Investigate the Impact of Carbon Dioxide Emissions on Total Fertility Rate in Taiwan: Human Development Index as Mediator

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Abstract: - This study is to investigate the dynamic relationships among carbon dioxide (CO_2) emissions, the Human Development Index (HDI), and the Total Fertility Rate (TFR) in Taiwan from 1992 to 2021 by using an innovative method, called quantile mediation analysis. Our findings show that CO_2 emissions negatively directly affect TFR. We also find that HDI, which measures the overall development of a country, has a partly mediation effect at the distribution of TFR within 0.2 to 0.6 quantiles. Moreover, the results reveal that there exists a U-shaped relationship between CO_2 emissions and TFR, and between CO_2 emissions and HDI at the higher 0.8 quantile level. According to these results, we suggest that the Taiwanese government continue investing in education, healthcare, and gender equality as critical human development sectors. Such investments can mitigate the negative impact of CO_2 emissions on TFR, and balance environmental factors and demographic outcomes. These policy implications are crucial for policymakers and researchers in environmental science, public health, and social policy.

Key-Words: - Carbon Dioxide Emissions (CO_2); Economic Growth; Environmental Kuznets Curve (EKC); Human Development Index (HDI); Quantile Mediation Analysis; Total Fertility Rate (TFR).

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1 Introduction

There exists a critical issue in the interaction between carbon dioxide (CO_2) emissions and the total fertility rate (TFR) because it illustrates the complex relationship between environmental factors and population dynamics. CO_2 emissions are a significant trigger of climate change, which significantly affects human health, economic development, and the natural environment. These effects can impact on reproductive behaviors and decisions, even affecting TFR, [1]. Studies by authors [1] and [2] have demonstrated that CO_2 emissions negatively affect TFR. However, extensive research, including the works in Bangladesh [3], China [4], and Saudi Arabia [5], has established a causative link between CO_2 emissions and the Human Development Index (HDI). Population dynamics must be fully considered when formulating climate change mitigation strategies.

Focusing on population dynamics, we use the Total Fertility Rate (TFR) as the key indicator. It measures the average number of children a woman is expected to have during her reproductive years. As the author [6] pointed out, environmental and demographic factors must be considered when making population policies. This is important because fertility rates are influenced by social, economic, and cultural factors, all of which are tied to environmental changes and how resources are used. Recent research has indicated that the link between TFR and the Human Development Index (HDI) would change at different stages of economic development, [7]. This highlights how important it is to consider these factors at various stages of economic development and shows how complex and non-linear the relationship between TFR and HDI is.

In addition, the Human Development Index (HDI) covers critical aspects like health, education,

and the economy, and shows direct and indirect links with the Total Fertility Rate (TFR). For example, the author [8] investigated the dynamic interactions among HDI, TFR, and mortality rates. According to author [9], explored how a decreasing TFR affects economic growth. These researches indicated that the TFR was linked to broader human development and economic status. In most countries, an increase in health, education, and economic development levels, or an improvement in HDI, typically corresponds to a decrease in the average number of children born per woman. This trend is observed in numerous studies and is widely acknowledged, [10]. However, research by authors [11] reveals an intriguing phenomenon: in some highly developed countries, fertility rates may increase as HDI rises further, suggesting a potential reversal in the TFR-HDI relationship in these advanced nations. This organizational framework is designed to meticulously investigate the interaction between CO_2 emissions and the TFR through the mediator of HDI for Taiwan's economic and environmental policymaking. Therefore, the main goal of this study is to investigate the dynamic relationship among carbon dioxide (CO_2) emissions, the Human Development Index (HDI), and the Total Fertility Rate (TFR) in Taiwan. Moreover, we examine the mediating role of the Human Development Index (HDI) by using quantile mediation analysis. In other words, we aim to analyze how CO_2 emissions affect TFR across different economic development stages, providing valuable insights for policymakers.

The structure of this paper is as follows: Section 2 explores the literature review. Section 3 presents the research methodology, and section 4 reports on data collection, scope, and empirical results. Section 5 presents a detailed justification of significant results. Section 6 provides conclusions and suggestions for future research in Section 7. Section 8 reports the contributions of this study.

2 Literature Review

Climate change is all about the long-term shifts in temperature and weather patterns, mainly caused by human activities. The most apparent signs of climate change include the rising global average temperatures and increasing extreme and unpredictable weather events, which have become major international issues in recent years. These changes threaten human well-being [12] and also impact the survival and reproduction of other species [13], affecting the sustainability of the entire Earth's ecosystem. The author [14] found the significant adverse effects of CO_2 emissions on fertility rates in the Middle East, North Africa (MENA), and the Economic Community of West African States (ECOWAS) regions during the period of 1970 to 2019. This emphasizes the urgency of understanding how CO_2 emissions impact the TFR. In other words, we should find out how climate change affects socioeconomic development.

According to author [15], pointed out that compared with low-income countries, high-income countries have the ability and willingness to invest in environmental protection once they reach a certain economic level, aiming to balance economic growth and environmental sustainability. This theoretical framework helps us provide a new perspective for understanding and exploring the relationship between CO_2 emissions and economic development, especially the impact on the economic aspects of the Human Development Index (HDI), [16].

When we investigate the relationships among CO_2 emissions, the Human Development Index (HDI) and the Total Fertility Rate (TFR), many existing studies only examine the relationship between two variables, [17], [18], [19], [20], [21], [22], [23]. This study emphasizes things that other studies missed. It investigates a dynamic interaction among carbon dioxide emissions, the total fertility rate, and the human development index. The study puts all these variables together to understand how they affect each other. This may provide new insights into developing integrated strategies that effectively address climate change, promote human development, and control population growth.

This research uses an integrate method called quantile mediation analysis to study the changing cause-and-effect relationships between CO_2 emissions and the TFR, with the HDI acting as a mediation factor from 1992 to 2021 in Taiwan. The study includes HDI as an important demographic factor to see how it affects the relationship between CO_2 emissions and TFR. Besides, based on studies by authors [24] and [25] on environmental pollution, this research further explores whether there exists an inverted U-shaped Environmental Kuznets Curve (EKC) relationship between CO_2 emissions and TFR, as well as between CO_2 emissions and HDI in Taiwan.

The EKC is a key framework to understand the nonlinear relationship between economic growth and environmental quality when evaluating economic development and human well-being. Therefore, the EKC hypothesis suggests that an inverted U-shaped relationship between economic growth and environmental degradation. This study is similar to the EKC hypothesis. It says that the environmental

conditions worsen as a country's income increases but improve after reaching a certain income level because of technological advancements and increased environmental awareness [26]. This idea can understand how different stages of economic development affect the environment [27].
Examining previous studies [28], [29], [30], and [31], we establish a theoretical hypothesis which guides the better policies and measures for government to solve problems.

3 Methodology

3.1 A quantile Regression

This study integrates the mediation analysis method [32] and the quantile regression method [33]. This novel method helps us understand how interacts the relationship between Taiwan's carbon dioxide emissions, human development index (HDI), and total fertility rate (TFR) from 1992 to 2021 [34], [35]. Furthermore, quantile regression can offer a comprehensive insight into their interaction, analyse the distributional skewness of variables and evaluate the impact of independent variables on the dependent variable across various quantiles [36]. According to the quantile regression, it firstly establishes a equation (1) to show the relation between the dependent variable y_t given the independent variable x_t .

$$y_t = u_t + x_t\beta \tag{1}$$

Then, we define the conditional distribution function in Equation (2). This formula explains the likelihood that y_t will be at most y, contingent upon x_t .

$$F_{\underset{x}{y}} = F\,(Y_t \leq y) = \mathrm{F}\,(y_t - x_t\beta) \tag{2}$$

To measure the regression issue, we formulate the subsequent Equation (3). The solution to this equation is β_θ , from which we derive the θ^{th}conditional quantile $Q_{\underset{x}{y}}(\theta) = \mathrm{X}\beta_\theta$.

$$\min_{\beta}\left[\theta\sum|y_t - x_t\beta| + (1-\theta)\sum|y_t - x_t\beta|\right]$$
$$\{t: Y_t \geq X_t\beta\} \quad \{t: Y_t < X_t\beta\} \tag{3}$$

3.2 Mediation Effect on Human Development Index

The purpose of this study is to investigate the dynamic association among carbon dioxide emissions, human development index (HDI) and total fertility rate (TFR) and examine if it exists the mediation effect of HDI. Here are important terms and steps in equations (4) to (6):
Key Terms:

b_1: The regression coefficient that explains how CO_2 affects TFR.
c_1: The regression coefficient that explains how CO_2 affects HDI.
d_1 and d_2: The regression coefficient that explains how CO_2 and HDI affect TFR
b_0, c_0, d_0: The intercept terms.
e_1, e_2, e_3: The error terms.

Equations We Used:

$$TFR = b_0 + b_1\,CO2 + e_1 \tag{4}$$

$$HDI = c_0 + c_1\,CO2 + e_2 \tag{5}$$

$$TFR = d_0 + d_1\,CO2 + d_2\,HDI + e_3 \tag{6}$$

Here are the steps we investigate the mediation effect of HDI how CO_2 emissions affect TFR:

Step 1: Direct Relationship Between CO_2 and TFR
If the coefficient $b1$ is significant in Equation (4), then CO_2 emissions directly related to TFR. This step is important because it shows a direct link between CO_2 and TFR, which is essential for mediation analysis.
Step 2: Relationship Between CO_2 and HDI
CO_2 emissions must be related to HDI, making c_1 in Equation (5) significant. This step confirms the first part of the mediation effect.
Step 3: Relationship Between HDI and TFR
HDI should be related to TFR, making d_2 in Equation (6) significant. This confirms that HDI affects TFR.
Step 4: Mediation Effect of HDI
When accounting for HDI, CO_2 should no longer be significantly related to TFR, making d_1 in Equation (6) insignificant. This indicates that HDI mediates the full effect of CO_2 on TFR.

If all these steps are met, it shows complete mediation. If only the first three steps are met and d_1 in Equation (6) remains significant but smaller than b_1 in Equation (4), it shows partial mediation.

Figure 1 illustrates our research framework, which defines the mediating effect of the Human Development Index (HDI) on the relationship between CO_2 emissions and TFR.

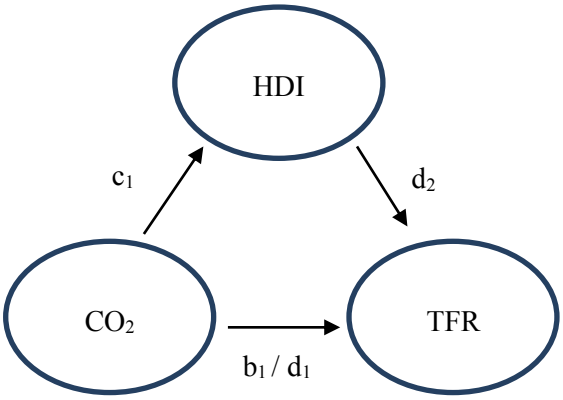

Fig.1: Research framework on the mediating effect of human development index

3.3 A Quantile Meditation Analysis

Utilizing the methods proposed by authors [34] and [35], our methodology now encompasses quantile mediation analysis. This addition permits the examination of all conceivable parameters throughout the quantile range, scrutinizing the disparities in the dependent variable's higher and lower values. This ability to evaluate the full range of quantiles represents a considerable improvement over the traditional fixed-parameter regression models, which are usually limited to a single coefficient. Moreover, this novel method enhances our dynamic and thorough comprehension of the potential effects of CO_2 emissions on the total fertility rate or the absence thereof. In the model, θ represents different quantiles. By integrating the prior regression equation (3) into equations (4) to (6), we can express it as equations (7) to (9), where the model is operationalized through the aggregation of weighted positive and negative error terms.

$$\min_{b} \sum_{t=1}^{T} [\theta |TFR_t - b_0 - b_1\, CO2_t| + (1-\theta)|TFR_t - b_0 - b_1\, CO2_t|] \quad (7)$$

$$\min_{c} \sum_{t=1}^{T} [\theta |HDI_t - C_0 - C_1\, CO2_t| + (1-\theta)|HDI_t - C_0 - C_1\, CO2_t|] \quad (8)$$

$$\min_{d} \sum_{t=1}^{T} [\theta |TFR_t - d_0 - d_1\, CO2_t - d_2\, HDI_t| + (1-\theta)|TFR_t - d_0 - d_1\, CO2_t - d_2\, HDI_t|] \quad (9)$$

3.4 A Quantile Environmental Kuznets Curve Model

The author [26] introduced the concept of the Environmental Kuznets Curve (EKC), a hypothesis that delineates the relationship between environmental quality and economic development. It posits that as an economy grows, indicators of ecological degradation initially worsen before improving once per capita income reaches a certain threshold, forming an inverted U-shaped curve. The United Nations Development Programme (UNDP), which incorporates gross national income (GNI) into the Human Development Index (HDI) assessment, not only reflects the scale of the economy but also reveals various characteristics and trends of economic growth. Therefore, this study integrates the EKC with quantile regression techniques, employing the nonlinear models presented in equations (10) and (11), which are widely recognized simplified econometric models internationally, [37]. This approach allows us to analyze whether there's an inverted U-shaped relationship between carbon dioxide (CO_2) emissions and the Total Fertility Rate (TFR) or the Human Development Index (HDI).

$$\min_{\alpha} \sum_{t=1}^{T} [\theta |TFR_t - \alpha_0 - \alpha_1\, CO2_t - \alpha_2\, CO2_t^2| + (1-\theta)|TFR_t - \alpha_0 - \alpha_1\, CO2_t - \alpha_2\, CO2_t^2|] \quad (10)$$

$$\min_{\beta} \sum_{t=1}^{T} [\theta |HDI_t - \beta_0 - \beta_1\, CO2_t - \beta_2\, CO2_t^2| + (1-\theta)|HDI_t - \beta_0 - \beta_1\, CO2_t - \beta_2\, CO2_t^2|] \quad (11)$$

At any quantiles of TFR or HDI, we use equations (10) and (11) to test the null hypothesis. This hypothesis asserts that α_1 and β_1 are greater than zero and α_2 and β_2 are less than zero. When the p-values derived from the t-tests for these equations are under 0.05, it denotes a statistically significant inverse U-shaped pattern, which agrees with the Environmental Kuznets Curve (EKC) concept suggested by the author, [26].

4 Results

In examining the causal relationships between CO_2 emissions and the TFR and the relationship between CO_2 emissions and the HDI in equations (7) and (8), we present the results of causality tests in Table 1. The notation $x \neq\!> y$ indicates that variable x does not influence variable y. Our research uncovers critical insights, chiefly through quantile regression analysis, which establishes a causative nexus between CO_2 emissions and the Total Fertility Rate (TFR) across the 0.2 to 0.6 quantiles of TFR distribution (as illustrated in Table 1 and Figure 2). It

suggests that within the TFR quantile distribution below 0.8, an elevation in CO_2 emissions is reliably and significantly linked with a negative shift in TFR. This outcome sets the stage for the initial segment of the mediation effect, underscoring a consistent and impactful relationship of CO_2 on TFR for quantiles below 0.8 in the TFR distribution. Furthermore, in our analysis, quantile regression techniques have revealed a substantial causal link between CO_2 emissions and the Human Development Index (HDI) within the 0.2 to 0.8 quantile range. This demonstrates a steady positive correlation between the rise in CO_2 emissions and the enhancement of HDI throughout the entire HDI quantile distribution (refer to Table 1 and Figure 3). To put it differently, there exists a uniform positive relationship between the escalation of CO_2 emissions and the advancement of HDI across the quantiles, suggesting a widespread influence of increased CO_2 emissions on the augmentation of HDI.

Table 1. Results from CO_2 to HDI and from CO_2 to TFR at Different Quantiles

Quantile	CO_2 ≠> HDI		CO_2 ≠> TFR	
	b_1	P-value	c_1	P-value
0.20	0.016	0.019*	-0.289	0.000*
0.40	0.023	0.002*	-0.315	0.000*
0.50	0.025	0.001*	-0.306	0.000*
0.60	0.027	0.000*	-0.304	0.000*
0.80	0.031	0.000*	-0.507	0.154

** Denotes significance at the 5%*

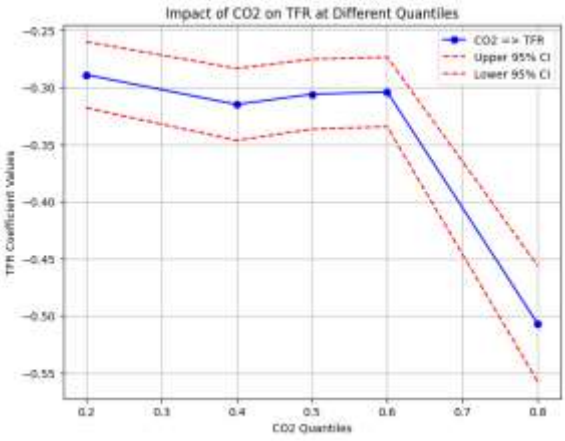

Fig. 2: Variation of the Quantile Regression Coefficients of TFR concerning CO_2

Note: The x-axis represents the carbon dioxide quantiles, while the y-axis denotes the regression coefficient values for the total fertility rate. The red dashed lines indicate the 95% confidence intervals for the quantiles.

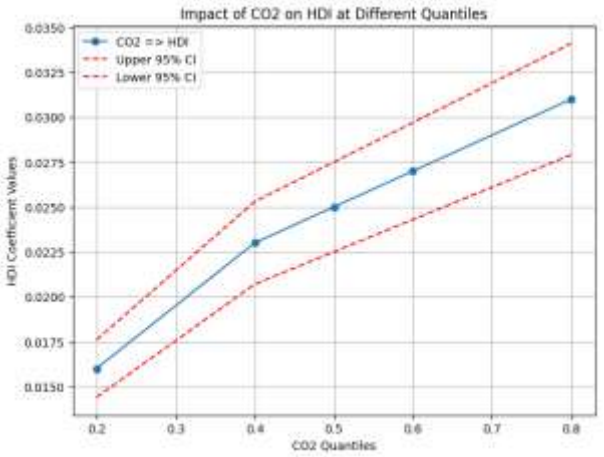

Fig. 3: Variation of the Quantile Regression Coefficients of HDI concerning CO_2

Note: The x-axis represents the carbon dioxide quantiles, while the y-axis denotes the values of the human development coefficients. The red dashed lines indicate the 95% confidence intervals for the quantiles

Table 2 and Figure 4 demonstrate that at any quantile distribution of TFR, the coefficient d_2 in equation (9) is significant, indicating a correlation between the mediator variable HDI and the dependent variable TFR. This finding establishes the second stage of the mediation effect. Furthermore, when accounting for the mediating influence of the Human Development Index (HDI), significant correlations are observed between carbon dioxide (CO_2) emissions and the dependent variable, Total Fertility Rate (TFR). This results in the coefficient d_1 being statistically significant, less than the coefficient b_1 in equation (4) within the 0.2 to 0.6 quantile range of TFR. This suggests that when the mediation effect transmitted through HDI is considered, the initially examined relationship between CO_2 and TFR vanishes. This outcome demonstrates partial mediation, as it does not satisfy all four steps outlined in equations (4) through (6).

Table 2. Results from CO_2 and HDI to TFR at different quantiles

Quantile	CO_2 ≠> TFR		HDI ≠> TFR	
	d_1	P-value	d_2	P-value
0.20	-0.309	0.000*	0.837	0.000*
0.40	-0.321	0.000*	0.829	0.000*
0.50	-0.328	0.000*	0.811	0.000*
0.60	-0.322	0.000*	0.812	0.000*
0.80	-0.297	0.000*	0.811	0.000*

** Denotes significance at the 5%*

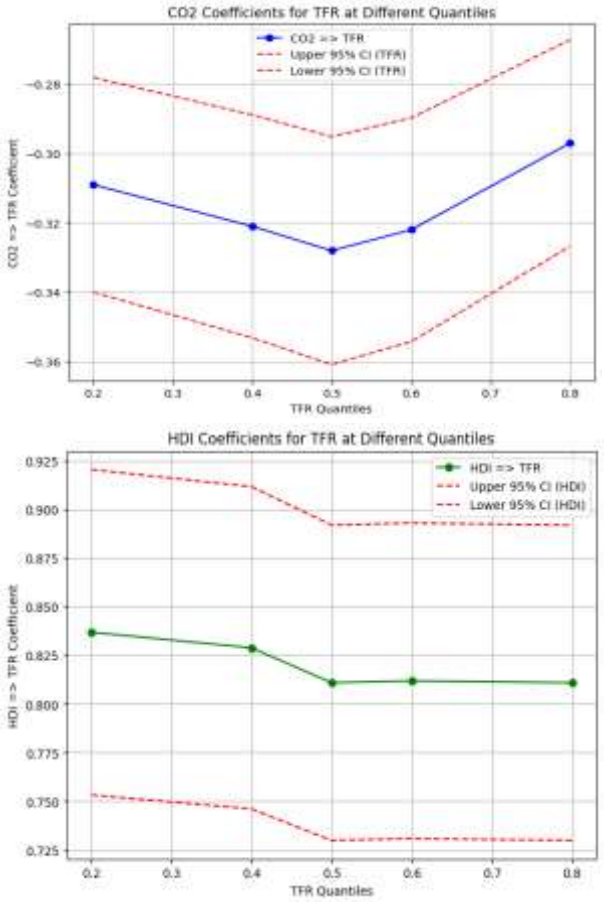

Fig. 4: Variation of the Quantile Regression Coefficients of TFR concerning CO_2 and HDI

Note: The x-axis represents the Total Fertility Rate quantiles, while the y-axis denotes the human development coefficients and carbon dioxide values. The red dashed lines indicate the 95% confidence intervals for the quantiles

In examining the Environmental Kuznets Curve (EKC) at designated quantiles of carbon dioxide emissions, we posited the following null hypotheses. Given the relationship between the Human Development Index (HDI) and carbon dioxide (CO_2) emissions, we test that $\alpha_1 > 0$ and $\alpha_2 \leq 0$. Given the relationship between the Total Fertility Rate (TFR) and CO_2, we test that $\beta_1 > 0$ and $\beta_2 \leq 0$. If the p-values for these coefficients are less than 0.05, it impliesthat there is a significant inverted U-shaped relationship at that quantile, supporting Krueger's EKC theory. The EKC theory suggests that environmental degradation increases in the early stages of economic growth but eventually decreases as income rises, due to better environmental awareness and technological progress. This pattern has been validated by empirical studies in various countries, including China and India.

Table 3 reveals that at the 0.8 quantile of the Total Fertility Rate (TFR), we find $\alpha_1 < 0$ and $\alpha_2 \geqq 0$ with p-value < 0.05, which indicates a U-shaped relationship between them. Consequently, this illustrates that the association between the Human Development Index (HDI) and carbon dioxide (CO_2) emissions at the 0.8 quantile of HDI is not supported by the Environmental Kuznets Curve (EKC) hypothesis.

Table 3. Results from CO_2 and Squared CO_2 to TFR at Different Quantiles of TFR

Quantile	$CO_2 \not\Rightarrow$ TFR		$CO_2^2 \not\Rightarrow$ TFR	
	α_1	P-value	α_2	P-value
0.20	-0.290	0.001*	-0.003	0.966
0.40	-0.347	0.000*	-0.050	0.500
0.50	-0.319	0.000*	-0.015	0.849
0.60	-0.297	0.000*	0.011	0.901
0.80	-0.825	0.000*	0.608	0.000*

*Note: *p<0.05*

Table 4. Results from CO_2 and Squared CO_2 to HDI at Different Quantiles of HDI

Quantile	$CO_2 \not\Rightarrow$ HDI		$CO_2^2 \not\Rightarrow$ HDI	
	β_1	P-Value	β_2	P-value
0.20	0.008	0.513	-0.006	0.613
0.40	0.018	0.075	-0.004	0.641
0.50	0.020	0.030*	-0.004	0.682
0.60	0.027	0.003*	-0.000	0.991
0.80	-0.607	0.002*	0.762	0.000*

*Note: *p<0.051*

In Table 4, the associations between the Human Development Index (HDI) and carbon dioxide (CO_2) emissions at the 0.80 quantiles of HDI are characterized erize $\beta_1 < 0$ and $\beta_2 \geqq 0$ with p-values below 0.05. This signifies notable U-shaped relationships at the 0.8 quantiles. Such findings diverge from the Environmental Kuznets Curve (EKC) theory, suggesting that at the 0.8 HDI quantiles, an increase in CO_2 initially leads to a decrease in HDI, followed by a rise.

5 Detailed Justification of Significant Results

When examining the Environmental Kuznets Curve (EKC) at specific quantiles of CO_2 emissions, we set up the following hypotheses: Given the relationship between the Human Development Index (HDI) and CO_2 emissions, we should find out that $\alpha_1 > 0$ and $\alpha_2 \leq 0$; Given the relationship between the Total Fertility Rate (TFR) and CO_2, we also should find out that $\beta_1 > 0$ and $\beta_2 \leq 0$. If the p-values for these coefficients are less than 0.05, it indicates that there

is a significant inverted U-shaped relationship at that quantile, which aligns with Krueger's EKC theory.

The EKC theory suggests that environmental degradation increases to a certain point as an economy grows. After reaching this point, as income rises, ecological quality improves. This inverted U-shaped relationship means that in the early stages of economic development, environmental quality gets worse. Still, it improves as economic growth leads to more environmental awareness and cleaner technologies.

Our study found some significant results in Table 3. At the 0.8 quantiles of TFR, we found out that there exists a U-shaped relationship, which means an increase in CO_2 emissions first leads to a drop in TFR but increase after reaching a certain level at higher TFR quantiles. This finding is similar to Krueger's EKC theory, which explains the negative impact of CO_2 emissions on fertility rates at first, then reaching a certain level reverses at higher development levels.

In addition, Table 4 shows a clear U-shaped relationship at the 0.80 quantiles of HDI, with $\beta_1 < 0$ and $\beta_1 \geq 0$ and p-values below 0.05. This finding is different from what the EKC theory says. It shows that when people live better (high HDI), more CO_2 emissions first makes their lives worse (HDI goes down). Then CO_2 emissions reach a certain level, people get better again (HDI goes up). This happens because of many things working together, like new rules to help the environment, better technology, and changes in the economy as the country grows.

Our findings show that we need to think about how CO_2 emissions, how well people live HDI, and how many babies are born TFR are connected in complicated ways. This means that when we make policies and measures to reduce CO_2 emissions, we need to consider how these connections change as a country grows. Our novel quantile mediation analysis gives significant proof of these complex connections, supporting the hypothesis of the EKC and providing useful advice for policymakers.

6 Conclusions

Many previous researches found that a causal relationship between carbon dioxide (CO_2) emissions and total fertility rate (TFR). These researches mostly used ordinary least squares methods and indicated a negative effect of CO_2 emissions on total fertility. However, our study uses an integrate and advanced method that combines mediation analysis with quantile regression. This method provides a dynamic and comprehensive explanation of the conditional distribution of the total fertility rate (TFR), instead of focusing on its conditional mean. In other words, this method can investigate a broad view how the impact of CO_2 emissions on TFR in Taiwan from 1992 to 2021.

Our study found that there exists the EKC hypothesis in Taiwan. This finding indicated that a significant U-shaped relation between CO_2 emissions and Total Fertility Rate (TFR) and between CO_2 emissions and Human Development Index (HDI) at the higher quantile distribution of the dependent variable. This suggests that we should use more sustainable energy sources to help the environment.

The hypothesis of Environmental Kuznets Curve (EKC) indicates that environmental degradation rises at the beginning of economic growth, but improves once over a certain income level. Our study demonstrates this hypothesis that there exists a U-shaped relationship between CO_2 emissions and the Total Fertility Rate (TFR), and between CO_2 emissions and the Human Development Index (HDI) at higher quantiles distribution of dependent variable. In our study, at 0.8 quantile distribution, it exists CO_2 emissions initially lead to a decrease in TFR, following an increase in TFR. Figure 4 shows a similar result that there exists a U-shaped relationship between CO_2 emissions and the Human Development Index (HDI). These results indicate that it exists the complex interactions among economic growth, environmental quality, and demographic variables. Moreover, it offers significant insights for policymakers to establish more effective strategies and measures.

Since this study provides valuable insights on the interact between environmental factors and population dynamics, the government should establish an effective and sustainable policy. For Example, the government should focus on the impact of carbon dioxide emissions on the total fertility rate at the different quantiles, especially given the effects of environmental factors on fertility during the demographic transition at higher quantile of total fertility rate. This measure can decrease CO_2 emissions and maintain human development standards.

In this study, we only examine the data of Taiwan, it may lead to the limit application of the findings. Therefore, we could include comparative studies in different countries or regions to understand these relationships better in the future research. Moreover, we include economic conditions, education, and health in our study, it could provide a comprehensive understanding of their effects on the relationship between CO_2 emissions and total fertility rates.

7 Future Research Directions

From the findings we found in this study, there are a few things we can further study in the future. One thing is to compare different countries or regions to understand whether it exists the same relationships. Applying new quantile mediation analysis techniques will significantly improve our understanding and validate research results in diverse socioeconomic and environmental contexts. 2. Although this study mainly focused on the Human Development Index (HDI) as a mediating variable, future research could consider other potential mediating variables. These variables could include measures of economic growth, education levels, or health status. Including these indicators would allow for a more thorough analysis of the various factors that influence these relationships. 3. It is vital to undertake long-term studies to track how CO_2 emissions influence changes in the Total Fertility Rate (TFR) and the Human Development Index (HDI) over time. 4. Incorporating qualitative research methods like interviews or case studies can enhance quantitative research results and provide a deeper understanding of the factors influencing the relationship between CO_2 emissions, total fertility rate, and the Human Development Index. This mixed-methods approach adds valuable depth and detail to exploring these complex interactions.

8 Contributions of This Study

This study provides multiple academic contributions:
1. Innovative analysis methods: through integration Interaction between CO_2 emissions, TFR and HDI In a single framework, our study provides more Get a complete understanding of these developments relation. In other research, they only examined the relationship between CO_2 emissions and TFR or between CO_2 emissions and HDI.
2. Methodological Innovation: Our quantile mediation analysis provides strong evidence supporting the EKC theory, highlighting the varying impacts of CO_2 emissions across different quantiles of TFR and HDI. This methodological innovation offers valuable insights for policymakers, suggesting that targeted interventions at specific quantiles can more effectively mitigate the negative impacts of CO_2 emissions.
3. New Insights: Our research confirms some established relationships and uncovers new insights into HDI's mediating role compared to other studies. By highlighting HDI's partial mediation effect, this study provides a more nuanced understanding of how CO_2 emissions influence demographic and development outcomes.

Overall, this study underscores the importance of considering the complex and non-linear relationships among environmental, demographic, and development variables. The findings offer practical implications for policymakers aiming to design effective and sustainable strategies to address the multifaceted challenges of climate change.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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