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Investigating the Implications of Technological Innovations and Clean Energy in Carbon Neutrality in Tunisia

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ABSTRACT

Environmental degradation poses a significant global challenge, compelling many nations to recognize the importance of financial development in driving the advancement of renewable energy. Urbanization also presents a critical opportunity for adopting sustainable energy sources. Against this backdrop, our study examines the impact of Tunisia's financial development, clean energy initiatives, technological innovation, and urbanization on carbon neutrality from 1990 to 2020, using the ARDL model. We assessed both short-term and long-term dynamics through the Bounds test and employed the Granger causality test to explore the relationships among the variables. The ARDL bounds test confirmed a long-term connection between these factors. Our findings suggest that while clean energy and technological innovations significantly reduce carbon emissions in the short term, technological innovations alone lead to increased CO_2 emissions in the long term. We conclude that to enhance environmental quality, Tunisia should further develop its financial sector, invest in green technologies, and accelerate the transition to renewable energy.

Keywords: Technological Innovation, Financial Development, Clean Energy, Carbon Neutrality, ARDL
JEL Classifications: O31, O44, Q56, C32

1. INTRODUCTION

Environmental issues like climate change have underscored the urgent need for stricter environmental regulations and the expansion of renewable energy sources to safeguard the environment and maintain a sustainable ecosystem. As a result, financial development and carbon neutrality have become two of the most critical challenges facing the global community today. Research has shown mixed results regarding the relationship between financial development and carbon emissions. Some studies, like those by Kong and Gallagher (2021), suggest that financial development can help reduce carbon emissions by promoting environmental conservation. Conversely, Qiao et al. (2022) found that financial development could contribute to environmental degradation, while Deng and Zhao (2022) reported no significant link between financial development and carbon emissions.

Tunisia has set ambitious goals to increase the use of renewable energy sources, with a key objective being the reduction of carbon emissions by decreasing fossil fuel consumption through technological innovation and urbanization. Currently, approximately 97% of Tunisia's electricity is generated from fossil fuels, primarily natural gas. In 2021, nearly 45% of Tunisia's natural gas needs were met through imports, mainly from Algeria, which has serious implications for the country's energy security and has led to rising electricity prices for consumers. Given the increasing energy consumption across its economy and declining domestic hydrocarbon production, Tunisia has placed a greater emphasis on energy efficiency and renewable energy as part of its broader energy transition strategy, which aligns with its sustainable economic and social development goals.

In response to these challenges, the Tunisian government raised its 2030 renewable energy target from 30% to 35% of total power generation (Tunisian Ministry of Energy, 2023). The primary goals are to reduce primary energy demand and increase the contribution of renewables to electricity production. However, Tunisia faces several obstacles in achieving these goals, including:

- The need for infrastructure to support renewable energy sources like solar and wind power.
- Simplified procurement procedures for power grid development.
- Clear institutional roles in the energy transition and enhanced human resource capabilities.
- The establishment of a dedicated financing mechanism.
- Greater involvement of local banks in financing renewable energy projects.

Tunisia is particularly vulnerable to the impacts of climate change, making it crucial to understand the factors contributing to the country's carbon emissions to mitigate them and ensure sustainable economic development.

Our research aims to explore the impact of financial development, technological innovation, clean energy, and urbanization on carbon neutrality in Tunisia. The paper is structured as follows: after the introduction, we review the relevant literature, followed by the presentation of our research methods, data, and model. Finally, we discuss the results. While numerous studies have explored the energy-growth-environment nexus, few have focused on the interplay between technological innovation, clean energy, financial development, urbanization, and carbon neutrality in Tunisia.

2. LITERATURE REVIEW

2.1. Studies on the Impact of Technological Innovation on Carbon Emissions

A growing body of research has explored the impact of technological innovation on carbon emissions. Several studies, including those by Dong et al. (2020a), Wang et al. (2019), Tajudeen et al. (2018), and Iftikhar et al. (2016), have used energy efficiency as a metric for technological innovation to assess its influence on carbon emissions. Their findings suggest that improvements in energy efficiency can significantly reduce carbon emissions. Other researchers, such as Petrovic and Labonov (2020), Churchill et al. (2019), and Fernandez et al. (2018), have focused on research and development (R&D) as a measure of technological innovation, examining the dynamic relationship between R&D and carbon emissions. Similarly, Erdogan et al. (2020), Cheng et al. (2019), and Hashmi and Alam (2019), have used patent development as a proxy for technological innovation. Li et al. (2021) found that at lower levels of innovation, new patents often contribute to increased carbon emissions ("brown" patents). However, once a certain threshold of patenting activity is reached, the nature of patents shifts towards being more environmentally friendly ("green" patents), particularly in China. Saqib et al. (2023) investigated the impact of technological innovations, financial inclusion, and renewable energy on reducing ecological footprints in emerging economies from 1990 to 2019. They emphasized the importance of integrating innovative technology and renewable energy with financial inclusion to achieve long-term environmental sustainability and growth. Liu et al. (2023) employed the ARDL Bounds test, Granger causality, and variance decomposition to analyze factors influencing carbon emissions in the U.S. They found that technological innovation leads to reduced emissions in the long term, suggesting that the U.S. can combat climate change through renewable energy and green finance. Ahmad et al. (2023) examined the impact of ICT, human capital, and globalization on environmental degradation in OECD countries, confirming that these factors contribute to environmental sustainability by reducing degradation.

Sun et al. (2023) studied the relationship between financial development, carbon footprints, technological innovation, renewable energy, and foreign direct investment in South Asian countries. They concluded that to improve environmental quality, these economies should further develop their financial sectors, discover green technologies, transition to renewable energy, and regulate foreign direct investment. Faheem et al. (2023) analyzed the effects of financial development, technological innovation, and GDP growth on the environment in Pakistan from 1990 to 2021 using the ARDL methodology. They highlighted the negative environmental impact of economic expansion but also noted the potential of technological innovation to drive sustainable practices and reduce environmental degradation. They advocated for prioritizing cleaner and more efficient technologies. Fan and Hossain (2018) explored the relationship between technological innovation, economic growth, trade openness, and carbon emissions in China and India from 1974 to 2016 using the ARDL Bounds test and Toda-Yamamoto Granger causality test. They found bidirectional causality between technological innovation and carbon emissions in China, while in India, the causality was unidirectional from technological innovation and economic growth to carbon emissions. Ahmad et al. (2024) investigated the roles of the economy, technology, and renewable energy in achieving carbon neutrality in China. They observed that renewable energy usage is strongly associated with lower CO_2 emissions and that technological innovation significantly reduces emissions in the long term, driving the development of renewable energy technologies. Sadiq et al. (2024) examined the impact of green finance, eco-innovation, renewable energy, and carbon taxes on CO_2 emissions in BRICS countries from 2001 to 2020 using the Cross-sectional ARDL method. Their results indicated that increasing green finance initiatives and renewable energy consumption significantly reduces CO_2 emissions, particularly when governments impose taxes on carbon-emitting activities. Chien (2024) studied the influence of technological innovation, carbon finance, green energy, environmental awareness, and urbanization on carbon neutrality in E7 countries from 2006 to 2020. The research revealed a positive relationship between these factors and carbon neutrality. Bergougui (2024) explored the relationship between green technologies, financial development, and ecological footprints in Algeria from Q1-1990 to Q4-2021 using the Fourier ARDL approach. Her findings demonstrated that while financial development increases ecological footprints, green technologies help reduce them in the long run, highlighting the critical role of environmental technologies in mitigating the negative impacts of financial development.

In addition to technological innovation, several other factors can influence carbon emissions.

2.2. Studies on Other Factors Affecting Carbon Emissions

The core principle of sustainability, as defined by Stern and Valero (2021), is to ensure that the current generation provides opportunities for the next generation that are at least as favorable as those they themselves have had, assuming that future generations will act similarly. Lin et al. (2023) assessed the impact of green financing on carbon emission reduction and green economic recovery in emerging economies by applying small Input-Output estimation parameters through Data Envelopment Analysis. Their findings revealed that green financing strategies, such as government subsidies and tax incentives, were effective in reducing carbon emissions in developing nations from 2016 to 2020. Velayutham (2023) explored the relationship between clean energy, economic growth, urbanization, trade openness, and CO_2 emissions in Sri Lanka using the ARDL model over the period from 1971 to 2014. He confirmed that both clean energy and urbanization contribute to long-term reductions in carbon emissions in Sri Lanka. Raihan and Tuspekova (2022) examined the dynamics between economic growth, energy consumption, urbanization, tourism, and CO_2 emissions in Singapore from 1990 to 2019 using the dynamic ordinary least squares (DOLS) approach. They found that a 1% increase in urbanization leads to a 1.9% rise in CO_2 emissions. Alraja et al. (2022) analyzed 669 questionnaires using structural equation modeling to explore the relationship between technological innovation, sustainable green practices, and SME performance during the COVID-19 pandemic. Their findings suggest that investing in research and development to produce high-quality products or adopting new technologies in production processes can lead to the use of more environmentally friendly materials and cleaner, renewable technologies, resulting in greater savings. Esquivias et al. (2023) investigated the link between carbon emissions, financial development, energy consumption, urbanization, and trade openness in India from 1960 to 2020 using the ARDL model. Their results indicated that each of these factors contributes to environmental degradation, with financial development showing a long-term positive impact on per capita carbon emissions. The study suggests that financial institutions could incentivize investments in energy-efficient technologies by offering interest rate reductions and incorporating carbon-related conditions into the terms of financial products like term loans for investment real estate.

Parveen et al. (2023) examined the effects of industrial output and financial development on carbon emissions in a panel of 10 newly industrialized countries (Brazil, China, India, Indonesia, Malaysia, Mexico, Philippines, South Africa, Thailand, and Turkey) from 1982 to 2019. They found that economic growth, urbanization, non-renewable energy, and industrial output have long-term positive effects on carbon emissions, while financial development and renewable energy have negative effects. Zhang et al. (2023) evaluated the impact of financial development, globalization, and pollution in six MENA countries from 1971 to 2015. They found that financial sector development significantly affects ecological quality, emphasizing the need for governments in the MENA region to promote renewable energy sources such as wind, solar, biofuel, and heat production to reduce carbon emissions and promote sustainable economic development. Obobisa (2023) analyzed the relationships between eco-innovation, clean energy, trade openness, human capital, economic growth, carbon neutrality, and sustainable development in OECD countries using regression models. The findings show that eco-innovation, clean energy utilization, and human capital negatively impact carbon emissions, with bidirectional causality observed between eco-innovation, clean energy utilization, human capital, and carbon emissions. Raihan and Bari (2024) investigated the impact of economic growth, fossil fuel consumption, and renewable energy utilization on carbon emissions in China from 1965 to 2022 using the ARDL model. The results indicated long-term cointegration among the variables, with a 1% increase in renewable energy utilization leading to a 1.39% reduction in carbon emissions in the long term and a 0.50% reduction in the short term. Charfeddine et al. (2024) analyzed the effects of information and communication technology, digitalization, renewable energy, and financial development on environmental sustainability across the ten most polluted countries from 1995 to 2018 using the Panel Vector Auto-Regression model. Their findings suggest that renewable energy contributes to environmental improvement. Although financial development initially worsens environmental quality, it leads to improvements from the 2nd year onwards. They also found bidirectional causality between ecological footprint and renewable energy consumption, indicating that clean and green energy are crucial determinants of environmental quality and should be prioritized in policy-making.

Akinpelumi et al. (2024) examined the influence of financial development and urbanization on the ecological footprint in Nigeria from 1986 to 2022 using the Nonlinear Autoregressive Distributed Lag (NARDL) model. Their results confirmed an asymmetric effect of urbanization and financial development on the ecological footprint in the short run, with only financial development impacting the ecological footprint in the long run. Nathaniel et al. (2024) explored the effects of clean energy, financial development, and globalization on the ecological footprint in a developing country using the novel dynamic ARDL simulation techniques and the bootstrap causality test. The findings revealed that green energy had no significant impact on the ecological footprint, while globalization and financial development significantly reduced it by 0.25% and 0.08%, respectively. They also found unidirectional causality from financial development to the ecological footprint and from financial development to green energy. Jiang et al. (2024) examined the impact of natural resources and renewable energy (biofuel and other renewable sources) on greenhouse gas (CO_2 and PM2.5) emissions in G7 countries from 1999 to 2021. They also investigated the effects of carbon taxes, financial development, and environmental policies on carbon neutrality using the Cross-sectional ARDL, Common Correlated Effect Means Group (CCEMG), and Augmented Mean Group (AMG) models. Their results demonstrated that biofuel, other renewable energy sources, carbon taxes, environmental policies, and eco-innovation decrease greenhouse gas emissions, while financial development and natural resource dependence have a positive impact on carbon neutrality.

3. METHODOLOGY AND VARIABLES' DESCRIPTION

3.1. Nature and Source of Data

The data used in our study are annual and sourced from the World Bank (WDI) and the International Monetary Fund (IMF) databases. Covering the period from 1990 to 2020, these data form the basis for our analysis. The table 1 provides detailed information on the variables incorporated in the model:

We utilized the total number of patents filed by both residents and non-residents (SUM) as a proxy for technological innovation (TI). The urban population is measured as a percentage of the total population, while carbon emissions are quantified in metric tons per capita. Financial development is gauged by the domestic credit extended to the private sector, expressed as a percentage of GDP. Clean energy usage is represented by the share of renewable energy in total final energy consumption. For analytical purposes, all-time series data have been transformed into their natural logarithmic form.

3.2. Model Method

There is limited empirical research exploring the relationship between clean energy, financial development, technological innovation, urbanization, and carbon neutrality in Tunisia. Our study draws inspiration from previous works by Ghosh et al. (2024), Ahmad et al. (2024), and Jian and Afshan (2023). Building on the foundations laid by these studies, we propose the following model:

$$CO2_t = f(FD_t, TI_t, CEN_t, UP_t) \quad (1)$$

Where $CO2_t$ is the carbon emissions for each year in Tunisia, FD_t is the financial development for each year in Tunisia, TI_t is the technological innovation for each year in Tunisia, CEN_t is the clean energy for each year in Tunisia.

After applying the logarithmic transformation, the empirical model can be expressed as follows:

$$LCO2_t = \alpha_0 + \alpha_1 LFD_t + \alpha_2 LTI_t + \alpha_3 LCEN_t + \alpha_4 LUP_t + \varepsilon_t \quad (2)$$

Note: ε is the error term; ($\alpha_0,\alpha_1,\alpha_2,\alpha_3,\alpha_4$) are the coefficients.

3.3. Model Results and Discussion

3.3.1. Descriptive statistics of variables

The descriptive statistics reveal that CO2 emissions during the analyzed period averaged 2.250150 metric tons per capita. The lowest recorded emissions, at 1.738372 metric tons per capita, occurred in 1990, while the peak value of 2.736460 metric tons per capita was observed in 2015. These findings are detailed in Table 2.

3.3.2. Graphical representation of variables

The reduction in carbon emissions from 2.57 metric tons per capita in 2019 to 2.4 metric tons per capita in 2020 in Tunisia reflects a significant and rare global trend, where emissions dropped primarily due to the COVID-19 pandemic's impact. In Tunisia, this decline was largely driven by stringent confinement measures that caused widespread disruptions, particularly in the transportation sector, a major contributor to emissions. This global decrease underscores the strong influence of economic activities and mobility on environmental outcomes.

During the same period, financial development in Tunisia exhibited an upward trend, increasing both from 2018 to 2019 and from 2019 to 2020. This growth may be linked to policy measures aimed at enhancing financial inclusion and supporting economic stability during uncertain times. Clean energy usage in Tunisia displayed a mixed trend: It increased in 2009, decreased in 2010, and then rose again in 2020. These fluctuations could be attributed to changes in government policies, investments in renewable energy infrastructure, or shifts in energy demand.

Technological innovation, measured by the number of patents, saw notable increases in 2011 and 2020. These spikes may indicate periods of heightened research and development activities or the introduction of supportive policies that encouraged innovation, particularly in response to global challenges like the demand for cleaner technologies. Meanwhile, urbanization in Tunisia has shown a stable growth pattern over the years, reflecting a gradual but steady increase in the urban population. This consistent growth is likely driven by ongoing rural-to-urban migration and the expansion of urban areas, which have significant implications for infrastructure development, resource consumption, and environmental sustainability.

Overall, these trends suggest a complex interplay between technological progress, financial development, and environmental sustainability in Tunisia. The period around 2020, in particular, offers a unique scenario where external shocks like the pandemic had profound impacts, leading to significant changes in emissions and other related factors. This period provides valuable insights into the potential for structural changes that could drive long-term environmental improvements, as shown in Figure1.

3.3.3. Estimation results

3.3.3.1. Test of stationarity of variable

Before applying the ARDL model, it is crucial to conduct stationarity tests to ensure the reliability of the results. The Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Zivot-Andrews (ZA) tests are widely used to evaluate whether the data series are stationary. These tests analyze the error components and check for the presence of autocorrelation. The findings from these stationarity tests are presented in the table 3.

Assessing the unit root of each variable is essential in this study. We utilized the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Zivot-Andrews (ZA) unit root tests, following the methodology outlined by Rizwanullah et al. (2020). The results from the ADF test indicate that all variables are stationary at order I (1). In contrast, the PP test reveals that only urbanization is stationary at order I (0), while carbon emissions, clean energy, technological innovation, and financial development are stationary at order I (1). To further investigate potential structural break points, we applied the Zivot-Andrews unit root test. The findings indicate that financial development, technological innovation, and clean energy are stationary at I (0), whereas carbon emissions and

Table 1: Description of variables

Variables	Description	Logarithmic forms	Units	Sources
CO_2	Carbon neutrality	LCO_2	CO_2 emissions: Metric tons per capita	WDI
CEN	Clean energy	LCEN	Renewable energy use: % of total final energy consumption	WDI
FD	Financial development	LFD	Domestic credit to private sector (%of GDP)	WDI-IMF
TI	Technological innovation	LTI	Number of patents applied by residents and nonresidents (SUM)	WDI
UP	Urbanization	LUP	Urban population growth (annual %)	WDI

Figure 1: The graphical representation of variables

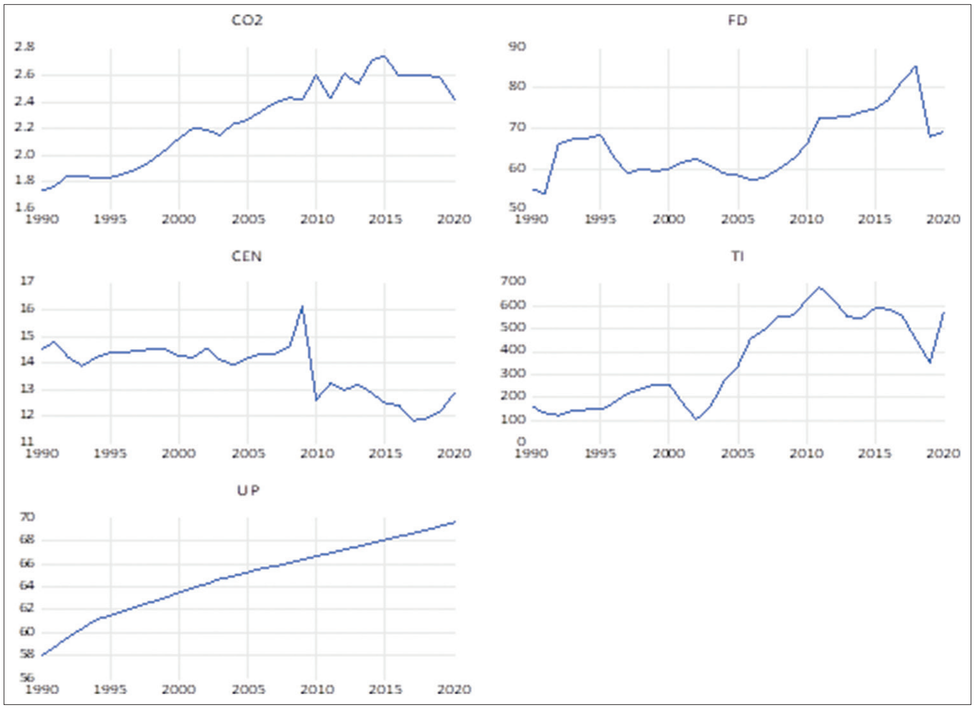
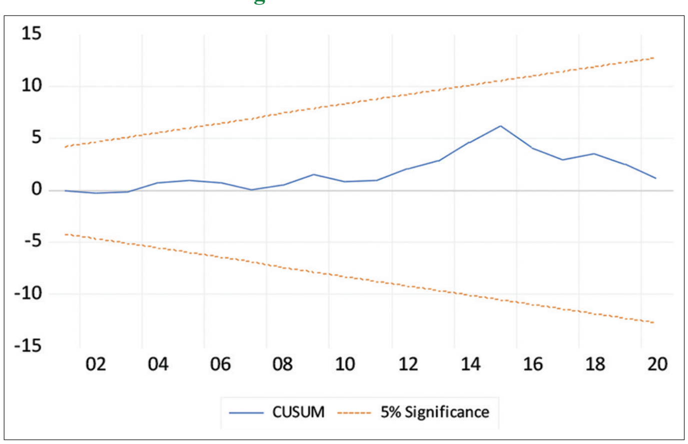


Figure 2: CUSUM test



urbanization are stationary at I (1). Based on these results, we can proceed with the ARDL approach in our study.

For model specification using the ARDL method, it is crucial to select the optimal lag order. The Akaike Information Criterion (AIC) guided us in determining the optimal lag length of one (ϱ=1) for the variables in our model.

3.3.3.2. VAR lag order selection criteria

Prior to conducting the ARDL bounds test to determine cointegration among financial development, clean energy initiatives, technological innovation, urbanization, and carbon neutrality in Tunisia, it is crucial to select the appropriate lag order for the variables. This study utilized the optimal lag order from the vector autoregression (VAR) model for this purpose. The results presented in Table 4 outline the lag selection criteria, indicating that the model performs better with a lag of 2 compared to lags of 1 and 0.

3.3.3.3. ARDL model estimation results

This section focuses on analyzing the findings derived from the ARDL model. The results, summarized in Table 5, explore the relationships among carbon neutrality, clean energy, financial development, technological innovation, and urbanization in the context of Tunisia.

The adjusted R-squared value of 0.97 indicates that our model is well-specified and effectively explains the variance in the dependent variable. To confirm the stability and robustness of our model, we conducted several diagnostic tests, including the normality test (Jarque-Bera), serial correlation test (Q-statistics and Breusch-Godfrey serial correlation LM tests), and heteroscedasticity test (Breusch-Pagan-Godfrey). The results of these tests are as follows in table 6:

3.3.3.4. Diagnostic test of the model

The diagnostic tests confirm that the model adheres to the essential assumptions required for valid statistical inference. The results indicate that the residuals are normally distributed, there is no serial correlation or heteroscedasticity present, and the model is properly specified. This strengthens our confidence in the reliability and robustness of the model's estimates and conclusions.

The Jarque-Bera test results suggest that the residuals are normally distributed, as the P-value exceeds 0.05. This finding indicates that the normality assumption for the residuals is satisfied, which is crucial for the validity of inferential statistics within this model.

The Breusch-Godfrey LM test demonstrates no evidence of serial correlation in the residuals, with a $P > 0.05$. This result implies that the residuals are independent over time, an important factor for ensuring the reliability of the model's estimates.

According to the Breusch-Pagan-Godfrey test, there is no heteroscedasticity detected in the model, as indicated by a P-value above 0.05. This outcome signifies that the variance of the residuals remains constant across observations, fulfilling one of the key assumptions of linear regression.

The Ramsey RESET test further supports the correct specification of the model, with a P-value exceeding 0.05. This finding suggests that there are no omitted variables or incorrect functional forms, reinforcing the validity of the model structure.

To confirm the existence of a long-run relationship among the variables, the study employs the cumulative sum (CUSUM) test (Brown et al., 1975). Previous research (Pesaran and Shin, 1999; Pesaran et al., 2001) has indicated that this test is effective in assessing the goodness of fit for the ARDL model. The CUSUM test is used to plot the residuals of the error correction model (ECM). If the statistics in the plot remain within the critical bounds at a 5% significance level, it indicates that the coefficients of the ARDL model are stable. The results are presented in Figure 2.

The Cumulative Sum of Recursive Residuals (CUSUM) test, as proposed by Pesaran and Pesaran (1997), confirms the stability of the model. This test indicates that the cumulative sum of the recursive residuals remains within the critical bounds, suggesting that the model's parameters are stable over the specified period. Such stability is essential for ensuring the reliability of the model's estimates and predictions.

3.3.3.5. Cointegration fundings

Before determining the short- and long-term relationships among the variables, it is essential to apply the ARDL bounds test, as proposed by Pesaran et al. (2001), to confirm the presence of cointegration. The results, presented in Table 7, indicate that the F-statistic exceeds both the lower and upper critical bounds at the 1% significance level when carbon neutrality is used as the dependent variable. Consequently, the alternative hypothesis of cointegration is accepted, confirming a long-term relationship among clean energy, financial development, technological innovation, and urbanization.

The results of the ARDL bounds test reveal that the F-statistic for our model is 4.93. This value surpasses the upper bound at the 1% significance level, indicating a robust long-run relationship among technological innovation, financial development, clean energy, urbanization, and carbon neutrality in Tunisia. This finding

Table 2: Descriptive statistics of variables

Variables	CO_2	FD	TI	CEN	UP
Mean	2.250150	65.59410	361.3226	13.76968	64.77171
Maximum	2.736460	85.58400	680.0000	16.07000	69.56800
Minimum	1.738372	53.76000	103.0000	11.82000	57.94600
Std. Dev.	0.315996	7.866109	194.7493	0.992591	3.240659

Table 3: Test of stationarity of variables

Logarithmic form of the variables	LCO_2	LFD	LTI	LCEN	LUP
ADF					
Log levels	−1.923	−1.92	−1.03	−2.03	−0.743
Log first difference	−6.88***	−5.188***	−4.36***	−7.91***	−3.157**
PP					
Log levels	−1.81	−1.98	−1.03	−1.84	−5.57***
Log first difference	−6.848***	−5.19***	−3.09**	−9.43***	-
ZA					
Log levels	−0.484	−3.56**	−4.6***	−5.58***	−11.28
TB	1999	2010	2006		2001
Log first difference	−8.44**	-	-	-	−3.25***
TB	1998			−11.28	2006

***,**, and* denote significance respectively at the 1%, 5%, and10%.
TB: Break point unit rout test
ADF: Augmented Dickey Fuller, PP: Phillips-Perron, ZA: Zivot-Andrews

Table 4: VAR lag order selection criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	177.3237	NA	4.75e-12	−11.88439	−11.64865	−11.81056
1	339.039	256.514	3.93e-16	−21.31303	−19.89859*	−20.87005
2	371.4596	40.2463*	2.79 e-16*	−21.8248*	−19.23165	−21.01266*

*Indicates lag order selected by the criterion
LR: Sequential modified LR test statistic (each test at 5% level), FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion

Table 5: ARDL model estimation results

Dependent variable: LCO_2		
ARDL (2, 0, 1, 1, 0)		
Variable	**Coefficient**	**Prob.***
$LCO_2(-1)$	0.448	0.013
$LCO_2(-2)$	0.386	0.065
LFD	−0.168	0.13
LCEN	−0.339	0.017
LCEN(−1)	0.306	0.03
LTI	−0.033	0.154
LTI(−1)	0.073	0.006
LUP	−0.07	0.92
C	0.776	0.776
Adjusted R-squared	0.97	
Durbin-Watson stat	1.624	

*P-values and any subsequent tests do notaccount for model selection.

Table 6: Robustness test of the estimated ARDL model

Diagnostic investigates	Coefficient	P-Value	Decision
Jacque-Bera	1.445	0.485	Residuals are normally distributed
Breusch-Godfrey LM Test	2.315	0.127	No serial correlation exists
Breusch-Pagan-Godfrey	1.674	0.166	No heteroscedasticity exists
Ramsey Reset test	1.924	0.174	The model is properly specified

Table 7: Cointegration test

Test statistics		
F. Statistic	4.93	
Number of independent variables-k	4	
Critical values (%)	**I (0)**	**I (1)**
1	3.29	4.15
5	2.39	3.38
10	2.08	3

Table 8: The short and the long run estimation

Short run estimation		Long run estimation	
LCO_2			
Variable	**Coefficient**	**Variable**	**Coefficient**
$\Delta LCO_2(-1)$	−0.386***	LFD	−1.024
ΔLCEN	−0.333***	LCEN	−0.198
ΔLTI	−0.033**	LTI	0.245*
ECT	−0.164***	LUP	−0.43

The coefficients marked with ***indicate significance at the 1% level, while **indicates significance at the 5% level, and *indicates significance at the 10% level

underscores the interconnectedness of these variables and their collective influence on achieving carbon neutrality in the country.

3.3.3.6. Estimated short and long run coefficients

We utilized the ARDL (2, 0, 1, 1, 0) model, and the results of the short-run estimation are presented in the table 8:

The findings from the short-run analysis offer valuable insights into the dynamics of carbon emissions in Tunisia. The significant negative coefficient of the error correction term (ECT) at the 1% level underscores the idea that deviations from long-term equilibrium are corrected over time, highlighting a stable relationship between carbon emissions and the identified explanatory variables.

In the short run, the negative impacts of clean energy and technological innovation on carbon emissions indicate that immediate increases in these factors contribute to reducing emissions. This reduction is likely due to more efficient energy production and innovative technologies that decrease reliance on fossil fuels, suggesting a promising direction for policies aimed at fostering clean energy initiatives and technological advancements. This finding contrasts with the research of Raihan and Tuspekova (2022), which concluded that there is no significant association between technological innovation and carbon emissions. However, it aligns with Charfeddine et al. (2024), who suggest that renewable energy contributes to environmental improvement, particularly in the ten most polluted countries.

In the long run, while clean energy, urbanization, and financial development negatively impact carbon emissions, the lack of statistical significance may indicate that their effects are overshadowed by other factors or that these impacts take longer to materialize within Tunisia's economy. This suggests a need for ongoing investment and policy support to enhance the effectiveness of these areas in reducing emissions. This finding supports the views of Ali et al. (2023), Kirikkaleli et al. (2022), and Kirikkaleli and Adebayo (2021), who noted that financial development promotes environmental sustainability through investments in energy technology research and sustainable sources. However, it contradicts the findings of Ibrahim et al. (2023), which indicated that financial development has a significant and negative influence on sustainable development, while highlighting that clean energy positively impacts sustainable development in Iraq. Furthermore, Raihan (2023) noted that financial development has no effect on environmental deterioration in Uruguay.

Conversely, the positive long-run effect of technological innovation on carbon emissions raises concerns. It suggests that while advancements in technology are beneficial, they may also lead to increased emissions if they encourage carbon-intensive industrial growth or processes. This result implies that as Tunisia progresses technologically, it may need to implement stringent environmental regulations to mitigate potential emissions increases associated with new technologies. This finding is consistent with Ghosh et al. (2024), who noted a positive association between technological innovation and carbon emissions in India.

Overall, the results highlight a complex interplay between these variables, emphasizing the need for a balanced approach that promotes clean energy and innovation while carefully managing their long-term impacts on carbon emissions. This insight calls for integrated policies that not only support technological progress but also prioritize sustainability to achieve carbon neutrality in Tunisia.

3.3.3.7. Direction of causality

The Granger causality test is a widely utilized technique for analyzing time series data to identify causal relationships between

Table 9: Causality between variables

Variables	Carbon neutrality	Financial development	Clean energy	Technological innovation	Urbanization
Carbon neutrality	-				
Financial development	→	-			
Clean energy	→	←	-		
Technological innovation	↔	≠	≠	-	
Urbanization	→	→	≠	→	-

economic variables. The outcomes of this test, as presented in Table 9, provide insights into the direction and nature of these relationships.

The Granger causality results provide a nuanced understanding of the dynamic relationships among the variables influencing carbon neutrality in Tunisia. Here are further interpretations of the findings:

Bidirectional Causality Between Technological Innovation and Carbon Neutrality: The bidirectional causality observed between technological innovation and carbon neutrality signifies a synergistic relationship that is crucial for sustainable development. This interplay suggests that advancements in technology, such as the development of cleaner energy solutions or more efficient production processes, directly contribute to reducing carbon emissions. Conversely, the pursuit of carbon neutrality incentivizes further innovation, as governments and industries seek new technologies to meet environmental targets. This reinforcing cycle implies that policies promoting research and development in green technologies are essential for achieving long-term sustainability. The parallels with studies by Saqib et al. (2023) and Fan and Hossain (2018) further validate the notion that fostering technological innovation is vital for ecological progress.

Unidirectional Causality from Urbanization, Financial Development, and Clean Energy to Carbon Neutrality: The unidirectional causality from urbanization, financial development, and clean energy to carbon neutrality highlights the foundational role these elements play in shaping environmental outcomes. Urbanization, when strategically managed, can lead to improved infrastructure and more efficient public services, reducing emissions through better transportation systems and energy efficiency initiatives. Financial development enhances the capacity to fund green projects, emphasizing the need for access to capital to support environmental initiatives. Clean energy, by directly substituting fossil fuels, is critical in reducing the carbon footprint. This underscores the necessity for comprehensive policies that integrate urban planning, financial incentives, and clean energy promotion to foster a sustainable environmental framework.

Unidirectional Causality from Urbanization to Financial Development and Technological Innovation: The causality from urbanization to financial development and technological innovation underscores the transformative potential of urban growth. As cities expand, they often become economic hubs that foster entrepreneurial activity, innovation, and investment. This dynamic creates a favorable environment for financial institutions to thrive and offer services that cater to new businesses and technologies. The growth of urban areas can stimulate demand for innovative solutions and financial products, driving progress in both sectors. This relationship indicates that policymakers should focus on creating urban environments that encourage innovation and provide robust financial support, facilitating a virtuous cycle of development.

One-Way Causality from Financial Development to Clean Energy: The one-way causality from financial development to clean energy emphasizes the critical role of a strong financial sector in enabling the transition to renewable energy sources. A well-developed financial market can provide the necessary resources for clean energy investments, ensuring that innovative projects have access to funding. This finding highlights the importance of financial policies that prioritize green investments and the development of financial instruments designed to support renewable energy initiatives. By fostering a financial environment conducive to clean energy, Tunisia can enhance its energy security and reduce its carbon emissions.

No Causality Between Urbanization and Technological Innovation: The absence of causality between urbanization and technological innovation suggests that urban growth alone does not guarantee technological advancements. This may indicate that the relationship between these two variables is influenced by other factors, such as educational opportunities, research institutions, or government policies that encourage innovation. The finding underscores the need for targeted initiatives that connect urban development with technological progress, ensuring that cities evolve into centers of innovation. Policymakers should consider strategies that foster collaborations between urban planners, educational institutions, and technology firms to bridge this gap.

4. CONCLUSION AND RECOMMENDATIONS

Tunisia recognizes that environmental degradation poses a significant threat to sustainable production and consumption. The rising energy consumption and demand have exacerbated the adverse effects of carbon dioxide emissions. In response to these challenges, Tunisia implemented stringent regulations and promoted green technology innovations in 2019.

This research investigates the impact of financial development, technological innovation, clean energy, and urbanization on carbon neutrality in Tunisia, utilizing the ARDL model for the period from 1990 to 2020. The cointegration relationship among the selected variables was confirmed through the Bounds test, indicating a long-term association between the dependent and independent variables. The ARDL results reveal that financial development, clean energy, technological innovation, and urbanization contribute to reducing carbon dioxide emissions in the short term. However, it is noteworthy that technological innovation is associated with an increase in carbon emissions in the long run. These findings contrast with the results of Esquivias et al. (2023), who reported that financial development and urbanization contribute to environmental degradation in India. Similarly, Raihan (2023) highlighted that urbanization negatively impacts the low-carbon economy in Bangladesh, suggesting that clean energy utilization and technological innovation are crucial for maintaining environmental sustainability. In contrast, Zhan et al. (2023) concluded that increased green finance and financial innovation significantly reduce CO_2 and greenhouse gas emissions in China. Additionally, Nathaniel et al. (2024) found that while green energy had no significant effect on the ecological footprint, financial development reduced it by 0.08%, demonstrating a unidirectional causality from financial development to the ecological footprint.

To enhance its efforts toward achieving carbon neutrality and promoting sustainable economic development, Tunisia should prioritize strengthening and enforcing regulations that support green technologies and practices. This includes incentivizing investments in renewable energy and fostering research and development initiatives aimed at reducing carbon emissions. Furthermore, urban planning must incorporate sustainability principles to mitigate the environmental impacts associated with urbanization, focusing on efficient public transportation, green infrastructure, and energy-efficient buildings. Additionally, financial institutions should play a pivotal role by prioritizing funding for projects that promote clean energy and sustainable technologies, which may involve developing green financial products and providing incentives for businesses that adopt environmentally friendly practices. It is also crucial for Tunisia to ensure that technological innovation aligns with environmental goals by implementing regulations that prevent increases in carbon emissions, promoting clean technology, and conducting environmental impact assessments for new innovations. Finally, future research should explore the specific mechanisms through which financial development, urbanization, and technological innovation influence carbon emissions, providing deeper insights into balancing economic growth with environmental sustainability. By adopting these measures, Tunisia can secure a sustainable future while effectively addressing the challenges posed by climate change.

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