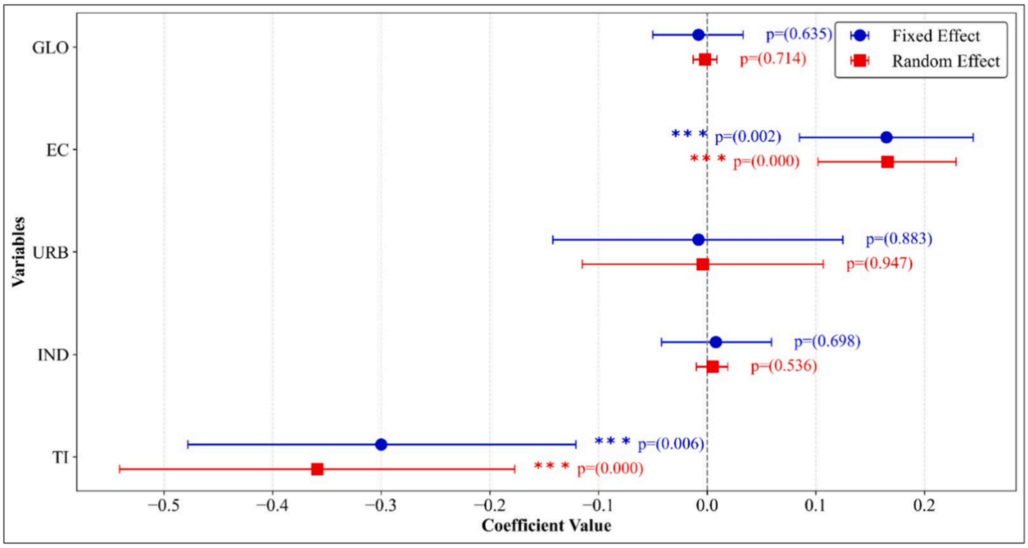

Fig. 3. Panel regression results. Note: The figure shows the estimated coefficients from panel regression models examining the impact of key variables GLO, EC, URB IND and TI on CO_2 emissions in G7. Both FE (blue circles) and RE (red squares) estimates are shown, with 95% confidence intervals represented as horizontal error bars. The stars next to each point show how statistically significant the results are (***significant at 1%), and the exact p values are also shown next to each coefficient. Source: Authors' illustration.

population. The results remained broadly consistent with the main findings, confirming energy use is the strongest positive driver of carbon emissions, while the effect of urbanisation remains sensitive to country-specific structural conventions. This supports the validity of urban population growth in the base line model to capture short-term structural changes. The findings of robustness and diagnostic tests are presented in Supplementary Material 5. Furthermore, panel unit root tests (Levin Lin Chu and IPS) were conducted for both level and first difference variables and the findings are shown in Table 5.

The Pesaran cross-sectional dependence (CD) test (Pesaran, 2021) indicates no cross-sectional dependency suggesting absence of cross-sectional dependence. Therefore, respectively, Table 6 and Table 7 displayed the Driscoll-Kraay standard errors and CCEMG which were applied for robustness.

5.6. Country-wise regression analysis

MLR shows the impact of independent variables on CO_2 emissions

Table 5
LLC/IPS Panel Unit Root Test Results.

Variable	Levin-Lin-Chu (LLC)			
	Level		First Difference	
	t-stat	p-value	t-stat	p-value
CO_2	3.624	0.999	−6.335***	0.000
GLO	−3.051***	0.001	-	-
EC	3.428	0.999	−6.109***	0.000
URB	−1.227	0.109	−4.318***	0.000
IND	−3.058***	0.001	-	-
TI	0.312	0.622	−4.315***	0.000
Variable	**Im-Pesaran-Shin (IPS)**			
	Level		**First Difference**	
	t-bar	p-value	t-bar	p-value
CO_2	0.327	1.000	−5.729***	0.000
GLO	−2.117**	0.038	-	-
EC	−0.118	1.000	−6.743***	0.000
URB	−1.767	0.273	−4.155***	0.000
IND	−2.131**	0.034	-	-
TI	−0.664	0.994	−4.314***	0.000

Note: *, **, *** represent 10%, 5% and 1% significance level, respectively.
Source: Authors' compilation.

Table 6
FE and RE Results with Driscoll-Kraay Standard Errors.

	FEM	REM
Intercept	0.433 (1.330)	0.010 (0.320)
p-value	0.748	0.975
t-value	0.33	0.03
GLO	−0.008 (0.014)	−0.002 (0.004)
p-value	0.536	0.570
t-value	−0.63	−0.58
D_EC	0.165*** (0.018)	0.166*** (0.017)
p-value	0.000	0.000
t-value	9.40	9.82
D_URB	−0.008 (0.047)	−0.004 (0.051)
p-value	0.860	0.941
t-value	−0.18	−0.07
IND	0.008 (0.015)	0.005 (0.004)
p-value	0.568	0.258
t-value	0.58	1.16
D_TI	−0.300* (0.156)	−0.359** (0.174)
p-value	0.066	0.049
t-value	−1.92	−2.07
R^2 Within	0.6524	-
R^2 Between	-	-
R^2 Overall	-	0.6479
F Significant	47.48	347.81

Note: *, **, *** represent 10%, 5% and 1% significance level, respectively. Coefficients are reported with Driscoll-Kraay standard errors in parentheses.
Source: Authors' compilation.

Table 7
Common Correlated Effect Mean Group (CCEMG).

Variables	Coefficient	St. Error	p-value	t-Statistic
GLO	−0.0277	0.0555	0.617	−0.50
EC	0.1255*	0.0342	0.000	3.67
URB	−0.2358	0.1599	0.140	−1.48
IND	−0.0421	0.0318	0.186	−1.32
TI	−0.1909	0.1349	0.157	−1.41
Constant	1.7743	2.7414	0.517	0.65

Note: *, **, *** represent 10%, 5% and 1% significance level, respectively.
Source: Authors' compilation.

across the G7 countries, focusing on Canada, France, Germany, Italy, Japan, the UK, and the USA. This study employed the ADF stationary test for each country to ensure the reliability of the country-wise analysis which reported in Appendix 2. The results of country-wise regression are presented in Table 8 and detailed results are provided in Supplementary Material 6.

The relationship between GLO and CO_2 emissions in Canada is significantly positive, with a coefficient of 0.235. In addition, the remaining G7 countries show no significant impact, implying that GLO does not measurably affect CO_2 emissions. However, these results indicate the heterogeneous effects of globalisation on CO_2 emissions.

EC has a statistically significant positive impact on CO_2 emissions across all the seven countries. In the USA, Italy, UK, Germany, Japan, Canada and France, a one-unit increase in EC will lead to increases of 0.259, 0.208, 0.234, 0.216, 0.152, 0.108 and 0.060 units of CO_2 emissions per capita. These findings suggest that energy consumption is a primary driver of CO_2 emissions in all the countries. Since the empirical model is estimated to be using level and differenced variables rather than logarithmic transformations the reported coefficients are interpreted as marginal effects rather than semi-elasticities. To improve cross-country comparability Table 9 presents the country-specific marginal effects of key predictors of CO_2 emissions.

URB shows a significant negative impact in the USA, where 1% increase in URB will result in a decrease in CO_2 emissions per capita by 0.441%. In contrast, the rest of the G7 countries show no significant results, indicating that URB has no measurable impact on CO_2 emissions.

Considering IND, a positive significant relationship is shown in Canada and Italy, an increase in IND by 1% leads to an increase in CO_2 emissions per capita by 0.064%, 0.096%. A significant negative impact is observed in Japan: a 1% increase in IND leads to a 0.158% decrease in CO_2 emissions. However, France, Germany, the USA, and the UK show insignificant impacts, denoting that IND has no measurable impact on CO_2 emissions.

Finally, in consideration of TI, results show insignificant results, highlighting that TI shows no considerable impact on CO_2 emissions in each country.

Table 9
Significant Marginal Effects and Policy Implications Across G7 Countries.

Country	Significant Effects	Main Policy Implications
Canada	GLO (+0.235*); EC (+0.108***); IND (+0.064*)	• Promote sustainable trade, energy efficiency and low-carbon industrial processers.
France	EC (+0.060*)	• Strengthen renewable energy transition and energy efficiency policies.
Germany	EC (+0.216***)	• Accelerate low-carbon energy system and reduce fossil fuel dependency.
Italy	EC (+0.2 08***); IND (+0.096**)	• Reduce fossil fuel use and promote low-carbon manufacturing.
Japan	EC (+0.152***); IND (−0.158**)	• Expand renewable energy while supporting green industrial upgrading.
UK	EC (+0.234***)	• Strengthen renewable energy infrastructure and energy efficiency.
USA	EC (+0.259***); URB (−0.441***)	• Promote urban sustainability initiatives and reduce fossil fuel dependence.

Note: Only statistically significant marginal effects are presented. Policy implications are based on significant country-specific estimates. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.
Source: Authors' compilation.

6. Discussion

6.1. Summary of key findings

Using the overall panel model and MLR, this study found that EC contributed to environmental degradation by consistently increasing CO_2 emissions across G7 countries, further confirming its dominance in emissions. TI demonstrates a reduction in the impact on CO_2 emissions at the panel level, but surprisingly, doesn't show a significant effect across countries due to the structural and policy heterogeneity across the G7 countries. Nevertheless, GLO shows a statistically insignificant impact on CO_2 emissions, whereas the MLR shows a statistically positive impact in Canada. Considering URB, it has a statistically insignificant effect on CO_2 emissions; however, at the country level, URB was found to have a significant negative impact on emissions in the USA. IND has a statistically insignificant effect on CO_2 emission in the overall panel. In

Table 8
Country-Wise Regression Results.

Variable	Canada	France	Germany	Italy	Japan	UK	USA
GLO	0.235* (0.115)	0.004 (0.069)	−0.025 (−0.025)	0.052 (0.053)	0.081 (0.057)	0.005 (0.032)	−0.03 (0.029)
p-value	0.055	0.959	0.326	0.341	0.172	0.874	0.319
t-value	2.04	0.05	−1.01	0.98	1.42	0.16	−1.02
EC	0.108*** (0.022)	0.06* (0.034)	0.216*** (0.021)	0.208*** (0.039)	0.152*** (0.025)	0.234*** (0.041)	0.259*** (0.019)
p-value	0.000	0.089	0.000	0.000	0.000	0.000	0.000
t-value	4.86	1.78	10.05	5.39	6.17	5.76	13.78
URB	−0.034 (0.100)	−0.181 (0.407)	0.038 (0.075)	0.104 (0.071)	−0.201 (0.133)	−0.168 (0.312)	−0.441*** (0.135)
p-value	0.736	0.661	0.619	0.156	0.148	0.597	0.004
t-value	−0.34	−0.44	0.50	1.48	−1.50	−0.54	−3.25
IND	0.064* (0.035)	-	0.027 (0.028)	0.096** (0.042)	−0.158** (0.073)	−0.056 (0.144)	0.1 (0.082)
p-value	0.08	-	0.346	0.034	0.043	0.704	0.004
t-value	1.84		0.97	2.29	−2.16	−0.39	1.22
TI	−0.119 (0.904)	−1.71 (1.131)	−0.538 (0.579)	−0.039 (0.66)	−0.266 (0.431)	−0.093 (0.185)	−0.071 (0.379)
p-value	0.897	0.145	0.364	0.954	0.544	0.622	0.853
t-value	−0.13	−1.51	−0.93	−0.06	−0.62	−0.50	−0.19
Constant	−0.066 (0.151)	−0.064 (0.041)	−0.04 (0.031)	−0.034 (0.03)	−0.077 (0.049)	−0.498 (2.75)	−0.061* (0.033)
p-value	0.668	0.136	0.213	0.270	0.129	0.858	0.08
t-value	−0.44	−1.55	−1.29	−1.14	−1.58	−0.18	−0.19
F-statistic	11.18***	6.29***	75.38***	25.45***	11.06***	18.75***	169.59***
p-value	0.000	0.0017	0.000	0.000	0.000	0.000	0.000
F-statistics (df1, df2)	(5, 20)	(4, 21)	(5, 20)	(5, 19)	(5, 20)	(5, 19)	(5, 19)
R^2	0.757	0.523	0.860	0.795	0.484	0.657	0.953
Adj R^2	0.696	0.431	0.824	0.741	0.355	0.566	0.940
Obs.	26	26	26	25	26	25	25
Akaike crit. (AIC)	9.874	−15.88	−19.832	−15.211	3.850	−4.957	−18.867
Bayesian crit. (BIC)	17.423	−9.595	−12.283	−7.898	11.398	2.356	−11.554

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Coefficients are reported with robust standard errors in parentheses. Source: Authors' compilation.

contrast, country-specific analyses demonstrate that IND actively shapes emissions in Canada, Italy, and Japan. The statistical insignificance of GLO, URB and IND at the panel level may reflect heterogenous country-specific effects, limited variations, or model specification constraints rather than the absence of influence.

6.2. Comparison with existing literature

This study reveals that EC has a strong, positive, and significant impact on CO_2 emissions, which is strongly aligned with findings of numerous studies (Dharmapriya et al., 2025b). This finding reveals energy consumption identified as a primary driver of environmental degradation in G7 economies attributing continued reliance of fossil fuel energy sources (oil, coal and natural gas) in advanced economies. According to the findings of the current study, TI have a significantly negative impact on emissions, which aligns with (Cheng et al., 2021). This reveals that TI serve as an emission reduction tool through facilitating cleaner energy strategies and developing energy efficiency in advanced economies.

6.3. Heterogeneity across G7 countries

According to country-wise analysis, GLO reports a significant positive impact on CO_2 emissions in Canada, suggesting that in Canada, GLO impacts ecological performance, which aligns with (Jahanger et al., 2024), who found that GLO offers to shape emissions. In contrast, in the rest of the G7 countries, GLO has an insignificant impact on emissions. EC acts as a leading role in enhancing environmental burden in all the G7 countries (Zhang et al., 2024), highlighting that the G7 heavily depend on fossil energy. URB reports a significant negative impact on the USA, indicating the importance of following efficient urban planning. This finding contrasts with a study that highlighted that OECD countries, including the USA, have no impact of URB on emissions (Ma and Ogata, 2024). The difference between these findings may be due to the study's sample size. However, the remaining G7 countries have an insignificant impact on CO_2 emissions. In consideration of IND, country-wise analysis reveals that, in Canada and Italy, significant positive relationships are observed, indicating that industry development still harms the environment, which aligns with (Keser et al., 2025). However, Japan showed an adverse effect of IND on CO_2 emissions, and the rest of the G7 countries had an insignificant impact, which is contrary to (Zeb et al., 2025), likely due to differences in sample sizes. TI exhibits an insignificant impact across the G7, indicating structural and policy heterogeneity across the G7 countries, which contrasts with (Fatima et al., 2024). The difference between these findings could be due to the econometric technique employed.

6.4. Country Level and Structural Explanation

The heterogeneous effects observed across G7 countries reflect differences in national energy structures, industrial composition and policy frameworks. While panel level results provide average effects, country specific estimates reveal that the impact of key drivers of CO_2 emissions is sharp by structural and institutional, characteristic, unique to each country.

6.4.1. Canada (GLO +EC positive)

In Canada the positive association between globalisation and CO_2 emissions can be attributed to its resource intensive export structure particularly in oil and gas sectors. This interpretation is consistent with International Energy Assessment (IEA) that identifies Canada's energy system as strongly linked to fossil fuel production and exports (IEA, 2026). Increase global integration may amplify production and energy demand thereby increasing emissions. Similarly, the strong positive effects of energy consumption reflect reliance on fossil-based energy systems despite ongoing transitions toward energy clean economy.

6.4.2. Japan (IND reduced CO_2)

In contrast, industrialisation in Japan is associated with low CO_2 emissions, which may reflect the countries advanced manufacturing technologies and strong environmental regulations. Japan's emphasis on energy efficiency, innovation, and clean production process enables industrial activity to occur with minimal ecological impact. This is also consistent with Japan's long-standing policy emphasis on energy-efficiency and industrial decarbonisation (OECD, 2026).

6.4.3. USA (URB reduced CO_2)

Urbanisation appears to be reduced emissions in USA, potentially reflecting the role of urban planning, technological adaptation and economics of scale in energy use. Higher urban density may facilitate public transport system energy efficient infrastructure, and smart city initiatives contribute to emission reduction. Such mechanisms are consistent with policy discussion emphasising urban energy efficiency, transport planning, and low carbon infrastructure in the USA (EPA, 2026).

6.4.4. Italy and Canada (IND increases CO_2)

In countries such as Italy and Canada, industrialisation increased emissions likely due to persistence of carbon intensive production processes and energy use. These findings suggest that industrial growth without sufficient technology upgrading or environmental regulations exacerbate higher carbon emissions. This explanation is also aligned with IEA and report from European Commission that emphasise that industrial emissions are mostly energy-related and need to adopt industrial decarbonisation mechanisms (European Commission, 2026).

6.4.5. Innovation (panel & country differences scale)

Although technological innovation reduced emissions at the panel level, it is insignificant in country specific models suggest that the effectiveness of innovation depends on a national absorptive capacity, policy incentives, and the sectoral allocation of R&D investments. Therefore, the adoption of low-carbon technologies and sustainable manufacturing practices is critical for achieving long-term emission reductions (OECD, 2023).

Overall, these findings highlight that decarbonisation strategies cannot be uniform across G7 economies. Instead, policy intervention must be tailored to country specific structural characteristics including energy mix, industrial composition and institutional capacity.

7. Policy implications

7.1. Energy transition and fossil fuel reduction

The estimated coefficient for energy consumption indicates that a one-unit increase in per capita energy consumption (MWh/person) is associated with an increase of approximately 0.166 metric tons of CO_2 emissions per capita. Conversely, a reduction in energy consumption by 1 MWh/person could reduce emissions by approximately 0.166 per capita, highlighting the substantial environmental gain from energy efficiency improvements. This underscores the critical need to mitigate dependence on fossil fuels. Policymakers should adopt stricter regulations on fossil fuel consumption and introduce carbon pricing mechanisms. Additionally, setting clear strategies to reduce coal and high-emission energy use gradually could help achieve net-zero carbon emissions.

Encouraging clean energy adoption is a crucial step to achieving a low carbon profile, and G7 countries, with their technical and financial capabilities, can lead the way to shift to clean energy. Accelerating large-scale investments in cleaner energy systems and energy storage systems is essential to reduce emissions and improve energy security.

7.2. Innovation driven decarbonisation strategies

The results suggest that 1% increase in research and development expenditure as a percentage of GDP leads to approximate decrease of 0.359 metric tons of CO_2 emissions per capita. This highlights that increased investment on green technologies can be result in substantial contribution to carbon reduction. For instance, the increment of 1% investments for research and development may give decline of 0.359 metric tons of CO_2 emissions per capita. Therefore, policymakers and governments can enhance investments in low carbon technologies, energy efficient industrial processes. Promote collaborations between industry expert researchers and the government to speed up eco-friendly technologies.

Some technological advancements that can harm the environment. Policymakers need to identify and discourage those technologies with high carbon intensity through setting stricter regulations and providing intensives to eco-friendly technologies.

7.3. Country-specific policy recommendations

At the country level, the magnitude of the entity effects varies. For instance, in Canada a 1 MWh/person reduction in energy consumption is associated with a decrease of approximately 0.108 metric tons of CO_2 emissions per capita, indicating a strong link between energy use and emissions. These quantitative estimates provide actionable benchmarks for policy makers. For example, achieving a 5 MWh/person reduction in energy consumption could reduce emissions by approximately 0.8 metric tons per capita at the panel level, demonstrating the scale of impact achievable through energy efficiency policies. In Canada 1 unit decrease in GLO index will achieve 0.235 reduction of metric tons of CO_2 per capita demonstrating encourage sustainable trade strategies can achieve carbon efficiency. Moreover, for Canada 1% decrease in industry growth could reduce nearly 0.064 metric tons of CO_2 per capita indicating Canada should reduce carbon-intensive processes to achieve net-zero emissions.

For France 1 MWh/person decline in EC is linked to 0.06 drop of metric tons of CO_2 emissions per capita implying Frensh policymakers should pay attention to reinforcing the renewable energy transition process to mitigate environmental harm. In Germany, 1 MWh/person reduction in EC is contributed to 0.2164 drop of metric tons of CO_2 emissions per capita. This signalling that governments should immediately strengthen low-carbon emission energy systems. In Italy, 1 MWh/person decrease in EC is led to decrease of 0.208 metric tons of CO_2 emissions per capita. Furthermore, Italy observed that 1% decrease in Industry, value added (% of GDP) supported reduction of 0.096 metric tons of CO_2 emissions per capita. These suggest that in Germany, it's essential to reduce dependence on fossil fuels, and the government need to promote the purchase of low-carbon-intensive materials for large-scale projects and eco-friendly manufacturing systems. The findings indicated that in Japan, 1 MWh/person drop of EC is associated with decline of 0.152 metric tons of CO_2 emissions per capita highlighting the necessity energy policies to speed up the renewable energy transition. In addition, Japan reported 1% rise in industry, value added (% of GDP) support the low carbon intensity through 0.158 reduction of metric tons of CO_2 emissions per capita implying that governments can provide financial incentives to industries to further encourage green infrastructure. The UK showed 1 MWh/person decrease of EC could achieve 0.234 drop of metric tons of CO_2 emissions per capita demonstrating that governments should continue expanding its capacity for renewable energy transition through infrastructure upgrades. The USA reported 1% increase in Urban population growth as a % of annual reduce metric tons of CO_2 emissions per capita by 0.441 suggesting the USA can expand its promotion of Urban (U7) engagements and align them with national policies, which can further reduce pollution. However, in the USA 1 MWh/person decrease of EC could contribute to approximately 0.259 decline of metric tons of CO_2 emissions per capita which underscore the USA need to reform environmental policies and regulatory frameworks to reduce reliance on fossil fuel consumption to achieve net zero emissions.

8. Conclusion and further research

8.1. Main findings and contribution

This study uses a panel regression model and a multiple linear regression model to explore the determinants of CO_2 emissions in G7 countries. The results of the analysis highlight the context-specific nature of the determinants of CO_2 emissions across G7 countries. Findings indicate that EC is the primary driver of CO_2 emissions in G7 economies. TI shows mitigating emissions in the overall panel but shows no measurable impact at the country level. In the overall model, GLO, URB, and IND show insignificant impacts. At the same time, in the country-level analysis, GLO influences CO_2 emissions in Canada, URB influences CO_2 emissions in the USA, and IND shows a positive and significant impact on Canada and Italy, and a negative impact on emissions in Japan.

This research contributed an updated analysis to the literature by examining the impact of GLO, EC, URB, IND and TI on CO_2 emissions in G7 countries. This study provided several policy recommendations to promoting cleaner energy, fostering green innovation, provide clear guidance to design initiatives to achieve economic development while reducing the environmental burden in the G7 economies.

8.2. Limitations

Despite the meaningful contribution, the current study has several limitations. This study only focuses on seven specific countries: Canada, France, Germany, Italy, Japan, the UK, and the USA and a limited time span. Another limitation is the unavailability of the most recent data for this analysis. In addition, given the observational nature of the data and the possibility of endogeneity, the findings should be interpreted as an association rather than definitive causal effects.

8.3. Direction for Further Research

Future researchers are encouraged to expand the analysis to higher country groups and a longer time span. Moreover, further studies could incorporate specific policy indicators, such as carbon pricing, renewable energy subsidies, environmental policy stringency index, climate policy uncertainty, green public investment, and fossil fuel subsidy reforms to better capture the role of government interventions in shaping CO_2 emissions.

CRediT authorship contribution statement

Lohansa Weerasinghe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Nadeesha Vithanage:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation. **Dinidu Rupasinghe:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Chandrakumar Keesha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation. **Ruwan Jayathilaka:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Clinical trial number

Not applicable

Consent for publication

Not Applicable

Consent to participate

Not Applicable

Statements and Declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethical approval

Ethical approval is not applicable to this manuscript.

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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. : Order of Integration of Variables by Country

Country	CO_2	GLO	EC	URB	IND	TI
Canada	I (1)	I (1)	I (1)	I (0)	I (1)	I (1)
France	I (1)	I (1)	I (1)	I (1)	Not Stationary	I (1)
Germany	I (1)	I (1)	I (1)	I (1)	I (0)	I (1)
Italy	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)
Japan	I (1)	I (1)	I (1)	I (1)	I (0)	I (1)
UK	I (1)	I (0)	I (1)	I (2)	I (1)	I (1)
USA	I (1)	I (1)	I (1)	I (2)	I (1)	I (2)

Note: I (0), I (1), and I (2) denote stationary at levels, first differences, and second differences, respectively. Variables classified as "Not Stationary" remained non-stationary throughout the unit root testing process. The integration was identified according to the statistical significance of the unit root test results at the 1%, 5%, and 10% levels

Appendix B. : Augmented Dickey-Fuller (ADF) Test Results

Variable	Canada						Order of Integration
	Level		First Difference		Second Difference		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	0.046	0.962	−5.132***	0.000	-	-	I (1)
GLO	−1.104	0.713	−4.266***	0.000	-	-	I (1)
EC	0.151	0.969	−5.590***	0.000	-	-	I (1)
URB	−2.910**	0.044	-	-	-	-	I (0)
IND	−1.787	0.387	−3.206**	0.019	-	-	I (1)
TI	−1.916	0.324	−3.076**	0.028	-	-	I (1)
	France						**Order of Integration**
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	0.683	0.989	−4.962***	0.000	-	-	I (1)
GLO	−2.229	0.195	−3.998***	0.001	-	-	I (1)
EC	2.080	0.998	−3.682***	0.004	-	-	I (1)
URB	−2.429	0.133	−4.309***	0.000	-	-	I (1)
IND	−1.718	0.422	−0.533	0.885	−0.883	0.793	-
TI	−1.347	0.607	−3.627***	0.005	-	-	I (1)
	Germany						**Order of Integration**
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	1.607	0.997	−3.721***	0.003	-	-	I (1)
GLO	−2.302	0.171	−3.629***	0.005	-	-	I (1)
EC	1.925	0.998	−2.830*	0.054	-	-	I (1)
URB	−2.512	0.112	−4.850***	0.000	-	-	I (1)
IND	−3.326**	0.013	-	-	-	-	I (0)
TI	−1.227	0.661	−4.011***	0.001	-	-	I (1)
	Italy						**Order of Integration**
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	−0.135	0.945	−3.511***	0.007	-	-	I (1)
GLO	−1.510	0.528	−4.213***	0.000	-	-	I (1)
EC	−0.503	0.891	−3.925***	0.001	-	-	I (1)
URB	−1.909	0.327	−3.708***	0.004	-	-	I (1)
IND	−2.021	0.277	−3.258**	0.016	-	-	I (1)
TI	−1.158	0.691	−2.711*	0.072	-	-	I (1)
	Japan						**Order of Integration**

(continued on next page)

(*continued*)

Variable	Canada						Order of Integration
	Level		First Difference		Second Difference		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	−0.145	0.944	−3.477***	0.008	-	-	I (1)
GLO	−1.154	0.693	−2.736***	0.068	-	-	I (1)
EC	0.090	0.965	−4.318***	0.000	-	-	I (1)
URB	−1.276	0.640	−3.271**	0.016	-	-	I (1)
IND	−2.601*	0.092	-	-	-	-	I (0)
TI	−0.979	0.760	−3.656***	0.004	-	-	I (1)
	UK						**Order of Integration**
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	1.450	0.997	−3.096**	0.02	-	-	I (1)
GLO	−3.420**	0.010	-	-	-	-	I (0)
EC	0.891	0.993	−3.652***	0.004	-	-	I (1)
URB	−1.886	0.338	−2.467	0.123	−5.480***	0.000	I (2)
IND	−2.514	0.112	−3.320**	0.014	-	-	I (1)
TI	0.066	0.963	−3.216**	0.019	-	-	I (1)
	USA						**Order of Integration**
	Level		**First Difference**		**Second Difference**		
	t-bar	p-value	t-bar	p-value	t-stat	p-value	
CO_2	0.005	0.958	−5.294***	0.000	-	-	I (1)
GLO	−1.320	0.620	−4.307***	0.000	-	-	I (1)
EC	−0.762	0.830	−6.052***	0.000	-	-	I (1)
URB	−2.493	0.117	−2.390	0.144	−3.044**	0.031	I (2)
IND	−1.337	0.612	−5.167***	0.000	-	-	I (1)
TI	1.091	0.995	−1.932	0.317	−4.151***	0.000	I (2)

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Appendix C. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2026.109642.

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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