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The Impact of Official Development Assistance on Carbon Dioxide Emissions in Cambodia*

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Abstract

This study employs an autoregressive distributed lag (ARDL) model to investigate the effect of Official Development Assistance (ODA) on carbon dioxide emissions in Cambodia from 1975 to 2022, while a Toda-Yamamoto Granger causality test corroborates the direction of causality. Our findings suggest that while ODA contributes to higher carbon emissions, human capital plays a crucial role in mitigating its negative environmental impact. The findings establish unidirectional causality between ODA, human capital, and emissions. Additional factors, such as GDP per capita and population growth, intensify environmental pressures, whereas trade openness influences emissions primarily in the short term. The research findings provide important policy recommendations for Cambodia.

Key Words: Official development assistance, Carbon dioxide emissions, Cambodia, Autoregressive distributed lag model, Toda-Yamamoto Granger causality test

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Ⅰ. Introduction

Cambodia's inclusion in the Least Developed Country (LDC) list in 1991 has made it highly reliant on Official Development Assistance (ODA) to spur economic growth. Indeed, among Southeast Asian nations, Cambodia is one of the three major ODA recipients－alongside Timor-Leste and Laos－receiving ODA equivalent to 7.266% of its Gross National Income (GNI) from 1990 to 2022. Given its substantial share, ODA plays a crucial role in Cambodia's socioeconomic development. At the same time, in May 2024, the United Nations Economic and Social Council (ECOSOC) endorsed Cambodia's graduation from LDC status by 2029, signaling the country's evolving development trajectory and growing economic resilience.

Notably, although ODA can promote essential infrastructure, industrialization, and technological upgrades that accelerate economic growth, it can also have complex environmental implications. On the one hand, ODA-funded projects may incorporate advanced carbon-mitigation initiatives, thus lowering carbon emissions (Kretschmer et al. 2013). On the other hand, the economic activity spurred by ODA－particularly through the expansion of industries and the increased use of fossil fuels－can intensify CO_2 emissions (Wang et al. 2022). This dual effect highlights the necessity of examining the environmental consequences of aid inflows, particularly in the context of Cambodia's rapid development.

In parallel, Cambodia has shown strong commitment to mitigating the adverse effects of climate change. The country has been a Party to the United Nations Framework Convention on Climate Change (UNFCCC) since 1996, ratified the Paris Agreement, and set an ambitious Intended Nationally Determined Contribution (NDC). Moreover, Cambodia has adopted a long-term carbon neutrality strategy aiming to achieve net-zero emissions by 2050. This pursuit of sustainable economic growth, supported by ODA and aligned with global climate goals, presents Cambodia with the challenge of balancing development needs with environmental protection.

Despite Cambodia's substantial inflows of ODA and its recognized commitment to climate action, the relationship between ODA and CO_2 emissions in the country has not been systematically examined. Existing studies that include Cambodia have primarily relied on panel data analysis, treating Cambodia as part of a broader group of countries rather than analyzing its case individually. These studies are reviewed in Section III. While Barkat et al. (2024), Lee et al. (2020), and Zeng et al. (2022) found that ODA reduces CO_2 emissions, Wang et al. (2022) and Wang et al. (2024) reported that ODA increases CO_2 emissions. In contrast, Stauder (2022) found no significant relationship between ODA and CO_2 emissions. However, the findings from these panel data studies cannot be directly attributed to Cambodia, as they estimate the average effect of ODA on CO_2 emissions across multiple countries rather than isolating its impact on a single nation.

To address this research gap, this study investigates the effect of ODA on carbon emissions in Cambodia, with particular attention to the roles of human capital. This study is distinct from existing works in that it is the first to analyze the impact of ODA on Cambodia's

CO_2 emissions employing a time series model. By focusing on a single-country analysis, this research provides an in-depth understanding of the environmental consequences of ODA in Cambodia. The study employs annual time series data spanning from 1975 to 2022. The autoregressive distributed lag (ARDL) model is employed to capture both the short- and long-run dynamics between ODA and carbon emissions. Furthermore, the Toda-Yamamoto Granger causality test is conducted to ensure robustness. Beyond ODA, this study includes human capital as a moderating variable, alongside other control factors such as GDP per capita, population, and trade openness, offering a more comprehensive understanding of the drivers of CO_2 emissions in Cambodia.

Accordingly, the primary objective of this study is to investigate and quantify the impact of ODA on CO_2 emissions in Cambodia. Furthermore, the research findings are expected to offer valuable insights for policymakers and development practitioners in Cambodia, aiding in the formulation and implementation of effective national policies related to ODA, environmental sustainability, and human capital development.

As Cambodia is expected to graduate from LDC status by 2029, the country is likely to experience a decline in ODA and an increased reliance on private sector-led development financing, such as foreign direct investment (FDI). This shift may reduce the direct role of ODA in shaping CO_2 emissions. However, understanding the historical and current effects of ODA on CO_2 emissions remains crucial, as it provides valuable insights for policymakers on how to navigate this transition. By examining the environmental implications of ODA, this research can help ensure that new financing mechanisms, including FDI and alternative development funding, are aligned with Cambodia's sustainable development goals and support a low-carbon growth trajectory.

The remainder of this paper is organized as follows. Section Ⅱ reviews the prevailing ODA flows and CO_2 emission trends in Cambodia. Section Ⅲ presents a literature review of relevant studies. Section Ⅳ details the theoretical framework and research methodology. Section Ⅴ discusses the empirical findings, and Section Ⅵ concludes with policy recommendations, providing guidance for sustainable development strategies in Cambodia.

Ⅱ. ODA and CO_2 emissions in Cambodia

Cambodia ranks as a leading recipient of ODA in Southeast Asia. According to data from the World Development Indicators (WDI), it holds the third position among regional recipients, following Timor-Leste and Laos. From 1990 to 2022, ODA accounted for an average of 7.27% of Cambodia's Gross National Income (GNI), compared to 8.71% in Laos and 10.87% in Timor-Leste. These figures emphasize the significant role of ODA in Cambodia's economic progress, reflecting its dependence on foreign assistance to support development initiatives and sustain economic growth.

<Table 1> Net ODA received in Southeast Asia (% of GNI)

Country	1990	2000	2010	2020	1990-2022
Cambodia	3.778	9.778	6.281	5.533	7.266
Indonesia	1.578	1.068	0.180	0.117	0.518
Malaysia	1.107	0.056	-0.002	-0.002	0.095
Philippines	2.297	0.604	0.251	0.374	0.639
Thailand	0.944	0.566	-0.006	0.040	0.186
Viet Nam	2.980	4.834	1.942	0.353	2.550
Lao PDR	12.105	14.069	5.827	2.965	8.706
Myanmar	7.372	1.187	0.717	3.703	2.405
Timor-Leste	0.039	44.884	8.723	8.586	10.872
World	0.251	0.143	0.194	0.226	0.194

Source: Author's compilation based on data from the World Development Indicators (WDI)

An in-depth analysis, <Table 2>, highlights that Cambodia’s key sources of official development assistance are Japan and China, which have consistently played dominant roles in supporting the country’s development. In 2022, Japan emerged as the largest donor, closely followed by China, with their combined contributions accounting for 39.69% of Cambodia’s total ODA. By 2023, China had overtaken Japan as the top donor, contributing 20.95% of ODA, while Japan provided 13.44%. South Korea and the United States were also notable bilateral donors, contributing 6.27% and 5.71%, respectively, in 2022. Among institutional donors, the World Bank and the Asian Development Bank (ADB) were significant, providing 15.27% and 11.76%, respectively. In contrast, United Nations agencies made relatively modest contributions to Cambodia’s ODA.

<Table 2> Major Donors of ODA to Cambodia

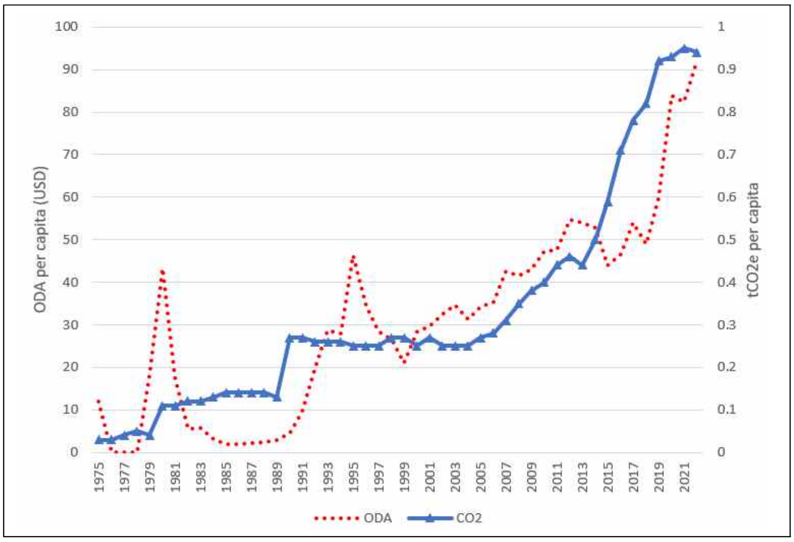
Donor	2022		2023	
UN agencies	Million USD	%	Million USD	%
FAO	2.36	0.12	3.01	0.17
IFAD	39.65	1.94	57.04	3.15
ILO	5.52	0.27	7.65	0.42
UNDP	8.58	0.42	5.28	0.29
UNESCO	4.03	0.20	3.43	0.19
UNICEF	28.34	1.39	23.93	1.32
WHO	9.20	0.45	11.34	0.63
Institutions	Million USD	%	Million USD	%
ADB	240.29	11.76	394.51	21.82
EU	82.10	4.02	55.79	3.09
Global Fund	39.23	1.92	44.09	2.44
World Bank	311.97	15.27	157.00	8.68
Bilateral	Million USD	%	Million USD	%
Australia	40.31	1.97	45.17	2.50
China	249.88	12.23	378.91	20.95
France	59.36	2.91	51.08	2.82
Germany	58.47	2.86	43.30	2.39
Japan	561.07	27.46	243.03	13.44
Korea	128.06	6.27	86.97	4.81
Sweden	16.90	0.83	14.96	0.83
Switzerland	13.77	0.67	17.99	0.99
UK	1.98	0.10	0.74	0.04
USA	116.62	5.71	133.38	7.38
Total	2,017.68	98.76	1,778.60	98.36
Others	25.38	1.24	29.63	1.64
Grand total	2,043.06	100.00	1,808.23	100.00

Source: Author's compilation based on data from Council for the Development of Cambodia.

<Figure 1> shows Cambodia's ODA per capita and CO_2 emissions per capita from 1975 through 2022. Although both indicators start at relatively low levels, ODA exhibits a series of notable spikes and dips in the 1980s and 1990s before increasing more steadily in the 2000s. Meanwhile, CO_2 emissions remain

relatively modest throughout the first two decades under observation but begin trending upward in the early 2000s. From around 2005 onward, there is a clearer, more sustained increase in both ODA and CO_2 emissions.

<Figure 1> ODA and CO_2 emissions in Cambodia



Source: Author's compilation based on data from the World Development Indicators (WDI)

Overall, the figure suggests that while Cambodia’s development assistance inflows grew substantially over time, carbon emissions also exhibited sustained long-run growth, particularly since the early 2000s. This broad relationship underpins the study’s focus on whether—and how—official development assistance might affect the country’s CO_2 emissions trajectory.

Ⅲ. Literature review

1. ODA and carbon dioxide emissions

Official development assistance can affect carbon emissions through both direct and indirect pathways, yet its ultimate impact remains disputed. In the direct channel, ODA funds projects promoting carbon mitigation technologies, including renewable energy (solar, wind, hydropower), which reduce reliance on fossil fuels (Kretschmer et al. 2013). Energy efficiency initiatives in sectors like construction and transportation further limit emissions (Chen and He 2013). Through technical assistance, ODA strengthens environmental education and skill-building initiatives. Meanwhile, budgetary support allocates resources to low-carbon policies (Barkat et al. 2024). Core contributions and pooled funds empower NGOs engaged in sustainable development, amplifying ODA’s positive effects (Barkat et al. 2024).

Indirectly, ODA fosters human capital and institutional capacity, improving education (Riddell and Niño-Zarazúa 2016) and healthcare (Barkat et al. 2016). These enhancements elevate living standards and environmental awareness, indirectly reducing poverty and high-carbon fuel dependence. As a result, communities become more adept at adopting greener practices and addressing climate challenges.

For empirical evidence supports ODA’s capacity to reduce emissions, Barkat et al. (2024) found a significant decrease in CO_2 in 127 developing countries from 1995 to 2019 due to environmentally sustainable investments. Similarly, Lee et al. (2020)

observed lower emissions in 30 nations receiving Korean ODA (1993-2017), while Gmidène et al. (2024) reported ODA's mitigating role in 45 Sub-Saharan African nations (2006-2022). Further studies in Nepal (Sharma et al., 2019), Ghana (Kwakwa et al., 2020), and Belt and Road Initiative countries (Zeng et al. 2022) support these positive results.

However, ODA may also raise emissions by stimulating economic growth. Wang et al. (2022) revealed that while ODA supports carbon mitigation technologies, heightened industrial output can increase CO_2levels. The scale of funds by ODA may increase emissions (Lee et al. 2020). Wang et al. (2024) showed that a 1% increase in Chinese aid correlated with a 0.0148% increase in recipients' CO_2 emissions. The same pattern was also found in low- and lower-middle-income nations (Wang et al. 2022) and Kenya (Powanga and Kwakwa 2024).

However, some findings suggest ODA's impact is statistically insignificant. Boly (2018) discovered that from 1980 to 2013, multilateral aid reduced emissions. However, bilateral aid showed no clear effect. Similarly, Stauder (2022) reported an insignificant negative correlation between ODA and CO_2 in 118 aid-receiving countries (2007-2018), indicating inconclusive evidence overall.

2. Human capital and carbon dioxide emissions

Human capital affect CO_2 emissions through direct and indirect pathways. In the direct channel, human capital fosters technological advancement: according to endogenous growth theory, it accelerates research and development (Romer, 1990; Barro, 2001). This innovation improves energy efficiency in production and consumption, decreasing dependence on fossil fuels and facilitating the shift to cleaner energy (Li et al. 2022; Wang 2023).

Indirectly, human capital promotes environmental awareness and behavioral shifts. Educated individuals are more likely to engage in sustainable practices, support clean energy adoption, and advocate for stricter environmental regulations (Alvarado et al. 2021). Policymakers with higher human capital are similarly equipped to design and implement effective regulations (Brasington and Hite 2005).

Empirical research across various regions supports these patterns. In newly industrialized countries, human capital reduced CO_2 emissions between 1979 and 2017 (Rahman et al. 2021). Comparable findings emerged from analyses of 78 developing nations in Asia, Africa, and Latin America (Jahanger et al. 2023), 122 countries worldwide (Khan 2020), and region-specific studies in China (Tian et al. 2024), Sri Lanka (Adikari et al. 2023), India (Sehrawat 2021), G20 countries (Sheraz et al. 2021), and OECD economies (Khan et al. 2021).

Nevertheless, human capital can also raise emissions. Zuo et al. (2019) argue that new technologies can lower the cost of both renewable and traditional energy, potentially increasing CO_2 emissions. Likewise, human capital–driven economic growth may generate higher emissions (Haini 2021). For instance, Bayar et al. (2022) showed that although human capital reduces emissions in some European Union states, it correlates positively with CO_2 in others (e.g., Latvia, Lithuania). Similar contradictions appear in 46 Asian nations (Oanh and Nguyen 2023), 15 Latin American and Caribbean countries (Ahmed et al. 2021), the BRICS bloc (Ganda 2021), and China (Sarkodie et al. 2020).

Beyond direct and indirect effects, human capital may moderate CO_2 outcomes. Gnangoin et al. (2022) discovered it diminishes the negative impact of non-renewable energy use in 20 emerging economies (1990–2021). Similarly, Khan et al. (2021) found that human capital reinforces the environmental benefits of fiscal decentralization in seven OECD countries from 1990 to 2018.

3. Trade openness, population, GDP per capita and carbon dioxide emissions

(1) Trade openness

Trade liberalization affects carbon emissions through three key mechanisms: scale, technology, and structural effects (Grossman and Krueger 1996). The scale effect arises when expanded market access boosts economic activity, leading to higher resource consumption and elevated CO_2 emissions, if environmental safeguards are lacking (Meng et al. 2022). The technology effect demonstrates how trade openness promotes the adoption of advanced, energy-efficient production techniques and managerial practices. This, in turn, enhances efficiency and reduces carbon footprints (Chen et al. 2019). Finally, the structural effect posits that countries concentrate on industries where they hold a comparative advantage, potentially raising or lowering emissions depending on whether those sectors are carbon-intensive or relatively clean (Wiebe et al. 2012). Empirical findings indicate that trade openness can increase emissions in

African nations (Kitila 2024) and the Middle East and North Africa (Ghaderi et al. 2023), yet it can diminish emissions in Sub-Saharan Africa (Ewane and Ewane 2023) and Southeast Asia (Pata et al. 2023). Some analyses, such as that by Pham and Nguyen (2024) in 64 developing nations, even find no significant relationship. These mixed results emphasize the complexity of trade's environmental impact, which depends on regulatory enforcement, technological readiness, and sectoral specialization. Consequently, policies aimed at aligning trade liberalization with environmental objectives are vital to mitigating carbon emissions.

(2) Population

Malthusian theory emphasizes the negative impact of population growth on environmental quality. It suggests that rapid population increases exceed the availability of resources (Lemmen 2014). As populations expand, demand for housing, transportation, and goods increases, intensifying energy use and often relying on fossil fuels (Holdren and Ehrlich 1974). Shifting demographic distributions can also drive the development of extensive infrastructure and transportation networks, further raising emissions (Holdren 1991; Yuan et al. 2019). Empirical evidence supports these statements: Chaurasia (2020) reported that population growth substantially accelerated energy consumption and CO_2 emissions in 44 countries between 1990 and 2019. As populations rise, it becomes increasingly challenging for natural resources to regenerate at the rate they are consumed. Consequently, implementing effective strategies—such as policies addressing fertility rates—is critical for mitigating emissions in regions experiencing rapid population growth.

(3) GDP per capita

Growing GDP per capita often correlates with increased carbon emissions because economic expansion typically requires more energy, frequently sourced from fossil fuels (Saidi and Hammami 2015; Kais and Sami 2016). This positive association has been consistently observed in regions such as Europe, North Asia, the Middle East, and Indonesia (Wahyudi and Ciptawaty 2023). As businesses and consumers gain purchasing power, they frequently demand more energy-intensive products and services, thereby elevating CO_2 levels. Nevertheless, the Environmental Kuznets Curve (EKC) hypothesis offers a more in-depth perspective of the GDP–emissions link. According to the EKC, emissions increase in the early stages of development. However, they eventually decline once income surpasses a certain threshold, driven by cleaner technologies, stricter regulations, and increased environmental awareness (Caron and Fally 2021). Evidence from G-20 nations confirms that GDP per capita is a key driver of CO_2 emissions, aligning with this inverted U-shaped pattern (Zaekhan and Nachrowi 2015). However, the realization of EKC benefits depends substantially on proactive policies and investments in green innovation. As a result, for high-growth economies, effective governance and technological progress remain integral to balancing economic advancement with lower carbon emissions.

In summary, based on the existing literature, studies reveal that ODA can both decrease and increase CO_2 emissions, yet a consensus on its environmental impact remains elusive. Existing studies on Cambodia have primarily employed panel data analysis, including Cambodia as one of several countries within a broader sample. For instance, Barkat et al. (2024), Lee et al. (2020), and Zeng et al. (2022) found that ODA reduces CO_2 emissions in panel datasets comprising 127 developing countries, 30 nations receiving Korean ODA, and 93 Belt and Road Initiative countries, respectively. In contrast, Wang et al. (2022) and Wang et al. (2024) reported that ODA increases CO_2 emissions in samples of 59 low-income and lower-middle-income countries and 118 Chinese ODA recipients, respectively. Additionally, Stauder (2022) found no significant relationship between ODA and CO_2 emissions in 118 aid-receiving countries.

However, the findings from these panel data studies cannot be directly applied to Cambodia. Panel data models estimate the average effect of ODA on CO_2 emissions across all countries in the sample, rather than isolating its impact on a single nation. To address this research gap, this study investigates the effect of ODA on carbon emissions in Cambodia, with particular attention to the direct and moderating roles of human capital. By focusing on a single-country analysis, this study provides a more in-depth understanding of the environmental consequences of ODA in Cambodia. By incorporating important control variables—GDP per capita, population, and trade openness—our analysis provides a more comprehensive understanding of ODA's environmental consequences. Consequently, this research contributes novel insights to the discourse on sustainable development in emerging economies, offering guidance for policymakers to balance economic growth, resource utilization, and climate targets within the

Cambodian context.

Ⅳ. Research methodology

1. Theory and model specification

This study employs the IPAT model as its foundational theoretical framework. The model was originally proposed by Ehrlich and Holdren (1971). The IPAT model conceptualizes environmental impact (I) as a function of three key anthropogenic drivers: population (P), affluence (A), and technology (T). Building on this foundation, the model was later refined into the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework, introduced by Dietz and Rosa (1997). The STIRPAT model incorporates regression techniques to account for the stochastic and nonlinear relationships among these determinants, enabling a more robust and precise quantification of each factor's contribution to environmental outcomes. The mathematical formulation of the STIRPAT model is as follows:

$$I_t = aP_t^b A_t^c T_t^d e_t \tag{1}$$

In this formulation, I represents environmental impact, a is a constant term, P denotes population, A signifies affluence, T represents technology, and b, c, and d are the elasticity coefficients of the respective independent variables. The term e accounts for random error. This study employs the STIRPAT model framework to analyze the impact of official development assistance (ODA) on CO_2 emissions in Cambodia. Here, CO_2 emissions (CO_2) are used as a proxy for environmental impact (*I*). The population variable (POP), which captures the demand for resource consumption across sectors such as energy, construction, and transportation—key contributors to carbon emissions. Affluence (*A*) is measured by GDP per capita (GDP), reflecting the association between economic growth and increased carbon emissions, often driven by industrialization. Technology (*T*) is proxied by human capital (*HUM*), as human capital serves as a driver of technological innovation and complements investments in research and development (Romer, 1990; Barro, 2001). In addition, official development assistance (ODA) is incorporated into the STIRPAT model to evaluate its effects on CO_2 emissions. To address potential omitted variable bias, trade openness is included. Trade openness can influence emissions through scale, technology, and structural effects, as outlined by Grossman and Krueger (1996). Incorporating these factors, the baseline STIRPAT model (Equation 1) is extended and reformulated into Equation 2, as detailed below.

$$CO2 = f\ (ODA,\ GDP,\ POP,\ TRA, HUM) \qquad (2)$$

The logarithmic transformation of this model, which enables the estimation of elasticity coefficients, is expressed as Equation (3):

$$\ln CO2_t = \beta_0 + \beta_1 \ln ODA_t + \beta_2 \ln GDP_t + \beta_3 \ln POP_t + \beta_4 \ln TRA_t + \beta_5 \ln HUM + \epsilon_t \qquad (3)$$

To develop more comprehensive policy recommendations based on this study, the moderating role of human capital in the relationship between ODA and carbon dioxide emissions is examined. This is achieved by incorporating an interaction term between ODA and human capital (HUM) into Equation (3).

$$\ln CO2_t = \beta_0 + \beta_1 \ln ODA_t + \beta_2 \ln GDP_t + \beta_3 \ln POP_t + \beta_4 \ln TRA_t + \beta_5 \ln HUM + \beta_6 (\ln ODA_t * \ln HUM_t) + \epsilon_t \quad (4)$$

Equation (4) serves as the foundation for the empirical estimations conducted in this study.

2. Autoregressive distributed lag (ARDL) model

For the empirical estimation, the STIRPAT model presented in Equation (4) is restructured into an Autoregressive Distributed Lag (ARDL) framework. The selection of the ARDL model (Pesaran et al., 2001) as the empirical framework for this study is justified by the characteristics of the dataset. As indicated by the unit root test results in <Table 4>, the variables under investigation exhibit different orders of integration, with some being stationary at level (I(0)) and others being stationary at first difference (I(1)). The ARDL approach is particularly advantageous in this context, as it can accommodate such a mixture of integration orders without requiring all variables to be stationary.

Furthermore, unlike conventional cointegration techniques such as the Johansen method, the ARDL model is well-suited for studies with limited sample sizes (Narayan 2005), making it an appropriate choice given the annual dataset in this work spanning from 1975 to 2022. Additionally, the ARDL framework allows for a more flexible lag structure, enabling it to effectively capture both short-term dynamics and long-run equilibrium relationships. This feature aligns with the primary objective of this study, which is to examine the impact of ODA on CO_2 emissions in Cambodia in both the short and long run.

Another advantage of the ARDL approach is its ability to provide a straightforward single-equation estimation framework that accounts for potential endogeneity and feedback effects among variables (Sam et al., 2019). By simultaneously estimating short-run and long-run dynamics within a single model, ARDL mitigates the complexity associated with system-based cointegration techniques such as the Johansen method, thereby facilitating more intuitive parameter interpretation. Given these methodological strengths, the ARDL model is the most suitable econometric approach for this study.

Accordingly, the ARDL specification adapted from Equation (4) is formalized as Equation (5).

$$\begin{aligned}\Delta \ln CO2_t &= \alpha + \sum_{i=1}^{a} \beta_i \Delta \ln CO2_{t-i} + \sum_{i=1}^{b} \gamma_i \Delta \ln ODA_{t-i} + \sum_{i=1}^{c} \delta_i \Delta \ln GDP_{t-i} \\ &+ \sum_{i=1}^{d} \eta_i \Delta \ln POP_{t-i} + \sum_{i=1}^{e} \mu_i \Delta \ln TRA_{t-i} + \sum_{i=1}^{f} \theta_i \Delta \ln HUM_{t-i} \\ &+ \sum_{i=1}^{g} \xi_i \Delta (\ln ODA_{t-i} * \ln HUM_{t-i}) + \lambda \ln CO2_{t-1} + \chi \ln ODA_{t-1} + \tau \ln GDP_{t-1} \\ &+ \sigma \ln POP_{t-1} + \omega \ln TRA_{t-1} + \phi \ln HUM_{t-1} + \psi \ln ODA_{t-1} * \ln HUM_{t-1} + \varepsilon_t \end{aligned} \tag{5}$$

Following the approach outlined by Pesaran et al. (2001), this study employs a three-step modeling process. The first step involves conducting a cointegration bounds test to evaluate the null hypothesis of no long-term relationship among the variables ($H0: \lambda = \chi = \tau = \sigma = \omega = \phi = \psi = 0$).

In the second step, the long-run relationship, as specified in Equation (6), is estimated to determine the long-term effects of the ODA and other independent variables on CO_2 emissions.

$$\ln CO2_t = \Omega_0 + \Omega_1 \ln ODA_t + \Omega_2 \ln GDP_t + \Omega_3 \ln POP_t + \Omega_4 \ln TRA_t + \Omega_5 \ln HUM_t + \Omega_6 (\ln ODA_{t*} \ln HUM_t) + \nu_t \quad (6)$$

where the long-run coefficients are calculated as $\Omega_1 = -\chi/\lambda,\ \Omega_2 = -\tau/\lambda,\ \Omega_3 = -\sigma/\lambda,\ \Omega_4 = -\omega/\lambda, \Omega_5 = -\phi/\lambda, \Omega_6 = -\psi/\lambda$ and ν_t is an error term.

Third, the associated error correction model, specified in Equation (7), is estimated to analyze the short-term effects of ODA on carbon emissions.

$$\Delta \ln CO2 = \alpha + \sum_{i=1}^{a} \beta_i \Delta \ln CO2_{t-i} + \sum_{i=1}^{b} \gamma_i \Delta \ln ODA_{t-i} + \sum_{i=1}^{c} \delta_i \Delta \ln GDP_{t-i} + \sum_{i=1}^{d} \eta_i \Delta \ln POP_{t-i} + \sum_{i=1}^{e} \mu_i \Delta \ln TRA_{t-i} + \sum_{i=1}^{f} \theta_i \Delta \ln HUM_{t-i} + \sum_{i=1}^{g} \xi_i \Delta (\ln ODA_{t-i} * \ln HUM_{t-i}) + \psi ECM_{t-1} + \varepsilon_t \quad (7)$$

The coefficient ψ of the error correction term (ECM) reflects the speed at which the system returns to equilibrium after experiencing a shock; hence, this coefficient is expected to be negative. The coefficients $\beta_i, \gamma_i, \delta_i, \eta_i, \mu_i, \theta_i$ and ξ_i represent the short-term impacts of the respective variables.

3. Data and source

This study utilizes annual time series data of Cambodia spanning the years 1975 to 2022. Carbon dioxide emissions are measured on a per capita basis (tCO_2 e per capita), with data sourced from the World Development Indicators (WDI). Official development assistance (ODA) is represented as the net ODA received, expressed as a percentage of Gross National Income (GNI), also obtained from the WDI. Gross domestic product per capita (USD per capita) and total population (in millions) are similarly derived from the WDI. Trade openness is measured as the sum of imports and exports as a percentage of GDP, with data sourced from the United Nations Conference on Trade and Development (UNCTAD). Human capital is proxied by the Human Capital Index, sourced from the Penn World Table (PWT 10.01).

V. Empirical results

1. Descriptive data

The descriptive statistics provided in <Table 3> summarize the variables utilized in this study, highlighting key characteristics of the dataset. The average CO_2 emissions per capita are 0.330 CO2e. The

ODA, averaging 7.493% of GNI, highlights its significant role in Cambodia's economic framework. GDP per capita, with a standard deviation of 507.094 USD, illustrates considerable variability. Skewness values remain within acceptable bounds, while kurtosis levels indicate that the data generally follow a normal distribution.

<Table 3> Descriptive statistic

	CO2	ODA	GDP	POP	TRA	HUM
Mean	0.330	7.493	547.918	11.337	29.997	1.581
Median	0.260	5.731	307.551	11.784	29.741	1.523
Maximum	0.950	46.285	1,759.608	16.768	78.000	2.206
Minimum	0.030	0.045	111.346	5.961	0.108	1.246
Std. Dev.	0.258	7.146	507.094	3.559	27.081	0.236
Skewness	1.219	3.495	1.123	-0.119	0.281	0.792
Kurtosis	3.548	19.291	2.904	1.633	1.657	2.909
Jarque-Bera	12.482	628.520	10.102	3.850	4.241	5.032
Probability	0.002	0.000	0.006	0.146	0.120	0.081
Observations	48	48	48	48	48	48

2. The unit root test

<Table 4> presents the results of the unit root tests conducted using the Augmented Dickey-Fuller (ADF) methodology. The findings reveal that all variables are either integrated of order zero, (I(0), or order one, I(1). The absence of variables integrated of order two, I(2), affirms the suitability of applying the ARDL model for this study, as it is designed to handle variables with mixed integration orders of I(0) and I(1). This ensures the robustness and reliability of the econometric framework employed in the analysis.

<Table 4> The ADF test

	Level form		1st difference form		
	t-statistic	Probability	t-statistic	Probability	Coint.
lnCO2	-2.548	0.305	-7.494	0.000	I(1)
lnODA	-5.295	0.000	n/a	n/a	I(0)
lnGDP	-2.597	0.284	-8.850	0.000	I(1)
lnPOP	-2.421	0.364	-3.921	0.023	I(1)
lnTRA	-1.169	0.904	-4.092	0.013	I(1)
lnHUM	-2.110	0.527	-3.947	0.018	I(1)

3. Cointegration bounds test

This study applies the bounds testing procedure within the ARDL modeling framework (Pesaran et al., 2001) to assess the presence of cointegration among the variables. The findings, detailed in <Table 5>, reveal that the calculated F-statistic (19.843) exceeds the upper critical value (5.837) at the 1% significance level. These results provide strong evidence of a long-term relationship between the variables in the model, emphasizing their long-term interrelation.

<Table 5> The bounds test

Calculated F-stat	19.843		
	Significance level	Lower bound	Upper bound
Critical F-stat	10%	2.781	3.813
	5%	3.257	4.431
	1%	4.427	5.837

4. Long-run and short-run coefficients

<Table 6> presents the long-term impact of ODA, GDP per capita, population, trade openness, and human capital on CO_2 emissions in

Cambodia. A 1% increase in ODA corresponds to a 1.203% rise in CO_2 emissions, emphasizing its positive contribution to environmental pressure. Similarly, GDP per capita significantly increases CO_2 emissions, with a 1% rise in GDP leading to a 2.809% increase in emissions, reflecting the environmental costs of economic growth. Population growth also shows a strong positive effect, as a 1% increase in population leads to a 1.470% rise in CO_2 emissions.

<Table 6> Long-run coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
lnODA	1.203***	0.208	5.781	0.000
lnGDP	2.809***	0.711	3.953	0.000
lnPOP	1.470***	0.109	13.482	0.000
lnTRA	0.018	0.073	0.242	0.810
lnHUM	-1.139***	0.092	-12.423	0.000
lnODA*lnHUM	-0.374***	0.050	-7.530	0.000

Note: The significance levels are denoted as *** (1%), ** (5%), and * (10%).

In contrast, human capital demonstrates a mitigating effect. A 1% improvement in human capital results in a 1.139% decrease in CO_2 emissions, highlighting the potential of education and skills development to mitigate environmental deterioration. Additionally, the interaction term between ODA and human capital is negative and significant (-0.374%), indicating that higher levels of human capital can reduce the negative environmental impact of ODA. However, trade openness shows no significant long-term effect on CO_2 emissions, with a coefficient of 0.018, suggesting its limited influence in the studied model.

<Table 7> illustrates the short-run estimation results. In the short term, ODA contributes to increased emissions (0.134), reflecting

immediate environmental deterioration from development activities. Over time, these short-term effects accumulate, reinforcing its long-run impact as development initiatives scale and resource consumption rises. Similarly, GDP per capita (1.870) and population (5.513) both increase emissions in the short run, consistent with the idea that economic growth and demographic expansion drive higher energy use and resource demands, which persist over time.

Trade openness exhibits a short-term positive influence (0.241), reflecting the environmental impact of increased trade activities; however, its negligible long-run effect suggests that these impacts stabilize or are offset over time. Human capital plays a critical mitigating role in both the short and long run. Its ability to reduce emissions in the short term (-1.064), alongside its moderating influence (-0.228) on ODA, suggests that investments in education and skills development have lasting environmental benefits. The negative error correction term (-0.542) indicates a consistent adjustment toward the long-run equilibrium, where these dynamics converge into sustained relationships. These findings reveal how short-term changes influence long-term environmental impacts.

<Table 7> Short-run coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ECM	-0.542***	0.049	-11.139	0.000
$\triangle \ln CO2_{t-1}$	0.871***	0.135	6.426	0.000
$\triangle \ln CO2_{t-2}$	-0.859***	0.120	-7.167	0.000
$\triangle \ln CO2_{t-3}$	0.116	0.071	1.629	0.118
$\triangle \ln ODA_{t}$	0.134*	0.077	1.745	0.095
$\triangle \ln ODA_{t-1}$	-0.670***	0.139	-4.819	0.000
$\triangle \ln ODA_{t-2}$	-0.073***	0.016	-4.718	0.000
$\triangle \ln GDP_{t}$	1.870*	1.063	1.758	0.093
$\triangle \ln GDP_{t-1}$	-2.267**	0.931	-2.435	0.024

$\triangle \ln POP_t$	5.513***	1.147	4.807	0.000
$\triangle \ln POP_{t-1}$	0.130	2.112	0.062	0.952
$\triangle \ln POP_{t-2}$	-6.612***	1.792	-3.689	0.001
$\triangle \ln POP_{t-3}$	2.936***	0.690	4.253	0.000
$\triangle \ln TRA_t$	0.241***	0.027	8.782	0.000
$\triangle \ln TRA_{t-1}$	0.078***	0.024	3.268	0.004
$\triangle \ln TRA_{t-2}$	0.067***	0.023	2.940	0.008
$\triangle \ln TRA_{t-3}$	0.185***	0.027	6.835	0.000
$\triangle \ln HUM_t$	-1.064***	0.299	-3.557	0.002
$\triangle \ln HUM_{t-1}$	0.965***	0.318	3.031	0.006
$\triangle \ln HUM_{t-2}$	1.922***	0.360	5.345	0.000
$\triangle \ln ODA_t * \ln HUM_t$	-0.228***	0.045	-5.018	0.000
$\triangle \ln ODA_{t-1} * \ln HUM_{t-1}$	-0.001	0.025	-0.040	0.968

Note: The significance levels are denoted as *** (1%), ** (5%), and * (10%).

For further discussion, the empirical findings suggest that ODA tends to increase CO_2 emissions, thereby intensifying environmental deterioration. A plausible explanation is that ODA has been primarily utilized to promote economic growth. According to the World Bank, Cambodia's economy grew at an average annual rate of 7.6% between 1995 and 2019, driven by sectors such as manufacturing, real estate, construction, and infrastructure, making it one of the fastest-growing economies globally. Cambodia achieved lower-middle-income status in 2015, substantially due to its focus on economic development. As indicated by statistics from the Council for the Development of Cambodia in <Table 8>, the majority of ODA has been allocated to the economic and infrastructure sectors. In 2022, 31.03% of total ODA was directed toward infrastructure, with 23.53% allocated specifically to transportation, accounting for nearly a quarter of total ODA received.

Beyond infrastructure, significant portions of ODA were allocated to energy, power, electricity, and rural development. While these activities promote economic growth, they also contribute to increased CO_2 emissions due to reliance on fossil fuels. Statistics from Climate Watch (2024) and the International Energy Agency (2024) indicate that, apart from land use, land-use change, and forestry (LULUCF), the energy sector is the primary contributor to CO_2 emissions in Cambodia. Between 2018 and 2022, transportation accounted for the largest share of energy-related CO_2 emissions at 45.87%, followed by electricity and heat production at 30.12%, and the industrial sector at 13.20%. Collectively, these three sectors contributed 89.19% of energy-related CO_2 emissions. The remaining emissions originated from the residential, commercial, public services, and other sectors. These statistics align with <Table 8> and the empirical findings of this study, reinforcing the conclusion that ODA allocated for infrastructure development has played a significant role in driving CO_2 emissions in Cambodia.

This aligns with the findings of Powanga and Kwakwa (2024), who observed that development assistance fueling economic activity increases emissions in Kenya, a major ODA recipient. Similarly, large-scale funding to drive economic growth has been shown to increase carbon emissions (Lee et al., 2020).

As China is a major donor of ODA to Cambodia, these results are consistent with Wang et al. (2024), who found that a 1% increase in Chinese foreign aid led to a 0.0148% rise in carbon emissions across 118 recipient countries between 2000 and 2018. Comparable patterns were confirmed by Wang et al. (2022), who reported that a 1% increase in ODA results in a 0.2259–0.2281% rise in CO_2 emissions among 59 low- and lower-middle-income countries. These findings emphasize the environmental trade-offs associated with ODA-driven economic growth.

<Table 8> Distribution of ODA in Cambodia

Sector / Sub-Sector	2022		2023	
	Mio USD	%	Mio USD	%
I. Social Sectors	340.20	16.65	362.29	20.04
Health	188.99	9.25	192.28	10.63
Education	138.85	6.80	158.08	8.74
Social Protection	12.36	0.61	11.93	0.66
II. Economic Sectors	520.08	25.46	483.00	26.71
Agriculture	253.83	12.42	217.97	12.05
Industrialisation & Trade	9.46	0.46	62.53	3.46
Rural Development	150.33	7.36	141.66	7.83
Bus. & Financial Services	44.21	2.16	4.69	0.26
Urban Plan & Management	62.26	3.05	56.15	3.11
III. Infrastructure	633.87	31.03	736.67	40.74
Technology, ICT	6.74	0.33	10.42	0.58
Energy, Power & Electric.	69.75	3.41	139.64	7.72
Transportation	480.75	23.53	480.46	26.57
Water and Sanitation	76.62	3.75	106.15	5.87
IV. Services Programmes	548.91	26.87	226.27	12.51
Community Development	25.13	1.23	19.73	1.09
Culture & Arts	6.84	0.33	4.31	0.24
Environment & Sustain.	25.01	1.22	34.76	1.92
Climate change	5.90	0.29	5.99	0.33
Gender	5.06	0.25	3.30	0.18
HIV/AIDS	1.77	0.09	0.76	0.04
Governance & Administ.	70.60	3.46	107.06	5.92
Tourism	5.48	0.27	1.42	0.08
Budget & BoP Support	184.54	9.03	5.88	0.33
Emergency and food aid	2.16	0.11	1.12	0.06
Other	216.42	10.59	41.94	2.32
Total	2,043.06	100.00	1,808.23	100.00

Source: Author's compilation based on data from Council for the Development of Cambodia.

With regard to human capital, the empirical evidence underlines its critical role in reducing carbon emissions. This finding aligns with the endogenous growth theory, which emphasizes human capital as a driver of technological innovation (Romer 1990). Advances spurred by human capital improve energy efficiency, reduce reliance on fossil fuels, and accelerate the transition to sustainable energy sources, leading to lower CO_2 emissions (Li et al. 2022). Moreover, higher levels of human capital foster environmental awareness and promote behavior changes that support sustainability. These results are consistent with Alvarado et al. (2021), who found that individuals with greater educational attainment are more likely to adopt sustainable energy practices and push for clean energy transitions, thereby contributing to the reduction of carbon emissions. This evidence highlights human capital's pivotal role in addressing environmental challenges and advancing a low-carbon future.

This study also highlights the significant moderating role of human capital in the relationship between ODA and CO_2 emissions. Human capital mitigates the negative environmental effects of ODA by enhancing the capacity for effective environmental management and compliance (Dasgupta et al. 2000). Furthermore, human capital influences the policy and regulatory environment, as knowledgeable policymakers and regulators can design and implement effective policies to manage ODA efficiently, reducing its environmental impact. These findings indicate the crucial role of human capital in reconciling development goals with environmental sustainability.

The positive coefficients for GDP per capita indicate that higher income levels are associated with increased carbon emissions. This relationship can be attributed to the expansion of economic activities and the intensified reliance on fossil fuels that often accompany economic growth. These findings are consistent with those of Saidi and Hammami (2015) and Kais and Sami (2016), who reported a positive correlation between GDP per capita and carbon emissions in 58 countries and regions such as Europe, North Asia, and the Middle East. From the perspective of the Environmental Kuznets Curve (EKC) hypothesis, Cambodia, as a low-income nation, has not yet reached the income threshold required to reduce emissions. Consequently, rising GDP per capita increases carbon emissions, leading to further environmental degradation (Caron and Fally 2021).

Similarly, the positive coefficient for population highlights that population growth leads to increased resource consumption, particularly in energy demand. A growing population drives economic activity by increasing the demand for energy-intensive goods and services, such as transportation, which are highly dependent on fossil fuels, thereby leading to further environmental degradation. This observation aligns with the arguments of Holdren and Ehrlich (1974) and Yuan et al. (2019), who emphasize the link between population growth and higher energy consumption.

In contrast, the findings suggest that trade openness has an insignificant effect on carbon emissions. This result may be explained by the offsetting influences of the scale and technology effects. The scale effect drives increased emissions through greater production and resource use, while the technology effect reduces emissions by promoting cleaner technologies. In Cambodia, the neutralization of these effects, combined with the relatively low level of trade openness, diminishes its overall impact on carbon emissions.

According to the descriptive statistics in <Table 3>, Cambodia's average trade openness was only 29.997% of GDP from 1975 to 2022, which may explain the weakened influence of scale and technology effects. These findings are consistent with Pham and Nguyen (2024), who observed no significant relationship between trade openness and environmental pollution in a study of 64 developing countries from 2003 to 2017.

5. The Toda-Yamamoto Granger causality test

To ensure the robustness of the findings obtained from the ARDL model, the Toda-Yamamoto method (Toda and Yamamoto 1995) was employed to conduct Granger causality tests among the variables under study. This approach was selected due to its ability to accommodate variables with different integration orders, such as I(0) and I(1), during the testing process.

The results of the Toda-Yamamoto Granger causality test, presented in <Table 9>, establish significant causality relationships between ODA, human capital, and CO_2 emissions. Specifically, the findings indicate unidirectional causality between ODA, human capital, and carbon dioxide emissions. This provides additional evidence supporting the robustness of the ARDL model's estimation results, further underscoring the influence of ODA and human capital on environmental consequences in the context of Cambodia. These causality results strengthen the study’s conclusions by validating the dynamic interactions identified in the main analysis.

<Table 9> Toda-Yamamoto Granger causality test

Variable	Wald Stat.	Prob.	Causality
lnODA → lnCO2	16.973***	0.005	Unidirectional
lnGDP → lnCO2	18.767***	0.002	Unidirectional
lnPOP → lnCO2	17.836***	0.003	Unidirectional
lnTRA → lnCO2	18.125***	0.003	Unidirectional
lnHUM → lnCO2	11.255**	0.047	Unidirectional
lnCO2 → lnODA	2.504	0.776	
lnGDP → lnODA	3.801	0.578	
lnPOP → lnODA	1.646	0.896	
lnTRA → lnODA	8.421	0.135	
lnHUM → lnODA	1.533	0.909	
lnCO2 → lnGDP	1.025	0.961	
lnODA → lnGDP	2.846	0.724	
lnPOP → lnGDP	1.232	0.942	
lnTRA → lnGDP	2.478	0.780	
lnHUM → lnGDP	1.208	0.944	
lnCO2 → lnPOP	6.026	0.304	
lnODA → lnPOP	10.901*	0.053	Unidirectional
lnGDP → lnPOP	4.104	0.535	
lnTRA → lnPOP	19.634***	0.002	Unidirectional
lnHUM → lnPOP	5.370	0.372	
lnCO2 → lnTRA	7.152	0.210	
lnODA → lnTRA	12.344**	0.030	Unidirectional
lnGDP → lnTRA	1.556	0.907	
lnPOP → lnTRA	9.154	0.103	
lnHUM → lnTRA	1.923	0.860	
lnCO2 → lnHUM	7.888	0.163	
lnODA → lnHUM	11.068**	0.050	Unidirectional
lnGDP → lnHUM	4.705	0.453	
lnPOP → lnHUM	7.954	0.159	
lnTRA → lnHUM	8.143	0.149	

Note: The significance levels are denoted as *** (1%), ** (5%), and * (10%).

6. Diagnostic tests of the ARDL model

To confirm the validity and reliability of the ARDL model's estimation results, a series of diagnostic tests were performed, as detailed in <Table 10>. The results indicate no serial correlation in the estimation, as evidenced by the insignificance of the LM test. The Breusch-Pagan-Godfrey test reveals no signs of heteroscedasticity, ensuring homoscedasticity in the residuals. The RESET test confirms that the model is correctly specified. Furthermore, the negative error correction term (-0.542) highlights the model's ability to consistently adjust toward the long-run equilibrium, reinforcing the robustness of the estimated relationships. Additionally, the R^2 values demonstrate a satisfactory level of goodness of fit, indicating that the model explains the variation in the dependent variable effectively. These diagnostic results collectively validate the reliability and robustness of the ARDL model employed in this analysis.

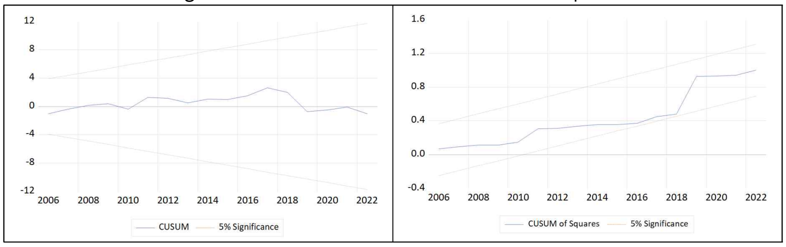
<Table 10> Diagnostic tests for the ARDL model

ECM	LM test	RESET test	R^2
Coefficient	Chi-square	F-statistic	0.940
-0.542***	2.299	1.781	
Prob.	Prob.	Prob.	
0.000	0.129	0.201	

Note: The significance levels are denoted as *** (1%), ** (5%), and * (10%).

Finally, the stability of the specified models was evaluated using the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUM of squares) tests, as shown in <Figure 2>. The results confirm that the models are both stable and consistent, ensuring the reliability of the estimation over the sample period.

<Figure 2> CUSUM and CUSUM of squares



7. Additional robustness assessment

To ensure the robustness and reliability of the study, an additional assessment is conducted apart from the Toda-Yamamoto Granger causality test. Specifically, a differentiated analysis of different types of ODA is performed. This includes estimating the long-run effects of ODA from different sources—namely, multilateral organizations and bilateral donors—on CO_2 emissions.

Among the major bilateral donors to Cambodia, Japan and China play significant roles in providing ODA. However, due to data limitations regarding China's ODA, the analysis focuses exclusively on Japan. The empirical results of this assessment are presented in <Table 11>.

<Table 11> Long-run coefficients from selected donor

	Multilateral Organization		Japan	
Variable	Coefficient	t-Statistic	Coefficient	t-Statistic
lnODA	0.206***	3.165	0.850***	6.354
lnGDP	0.215*	1.726	0.214***	10.875
lnPOP	1.721***	4.955	0.483	1.644
lnTRA	2.170	0.949	1.022	1.249
lnHUM	-1.040***	-3.275	-0.406***	-6.744
lnODA*lnHUM	-0.051***	-3.562	-0.277***	-8.516

Note: The significance levels are denoted as *** (1%), ** (5%), and * (10%).

The empirical findings presented in <Table 11> indicate that ODA from both multilateral organizations and Japan contributes to an increase in CO_2 emissions in Cambodia. However, the magnitude of the impact differs, with ODA from multilateral organizations (0.206) having a smaller effect compared to ODA from Japan (0.850). Furthermore, human capital plays a moderating role by mitigating the negative impact of ODA on CO_2 emissions in both cases. These findings align with the empirical results on the overall effect of total ODA on CO_2 emissions in Cambodia, as reported in <Table 6>. This consistency strengthens the reliability of the study's conclusions and reinforces the robustness of the research findings.

Ⅵ. Conclusions and policy implications

This study provides a comprehensive analysis of the impact of ODA on carbon dioxide emissions in Cambodia, with the moderating role of human capital. The research employs the ARDL model to examine the data from 1975 to 2022, supplemented by the Toda-Yamamoto Granger causality test to enhance the robustness and validity of the findings. The empirical results reveal that ODA contributes to increased CO_2 emissions in Cambodia. However, human capital plays a crucial role in mitigating environmental deterioration. It significantly reduces emissions and helps moderate the negative environmental consequences of ODA. The Toda-Yamamoto Granger causality test establishes a unidirectional causality between ODA, human capital and CO_2 emissions, demonstrating their roles in determining environmental impacts. Moreover, additional variables, such as GDP per capita and population growth, intensify environmental deterioration, while trade openness is shown to have short-term effects on emissions, with minimal long-term impact. The findings of this study provide critical policy implications for Cambodia in three key areas.

1. Policy implications for donor responsibility

The findings indicate that ODA-related CO_2 emissions in Cambodia are primarily associated with the transportation infrastructure sector. As Cambodia’s major development partners, China and Japan play a crucial role in shaping the country’s infrastructure landscape. Given the significant environmental impact of these projects, donor nations should adopt sustainable and low-carbon strategies to align ODA with climate-resilient development goals.

For China, its ODA falls under the category of South-South cooperation, which is intended to yield mutual benefits for both China and Cambodia. Over the years, China has been a major source of funding for infrastructure and natural resource development projects. These funds have primarily supported Chinese state enterprises in numerous developing countries, including Cambodia (Ky et al., 2012). Most of China’s development assistance is provided in the form of concessional loans, particularly for large-scale transport infrastructure projects. Two of the largest ODA-funded transport projects in Cambodia are the $1.1 billion Phnom Penh Airport and the $880 million New Siem Reap International Airport.

To mitigate the environmental impact of these projects, China should take greater responsibility for ensuring the sustainability of its ODA-financed infrastructure. Specifically, China should adopt low-carbon technologies by integrating energy-efficient and emissions-reducing solutions during all stages of project implementation. For example, transitioning from diesel-powered construction machinery to electric or hybrid alternatives can significantly reduce on-site emissions.

Using eco-friendly construction materials is another crucial step. Employing geopolymer cement instead of traditional Portland cement can reduce CO_2 emissions by up to 80%, making infrastructure projects more sustainable. Additionally, reliance on diesel generators at construction sites should be minimized by replacing them with solar or wind energy sources to further decrease emissions.

For Japan, since the 1991 Paris Peace Agreement, Japan has been actively engaged in Cambodia's reconstruction and development, aligning its ODA initiatives with Cambodia's Rectangular Strategy, National Strategic Development Plan (NSDP), and Industrial Development Policy (IDP). Unlike China, Japan predominantly provides ODA in the form of grants rather than loans, and while its assistance is distributed across various sectors—including those linked to the Millennium Development Goals (MDGs)—the transportation infrastructure sector continues to receive the largest share. One key example of Japan's ODA allocation is the $158 million National Road No.5 Improvement Project, covering the Thlea Ma'am–Battambang and Sri Sophorn–Poipet sections. Therefore, Japan should take on environmental responsibilities comparable to those of China. Japan should not only implement low-carbon technologies and materials, but also integrate green financing mechanisms into its ODA framework to promote sustainable infrastructure development. A crucial step in this process is mandating environmental criteria in project bidding, ensuring that all ODA-funded infrastructure projects adhere to sustainability standards. Contractors should be required to utilize low-carbon materials and incorporate eco-friendly energy sources throughout the construction process.

2. Policy implications for regulation enforcement and governance

Cambodia’s environmental policy framework is primarily structured around key regulatory instruments, including the Circular Strategy on Environment 2023-2028, Cambodia’s Environmental Protection Strategic Plan (EPSP) 2024-2028, and the Cambodia Clean Air Plan 2021. Policies specifically linked to ODA are implemented under the Development Cooperation and Partnerships Strategy 2024-2028 (Royal Government of Cambodia 2023a). These strategies aim to advance a low-carbon economy, enhance renewable energy adoption and energy efficiency, strengthen climate resilience, and promote environmental sustainability and a green economy. A key goal of these policies is to reduce CO_2 emissions by 19% by 2030 compared to a business-as-usual scenario. The ultimate objective is to achieve Cambodia’s Pentagonal Strategy targets of carbon neutrality and 60% forest cover by 2050. Strengthening the enforcement capacity of existing policies and governance mechanisms is crucial to ensuring that ODA effectively contributes to Cambodia's environmental objectives rather than increasing carbon emissions. The following measures are essential to improving policy enforcement and governance.

First, enhancing institutional capacity for effective regulation enforcement: a key challenge in enforcing existing environmental regulations effectively is Cambodia's limited administrative capacity to manage ODA efficiently (Chanboreth and Hach 2008). The proliferation of aid donors and the massive volume of financial assistance have created significant administrative burdens. While some ODA projects are implemented by foreign agencies－such as the China Road and Bridge Corporation, Electricité du Cambodge, and the Shanghai Baoye Group－the Cambodian government remains the primary institution responsible for managing international aid inflows. However, governance weaknesses undermine enforcement efforts. Cambodia ranks 158th out of 180 countries on the Corruption Perceptions Index, with a score of 21 out of 100, highlighting systemic inefficiencies and governance challenges. Administrative inefficiencies and widespread corruption hinder the effective implementation of environmental regulations. This includes challenges in enforcing sanctions such as project suspensions, fines, or legal actions against contractors who fail to comply with CO_2 emissions regulations. Strengthening governance through improved transparency, reducing bureaucratic inefficiencies, and reinforcing anti-corruption measures is essential. These efforts are crucial for enhancing policy implementation and ensuring more effective enforcement.

Second, fostering stakeholder engagement: the top-down administrative approach to ODA management has often led to suboptimal or even negative environmental consequences (Anderson and Raksmey 2021). The exclusion of local knowledge from decision-making processes limits the effectiveness of policy implementation. To address this issue, greater stakeholder engagement—including civil society organizations, local communities, academic institutions, and private sector representatives—is necessary. Incorporating these stakeholders into ODA project discussions can help assess project impacts, recommend improvements, and monitor compliance records. Strengthening the role of multi-stakeholder platforms, such as Cambodia’s Technical Working Groups (TWGs), would enhance collaboration, accountability, and the overall effectiveness of environmental policy enforcement. Expanding participatory governance mechanisms can help ensure that ODA-funded projects align with national sustainability goals. Additionally, these mechanisms play a crucial role in mitigating potential environmental deterioration.

3. Policy implications for shifts in ODA allocation

Cambodia is expected to graduate from its LDC status by 2029 while attempting to sustain its economic development momentum. The country's long-term development policy framework, the Rectangular Strategy, has been in place since 2004. In 2023, Cambodia introduced the Pentagonal Strategy, which builds upon the Rectangular Strategy to further guide socio-economic development.

Both strategies aim to transform Cambodia into an upper-middle-income country by 2030 and a high-income country by 2050. To achieve these goals, Cambodia must sustain an economic growth rate of approximately 7% per annum while ensuring resilient, sustainable, and inclusive development. Furthermore, human resource development is imperative for achieving these objectives. Therefore, investing in education, training, and capacity-building is necessary to ensure a skilled workforce capable of supporting sustainable development efforts (Royal Government of Cambodia 2023b).

Human capital plays a crucial role not only in fostering economic growth but also in environmental sustainability. Empirical findings from this study indicate that human capital helps mitigate CO_2 emissions resulting from ODA. This, in turn, facilitates the transition to low-carbon development pathways. However, Cambodia's current status in terms of human capital development remains a challenge. The country ranks 148th out of 193 countries in the Human Development Index (HDI), with a score of 0.6. According to the Asian Development Bank (2019), Cambodia’s net enrollment rate in primary education increased from 77.8% in 1998 to 92.6% in 2018. Despite this progress, secondary education continues to face challenges such as low enrollment rates, poor quality, and high dropout rates. Currently, only 894,207 youths aged 15 – 24 (26.5%) are attending school, with 46.5% enrolled in upper secondary education.

As highlighted by the Council for the Development of Cambodia, 67.45% of total ODA received in 2023 was allocated to the economic and infrastructure sectors, whereas only 8.74% was allocated to the education sector. This imbalance in ODA allocation raises concerns regarding Cambodia's ability to achieve sustainable and inclusive development through a low-carbon pathway. Given the critical role of human capital, Cambodia should prioritize increasing ODA allocations to education to enhance human capital development. Particular emphasis should be placed on secondary and higher education to ensure a well-equipped workforce. Additionally, a larger share of ODA should be allocated to the implementation of Cambodia's Technical and Vocational Education and Training (TVET) Policy, which aims to enhance workforce skills and expand equitable access to education. By prioritizing these areas, Cambodia can establish a foundation for sustainable development while achieving long-term socio-economic transformation.

Reference

Adikari, Priyangani, Haiyun Liu, Dmslb Dissanayake, and Manjula Ranagalage. 2023. "Human capital and carbon emissions: The way forward reducing environmental degradation." *Sustainability* 15(4): 2926.

Ahmed, Mansoor, Wen Huan, Nafees F. Ali, Ahsan Shafi, Muhsan Ehsan, Kamal Abdelrahman, Anser A. Khan, Saiq S. Abbasi, and Mohammed Fnais. 2023. "The effect of energy consumption, income, and population growth on CO2 emissions: Evidence from NARDL and machine learning models." *Sustainability* 15(15): 11956.

Ahmed, Zahoor, Solomon P. Nathaniel, and Muhammad Shahbaz. 2021. "The criticality of information and communication technology and human capital in environmental sustainability: Evidence from Latin American and Caribbean countries." *Journal of Cleaner Production* 286: 125529.

Alvarado, Rafael, Qiushi Deng, Brayan Tillaguango, Priscila Méndez, Diana Bravo, José Chamba, María Alvarado-Lopez, and Munir Ahmad. 2021. "Do economic development and human capital decrease non-renewable energy consumption? Evidence for OECD countries." *Energy* 215: 119147.

Anderson, Brevin and Him Raksmey. 2021. "Foreign aid and development assistance." D. S. Udom, B. J. Murg, O. Virak, and M. Renfrew (eds.), *Cambodia 2040. International Relations and Governancez*. Phnom Penh: Future Forum & Konrad-Adenauer-Stiftung. 100-119.

Asian Development Bank. 2019. *Cambodia and Asian Development Bank: Partnership for inclusive growth.* Manila: Asian Development Bank.

Barkat, Karim, Mouyad Alsamara, and Karim Mimouni. 2024. "Beyond economic growth goals: Can foreign aid mitigate carbon dioxide emissions in developing countries?" *Journal of Cleaner Production* 471: 143411.

Barkat, Karim, Zouhair Mrabet, and Mouyad Alsamara. 2016. "Does official development assistance for health from developed countries displace government health expenditure in Sub-Saharan countries?" *Economic Bulletin* 36(3): 1616-1635.

Barro, Robert J. 2001. "Human capital and growth." *American Economic Review* 91(2): 12-17.

Boly, Mohamed. 2018. " CO2 mitigation in developing countries: The role of foreign aid." *Études et Documents* 1: 1-36.

Brasington, David M. and Diane Hite. 2005. "Demand for environmental quality: A spatial hedonic analysis." *Regional Science and Urban Economics* 35(1): 57-82.

Caron, Justin, and Thibault Fally. 2021. "Per capita income, consumption patterns, and CO2 emissions." *Journal of the Association of Environmental and Resource Economists* 9(2): 235-271.

Chanboreth, Ek and Sok Hach. 2008. "Aid effectiveness in Cambodia." Working Paper No. 7. Washington, DC: Wolfensohn Center for Development at Brookings.

Chaurasia, Aalok. 2020. "Population effects of increase in world energy use and CO_2 emissions: 1990-2019." *The Journal of Population and Sustainability* 5(1): 87-125.

Chen, Yulong, Zheng Wang, and Zhangqi Zhong. 2019. "CO_2 emissions, economic growth, renewable and non-renewable energy production, and foreign trade in China." Renewable Energy 131: 208-216.

Chen, Zexian and Jingjing He. 2013. "Foreign aid for climate change-related capacity building." Working Paper No. 2013/046. Helsinki: The United Nations University World Institute for Development Economics Research.

"Climate Watch." https://www.climatewatchdata.org/. (access: 2024/11/10).

Dasgupta, Susmita, Hemamala Hettige, and David Wheeler. 2000. "What improves environmental compliance? Evidence from Mexican industry." *Journal of Environmental Economics and Management* 39(1): 39-66.

Dietz, Thomas and Eugene A. Rosa. 1994. "Rethinking the environmental impacts of population, affluence, and technology." *Human Ecology Review* 1(2): 277-300.

Ehrlich, Paul R. and John P. Holdren. 1971. "Impact of population growth." *Science* 171(3): 1212-1217.

Ewane, Enongene B. and Etah I. Ewane. 2023. "Foreign direct investment, trade openness, and environmental damage in SSA countries: A quadratic modeling and turning point approach." *American Journal of Environmental Economics* 2(1): 9-18.

Ganda, Fortune. 2021. "The environmental impacts of human capital in the BRICS economies." *Journal of the Knowledge Economy* 12(3): 1-24.

Gmidène, Samia, Saida Zaidi, and Olfa Chouikha. 2024. "Testing the nexus between official development assistance, governance quality, and CO2 emissions: Fresh evidence from Sub-Saharan African countries." *Open Journal of Business and Management* 12(5): 3722-3742.

Gnangoin, Thierry Y., Diby F. Kassi, Akadje J. R. Edjoukou, Ouyang Kongrong, and Dai Yuqing. 2022. "Renewable energy, non-renewable energy, economic growth, and CO2 emissions in the newly emerging market economies: The moderating role of human capital." *Frontiers in Environmental Science* 10: 1-15.

Grossman, Gene M. and Alan B. Krueger. 1996. "The inverted-U: What does it mean?" *Environment and Development Economics* 1(1): 119-122.

Haini, Hazwan. 2021. "Examining the impact of ICT, human capital, and carbon emissions: Evidence from the ASEAN economies." *International Economics* 166: 116-125.

Holdren, John P. 1991. "Population and the energy problem." *Population and Environment* 12(3): 231-255.

Holdren, John P. and Paul R. Ehrlich. 1974. "Human population and the global environment: Population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force." *American Scientist* 62(3): 282-292.

"International Energy Agency." https://www.iea.org/countries (accessed 2024/11/15).

Jahanger, Atif, Bo Yang, Weichiao Huang, Muntasir Murshed, Muhammad Usman, and Magdalena Radulescu. 2023. "Dynamic linkages between globalization, human capital, and carbon dioxide emissions: Empirical evidence from developing economies." *Environment, Development and Sustainability* 25: 9307-9335.

Khan, Muhammad. 2020. "CO2 emissions and sustainable economic development: New evidence on the role of human capital." *Sustainable Development* 28(5): 1279-1288.

Khan, Zeeshan, Shahid Ali, Kangyin Dong, and Rita Y. M. Li. 2021. "How does fiscal decentralization affect CO2 emissions? The roles of institutions and human capital." *Energy Economics* 94: 105060.

Kitila, Getachew M. 2024. "Deciphering the complex interplay: Heterogeneous, threshold, and mediation effects of trade openness on CO2 emissions in Africa." PLOS ONE 19(10): e0309736.

Kretschmer, Bettina, Michael Hübler, Michael Hübler, and Peter Nunnenkamp. 2013. "Does foreign aid reduce energy and carbon intensities of developing economies?" *Journal of International Development* 25(1): 67-91.

Kwakwa, Paul A., Hamdiyah Alhassan, and George Adu. 2020. "Effect of natural resources extraction on energy consumption and carbon dioxide emission in Ghana." *International Journal of Energy Sector Management* 14(1): 20-39.

Ky, Sereyvath, Cheonwoo Lee, and Peter J. Stauvermann. 2012. "A comparative study on characteristics of ODA of China-Japan-Korea to Cambodia." *Journal of East Asian Economic Integration* 16(4): 333-361.

Lee, Suekyoung, Gayoung Choi, Eunmi Lee, and Taeyoung Jin. 2020. "The impact of official development assistance on the economic growth and carbon dioxide mitigation for the recipient countries." *Environmental Science and Pollution Research* 27: 41776-41786.

Lemmen, Carsten. 2014. "Malthusian assumptions, Boserupian response in transition to agriculture models." M. Fischer-Kowalski, A. Reenberg, A. Schaffartzik, and A. Mayer (eds.). *Ester Boserup's Legacy on Sustainability*. New York: Springer. 87-102.

Li, Shijie, Yang Yu, Atif Jahanger, Muhammad Usman, and Yifan Ning. 2022. "The impact of green investment, technological innovation, and globalization on CO2 emissions: Evidence from MINT countries." *Frontiers in Environmental Science* 10: 868704.

Meng, Yue, Haoyue Wu, Yunchen Wang, and Yinying Duan. 2022. "International trade diversification, green innovation, and consumption-based carbon emissions: The role of renewable energy for sustainable development in BRICST countries." *Renewable Energy* 198: 1243-1253.

Narayan, Paresh K. 2005. "The saving and investment nexus for China: Evidence from cointegration tests." *Applied Economics* 37(17): 1979-1990.

Oanh, Tran T. M. and Nguyen T. Ha. 2023. "Impact of income inequality on climate change in Asia: The role of human capital." *Humanities & Social Sciences Communications* 10: 1-11.

Pata, Ugur K., Mehmet M. Dam, and Funda Kaya. 2023. "How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO2 emissions? An EKC analysis for ASEAN countries." *Environmental Science and Pollution Research* 30: 14821-14837.

Pesaran, Hashem M., Yongcheol Shin, and Richard Smith. 2001. "Bound testing approaches to the analysis of level relationships." *Journal of Applied Econometrics* 16(3): 289-326.

Pham, Diem T. T. and Hoai T. Nguyen. 2024. "Effects of trade openness on environmental quality: Evidence from developing countries." *Journal of Applied Economics* 27(1): 1-22.

Powanga, Luka, and Paul A. Kwakwa. 2024. "Determinants of carbon emissions in Kenya and policy implications." *Journal of Environmental Management* 370: 122595.

Rahman, Mohammad M., Rabindra Nepal, and Khosrul Alam. 2021. "Impacts of human capital, exports, economic growth, and energy consumption on CO2 emissions of a cross-sectionally dependent panel: Evidence from the newly industrialized countries (NICs)." *Environmental Science & Policy* 121: 24-36.

Riddell, Abby and Miguel Niño-Zarazúa. 2016. "The effectiveness of foreign aid to education: What can be learned?" *International*

Journal of Educational Development 48: 23-36.

Romer, Paul. M. 1990. "Endogenous technological change." *Journal of Political Economy* 98(5): S71-S102.

Royal Government of Cambodia. 2023a. *Development cooperation and partnerships strategy 2024-2028*. Phnom Penh: Royal Government of Cambodia.

______. 2023b. *Pentagonal Strategy-Phase I: Growth, Employment, Equity, Efficiency and Sustainability - Building the Foundation Towards Realizing the Cambodia Vision 2050*. Phnom Penh: Royal Government of Cambodia.

Saidi, Kais and Sami Hammami. 2015. "The effect of energy consumption and economic growth on CO2 emissions: Evidence from 58 countries." *International Journal of Energy Economics and Policy* 3(3): 91-104.

______. 2016. "An econometric study of the impact of economic growth and energy use on carbon emissions: Panel data evidence from fifty-eight countries." *Renewable and Sustainable Energy Reviews* 59: 1101-1110.

Sam, Chungyan, Robert McNown, and Sookhoon Goh. 2019. "An augmented autoregressive distributed lag bounds test for cointegration." *Economic Modelling* 80: 130-141.

Sarkodie, Samuel A., Samuel Adams, Phebe A. Owusu, Thomas Leirvik, and Ilhan Ozturk. 2020. "Mitigating degradation and emissions in China: The role of environmental sustainability, human capital, and renewable energy." *Science of the Total Environment* 719: 137530.

Sehrawat, Madhu. 2021. "Modelling the nexus between human capital, income inequality, and energy demand in India: New evidence from asymmetric and non-linear analysis." *Environmental Science and Pollution Research* 28: 3632-3643.

Sharma, Kishor, Badri Bhattarai, and Salma Ahmed. 2019. "Aid, growth, remittances, and carbon emissions in Nepal." *Energy Journal* 40(1): 129-142.

Sheraz, Muhammad, Xu Deyi, Jaleel Ahmed, Saif Ullah, and Atta Ullah. 2021. "Moderating the effect of globalization on financial development, energy consumption, human capital, and carbon emissions: Evidence from G20 countries." *Environmental Science and Pollution Research* 28: 13115-13130.

Stauder, Matthew. 2022. "Do overseas development assistance and foreign direct investment impact the carbon dioxide emissions of developing countries?" *The Capitol Economics Journal* 2(1): 61-71.

Tian, Yichuan, Wang Xu, Zisheng Han, Guanglin Lai, and Tao Ma. 2024. "Harnessing knowledge: The impact of human capital on synergetic control of CO2 and air pollutant emissions." *Polish Journal of Environmental Studies* 33(1): 101-110.

Toda, Hiro Y. and Taku Yamamoto. 1995. "Statistical inference in vector autoregressions with possibly integrated processes." *Journal of Econometrics* 66(1-2): 225-250.

Wahyudi, Heru S. and Ukhti Ciptawaty. 2023. "Pengaruh GDP per kapita dan konsumsi energi terhadap emisi CO2 di Indonesia." *Journal on Education* 6(1): 6508-6517.

Wang, Haijun, Yongming Wang, Xue Zhang, and Cheng Zhang. 2024. "The effect of foreign aid on carbon emissions in recipient countries: Evidence from China." *Technological Forecasting and Social Change* 200: 123104.

Wang, Qiang, Jiaqi Guo, and Rongrong Li. 2022. "Official development assistance and carbon emissions of recipient countries: A dynamic panel threshold analysis for low- and lower-middle-income countries." *Sustainable Production and Consumption* 29: 158-170.

Wang, Yibo. 2023. "Exploring resource endowment and human capital impact on regional energy efficiency in China in the context of COP26." *Resources Policy* 81: 103422.

Yuan, Man, Chaohui Yin, Yi Sun, and Weiqiang Chen. 2019. "Examining the associations between urban built environment and noise pollution in high-density high-rise urban areas: A case study in Wuhan, China." *Sustainable Cities and Society* 50: 101678.

Zaekhan, Zaekhan and Nachrowi Djala. 2015. "The impact of renewable energy and GDP per capita on carbon dioxide emissions in the G-20 countries." *Economics and Finance in Indonesia* 60(2): 145-174.

Zeng, An, Yuhui Sheng, Baihe Gu, Zhengzao Wang, and Mingyue Wang. 2022. "The impact of climate aid on carbon emissions reduction and the role of renewable energy: Evidence from the Belt and Road countries." *Environmental Science and Pollution Research* 29(51): 77401-77417.

Zuo, Na, Jack Schieffer, and Steven Buck. 2019. "The effect of the oil and gas boom on schooling decisions in the U.S." *Resources and Energy Economics* 55: 1-23.

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<국문요약>

캄보디아에 대한 공적개발원조가 이산화탄소 배출에 미치는 영향

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본 연구는 1975년부터 2022년까지의 기간을 대상으로 캄보디아의 이산화탄소 배출에 대한 공적개발원조(ODA)의 영향을 분석하기 위해 자기회귀 시차분포(ARDL) 모형을 적용하였으며, Toda-Yamamoto 그레인저 인과관계 검정을 통해 인과 방향을 검증하였다. 분석 결과, ODA는 탄소 배출을 심화시키는 동시에, 인적 자본이 이러한 부정적 환경 영향을 유의미하게 완화함을 확인하였다. 또한 ODA와 인적 자본에서 배출량으로의 단방향 인과관계가 존재함으로써, 이들이 환경 결과를 결정하는 핵심 요인임을 시사한다. 한편 1인당 국내총생산과 인구증가는 환경적 압력을 가중시키는 반면, 무역개방도는 주로 단기적으로 배출에 영향을 미치는 것으로 나타났다. 본 연구의 결과는 캄보디아의 정책 입안자들에게 중요한 시사점을 제공한다.

주제어: 공적개발원조, 이산화탄소 배출, 캄보디아, 자기회귀 시차분포 모형, Toda-Yamamoto 그레인저 인과관계 검정