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Article

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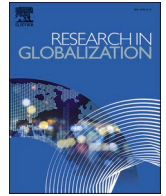
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Economic growth and environmental sustainability: The role of foreign direct investment and technological innovation on carbon emissions in Ghana

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ABSTRACT

Debates on foreign direct investment, technological innovation and carbon emission seem unsettling in the literature. We contribute to the literature by investigating the relationships between foreign direct investment, technological innovation, and carbon emissions in Ghana. Using the Autoregressive Distributive Lag (ARDL) method, the analysis reveals that foreign direct investment contributes to reduced emissions in the short run but significantly increases carbon emissions in the long run, aligning with the pollution haven hypothesis. This indicates that Ghana may have a robust environmental regulation that ensures eco-friendly foreign direct investments in the short run, with weak enforcement of regulations resulting in high emissions in the long term. Technological innovation in the Ghanaian context contributes to increased CO₂ emissions. However, the interaction effect of foreign direct investments and technological innovation reduces carbon emissions, emphasizing the importance of aligning foreign investments with sustainable technological advancements in Ghana. The study also identifies the Environmental Kuznets Curve (EKC) effect, where emissions rise with economic growth but decelerate at higher GDP levels. The findings underscore the need for stronger environmental regulations and a shift towards sustainable, cleaner energy and technological development to mitigate the environmental impacts of economic growth in Ghana and similar developing countries.

Introduction

Anthropogenic-induced climate change activities have emerged as a critical environmental and economic issue (Rafique, Li, Larik, & Monaheng, 2020). Human activities, particularly the emission of greenhouse gases, have undeniably contributed to global warming, with global surface temperatures rising by 1.1°C above pre-industrial levels (1850–1900) between 2011 and 2020. This warming is unevenly distributed, with land temperatures increasing more than ocean temperatures. The ongoing rise in greenhouse gas emissions is driven by unsustainable energy consumption, land-use changes, and patterns of production and consumption. The Intergovernmental Panel on Climate Change (IPCC) warns that global temperatures could reach 1.5°C by 2050, leading to severe consequences, such as rising sea levels that could displace millions of people in coastal and low-lying areas (Lau, Choong

& Eng, 2014). Additionally, human-induced climate change has intensified the frequency of extreme weather events, disproportionately impacting vulnerable communities. Despite awareness of these risks, historical and current emissions continue to rise, worsening climate-related challenges (IPCC, 2023). The far-reaching consequences of climate change extend to ecosystems, human health, economies, and societies worldwide (Vitenu-Sackey, 2020). Urgent action is required to mitigate its impacts, especially in vulnerable regions, including Africa. To this end, carbon dioxide (CO₂) emissions are highlighted as the primary driver of global warming (Chen, Fan, Li, Liu, & Song, 2020), and their levels are increasing in Sub-Saharan Africa, including Ghana, where resource-based livelihoods are pronounced (Kuuwill, Kimengsi, & Campion, 2022). Data from the World Bank Development Indicators shows that CO₂ emissions in Ghana surged by approximately 49% between 2010 and 2020. This rise has contributed to adverse climate

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impacts, such as rising temperatures and unpredictable rainfall, affecting Ghana's agriculture and economy (Nubuor, 2017).

Ghana is vulnerable to climate change as it threatens future growth and development, negatively affecting infrastructure, hydropower production, food security, and coastal and agricultural livelihoods (World Bank Report, 2023). In response to the global climate crisis, Ghana has joined international efforts like the Paris Agreement and Kyoto Protocol to reduce CO₂ emissions and promote sustainable development (Duodu, Kwarteng, Oteng-Abayie, & Frimpong, 2021). Additionally, the government has established the Environmental Protection Agency to develop a national climate change policy and foster sustainable investments (Abokyi et al., 2019).

While these efforts are in place, addressing climate change warrants identifying the determinants of CO₂ emissions, which have been noted to have contributed significantly to climate change for a tailored action. In this sphere, Foreign Direct Investment (FDI), which involves the cross-border flow of capital, knowledge, management practices, and technology transfer between countries, is flagged as a key determinant of CO₂ in many parts of developing countries (Chen, Paudel & Zheng, 2022). For instance, Solarin, Al-Mulali, Musah, and Ozturk (2017) noted that FDI increases pollution in developing countries due to less stringent environmental policies, which drive the inflows of polluting FDI from developed worlds with strict environmental policies to the developing worlds. On the contrary, it is argued that FDI lowers emissions in developing countries through the transfer of eco-friendly technologies and improved management practices (Edziah, Kporsu, Lee, 2013; Sarkodie, Adams & Leirvik, 2020). While this argument is succinctly established in the literature, the economic growth literature also underscores the pivotal role of FDI in the sustainable development of developing countries (Abor, Adjasi & Hayford, 2008; Tran, Phan, Tran, & Le, 2022; Wang, Gao, Wei, Majeed & Alam, 2022). Ironically, FDI seems a triple-edged cutting sword that facilitates economic growth and development, lowers carbon emissions in some cases while increasing carbon emissions, and contributes to climate change in other instances. In light of this, Liu, Zhu, and Wang (2021) iterated that governments and researchers must promote investment in human capital, R&D, and innovation to facilitate economic growth while mitigating CO₂ emissions. The foregoing suggests that issues relating to FDI and CO₂ emission have yielded highly contentious mixed findings, prompting continuous studies.

In recent years, Ghana has witnessed a notable influx of Foreign Direct Investment (FDI), as seen in Fig. 1.

Additionally, according to the Ghana Investment Promotion Centre (GIPC), FDI inflows increased by 39% to \$2.6 billion in 2021, owing to

projects in extractive industries (UNCTAD, 2021). This surge is expected to stimulate economic growth; however, it raises concerns about environmental sustainability, especially in light of the country's commitments to reduce carbon emissions.

In the context of Ghana, like other parts of Africa, studies have wrangled that the pursuit of economic growth through foreign direct investment (FDI) is increasingly at odds with its environmental sustainability goals (Solarin et al., 2017). The argument advances that the influx of foreign industries, often accompanied by relaxed environmental regulations, has exacerbated environmental degradation in Ghana, contributing to the country's vulnerability to climate change impacts (Lan, Kakinaka & Huang, 2012; Solarin et al., 2017). Moreover, the country's changing climatic conditions, characterized by rising temperatures and irregular rainfall patterns, have severe implications for the economy, particularly agriculture (Nubuor, 2017). Hence, the increasing trend of CO₂ emissions in Ghana, which is aligned with the global pattern, underscores the urgent need for mitigation strategies (Lau et al., 2014). For instance, a panel data analysis from 1990 to 2017 for Sub-Saharan African countries showed that FDI, income level, and governance worsen climate change (Sarkodie et al., 2020).

Simultaneously, technological innovation has gained traction as a potential driver for sustainable development in Ghana. Fig. 2 reveals the trend of patent applications by non-residents as an indicator of technological innovation in Ghana.

Despite a historical lack of emphasis on R&D, recent data from the World Intellectual Property Organization indicate that patent applications by non-residents in Ghana rose from 8 in 2020 to 19 in 2021, reflecting a growing interest in innovation. This shift suggests that technological advancements could play a crucial role in mitigating emissions, particularly when aligned with foreign investments.

Using the system Generalized Method of Moment (GMM), Adedoyin et al. (2022) showed that clean FDI inflows assist in ameliorating emissions. Abdul-Mumuni et al. (2022), employing the panel ARDL approach, found that a positive shock in foreign direct investment increases carbon dioxide emissions while a negative shock lowers it in Sub-Saharan Africa. While FDI can potentially contribute to technological advancements and cleaner production processes, reducing CO₂ emissions, its overall impact remains unsettled (Lee, 2013; Sarkodie et al., 2020).

A critical assessment of the literature, especially in Africa, primarily follows the global pattern of examining the relationship between FDI and CO₂ emissions, often overlooking the crucial role of technological innovation as a potential moderator of this relationship (Kiviyiro & Arminen, 2014; Ojewumi & Akinlo, 2017; Sarkodie et al., 2020; Opoku

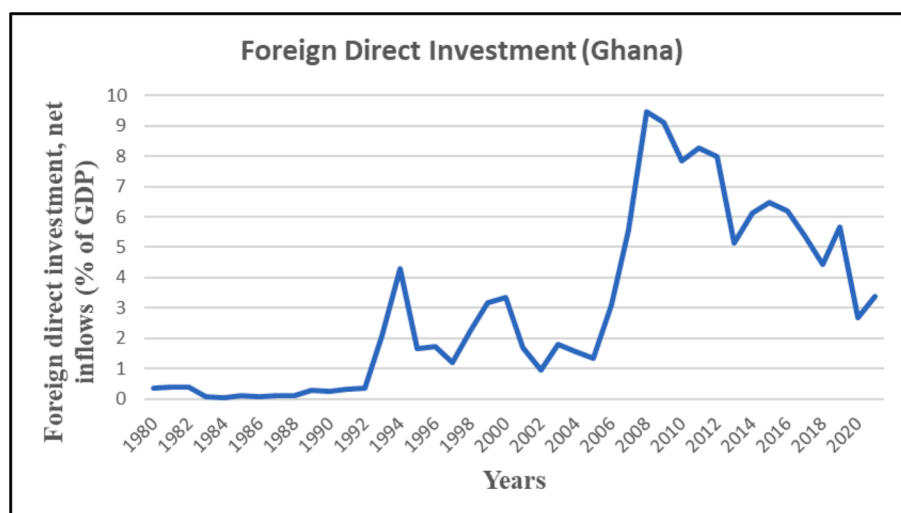


Fig. 1. Trend of Ghana's FDI Received from 1980 to 2021. Source: World Bank Indicators.

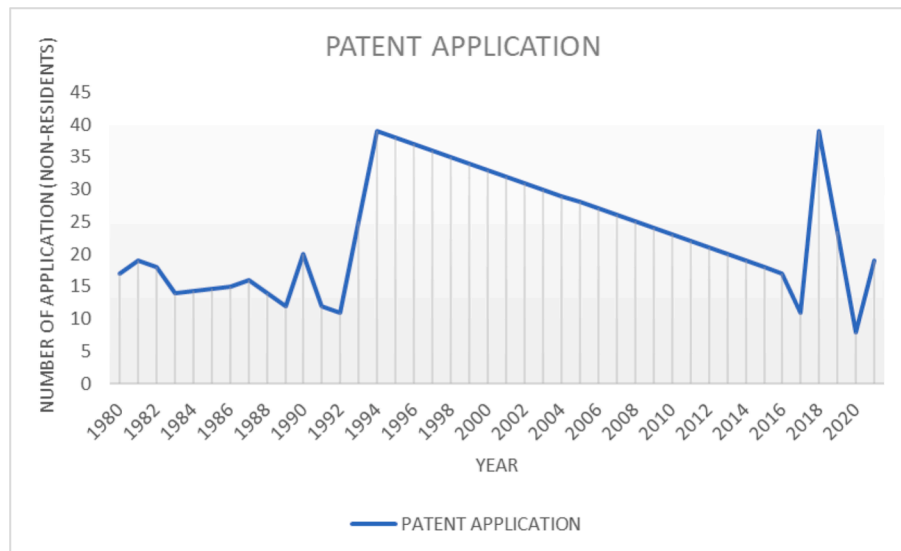


Fig. 2. Trend of Technological Innovation in Ghana from 1980 to 2021. Source: World Development Bank Indicators, 2022.

et al., 2021; Abdul-Mumuni et al., 2022; Adedoyin, Bekun, Eluwole, & Adams, 2022). For example, Obobisa et al. (2022) showed that green technological innovation and renewable energy consumption significantly negatively impact CO₂ emissions. Ali et al. (2022) discovered that the interaction between technological innovation and quality governance decreases CO₂ emissions. While there seems to be convergence in the crucial role of technological innovation in moderating the effect of FDI on CO₂ emissions, as shown by previous studies in different regions, research in this regard in the Ghanaian context remains a crevice. Against the scientific and policy orifice established, we investigated (a) the individual effect of FDI and technological innovation on CO₂ emissions and (b) the effect of the complementarity between technological innovation and FDI on CO₂ emissions in Ghana. This adds to the literature on FDI, technological innovation, and CO₂ emission in developing countries, especially Ghana, which has under-researched and provided insight for tailored policy intervention.

Methodology

Data

The study used time-series secondary data from 1980 to 2021 for Ghana, which was drawn from the World Bank Development Indicators (WDI) and the Africa Development Bank Socio-Economic Database (AfDB). The data for the dependent variable was obtained from the AfDB, while data for all the independent and control variables were sourced from the WDI. The key variables in the study include CO₂ emissions, technological innovation, and FDI inflows. CO₂ emission is the dependent variable because it is a widely accepted indicator of environmental pollution and a key contributor to climate change, accounting for approximately 70% of total global emissions (Lau et al., 2014). This makes it a critical focus in evaluating environmental impacts. Moreover, numerous studies including Shahbaz et al. (2020), Obobisa et al. (2022), and Wen et al. (2022) have used CO₂ emissions as an indicator for environmental pollution, thus aligning with the objectives of this study. Given the study's aim to analyze the linkage between FDI, technological innovation, and environmental outcomes, CO₂ emissions provide a comprehensive and relevant measure. Following the empirical literature on the pollution haven and halo hypothesis, particularly in the African context (e.g., Ssali et al., 2019; Essandoh et al., 2020; Rafique et al., 2020; Bakhsh et al., 2021; Ali et al., 2022), this study includes trade openness (TO), urbanization (Urb), real GDP per capita (GDP), and industrialization (IND) as control variables due to

their established relationship with environmental outcomes.

The Autoregressive Distributed Lag (ARDL) Bounds Testing Approach was selected for this study due to its versatility and advantages in testing long-run equilibrium relationships in multivariate time series models. The ARDL method, developed by Pesaran, Shin, and Smith (2001), can be applied regardless of whether the explanatory variables are integrated of order zero I(0), one I(1), or mutually cointegrated, which provides flexibility not offered by other cointegration techniques such as Johansen's method. Additionally, the ARDL model is straightforward to implement, and it is relatively more efficient in small or finite samples, which is relevant given the limited dataset available for Ghana. However, it is important to acknowledge certain limitations: ARDL is not suitable when variables are integrated of order two I(2), making it crucial to conduct pre-tests for unit roots; it is also sensitive to lag length selection, which requires careful consideration to avoid model misspecification. Moreover, the ARDL approach may be less reliable in the presence of structural breaks unless appropriate tests are incorporated. Despite these limitations, the ARDL model remains an appropriate choice for this study, given its ability to handle a mix of integrated variables and its efficiency in small samples.

2.2. Model specification

The conceptual framework by Grossman and Krueger (1991) and the pollution hypothesis by Walter and Ugelow (1979) posit that FDI might reduce CO₂ emissions, suggesting that FDI transfers eco-friendly technologies to host countries. The theory argues that adopting these eco-friendly technologies reduces CO₂ emissions and improves environmental quality. In light of this theoretical analysis, Fig. 3 presents a simplified conceptual framework showing the relationship among FDI, technological innovation, and carbon dioxide emissions, and also incorporating other explanatory factors such as economic growth, trade openness, industrialization, and urbanization based on current literature (Kwakwa et al., 2023).

2.2.1. Empirical model Specification

From this conceptual framework and based on the theoretical underpinnings, the basic model for the empirical analysis is specified as:

$$Y_t = \beta X_t + \varepsilon_t \quad (1)$$

$$CO_{2t} = f(FDI_t, TI_t) \quad (2)$$

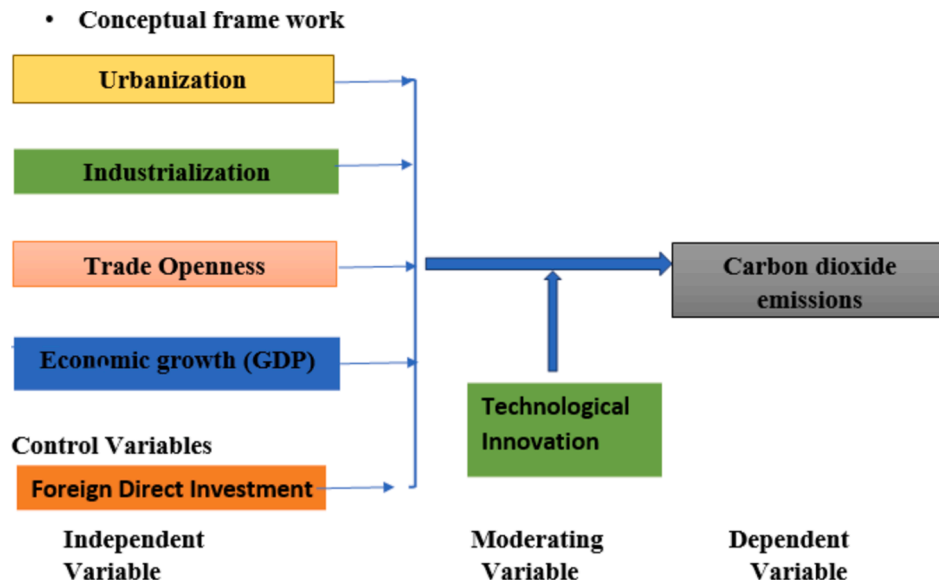


Fig. 3. Conceptual framework.

$$CO_{2t} = \beta_0 + \beta_1 FDI_t + \beta_2 TI_t + \varepsilon_t \quad (3)$$

From the conceptual framework, the dependent variable for this study is carbon dioxide emissions; the policy variables are foreign direct investment (FDI) and technological innovation (TI). Following the empirical literature by studies such as Ssali et al. 2019; Essandoh, et al. 2020; Rafique et al. 2020; Bakhsh et al. 2021; and Ali et al. 2022 on pollution haven and halo hypothesis, especially in the African region, we included trade openness (TO), urbanization (Urb), real GDP per capita (GDP), and industrialization (IND) as control variables. With these, the empirical analysis considers the basic functional form of the carbon dioxide emissions equation as:

$$CO_{2t} = f(FDI_t, TI_t, GDP_t, GDP^2_t, TO_t, URB_t, IND_t, FDI_t * TI_t) \quad (4)$$

where CO_{2t} represents carbon dioxide emissions, the patent applications that are used as a proxy for technological innovations (TI), t means time and FDI, GDP, GDP^2 , TO, URB, IND and $FDI_t * TI_t$ represent the foreign direct investment, gross domestic product, GDP squared, trade openness, urban population, industrialization, and the interaction of FDI and TI, respectively. Equation (4) is a deterministic equation which is transformed into an econometric model as follows:

$$CO_{2t} = \beta_0 + \beta_1 FDI_t + \beta_2 TI_t + \beta_3 GDP_t + \beta_4 GDP^2_t + \beta_5 TO_t + \beta_6 URB_t + \beta_7 IND_t + \beta_8 FDI_t * TI_t + \varepsilon_t \quad (5)$$

We linearized the independent variables for robust estimations, resulting in equation (6) below:

$$CO_{2t} = \beta_0 + \beta_1 \ln FDI_t + \beta_2 TI_t + \beta_3 \ln GDP_t + \beta_4 \ln GDP^2_t + \beta_5 TO_t + \beta_6 \ln URB_t + \beta_7 \ln IND_t + \beta_8 \ln FDI_t * TI_t + \varepsilon_t \quad (6)$$

where β_0 is the constant term, representing the CO_2 when all the explanatory variables are held constant. $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$, and β_7 are the respective coefficients of the explanatory variables, which shows how carbon dioxide emission will change, given a unit change in their respective independent variables. ε_t represents the error term, capturing all antecedent and omitted variables that may likely influence our findings. See Table 1 for the variables used, their description, and measurement.

Table 1
Description of variables.

Variable	Symbol	Description and measurement	Source
Carbon dioxide emissions	CO ₂	Metric tons per capita	AfDB
Foreign Direct Investment	InFDI	FDI inflows (US\$)	WDI
Technological innovation	TI	Patent applications (non-residents)	WDI
Economic growth	InGDP	Gross domestic Product (GDP per Capita)	WDI
Trade openness	TO	Total trade as % of GDP	WDI
Industrialization	InIND	Manufacturing Value Added (Current US\$)	WDI
Urbanization	InURB	Urban population (% of total population)	WDI

2.3. Estimation procedure

The study employed the Autoregressive Distributive Lag (ARDL) model to estimate the effects of FDI and technological innovation on CO_2 emissions in Ghana. In the first phase of the estimation process, we investigated the stationarity properties of the variables to control for potential spurious regression using the Augmented Dickey-Fuller (ADF) test as the main technique for testing for unit roots (stationarity) (Shahbaz et al., 2020). Further, we used the Phillips-Perron unit root test to confirm the results of the ADF test. This ensures a zero chance of spurious regression results as the combination of stationary and non-stationary variables in the same model has a high chance of yielding such results, resulting in misleading findings and misguided policy recommendations. Using the optimal lag selected, the study tested for cointegration using the Pesaran, Shin, and Smith (PSS) bounds test to investigate the long-run equilibrium relationship among FDI, technological innovation, and CO_2 emissions in Ghana. Once the cointegrating relationship is ascertained, the long run and error correction estimates of the ARDL model are obtained as given in (7 and 8):

$$\begin{aligned}
CO2_t = & \alpha_0 + \sum_{k=1}^p \alpha_1 CO2_{t-k} + \sum_{k=1}^q \alpha_2 InFDI_{t-k} + \sum_{k=1}^q \alpha_3 TI_{t-k} + \sum_{k=1}^q \alpha_4 InGDP_{t-k} \\
& + \sum_{k=1}^q \alpha_5 InGDP^2_{t-k} + \sum_{k=1}^q \alpha_6 TO_{t-k} + \sum_{k=1}^q \alpha_7 InURB_{t-k} + \sum_{k=1}^q \alpha_8 InIND_{t-k} \\
& + \sum_{k=1}^q \alpha_9 InFDI * TI_{t-k} + \varepsilon_t
\end{aligned} \quad (7)$$

The short-run error correction representation of the series is as follows:

$$\begin{aligned}
\Delta CO2_t = & \alpha_0 + \sum_{k=1}^p \beta_1 \Delta CO2_{t-k} + \sum_{k=1}^p \beta_2 \Delta InFDI_{t-k} + \sum_{k=1}^q \beta_3 \Delta TI_{t-k} \\
& + \sum_{k=1}^q \beta_4 \Delta InGDP_{t-k} + \sum_{k=1}^q \beta_5 \Delta InGDP^2_{t-k} + \sum_{k=1}^q \beta_6 \Delta TO_{t-k} \\
& + \sum_{k=1}^q \beta_7 \Delta InURB_{t-k} + \sum_{k=1}^q \beta_8 \Delta InIND_{t-k} + \sum_{k=1}^q \beta_9 \Delta InFDI * TI_{t-k} \\
& + \beta_{10} ECM_{t-1} + \varepsilon_t
\end{aligned} \quad (8)$$

where Δ represent the difference operator and the error correction term is represented by ECM_{t-1} with a coefficient β_9 which is expected to be negative and statistically significant to confirm the existence of a cointegrating relationship further. See Fig. 4 for a visual representation of the econometric procedures adopted. Following the convergence of the relatively scanty studies examining the interplay of FDI and TI, we hypothesized the policy variables as follows: (a) FDI negatively correlates with CO₂ emissions in Ghana, (b) TI negatively correlates with CO₂ and (c) the interaction of FDI and TI have a negative effect on CO₂ emissions in Ghana.

Results

Descriptive statistics

Table 2 indicates that, on average, a person in Ghana contributes about 0.335 metric tons of CO₂ compared to the global average of about 4.660 metric tons per capita in 2021 (Magne, Khatiwada, & Cardozo, 2024). The median, at 0.314, is close to the mean, indicating a symmetric distribution. The range of emissions, from a minimum of 0.150 to a maximum of 0.659 metric tons per capita, coupled with a standard deviation of 0.153, shows moderate variability in carbon emissions across the population. FDI has a mean of 1.192 US\$. The median is slightly higher at 1.421 US\$, indicating a slight skew towards higher FDI inflows. The significant variation, reflected in a standard deviation of 5.702 US\$, suggests that some periods or specific events might have led to substantial FDI inflows. Technological innovation (TI), measured by

non-residents' patent applications, has a mean of 23.012. The median value of 21.500 suggests a somewhat balanced distribution, with most years seeing around 21 to 23 patent applications from non-residents. The range, from a minimum of 8 to a maximum of 39 patent applications, indicates considerable variability in technological innovation, as highlighted by the standard deviation of 8.729. Economic growth (InGDP), measured as GDP per capita, means 4.522 US\$. The median of 4.902 US\$ suggests that most years are close to this average, with a relatively balanced distribution of GDP per capita. The range of values, from a minimum of 1.042 US\$ to a maximum of 9.3816 US\$, and the standard deviation of 2.932 US\$, reflect significant differences in economic growth rates across the observed period. Trade openness (TO), representing total trade as a percentage of GDP, has a mean value of 5.422. The median of 6.222% indicates a distribution slightly skewed towards higher trade openness. The range, with a minimum of 6.881% to a maximum of 8.382% and a standard deviation of 2.372%, suggests moderate variability in trade openness in Ghana. Industrialization (InIND), measured by manufacturing value added in current US dollars, has a mean of 3.132 US\$. The median of 2.932 US\$, with a maximum of 8.562 US\$ and a minimum of 1.831 US\$, shows substantial variation in industrialization levels. The standard deviation of 2.182 US\$ further indicates significant variability, suggesting that Ghana's industrial sector experiences fluctuating economic contributions. Urbanization has a mean of 9,303,215, representing about 27.8% of the total population. The median value of 8,490,900, along with the maximum of 18,192,301 and minimum of 3,366,222, highlights a significant range in urban population distribution. The large standard deviation of 4,498,970 underscores the variability in Ghana's urbanization rates across different periods or regions.

3.1.2. Unit root test

Table 3 shows that CO₂ emissions and the squared GDP term (InGDP²) are non-stationary at levels but become stationary after first differencing, indicated as I (1). In contrast, foreign direct investment (InFDI), technological innovation (TI), economic growth (InGDP), industrialization (InIND), trade openness (TO), and urbanization (URB) are stationary at levels denoted as I (0), meaning they are stable over time.

The F-statistic (Table 4) calculated is 13.100, which is significantly larger than the critical values at all significance levels (1%, 5%, and 10%). This indicates a rejection of the null hypothesis of no cointegration. Therefore, based on the F-test results, there is strong evidence of a long-run relationship between the variables in the model. The results suggest a long-run relationship between FDI, technology innovation, and the control variables used in the model estimations. This permits us to examine such a long-term relationship to unveil their directions and implications.

3.2. Short and long-run estimates of foreign direct investment, technological innovation and CO₂ emissions in Ghana

Short-run estimates of the ARDL model are presented in Table 5. The result shows that at the 5% significance level, FDI significantly reduces CO₂ emissions in Ghana by about 0.009 metric tons per capita. However, technological innovation is not statistically significant in explaining CO₂ emissions in Ghana in the short-run model. The interaction between foreign direct investment and technological innovation reduces CO₂ emissions by about 0.002 metric tons per capita in the short run, although this relationship is significant at the 10% alpha level. The results also show that economic growth, measured in gross domestic product, is positively associated with carbon emissions. In contrast, higher levels of economic growth are associated with reduced emissions, although these relationships are not statistically significant in the short run. At the 1% statistically significant level, the analysis reveals that a 1% increase in trade openness is associated with about 4.472 metric tons per capita reduction in CO₂ emissions. Similarly, urbanization reduces

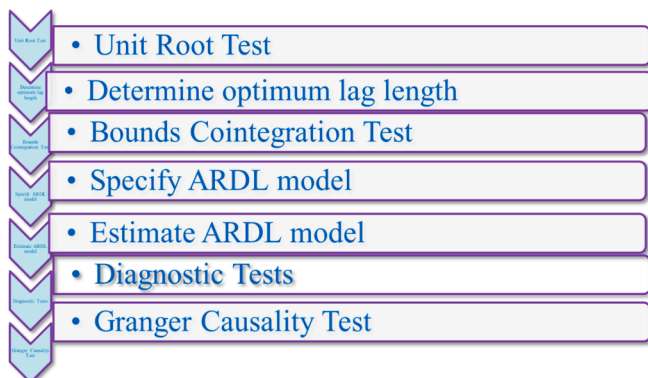


Fig. 4. Chart of the econometric method.

Table 2
Descriptive statistics.

Variable	CO ₂	FDI	IND	GDP	TI	TO	URB
Mean	0.3353	1.1915	3.1316	4.5216	23.0119	5.4216	9303215.
Median	0.3142	1.4208	2.9316	4.9016	21.5000	6.2216	8490900.
Maximum	0.6588	3.3616	8.5616	9.3816	39.0000	8.3816	18,192,301
Minimum	0.1500	2000000.	1.8314	1.0415	8.0000	6.8814	3366222.
Std. Dev.	0.1529	5.7015	2.1816	2.9316	8.7287	2.3716	4498970.
Observations	42	42	42	42	42	42	42

Table 3
Results of augmented dickey-fuller (ADF) unit root test.

Variable	Levels		1st Difference		Int.
	Constant	Trend & Constant	Constant	Constant & Trend	
CO ₂	-1.2802	-2.3672	-5.7113***	-6.3004***	I(1)
lnFDI	-5.0305***	-5.7442***	-13.1594***	-13.3438***	I(0)
TI	-2.7641*	-2.6962	-7.2307***	-7.2300***	I(0)
lnGDP	-3.1867*	-3.1013	-12.2266***	-12.1314***	I(0)
lnGDP ²	-3.2272	-3.1404	-4.6870***	-4.7925**	I(1)
lnIND	-5.8051***	-5.7500***	-8.9650***	-8.8436***	I(0)
TO	-4.1715**	-4.7645**	-10.3779***	-6.6518***	I(0)
lnURB	-4.9290***	-0.17	-0.7494	-4.826651**	I(0)

Note: (***), (**) and (*) denotes significance level at 1%, 5% and 10% respectively.

Table 4
F-tests for cointegration.

F-Bounds Test		Null Hypothesis: No levels of relationship		
Test Statistic	Value Lag Length	Significant Level.	I (0)	I (1)
F-statistic	13.1002	10 %	2.26	3.34
		5 %	2.55	3.68
		2.5 %	2.82	4.02
		1 %	3.15	4.43

Note: Where I (0) and I (1) denote the lower and upper band critical values at 10%, 5%, and 1% significance level.

Table 5
Short-run Results of ARDL estimation.

Variable	Coefficient	Standard Error	
$D(\ln FDI(-1))$	-0.0090**	0.0033	0.0271
$D(TI)$	-0.0016	0.0018	0.3887
$D(\ln FDI*TI)$	-0.0204*	0.0103	0.0841
$D(\ln GDP)$	0.1311	0.1914	0.5126
$D(\ln GDP^2)$	-0.0026	0.0059	0.6679
$D(TO)$	-4.4719***	1.1119	0.0038
$D(\ln URB)$	-12.0842**	4.1845	0.0203
$D(\ln IND)$	-0.0260***	0.0047	0.0005
$ECM(-1)$	-0.8924	0.0581	0.0000
C	-14.8560***	0.9538	0.0000

Note: (***), (**) and (*) denotes significance level at 1%, 5% and 10% respectively.

CO₂ emissions by 12.084 metric tons per capita. This relationship is significant at the 5% alpha level. Our results also highlight that industrialization negatively affects CO₂ emissions in the short run. For instance, a 1% increase in industrialization induces close to 0.026 metric tons per capita reduction in CO₂ emissions. The error correction term (ECM(-1)) reveals a statistically significant association with CO₂ emissions in Ghana at a 1% significant level. The estimate indicates that approximately 0.892 metric tons per capita of CO₂ emissions in the short-run equilibrium are corrected in each period, bringing carbon emissions back to their long-run equilibrium. The coefficient of the (ECM(-1)) estimate is negative and less than one. This shows a stable

Table 6
Results of Long-run estimates.

Variable	Coefficient	Standard Error	Prob.
$\ln FDI$	0.2163*	0.0965	0.0553
TI	0.0227*	0.0104	0.0613
$\ln FDI*TI$	-0.1737**	0.0747	0.0486
$\ln GDP$	2.3294*	1.0338	0.0543
$\ln GDP^2$	-0.0713*	0.0322	0.0576
TO	2.3118**	8.1719	0.0222
$\ln URB$	0.0258	1.6323	0.9878
$\ln IND$	-0.1763**	0.0725	0.0411
C	-14.8560	0.9535	0.0000

Note: (***), (**) and (*) denotes significance level at 1%, 5% and 10% respectively.

adjustment process.

However, different dynamics are revealed in the long-run estimates (Table 6). The results highlight that a 1% increase in foreign direct investment increases carbon emissions by about 0.216 tons per capita in the long run. Also, increasing technological innovation is associated with 0.023 metric tons per capita increase in CO₂ emission. In the long run, the interaction between foreign direct investment and technological innovation reduces carbon emission by 0.174 metric tons per capita, which is not different from the short-run relationship. The long-run relationship also exposes that economic growth in Ghana is associated with an increase of about 2.329 metric tons per capita in carbon emissions. However, the relationship is negative at very high levels of economic growth, where carbon emission is reduced by 0.071 metric tons per capita. Trade openness also has a positive association of about 2.312 metric tons of increase in carbon emission in the long run. This relationship is similar to urbanization, which is associated with about 0.026 metric tons increases in emissions. Industrialization is still proven to negatively affect carbon emissions in the long run at the 5% alpha level by about 0.176 metric tons per capita. See Fig. 5 for visual presentation of the estimated results.

Discussion

Foreign direct investment, technological innovation and carbon emission in Ghana

Our analysis reveals that increasing foreign direct investment reduces carbon emissions in Ghana in the short run. A possible explanation for this is the transfer of eco-friendly technologies and technical efficiencies from investing countries, usually developed ones, as argued by the pollution halo hypothesis (Adams, 2008; Lee, 2013; Sarkodie et al., 2020; Zeng & Zhou, 2021). The result, therefore, flags the positive dividend of climate change mitigation associated with technology and technical efficiency transfer to developing world subregions through reduced emissions. This agrees with Gyimah, Nwigwe, Nyantakyi, and Yao (2023), who found a negative relationship between foreign direct investment from China and Ghana's carbon emissions. While our study confirms this conventional knowledge argued in the literature, our long-run analysis reveals striking evidence of foreign direct investments increasing carbon emissions in Ghana in the long run. This supports the

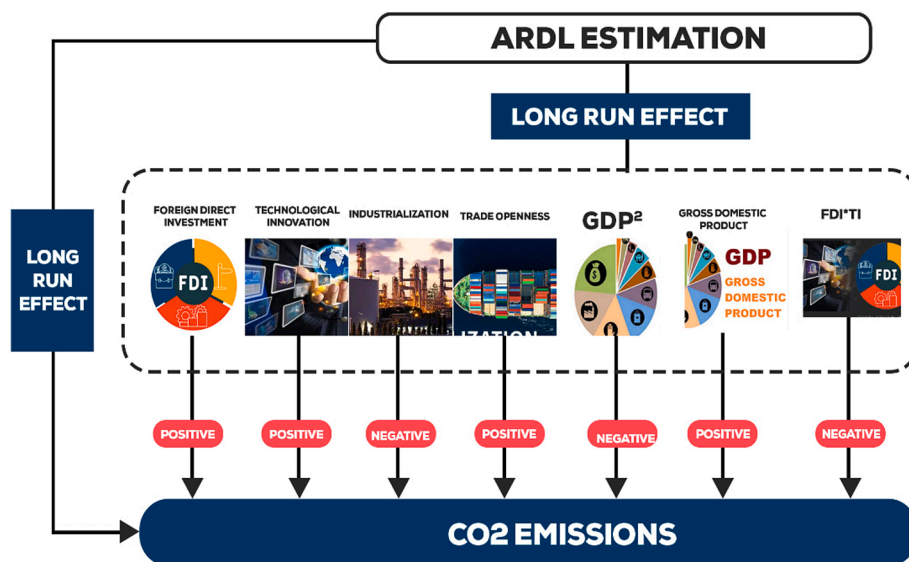


Fig. 5. Graphical representation of long-run estimation results.

pollution haven hypothesis, as evidenced by previous studies (Solarin et al., 2017). The hypothesis succinctly posits that polluting industries in developed countries with strong environmental regulations usually outsource their production lines to countries with weaker environmental regulations (ibid). This eventually increases the emissions of such countries. We infer from our results that this dynamic relationship between foreign direct investment and emission may be due to a weak environmental regulatory enforcement framework. Previous studies argue that developing countries have weaker environmental regulations, attracting polluting FDIs (Justice et al., 2021; Ali et al., 2022). Departing from this traditional argument, we advance that the case of Ghana seems complex. The country may have robust environmental regulations that either attract eco-friendly foreign direct investments or oversee that such investments comply with the regulatory standards outlined at the initial stage. However, enforcing these regulations at the later stage of operation becomes weaker, motivating foreign direct investments to adopt cheaper and polluting energies in their production process, leading to high emissions in the long run. Contributing to the ongoing epistemic discussion, we suggest that although some developing countries, such as Ghana, may possess robust regulatory frameworks, the primary issue of increased emissions, potentially contributing to climate change, lies in enforcing these regulations. On a different account, we argue that foreign direct investments may have fueled economic growth, boosted economic activities and wealth, driving demand for energy-intensive goods. Like many developing worlds, the high demand for energy-intensive goods and increased transportation for economic activities may have contributed to the long-term relationship between foreign direct investments and emissions observed, as fossil fuels remain Ghana's primary energy source. Our results agree with Luo, Ran, Rasool, and Cohan (2022), whose studies across China, India and Singapore confirm a positive relationship between foreign direct investment and carbon emissions in these countries. Oladipupo and Ajide (2024) also advance similar arguments that Chinese foreign direct investment in Africa increases the carbon emissions of Africa in the long run. However, contradictory evidence exists in South Africa, where foreign direct investment reduces carbon emissions in the long run (Ekwueme, Obiora, Okeke, & Ibuot, 2021). We argue that strengthening eco-friendly regulatory enforcement presents a twin benefit of attracting or overseeing that foreign direct investments adopt friendly technologies in their operations. This will lead to economic growth while helping fight against climate change, consequently leading to inclusive growth and vulnerability reduction in Ghana and other developing regions.

Although our results show an insignificant relationship between technological innovation and CO2 emissions in the short run, there is a positive correlation between technological innovation and carbon emissions in the long run. This contrasts with the technological spillover hypothesis that increasing technological innovation reduces emissions, as confirmed in many parts of the world, including China (Liu, Zhao, Zhao, Zhang, & Xiu, 2022) and OECD countries (Ganda, 2019). Based on these results, we caution against traditionalizing the assertion that technological innovation leads to reduced emissions in the context of Ghana, which is likely to be the case in neighbouring African countries. Our caution is based on the argument that not all technological innovations are environmentally friendly. In many developing countries like Ghana, where implementing environmental regulation seems very weak, technological advancements might focus on economic competitiveness rather than environmental sustainability.

Also, technological innovation in Ghana may increase production and consumption, typically producing higher emissions. For example, advancements in industrial processes might lead to more efficient production but at a larger scale, offsetting any gains in efficiency with greater overall emissions. This could mean that new technologies in developing countries like Ghana are not mainly designed to minimize emissions or utilize limited renewable energy sources. Our findings corroborate those of Khan et al. (2021) and Ali et al. (2022), who highlighted similar cases where technological innovation does not necessarily lead to reduced emissions. On the contrary, Ofori et al. (2024) show parallel findings that technological innovation reduces emissions among BRICS countries. The interaction term reflects the combined effect of foreign direct investment and technological innovation on CO₂ emissions. The negative coefficient indicates that this interaction significantly reduces emissions, with technological innovation enhancing FDI's impact. Thus, when foreign direct investment is paired with higher technological innovation, the emission reductions exceed their separate contributions. This finding underscores a synergistic relationship between foreign direct investment and technological innovation in mitigating carbon emissions (Bakhsh et al., 2021; Ali et al., 2022). Our results suggest that developing countries can achieve more sustainable environmental outcomes by fostering eco-friendly foreign direct investment and advancing technology (ibid). This is evident in the short-run and long-run analyses where the interaction of foreign direct investment and technological innovation consistently reduce carbon emissions in Ghana.

4.2. Relationship between the control variables and carbon emissions in Ghana

Further, our results show that economic growth is positively associated with increased emissions in Ghana. This suggests that the economic growth of developing countries like Ghana may come at the expense of the environment since fossil fuels remain the primary, cheaper energy source (Adzawla, Sawaneh, & Yusuf, 2019). Interestingly, higher levels of economic growth yield a negative association with carbon emissions. This supports the environmental Kuznet hypothesis that at high levels of economic growth, degradation and pollution are reduced but are inevitable at the low stage of economic growth, as can be learned in the development history of the so-called developed countries. From this, we submit that supporting developing countries in adopting cleaner energy in their economic development process at a relatively cheaper cost and with a reliable supply is a logical path toward the global fight against climate change. This can also help promote/sustain the already achieved levels of sustainable development goals. Our results align with the studies by Minlah & Zhang (2021) and Doku et al. (2021), who found empirical evidence supporting the environmental Kuznet curve in Ghana. Therefore, we iterate that emission reduction seems a dark and slippery road until developing countries attain developed status where high economic growth manifests in good living standards, propelling a drive towards environmental quality. A major policy intervention to abate this could be an investment in competitive, eco-friendly technology and a reliable, sustainable energy supply for the sustainable growth process of developing countries. This substantiates our advancement for cleaner energy adoption support from advanced worlds whose previous economic development came at the cost of environmental quality, deriving significant climate change observed over the years (Wang et al., 2022; Liu et al., 2018; Mahmood, Alkhateeb, & Furqan, 2020).

In the short run, trade openness significantly reduces CO₂ emissions. However, in the long run, increasing trade openness increases emissions. From an economic perspective, trade openness breeds competition, where every producer sorts cheaper means of production (Duodu et al., 2021). As competition increases, one way to beat the cost of production is to look for more affordable technologies. This leads to the increased use of unclean energy sources such as fossil fuels (Wang & Zhang, 2021). Hence, although trade openness is undoubtedly good for the economic growth and development of African countries, adopting high regulation standards to control the adoption of uncleaned energy sources as competition increases may help the goal of boosting economic growth while fighting climate change (Asamoah et al., 2019; Ofori et al., 2022). Our study results on urbanization increasing emissions in Ghana reflect the environmental impact of expanding urban areas, which is consistent with Tan et al. (2021). We submit that a possible reason for explaining this is the adoption of high-emission technologies to expand urban infrastructures in Ghana (Amponsah et al., 2022). Secondly, horizontal city expansion, manifesting in small housing units, demands more land surface area, leading to increased conversion of lands and forests for urban purposes and contributing to high emissions. We, therefore, argue that adopting vertical housing systems will maximize the use of land cum minimizing the emissions that come with land conversion for urban purposes. Lastly, industrialization correlates with reduced emissions in Ghana. This contradicts historical records from other parts of the world, pointing to high pollution levels associated with industrialization (Elfaki, Khan, Kirikkaleli, & Khan, 2022; Raheem & Ogebe, 2017). While adopting some level of eco-friendly technology in industrialization may explain our results, we advocate for further empirical studies from Ghana using different data sets and other parts of developing regions to validate our assertion.

Conclusion and policy implications

Reducing carbon emissions as a strategy for mitigating climate

change and its negative impacts on lives and livelihoods has occupied the global scientific and policy space in recent decades. In this context, we investigated the complex dynamics between foreign direct investment (FDI), technological innovation (TI), and carbon emissions in Ghana, providing new insights into the environmental consequences of economic development. The results indicate that FDI significantly reduces CO₂ in the short run but increases CO₂ emissions in the long run, supporting the pollution halo and haven hypothesis respectively. Learning from Ghana's case, our results imply that most developing countries possibly have a weak environmental regulations implementation framework, enticing FDIs to shift towards pollution practices in the long run. The individual effect of technological innovation increases carbon emissions, challenging the idea that technological innovation reduces CO₂ emissions. This implies that technological innovation in Ghana, like other developing regions, may focus more on economic competition than improving environmental quality in developing regions. However, interacting FDI and TI shows a decreasing effect on CO₂ emission. This indicates that combining FDI with eco-friendly technological innovation will greatly facilitate the twin objectives of economic growth and environmental quality in global climate mitigation, economic growth and sustainability efforts. A possible way to achieve this is to invest in research and innovation, which should be necessary conditions for FDI inflows in Ghana and other developing regions.

Economic growth significantly boosts CO₂ emissions, reflecting Ghana's energy-intensive nature of industrial and economic activities. However, the presence of the Environmental Kuznets Curve (EKC) effect, where emissions growth decelerates at very high levels of GDP, suggests that high livelihood standards and sustainable development practices could eventually mitigate these impacts. Our finding supports the argument that environmental degradation is inevitable in the pursuit of economic growth in developing countries, just as is evident in the growth trajectories of developed countries. Hence, supporting developing countries, including Ghana to adopt cleaner energy sources is crucial to reducing long-term emissions, leading to positive implications for global climate change mitigation. Trade openness exhibits a dual impact: while it reduces emissions in the short run, it increases emissions in the long run. This is possibly due to the adoption of cleaner technologies at the onset of increased trade activities and a later shift towards pollution sources as competitiveness increases. The results also reveal a complex relationship where industrialization surprisingly correlates with reduced emissions, indicating that industrial activities in Ghana might be incorporating more sustainable practices. However, further investigations in this light are needed to validate our assertion. Urbanization contributes to a rise in emissions, likely due to the expansion of urban areas and the adoption of high-emission technologies in infrastructure development.

These findings highlight the need for sustainable urban planning and industrial policies prioritizing environmental health. Encouraging partnerships between foreign investors, local industries, and research institutions could foster the development of cleaner technologies and practices in Ghana and other regions. In light of these findings, we argue that developing regions should strengthen their environmental regulation implementation, taking critical lessons from the case of Ghana. This should be focused on ensuring that both FDI and technological innovations adhere to stringent environmental standards to prevent long-term increases in CO₂ emissions. Promoting the development and adoption of technologies that reduce emissions, particularly in the industrial and urban sectors, is crucial. Additionally, facilitating access to affordable and reliable clean energy sources will reduce the reliance on fossil fuels as economic growth accelerates. Finally, fostering international collaboration to enhance the technological capabilities of local industries while adhering to international environmental standards is vital for Ghana and, more generally, developing countries. This will contribute to low emissions, yielding positive results towards mitigating global climate change and its vulnerability impacts. Future research

should expand beyond the borders of Ghana to foster the external validity of our submissions.

CRedit authorship contribution statement

Helina Siripi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ametus Kuuwill:** Writing – review & editing, Writing – original draft, Methodology. **Mark-Daniels Tamakloe:** Writing – review & editing.

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.

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