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RESEARCH ARTICLE

Exploring the link between technological innovation, economic development, and CO2 emissions in the US. Application of the ANN and EKC techniques

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Abstract
The developed world, which includes the United States of America (US), constantly works to reduce carbon dioxide emissions for the benefit of its people's health while advancing technical innovation to achieve impressive economic development. This motivates this study to use artificial neural network (ANN) and the Environmental Kuznets Curve (EKC) technique to explore the relationship between technological innovation, economic development, and CO2 emissions in the US in order to add to the body of knowledge already in existence. For this study, secondary data from 1990 to 2023 was gathered from the World Bank and globaleconomy.com. The results show that, whereas the artificial neural network shows that economic development contributes more to C02 emissions, the Environmental Kuznets Curve shows that higher levels of technical innovation and economic development lower C02 emissions. Hence, in order to maintain C02 emissions at the lowest possible level and improve the nation's atmospheric conditions, the US government should guarantee sustainable policies that will promote economic development and technological innovation.

Keywords: Technological innovation; Economic development; CO2 emissions; EKC; ANN

Introduction

Worldwide, society faces the urgent task of reducing the harmful impacts of human-caused carbon dioxide (CO2) emissions and their impact on climate change due to the growing emphasis on economic growth (Chen et al., 2016; Gardiner & Hajek, 2020; Lv et al., 2019). Environmental pollution is believed to increase during the initial phase of economic development and then decline as income levels rise, according to Grossman and Krueger (1995). According to Saha et al. (2020), 41 states in the US, including Washington, D.C., are reducing CO2 emissions while raising the US GDP. This provided additional support for the findings of Wang and Kim (2024), who found that several U.S. states had just attained absolute decoupling—a reduction in CO2 emissions while maintaining economic growth. The use of low-emission technologies, such as nuclear power, the conversion of coal to gas, and the restructuring of the economy to create a more sustainable one, are partially to blame for this.

The negative effect of economic growth on environmental quality has resurfaced because of the significant rise in CO2 emissions caused by global warming and climate change. The pressing need to tackle this dilemma has led to a heightened emphasis on the relationship between energy usage, technological advancement, and ecological sustainability. This intricate connection is a significant topic in scholarly and policy debates since it has the capacity to influence the direction of our environmental, economic, and social destiny. Technological developments are crucial to the global initiative to decrease CO2 emissions (Gu et al., 2019; Khan et al., 2020). These advances include a wide range of areas, such as energy generation, transportation, industry, and construction.

Technological innovation is crucial in creating new, efficient, and environmentally friendly solutions as societies want to shift towards cleaner and more sustainable energy systems (Bibri et al., 2023). Advancements in renewable energy technology, energy-efficient appliances, electric vehicles, and sustainable materials have greatly changed our energy situation and provided optimism for a more environmentally friendly and sustainable future. Technological innovation's growing popularity is crucial, but it does not function independently. The energy industry contributes significantly to worldwide CO2 emissions and is strongly connected to economic and political factors (Babatunde et al., 2017; Rehman et al., 2022). The energy intensity of economies, which quantifies the energy spent per unit of economic production, is a crucial indicator for understanding this connection. High energy intensity indicates inefficiencies in energy utilisation and implies a higher environmental impact per unit of economic output. As nations develop, their energy usage typically rises, leading to a possible increase in CO2 emissions (Waheed et al., 2019; Wang et al., 2016).

Technological advancements that enhance energy efficiency can break the link between economic growth and energy consumption by enabling economic expansion while keeping energy usage the same or decreasing it. Economic and political uncertainty has become a crucial issue that could help explain the mechanisms and trajectory of energy systems and environmental results. Economic downturns, political conflicts, and policy changes can greatly impact technical innovation, energy intensity, and CO2 emissions, according to Geels (2013) and Adebayo et al. (2023). These uncertainties can either facilitate or impede countries' shift towards cleaner energy sources and energy-efficient practices by interacting with other factors. Uncertainty in the economic and political spheres can affect the connection between energy intensity and CO2 emissions. It can also either enhance or reduce the impact of energy intensity on CO2 emissions. Businesses may be motivated to implement sustainable practices in response to economic and political concerns (Su et al., 2022). For example, they can use resources to enhance energy efficiency in order to lower expenses and guarantee stability amid unpredictable political and economic conditions. This scenario may result in decreased energy intensity and fewer CO2 emissions. Moreover, political instability may lead to a greater emphasis on addressing climate change and investing in renewable energy (Ren et al., 2023). Policymakers should view the development of green technology as a means to enhance economic stability and promote job growth. The anticipated economic and political uncertainties are projected to have a positive effect on the partnership by encouraging technical innovation. In periods of economic and political instability, governments and businesses may be inclined to seek out and implement new strategies to tackle increasing environmental issues (Su et al., 2022). Economic uncertainty, including financial market instability or economic downturns, can affect enterprises' motivation and ability to invest in and participate in research and development for technology that reduces CO2 emissions. Amid economic volatility, corporations can reduce research and development (R&D) funding, leading to a deceleration in the advancement and implementation of sustainable technology and a possible rise in CO2 emissions. Businesses might be reluctant to allocate limited resources to research and development if they are uncertain about the stability of the regulatory environment (Dunyo & Odei, 2023). Economic uncertainty can influence the relationship between technical innovation and CO2 emissions reduction by affecting R&D investment, resource allocation, risk aversion, and policy support for countries' emission reduction initiatives. Minimising these uncertainties by maintaining stable economic conditions and implementing clear, consistent

emissions rules is essential to promoting technological innovation activities focused on efficiently tackling CO2 emissions. This study objective contributes to the growing literature by exploring the link between technological innovation, economic development, and CO2 emissions in the US using the application of ANN (a machine learning technique) and the EKC technique, which will significantly improve previous related studies.

Literature review and hypothesis development

A portion of the literature on the connection between global economic growth, technological innovation, and CO2 emissions was examined in this research study. The relationship between CO2 emissions and economic growth has been the subject of a global research explosion and broad scholarly awareness (e.g., Gardiner & Hajek, 2020; Adebayo et al., 2023; Waheed et al., 2019). However, a number of shortcomings exist in this emerging field of research that limit our ability to completely understand the influences on the variables controlling global CO2 emissions. Research exploring the causal relationship between energy intensity, technological innovation, and CO2 emissions between high- and low-income nations concurrently is scarce, despite the relevance of this connection being theorised and seen. Because it attempts to close a gap in the literature, this paradigm adds interest to the current investigation. Moreover, although an expanding corpus of studies has improved our comprehension of the relevance and impacts that carbon dioxide emissions may have on economic growth (Rehman et al., 2022; Ren et al., 2023), we still know very little about the potential mechanisms through which carbon dioxide emissions may influence the performance of economic growth. This is significant because it supports the idea that reducing CO2 emissions promotes green growth and is necessary for sustainable development (Bai et al., 2022; Hickel & Kallis, 2020). According to Saha and Jaeger's (2020) report, more than 80% of U.S. states have disconnected their emissions from economic growth. The states mentioned vary in size and are distributed across different regions of the country, such as Maine and New York in the Northeast, Alabama and Georgia in the South, Indiana and Ohio in the Midwest, and Alaska and Nevada in the West. Maryland had the highest reduction in emissions at 38%, followed by New Hampshire at 37%, the District of Columbia at 33%, Maine at 33%, Alaska at 29%, and Georgia at 28% among the 41 states. Despite federal reversals of climate regulations, this discovery suggests that the United States can still make substantial advancements in addressing climate change at the state level.

In order to investigate the relationship between technological innovation, carbon dioxide emissions, and economic growth from 1985 to 2019 in 35 Belt and Road countries, Khan et al. (2023) used three-stage least square models, ordinary least squares, two-step system generalised method of moments, two-step difference generalised method of moments, seemingly unrelated regression, and three-stage least square models. Their findings show that technological innovation improves environmental quality while reducing carbon dioxide emissions.

Furthermore, Javed et al. (2023) examined oil prices, economic growth, and foreign direct investment in Italy between 1971 and 2019. The study's findings indicate that GDP positively affects carbon emissions, while the GDP square term negatively affects emissions, supporting the environmental Kuznets curve hypothesis using non-Linear ARDL. Wang et al. (2024) claim that the effect of economic growth on environmental degradation first increases with rising income levels before showing a declining tendency. Furthermore, trade protection appears to be detrimental to enhancing the quality of the environment globally, supporting the validity of the EKC hypothesis within the parameters of the study.

The Environmental Kuznets Curve (EKC) was used by Adebanjo et al. (2022) to investigate the relationship between air pollution and the Jordanian economy. Their research indicates that the country's CO2 emissions are negatively impacted by Jordan's economic growth, which is consistent with the EKC hypothesis, which suggested an inverse relationship between CO2 emissions and economic growth (inverse U-shaped hypothesis). According to Ozokcu (2017), the Environmental Kuznets Curve (EKC) is a theory that suggests a relationship between environmental deterioration and economic growth, with a pattern that resembles an inverted U. In the interim, it's

critical to emphasise that economic expansion has the potential to increase carbon dioxide emissions. However, it is imperative to acknowledge that this correlation may undergo a reversal at a given level. Therefore, it is plausible to argue that, as demonstrated by Halicioglu (2009), a rise in economic growth will probably lead to a steady drop in carbon dioxide (CO2) emissions. As a result, one could contend that achieving economic growth is a feasible way to achieve a state that is more environmentally sustainable. By examining the relationship between technological innovation, economic development, and CO2 emissions in the US using the application of ANN (a machine learning technique) and EKC technique—which will greatly enhance previous related studies—the main goal of this study is to close a gap that has been identified in the body of current scholarly work.
The following is a development of the study's hypothesis, which is based on the EKC theory.
H1: Economic development significantly declines CO2 emissions
H2: Technological innovation significantly reduces CO2 emissions.

Data and methodology

Data description

Secondary data was collected from the World Bank Development Indicator and TheGlobalEconomy.com, respectively, with a period of 1990 to 2024 because it is more recent to align with the current happenings and based on the data availability using the purposive sampling technique. The US technological innovation proxied by the innovation index is collected via the USA Innovation Index (data, chart | TheGlobalEconomy.com) (measured in points), while the carbon dioxide (CO2) emissions and economic development proxied by the GDP and per capita income are collected via World Bank development indicators. The CO2 emissions are measured in million kilotons, the GDP is measured in billions of dollars, and the per capita income, which is calculated by the US gross national income divided by their population, is measured in dollars.

Methodology

This study adopted a quantitative causal design that examines the links between the variables of interest in this study, and the method of analysis includes summary statistics to summarise the dataset using the mean and standard deviation, the Environmental Kuznets Curve (EKC), which is an econometrics technique, and machine learning techniques such as artificial neural networks (ANN). The correlation matrix was also applied to examine the direction and strength of the link between the variables. The SPSS and STATA software were used for the analysis of this study.

EKC model structure

The EKC hypothesis according to the work of Adebanjo et al. (2022) and Ozokcu (2017) which can be model mathematically as

$$InCO2_t = \beta o + \beta_1 InGDP_t + \beta_2 (InGDP_t)^2 + Ɛ_t \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$InCO2_t = \beta o + \beta_1 PCI_t + \beta_2 (InPCI_{it})^2 + Ɛ_t \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$InCO2_t = \beta o + \beta_1 Tech_t + \beta_2 (InTech_t)^2 + Ɛ_t \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This study uses the EKC to comprehend how environmental degradation and GDP, or other indicators of economic development, relate to one another (Adebanjo et al., 2022). The inverse U-shaped hypothesis would be typical, as seen in figure 1 below. The study's focus and the outcome variable of the EKC model are environmental degradation, such as carbon dioxide (CO2) emissions in the US, with GDP, per capita income (PCI), and technological innovation (Tech) serving as the independent variables. The constant term in the model is denoted by β_0, while the independent variable's coefficient estimates are represented by β_1 to β_2, and the period in years is indicated by t.

According to Ozokcu (2017), the EKC hypothesis shows an inverse relationship between economic growth and CO2 emissions. A growth in personal income in the early phases of economic development also results in an increase in personal affluence. Up to a certain point (the turning point), the level of specialisation increases. The rate at which the environment deteriorates per capita decreases with sustained economic expansion. This is depicted in the standard EKC figure below. The EKC curve, which represents the hypothesised link between wealth per capita and degradation per capita, predicts whether or not the latter will remain high while maintaining the current level of degradation. The EKC theory is as follows: The first impact of economic activity on the base of resources usually results in a minor quantity of pollution that is biodegradable. Industrialization is accompanied by an acceleration of resource depletion and waste generation, especially in agriculture and other extractive and industrial operations. While low levels of development allow for gradual pollutant discharge, acceleration, and levelling off, higher levels of development result in a decrease in environmental pollution through structural change in information-intensive industries and services, along with rising environmental regulations and costs (Panayotou, 1993). The Kuznets-Phillips curve (EKC) is the value, as shown in figure 1, at which the indicator of environmental deterioration E reaches its maximum. This value is expressed as $Y^* = \exp(-\beta_1/2\beta_2)$, according to Panayotou (1993). As a diagnostic strategy for the machine learning and EKC models used in this study, the dataset's normality and the model's stability were examined in the interim.

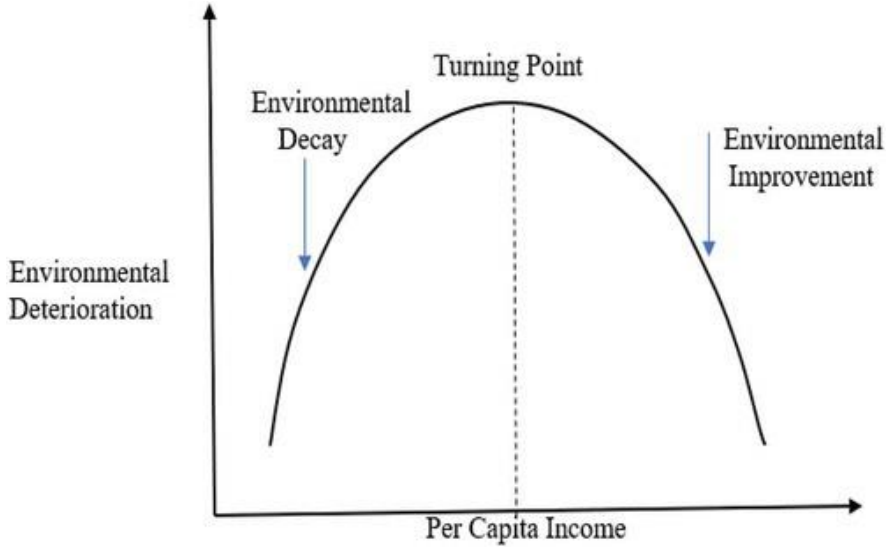

Figure 1: EKC structure

Artificial neural network (ANN)

It's a useful method that models the two hidden layers, the input variables, and the output variable (CO2 emission). Here, it makes perfect sense to use an artificial neural network to determine or predict carbon dioxide emissions. It is not only a superior tool for predictive analytics but also a substitute for regression analysis.

The neural network equation is formed by combining the independent variables, their corresponding weights, and the intercept term for each neuron in a linear fashion. The neural network equation looks like this:

$$\ln K = \delta_o + \ln\delta_1 X_1 + \ln\delta_2 X_2 + \ln\delta_3 X_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where K is the output variable of ANN model.

δ_1 to δ_3 are the weights or the beta coefficients

X_1 to X_3 are the independent variables or the inputs such the GDP, PCI and TECH, and the Hidden layers pattern are H (1,1) to H (1,3).

Intercept = δ_0

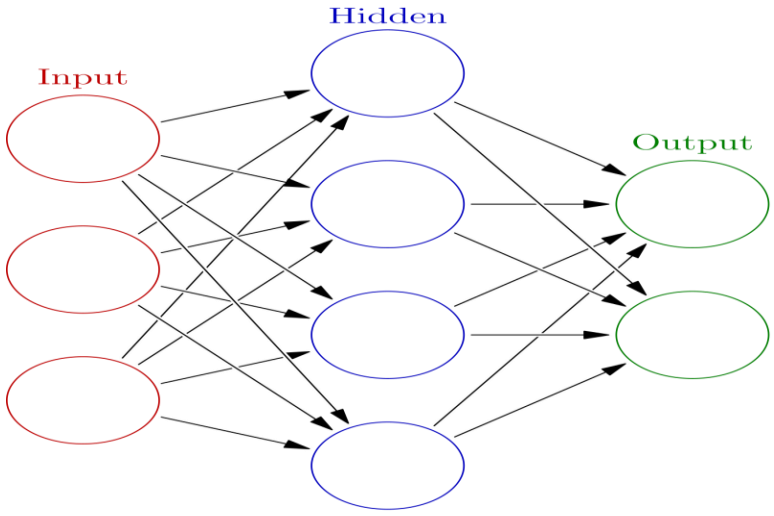

Figure 2: Typical structure of artificial neural network

Results and Discussion

Table 1 summarises the dataset with mean and standard deviation, which shows that the average log of the per capita income of US individuals has a mean value of about 10.7 USD, exceeding other variables like the average log of CO2, the average log of GDP, and the average log of technological innovation, followed by the log of GDP with a mean value of about 9.5 billion USD, and the variable with the least variability is the log of technological innovation with a standard deviation value of about 0.06 points.

Table 1: Summary statistics

Variables	N	Mean	Standard Deviation
lnCO2	34	1.651	0.072
lnGDP	34	9.464	0.431
lnTech	34	4.036	0.063
lnPCI	34	10.686	0.345

Source: Author's computation

Table 2: EKC equations

Overall Model P-value = 0.0000, R-squared = 0.4907, Root MSE = 0.05291				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnGDP	5.074	0.983	5.16	0.000
$lnGDP^2$	-0.271	0.052	-5.20	0.000
Constant	-22.032	4.623	-4.77	0.000
Overall Model P-value = 0.0272, R-squared = 0.2074, Root MSE = 0.066				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnTech	50.733	25.570	1.98	0.056
$lnTech^2$	-6.338	3.172	-2.00	0.055
Constant	-99.834	51.524	-1.94	0.062
Overall Model P-value = 0.0001, R-squared = 0.4490, Root MSE = .05503				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnPCI	8.687	1.830	4.75	0.000
PCI^2	-0.410	0.085	-4.77	0.000
Constant	-44.349	9.745	-4.55	0.000

Source: Author's computation

Table 2 shows that coefficient estimates of the squared of the log of the GDP and PCI have a significant negative effect at 5% level on the carbon dioxide (CO2) emissions, which implies that the economic development proxied by the GDP and the per capita income contribute negatively significantly to the CO2 emissions in the US, indicating that a high level of US GDP and per capita income helps to reduce the CO2 emissions in the United States of America, supporting the EKC theory and the first research hypothesis (H1) that economic development significantly declines CO2 emissions. The coefficient estimates of the squared of the technological innovation are statistically significant at the 10% level and have a significant negative influence on the CO2 emissions, implying that high technological innovation in the US will minimise the CO2 emissions within the United States, supporting the second research hypothesis (H2) that the technological innovation significantly reduces CO2 emissions. Besides, among the three EKC equations, the first one outperformed the other with the highest R-squared of about 49.1% and the least root mean square error of about 0.05.

Figure 3 shows the CUSUM plot for the best-fit EKC model, and we can see that the model parameters in the red line fall within the two 95% confidence intervals, indicating that the model is stable. Besides, Figure 4 demonstrated the graph of CO2 emissions against the GDP, technological innovation (Tech), and per capita income (PCI), which agrees with the inverse U-shaped postulated by the EKC theory.

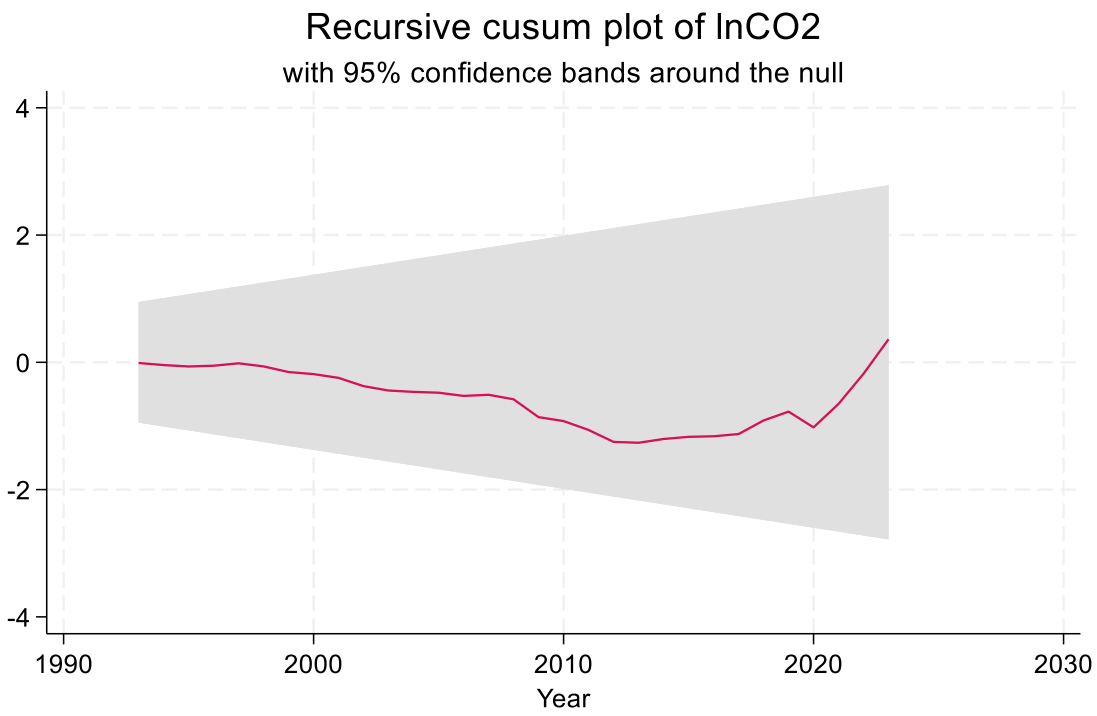

Figure 3: CUSUM test for EKC model stability

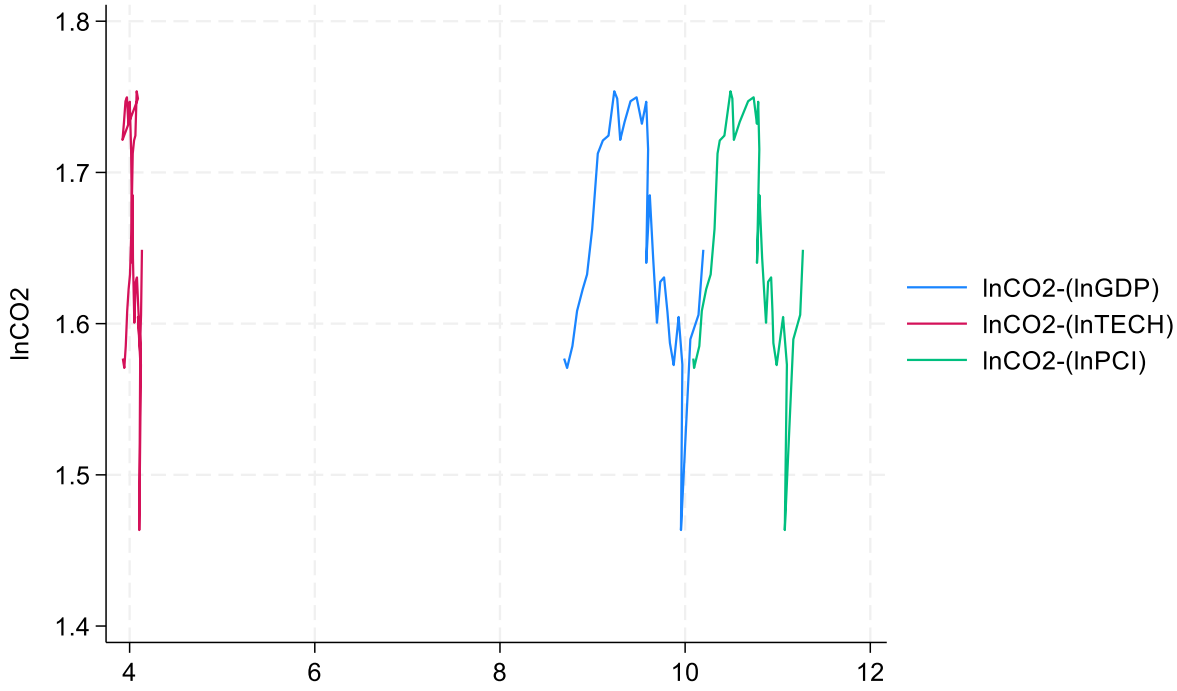

Figure 4: Graph of CO2 emission against the GDP, Technological innovation (TECH) and Per capita income (PCI)

Figure 5 demonstrates the output of the artificial neural network model structure with the hidden layers H (1,1), H (1,2), and H (1,3) representing the input and output with a minimal error bias of 0.001 (see Table 3). The input variables are the log of the GDP, the log of technological innovation, and the log of per capita income, while the output variable is the log of CO2 emissions. Figure 6 shows the contribution of the independent or input variables, and we can see that the log of GDP has the highest contribution growth pattern, followed by the log of per capita income and the log of technological innovation.

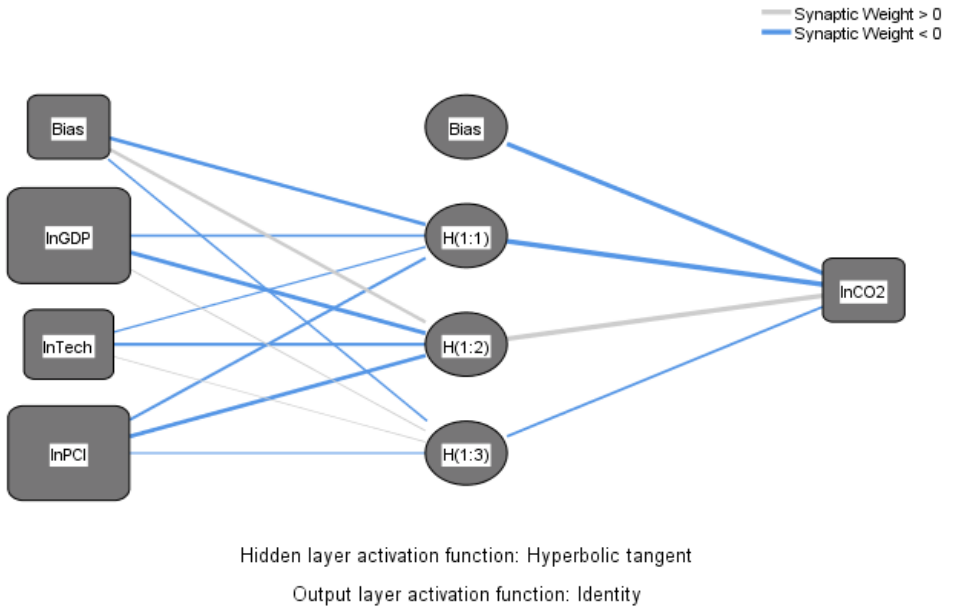

Figure 5: ANN Model Structure

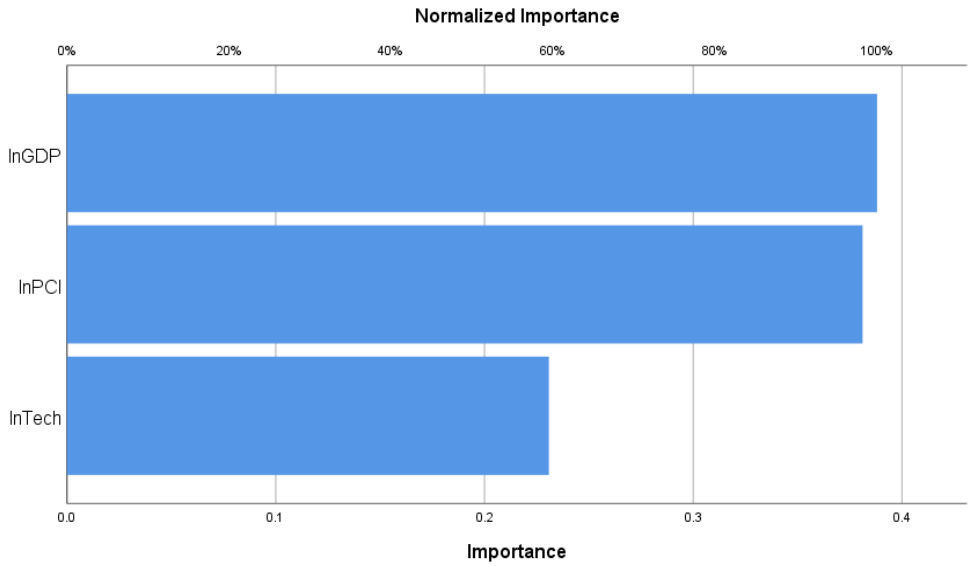

Figure 6: Independent variables contribution chart

Table 3: Independent Variables importance and the ANN model summary

	Importance	Normalized Importance
lnGDP	0.388	100.0%
lnTech	0.231	59.5%
lnPCI	0.381	98.2%
Model	Percent	Error
Testing	76.5	0.001
Training	23.5	

Source: Author's computation

Table 3 shows the importance of the independent variables in the ANN model, and it reveals that the log of GDP has the highest contribution of 100%, followed by the log of per capita income with a contribution of 98.2%, and the log of technological innovation with a contribution of 59.5%. The ANN model's testing accuracy is 76.5% with a very minimal error bias of 0.001.

Table 4: Correlation matrix

	lnCO2	lnGDP	lnTech	I lnPCI
lnCO2	1.000			
lnGDP	-0.2150	1.000		
lnTech	-0.3245	0.7447	1.000	
lnPCI	-0.2109	0.9986	0.7251	1.000

Source: Author's computation

Table 4 shows that the log of CO2 has a weak and negative correlation with the log of GDP, the log of technological innovation, and the log of per capita income, indicating that the higher the technological innovation and the economic development of the US proxied by the GDP and per capita income, the lower the CO2 emissions. Besides, the log of technological innovation has a strong and positive link with economic development, indicating that the higher the US technological innovation, the higher the country's economic development. This suggests that improved technological innovation aids the economic development of a nation.

Table 5: Skewness and kurtosis tests for normality

Variables	N	Pr(skewness)	Pr(kurtosis)	Prob>chi2
lnCO2	34	0.5730	0.6970	0.7854
lnGDP	34	0.5884	0.0630	0.1370
lnTech	34	0.6197	0.0193	0.0649
lnPCI	34	0.6238	0.0484	0.1177

Source: Author's computation

Table 5 shows the normality of the dataset using the skewness and kurtosis tests, which show that $P > 0.05$, indicating that we do not reject the null hypothesis and suggesting that the data is normally distributed.

Discussion of findings

The analysis of this study shows that the squared log of GDP and PCI coefficients have a significant negative impact at a 5% level on carbon dioxide (CO2) emissions. This suggests that higher levels of GDP and per capita income in the US contribute significantly to reducing CO2 emissions, supporting the Environmental Kuznets Curve theory and the first research hypothesis (H1) that economic development leads to a decline in CO2 emissions. The regression analysis shows that the coefficient estimates for the squared technological innovation are statistically significant at the 10% level. They have a significant negative impact on CO2 emissions, indicating that high technological innovation in the US will reduce CO2 emissions within the country. This supports the second research hypothesis (H2) that technological innovation significantly decreases CO2 emissions. Among the three EKC equations, the first one demonstrated superior performance, with the highest R-squared value of approximately 49.1% and the lowest root mean square error of around 0.05. This corroborates Khan et al.'s (2023) research, which demonstrates that technological innovation enhances environmental quality and decreases carbon dioxide emissions. According to the Environmental Kuznets Curve (EKC) hypothesis, economic growth has a negative effect on a country's CO2 emissions. This is in line with the findings of Adebanjo et al. (2022), which show that economic growth and CO2 emissions are related in an inverse U-shaped way. This also supports the findings of Saha and Jaeger (2020) that over 80% of U.S. states have decoupled their emissions from economic development.
The results indicate that the ANN model improved the precision of the model outcomes. The log of GDP had the highest contribution of 100%, followed by the log of per capita income with a contribution of 98.2%, and the log of technological innovation with a contribution of 59.5%. The testing accuracy of the ANN model is 76.5% with a negligible error bias of 0.001.
The correlation matrix revealed that the logarithm of CO2 emissions has a weak negative correlation with the logarithm of GDP, technological innovation, and per capita income. This suggests that higher levels of technological innovation and economic development, as represented by GDP and per capita income, are associated with lower CO2 emissions in the US. Furthermore, there is a clear and positive correlation between the rate of technological innovation and economic growth, suggesting that as technological innovation increases in the US, so does the country's economic development. Improved technological innovation in the United States and other countries contributes to economic development.

Conclusion

Nations worldwide, especially industrialised ones like the US, work to reduce carbon dioxide emissions to promote a healthy environment for their population and enhance technical innovation for significant economic growth. This study aims to enhance current knowledge by investigating the relationship among technological innovation, economic growth, and CO2 emissions in the US. This will be achieved through the utilisation of ANN (a machine learning method) and the EKC technique, leading to advancements in previous research in this area. The results suggest that economic development, as measured by GDP and per capita income, has a greater contribution to CO2 emissions, according to the Artificial Neural Network (ANN) model. Additionally, the Environmental Kuznets Curve (EKC) indicates that increased economic development and technological innovation lead to a decrease in CO2 emissions. The correlation matrix showed that there is a positive relationship between the level of technical innovation in the US and the country's economic development. The US government should implement sustainable policies to increase economic development and technical advancements, thereby reducing CO2 emissions and improving the country's atmospheric conditions, which will enhance environmental quality.

Declaration

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Authors contribution: The authors work hand in hand with each other from the beginning of the research until the end

Data availability: Data is available with the corresponding author and can be accessed upon diligent request.

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