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Nexus among Renewable Energy, Economic Growth, Technology Innovation, CO_2 Emissions, and Life Expectancy in NAFTA: What's the Forum's Response Amid Time Frequencies?

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ABSTRACT

This study examines the nexus between renewable energy (RE), economic growth (ECOG), technological innovation (TEI), CO_2 emissions, urbanization (URB), and life expectancy (LEX) in NAFTA countries driven by the sustainable development framework. Using advanced wavelet coherence with data from 1990M1-2023M12, along with WAMC techniques, the analysis revealed intricate temporal and frequency-based interactions. Technological innovation and renewable energy boost life expectancy by reducing environmental degradation. As for urbanization and economic growth, these modified results anticipate dependent variables by the quality of infrastructure and policies. In the short run, tested causality relationships between variables show non-directional, while medium- and long-term scenarios evidence mutual reinforcement of the variables with life expectancy leading to renewable energy adoption and emissions reduction. The tests confirm WAMC's almost perfect integration of factors within time scales, stressing thus their collective outcome on life expectancy. Therefore, this study emphasizes the status of appropriate sustainable policies integrating health, energy, and environmental objectives and creating effective measures toward long-term sustainability in NAFTA.

Keywords: Renewable Energy, Public Health, Technology Innovations, Life Expectancy, NAFTA
JEL Classifications: Q18, Q42

1. INTRODUCTION

Environmental quality and human longevity are indeed the central themes of the 21st century (Naidu et al., 2021; Zhang et al., 2025). With increases in temperature by 1.1°C since pre-industrial times, it becomes increasingly imperative to understand the effects of environmental degradation on health and life expectancy (LEX) (Khan et al., 2024; Ofremu et al., 2024). This ecological crisis coincides with unprecedented trade, technological innovations (TEI), and urbanization (URB), creating a complex web of factors affecting human longevity (Fumey et al., 2024; Yang et al., 2023). Recent global statistics reveal that average life expectancy worldwide has already reached 72.8 years (Cao et al., 2023; Karamitanha et al., 2023); however, considerable regional differences still exist, primarily related to different levels of environmental quality, economic development, and technology (Moro et al., 2025; Pal and Mahalik, 2025).

Furthermore, the COP28 United Nations Climate Change Conference held in Dubai in 2023 made a historic turnabout in the global climate action agenda, with nations agreeing to phase out fossil fuels and triple renewable energy capacity by 2030 (COP28, 2023). The agreement resonates widely across North America, where these dynamics play out diversely across the United States, Canada, and Mexico (Leiserowitz et al., 2021; Morgan et al., 2021). The region is an interesting case study, mainly because Canada has pledged 100% clean electricity by 2035 (Agu et al., 2023; Vine, 2021), Mexico is supposed to expand solar capacity (Clavel et al., 2024; Icaza-Alvarez et al., 2023), and the United States needs a 50-52% greenhouse gas reduction by 2030 (Fam and Fam, 2024; Zhao et al., 2024). These three countries are closely linked through their economies and trade, but exhibit differences in life expectancy by 7.2 years between the highest and lowest numbers (Segbefia et al., 2023). The existences differ against a host of policies that characterize the environment, adoption rates of renewable energy, and levels of technological innovation, hence serving as a dramatic focus of research into determinants of life expectancy (Sampene et al., 2024; Wiredu et al., 2024).

Consequently, the study examines how life expectancy (LEX) relates to five major determinants: carbon emissions, renewable energy adoption (RE), economic growth (ECOG), technological innovation (TEI), and urbanization (URB) in these North American nations. Understanding these relationships is very important for policymakers and health professionals trying to improve population health outcomes as they confront the environmental challenge. Hendrawaty et al. (2022) show a complex nexus between ECOG and LEX. The findings of the short-run analysis show that it is possible to be economically favorable on LEX but negatively impact it in developing countries such as Indonesia, the Philippines, and Thailand. It was also found that financial development may improve LEX within countries. Singapore, a developed country, is not similarly burdened, implying that those nations would have different effects on ECOG and LEX, with developing countries falling within the opposing side and developed ones in the upbeat bar. However, Sirag et al. (2020) assert that there exists a non-linear relationship such that LEX only increases to a certain point and has almost certainly a positive association with ECOG, beyond which it turns negative owing to demographic transitions.

Increased LEX shared by high-income countries establishes the renewable energy (RE) pattern (Yang et al., 2023). It was found that there is a strict correlation between RE and high LEX since the ECOG that comes with renewable energy benefits healthcare and better living conditions. Also, RE reduces CO_2 emissions in emerging market economies, directly improving health benefits and LEX because low emission levels are associated with less polluted air and lower health risks caused by pollution (Bilgili et al., 2021; Mahalik et al., 2022). CO_2 emissions can slash life expectancy (LEX) anywhere, whether rich or poor. Of course, in the Aral Sea basin, the over-emission of CO_2 compromises life expectancy (Saidmamatov et al., 2024). Considering the entire scope of intervention policies, including environmental and health dimensions, is imperative. Similarly, decreasing LEX signified in 68 developing and emerging economies associated with CO_2 emissions-consumption-based or production-based-implied high emissions levels in emerging states (Mahalik et al., 2022).

Biomedical research and innovation have been essential factors in recent work toward increasing longevity and the state of health itself (Garmany et al., 2021). Empirical evidence shows that innovation in pharmaceutical technology, a highly research-intensive medical field, is critical in enhancing health outcomes, including life span (Melnychuk et al., 2021). Innovations that have good promise in extending human life up to the ancient age are antiaging or life-extension technologies that deal with maladies of the advanced years and internal causes like molecular and cellular damage (Grinin et al., 2024). Age-societal elements will delay or prevent it from coming to most people (Vijg and de Grey, 2014). However, increases in health expenditure mitigate the deleterious effects, reinforcing the evidence that healthcare investment in urban settings is of primary significance (Rahaman et al., 2023). In South Asian nations, urbanization has been shown to adversely affect the life expectancy of individuals as they become the victims of income inequality and lack of health spending (Ahmad et al., 2023). Tackling socioeconomic disparities and improving city healthcare access will eventually help close the LEX gap between urban and rural people. It will also make urban life healthier (Løvhaug et al., 2022; Malmusi et al., 2022).

The complex interplay between renewable energy (RE) and economic growth (ECOG) with technological innovations (TEI) and CO_2 emissions, urbanization (URB), and life expectancy (LEX) is pertinent for sustainable development (Kamran et al., 2024; Lee et al., 2022; Yeboah et al., 2024). Understanding the interplay between these variables to develop strategies for healthy, enduring ecological sustainability and economic flexibility in the wake of the North American Free Trade Agreement (NAFTA), which continues to evolve the financial environment as well as the environmental policy framework in the United States, Canada, and Mexico, lies within the scope of this study. Advanced time-frequency analysis will be applied to assess these relationships, providing insight from which policy can be derived for a more flourishing, sustainable, and well-off future for the region within the NAFTA context. These questions shall guide the investigation toward understanding how the variables interact, giving meaning to the time-powering relationships within that context. (RQ1) What is the link between RE and LEX in the NAFTA region, and how does it vary over time? (RQ2) How do ECOG and TEI influence CO_2 emissions and URB, and how does this impact LEX in the NAFTA countries? (RQ3) What are the time-frequency dynamics of the relations among ECOG, RE, and LEX in the context of NAFTA? (RQ4) How do CO_2 emissions and URB fluctuations affect LEX in the NAFTA region, and to what extent can TEI mitigate these effects?

The paper is prepared as follows: Part Two presents related literature and a concise literature gap and contribution stipulations, Section Three captures the theoretical and empirical modeling, and Section Four embodies the empirical and discussions, while Part Five contains the conclusions of the paper and policy directions.

2. REVIEW OF LITERATURE

2.1. Carbon Emissions (CO_2) and Life Expectancy (LEX)

Most studies prove that the link between CO_2 emissions and life expectancy (LEX) is complex and multidimensional (Azam and

Adeleye, 2023). Generally speaking, a negative correlation exists in that increased CO_2 is usually associated with LEX reduction in regional and economically diversified contexts. The decrease in LEX in the Aral Sea basin occurs through CO_2 emissions (Saidmamatov et al., 2024). While spending on health, GDP, and agricultural output boosts LEX, CO_2 emission diminishes it, and the signs indicate comprehensive policy intervention (Saidmamatov et al., 2024). Mahalik et al. (2022) found that in emerging countries, CO_2 hurts LEX, while in developing countries, CO_2 emissions increase LEX. This is considered to be due more to consumption than production and thus reveals complex interactions between CO_2 emissions and health outcomes. Empirical findings indicate that LEX decreases with per-capita CO_2 emissions, and higher emissions reflect lower LEX (Chang, 2023). This shows how crucial the improvement of environmental factors in public health outcomes and ecologically viable living practices should be. Szymańska (2024) demonstrated a statistically significant negative association between CO_2 emissions and LEX at birth in 27 EU countries, meaning higher CO_2 emissions are detrimental to health status. This accentuates the role of environmental factors in concert with socio-economic conditions. Liquid and solid fuel emissions have a very high adverse effect on LEX throughout Asia and the Pacific; liquid fuel emissions have the most noteworthy adverse effect. Also, there are varied impacts on different income groups and accentuated demands for health policy (Azam, 2023). The result has strongly connected all the quantiles between the CO_2 emission and LEX. As evidenced in other studies, high CO_2 emissions decrease LEX; thus, the use of cleaner sources of energy is of great significance to environmental sustainability for health improvements (Younus et al., 2022). According to Matthew et al. (2020), LEX responds positively to each 1% increase in the variable of CO_2 emissions, increasing by 0.123% in West Africa, proving that even though carbon is negative to agricultural output, it increases LEX through some routes. The connotation between CO_2 emissions and LEX in India is positive and significant. Between 1990 and 2020, higher CO_2 emissions correlated positively with increased LEX, which indicates that despite the environmental concern, LEX also benefits from using fossil fuels (Yang and Ying, 2024). The primary trend of thought is that CO_2 adversely affects LEX, but in specific settings, such as developing countries, it does not have the same adverse effects. Further, this will lead to making policies that are not merely tunnel-viewed but consider the local economic and environmental contexts.

2.2. Renewable Energy (RE) and Life Expectancy (LEX)

Renewable Energy (RE) and Life Expectancy (LEX) applications are significantly recognized across and over various regions with their respective income levels. More recent studies are increasingly finding that applications of RE improve health outcomes through environmental quality, hence longevity (Liu and Zhong, 2022; Yang et al., 2023). The literature has proved this link well across various contexts, from Nordic economics to West African lower-middle-income states. The usage of RE in the Nordic region correlates positively with LEX. Equally, the study shows that investment in RE is associated with sustainable economic growth, favoring good health and a longer LEX (Dai et al., 2024). Based on Uzoechina et al. (2024), RE contributes positively and significantly to LEX in lower-middle-income West African states in the short and long run; hence, having good health status and well-being in the subregion largely depends on increasing RE. There is an excellent degree of causality between LEX and the consumption of RE in contributing positively toward the health expenditure LEX nexus in Asian countries, implying that greater use of RE improves the quality of life (Sugözü and Dorbonova, 2024). In addition, it is established that in the BRICS-T countries, RE enhances LEX; empirical evidence shows that promoting RE is about extending LEX and, thereby, one of the critical determinants of economic growth (Dam et al., 2023). Furthermore, other findings show how RE consumption can positively influence LEX in China. Long-run relations between RE and LEX in this study suggest that the greater use of RE may lead to better health outcomes (Liu and Zhong, 2022). A positive and significant value of the coefficient between RE and LEX in the MINT countries can be viewed from the result. Higher uses of RE sources will increase LEX due to improved health conditions and less air pollution (Ebhota et al., 2023). However, the other findings indicated that RE use has a constructive effect on human development and might indirectly affect the factors of LEX in the countries under survey (Azam et al., 2023). Although this supports that increased consumption of RE leads to an increased life span, it should be brought into a broader perspective relating to economic factors and qualitative healthcare systems that might also play a significant role in health parameters.

2.3. Economic Growth (ECOG) and Life Expectancy (LEX)

Economic growth (ECOG) and life expectancy (LEX) could be very tangled and complex; positive and negative interactions are likely to be evidenced. ECOG has reduced LEX through better health services, education, and infrastructural investments. High LEX may become burdensome for ECOG in the case of high-income states due to a shortage of the working population (Amin et al., 2024; Hendrawaty et al., 2022). Findings show how, within ASEAN-5 countries, ECOG has contributed to increased LEX. This underlines that further economic development and investments in health have improved health outcomes and quality of life (Amin et al., 2024). It could be that ECOG and LEX are jointly caused, with the former depending on the decline in dependency ratios, unemployment, and poverty, and the latter depending positively on health spending and negatively on poverty rates (Setiawan et al., 2023). The specific outcomes of the analysis are that ECOG may lower LEX in the short run for developing countries such as Indonesia, the Philippines, and Thailand. On the other hand, however, it affects developed countries like Singapore insignificantly (Hendrawaty et al., 2022). Agrawal (2024) established the link between ECOG, represented by the GDP per capita, and LEX. Data from 20 countries were analyzed and found that LEX can be affected, although the influence of GDP growth might not be direct. For Nigeria, a positive and direct link has been thrown up by ECOG and LEX; thus, the higher the ECOG rate improves, the better LEX tends to be, and health becomes a significant contributory factor to economic development (Lawal et al., 2023). More so, other studies found that ECOG had a constructive impact on LEX in selected Asian nations; for every one-unit increase in ECOG, it results in a 0.0065% increase in

LEX, and this reflects the improvement in living standards and health expenditure (Fouzia et al., 2024). Improvements in LEX shocks are positively linked to long-run output, increasing it by 57.49% in sub-Saharan Africa, 14.94% in the OECD, and 11.58% in Canada between 1960 and 2018 (Tserenkhuu and Kosempel, 2023). The LEX is positively influenced by ECOG, as represented by ECOG, such that a 1% rise in ECOG leads to a 0.014 surge in LEX. There exists one-way causality in the short run, meaning that the variables are connected through time (Bashir et al., 2022). While ECOG usually prolongs LEX due to better health and social services, the reverse function might raise other problems in an aging population. Harmonization of such factors is highly essential for attaining sustainable development.

2.4. Technological Innovation (TEI) and Life Expectancy (LEX)

This situation indicates that TEI has a very high contribution to raising LEX because of the interplay of LEX with ECOG, investment in renewable energy, and the environment. As all these linked issues suggest, TEI may produce health improvements that assure longer lives (Sampene et al., 2024; Zhang et al., 2021). The effects of pharmaceutical innovation on longevity declare that the higher the drug vintage, the higher the LEX. Drug vintage has raised the average age at death by about 6 months in the United States and 1.23 years in 26 nations (Lichtenberg, 2022). TEI, particularly environmental technologies, was crucial in increasing the LEX, of people in Latin America. Critical factors were the cleaner energy transition and industrial growth, while PM2.5 and CO_2 emissions hamper LEX's clear pathway toward sustainable development (Sampene et al., 2024). More importantly, TEI is positively dependent upon increasing LEX because a more prolonged life raises savings, lowers interest rates, and increases the net present value of innovations, thus stimulating higher investment in R&D and faster technological progress. The long-run ECOG would also occur (Baldanzi et al., 2019). TEI is couched as the solution to demographic aging, promoting an active and autonomous LEX course. It's meant to improve longevity through healthy and socially inclusive aging with independence, perceived as a challenge brought about by aging (Jarke, 2021). The paper has shown how information and communication technology influences LEX within the Middle East region; for every 1% increase in ICT, there is a corresponding increase in LEX of 0.551%, indicating the application of TEI as the secret to health conditions (Ronaghi, 2022). It is established that increasing life expectancy enhances household incentives to invest in R&D and physical capital, positively impacting TEI and productivity growth, thereby underscoring that TEI goes hand in hand with LEX within industrialized economies (Gehringer and Prettner, 2017). Mkhize-Kwitshana et al. (2023) review some of the state-of-the-art technologies adopted by the healthcare industry, including telemedicine and data analytics, to render further preventive medicine effective. Those would improve health outcomes and further LEX by enabling early disease detection and personalized health intervention. Though promising, especially in the stride of technology towards increasing LEX in humans, one should not fail to mention the darker sides arising with over-dependency on technology and fair distribution or availability among population segments.

2.5. Urban Population (URB) and Life Expectancy (LEX)

Urban population dynamics (URB) and life expectancy (LEX) are entangled in complex socio-economic causation and health policies. On the one hand, in countries suffering from demographic aging and health inequity, the contribution of URB to the advantages and disadvantages regarding LEX has been differential. It was meant to project the size of a URB and how various policies would impact growth in Xi'an from 2019 to 2050 (Li et al., 2023), showing that from 2020, it increased to 22.7 months and further to 23.7 months in 2021, hence showing a shift toward rural disadvantage in the COVID-19 era with significant changes in the mortality burden (Han et al., 2023). In South Asia, URB adversely influences the LEX of males and females. However, health expenditure perhaps moderates the effects, suggesting that better health facilities are integral to improving LEX in urban areas (Ahmad et al., 2023). Also, in the ASEAN-5 countries, the URB hurts LEX and reflects health challenges associated with rapid urban development. Strategic urban planning and healthcare investment will be needed to reduce risks and improve LEX (Amin et al., 2024). According to Premaratna et al. (2023), this addresses the fact that a very fast-growing elderly population in urban centers results from increased LEX because of successful human development. Still, such speed in URB has damaged the elderly care and social support systems in developing countries. The elements that, in general, determine the population aging of European cities are the share of older people and their spatial distribution according to gender, city size, and economic advance (Lewandowska-Gwarda and Antczak, 2020). Mortality rates for the ages 60-79 years are initially lower in urban areas but shift to higher mortality in rural areas when 80 and over, and this attests to the importance of using LEX in making the mortality comparisons (Ebeling et al., 2022). For Indian states, the total URB and the percentage of the URB have positive effects on LEX at birth, meaning increased urbanization and better health outcomes support the demographic transition theory (Tripathi, 2021). Despite all these benefits of urban life, challenges ranging from health inequity to environmental problems created by urbanization highlight the dire need for an integrated approach toward urban planning and public health policy. Meeting such challenges will improve LEX in a diverse range of populations.

2.6. Literature, Gap, and Contributions

Earlier studies have scrutinized the individual nexus of RE, life expectancy, and economic growth in different contexts and study areas (Alhassan et al., 2021; Lawanson and Umar, 2021; Rahman and Alam, 2022). The explorations have been made into isolated impacts on life expectancy caused by RE, ECOG, CO_2 emissions, URB, or innovations without a comprehensive and holistic view in the NAFTA context. However, they have never been integrated into understanding how they jointly influence the NAFTA region. Most studies have considered static or linear models (Segbefia et al., 2023), ignoring complex time-varying relationship dynamics between these variables. Although the role of urbanization as a determinant of life expectancy has been acknowledged in other economies, its possible interaction with highly technologically innovative and environmental determinants such as CO_2 emissions has not been pursued exhaustively in a multivariate framework tracking variations over time in NAFTA. A significant gap exists to be filled by a more integrated dynamic investigation into these variables' joint influences on life expectancy across the diverse socio-economic sceneries of the United States, Canada, and Mexico.

Therefore, the current study significantly contributes to using advanced wavelet analysis on time-frequency relationships between RE and ECOG, CO_2 emissions, technology innovation, urbanization, and life expectancy in the NAFTA region. Unlike previous studies that treat these variables in isolation or are scoped to a limited time, this study integrated them in a multivariate framework accounting for their dynamic interrelations over time. The wavelet decomposition brings these factors into greater detail at different frequencies, including short-term and long-term effects on life expectancy. Focused on the NAFTA region, the study brings new perspectives on these countries' sustainability and public health challenges through policy-relevant results for achieving better health outcomes due to environmental and economic policy interventions. Further, this notable approach extends the methodological innovations in studying life expectancy, ecological sustainability, and economic development.

3. METHODOLOGY

This part prioritizes outlining the research variables, discussing the underlying theory, estimating methods, and conducting preliminary analysis. As mentioned earlier, the subsections thoroughly explain the components.

3.1. Theoretical Overview

Sustainable Development Theory argues that economic growth must go hand-in-hand with environmental sustainability and social well-being (Cho and Choi, 2021; Ruggerio, 2021; Wiredu et al., 2024; Yeboah et al., 2024). This theory posits that these three elements are interdependent, with economic growth and technological innovations contributing to sustainable ecological quality and enhancing life expectancy (Ahmad et al., 2023; Guzel et al., 2021; Zhang et al., 2021). It assumes that development should serve the near-term requirements of mankind without compromising future generations, be it from a particular sector of society or as we advance through improved technological advancement (Popkova et al., 2022; Silva, 2021). This proposition suits the current study as it examines the interaction between renewable energy, economic growth, technological innovation, CO_2 emissions, urbanization, and life expectancy within the NAFTA region. Under the study, this framework would be deployed to explore how these variables relate to sustainable development, focusing mainly on life expectancy as an outcome of these interactions. The introduction of life expectancy into the sustainability dialogue could be termed as new, for it has underlined the role of public health in ensuring sustainable development. In this manner, human beings are central to sustainability debates, giving it a wider ambit rather than just considerations of the environmentally-friendly and economically viable ends but ensuring improved quality of life as a significant dimension of long-term sustainability, quite crucial in Africa compared to socio-economic conditions of the NAFTA countries (Al-Raeei, 2024; Hariram et al., 2023; Zhang et al., 2021). Hence, past research findings and data availability support the variables selected in this study. The indicator RE was selected based on the empirical studies of (Mujtaba et al., 2022); CO_2 (Dong et al., 2022); ECOG (Acheampong and Opoku, 2023); TEI (Zhang et al., 2023); URB (Almulhim and Cobbinah, 2023), and the LEX indicator was also selected based on the empirical analysis of (Matthew et al., 2020; Osei-Kusi et al., 2024).

3.2. Data Description

The NAFTA region includes the United States, Canada, and Mexico. The differences in the research questions are matched well by a sample from these countries. They represent a varied and dynamic economic and environmental terrain with very different commercial, social, and ecological features that ensure economic development, urbanization, and life expectancy. This has also determined the time scope of the research due to the availability of data from these nations, in which the exploration is between 1990M1 and 2023M12, this allows more advanced time-frequency analysis and increase the sample sizes necessary for wavelet decomposition, temporal disaggregation has been applied to the series and high-frequency estimates for more inspired examination of variable relationships.

The availability of data impacted the time for this study, as the exploration data spans the years 1990–2023. The Quadratic Match-sum approach was used for this, as recommended by (Adebayo et al., 2024; Shah et al., 2022; Ullah et al., 2023), which helps reveal cyclical patterns concealed in monthly averages. Furthermore, additional data points reinforce the statistical power of our wavelet analysis. Thus, from (WDI, 2023), the CO_2, TEI, RE, URB, ECOG, and LEX statistics were obtained. Table 1 offers a summary of the constructs for each sequence.

3.3. Estimation Models

To analyze a dynamic time-frequency connection between RE, TEI, ECOG, CO_2 emissions, and LEX in NAFTA. We use a comprehensive wavelet-based methodology for estimation based on the bivariate or multivariate technique. We break free from

Table 1: Summary of variables

Indicators	Acronyms	Measurement	Source
Life Expectancy	LEX	Life expectancy at birth, total (years)	(WDI, 2023)
Technology Innovation	TEI	Patent applications, residents, and non-residents	(WDI, 2023)
Renewable Energy	RE	Renewable energy investment (% of total final energy investments and consumption)	(WDI, 2023)
Urbanization Population	URB	URB (% of the total population)	(WDI, 2023)
Economic Growth	ECOG	GDP per capita (constant 2015 US$)	(WDI, 2023)
Carbon Emissions	CO_2	CO_2 emissions (metric tons per capita)	(WDI, 2023)

the limitations of static models, which are common in economic research, by utilizing wavelet methods. Instead, it offers a more complex and dynamic understanding. Put another way, it looks into how the underpinned factor units address either separately or together using two main wavelet techniques: Discrete Wavelet Transform (DWT) for multivariate investigation and Continuous Wavelet Transform (CWT) for pairwise observations. These techniques were selected based on their capacity to reveal various facets of time-frequency domain relationships (Yeboah et al., 2024).

3.4. Bivariate Wavelet

The bivariate wavelet approach efficiently analyzes how the variables interact with time and frequency. This method facilitates data breakdown and gives stakeholders lucid insights to aid in well-informed decision-making. Torrence and Compo. (1998) methodology is used to normalize the wavelet cross-spectrum. Equation (1) shows how to determine the wavelet coefficient squared.

$$\chi^2(\mu,\lambda) = \frac{\left|\kappa(\xi^{-1}\delta_{\mu,\lambda}(\varphi,\xi))\right|^2}{\kappa(\upsilon^{-1}\left|\delta_{\mu}(\varphi,\xi)\right|^2)\kappa(\xi^{-1}\left|\delta_{\lambda}(\varphi,\xi)\right|^2)} \tag{1}$$

The spot is denoted by φ, while the technique's strained properties are indicated by ξ. With $0 \le \chi^2_{\mu\lambda}(\varphi,\xi) \le 1$, κ is a smoothing value that strikes a compromise between stability and significance. A weak or strong combination is indicated by a value close to zero or one. Since the imaginary spread of the CWT coefficient is unknown, the Monte Carlo system is used to assess numerical results. The accuracy of the algorithm and the detected phase difference reveal disturbances in the oscillatory outlines. According to Yeboah et al., (2024) these point variations peak pauses in the rhythmic behavior. The phase differences $\mu(\eta)$ and $\lambda(\eta)$ are defined as follows:

$$\vartheta_{\mu,\lambda}(\varphi,\xi) = \tan^{-1}\left(\frac{\pi\left\{\int(\xi^{-1}\delta_{\mu,\lambda}(\varphi,\xi)\right\}}{\chi\left\{\int(\xi^{-1}\delta_{\mu,\lambda}(\varphi,\xi)\right\}}\right) \tag{2}$$

π and χ represent the hypothetical and actual ideation. The dimensional phase patterns illustrate the effect of coherence, offering a thorough description of the technique (Owusu Junior et al., 2021; Woode et al., 2024; Yeboah et al., 2024).

3.5. Wavelet Multivariate

To accommodate simultaneous addition among the different recurrence rates of the features, we deployed techniques comprising the wavelet multiple correlation (WAMC) and the cross-correlation (WAMCC) methods, which are critical for gaining insights into their collective dynamics, revealing the intensity of interaction relationships and the direction of influences at different frequencies. For WAMC, lower values designate weaker integration, while higher values signify stronger integration. The WAMCC further relates the susceptibility of these parameters to directing inflation rates in NAFTA, whether positively (covering factor) or negatively (principal factor). The model accounts for all such influences at different frequencies.

Let $m_t = m_{1t}, m_{2t}.,m_{nt}$ represent a random sequence with varying structures and let $\delta_{\varsigma t} = v_{1\varsigma t}, v_{2\varsigma t}.,v_{n\varsigma t}$ be the resulting scale derived by applying the MODWT. Fernández-Macho (2012), describes the WAMC by $\zeta m(\phi_\varsigma)$ as a set of multiscale from mt. χ^2 obtained from linear regression of $v_{i\varsigma t}, \tau = 1,2.,n$ metrics for χ^2 is figured at each scale ϱ_ς. According to the literature, the χ^2 conforms to the degeneration of a metric $\{z_\rho, \rho \neq \tau\}$ is z_t, The WAMC is accentuated in Eqn. 3.

$$\zeta\phi(\varrho_\varsigma) = \frac{Corr(\psi_{\tau\varsigma t},\ \hat{\alpha}_{\tau\varsigma t})Cov(\psi_{\tau\varsigma t},\ \hat{\alpha}_{\tau\varsigma t})}{\left(Var(\psi_{\tau\varsigma t})Var(\hat{\alpha}_{\tau\varsigma t})\right)^{\frac{1}{2}}} \tag{3}$$

$\psi_{\tau\varsigma}$ is maximizes the $\zeta h(\phi_\varsigma)$ and $\hat{\alpha}_{\tau\varsigma t}$ estimates are derived from a regression model of $\psi_{\tau\varsigma}$ on the residual wavelet coefficients γ_j. The conjecture of WAMC and WAMCC is feasible by retaining an erudite and fluctuating algorithm $\mathfrak{X}_t$ for $t = 1,2.,T$ be $\mathfrak{X} = \{h_1, h_2, ..., \phi_T\}$. This involves integrating a sequential MODWT $\beth$ across $\{h_{1i}., h_{1T}\}$, for $\tau = 1,2...,\eta$, the $\beth$ *length-T* trajectories of coefficients of MODWT $\tilde{\text{Ш}}_\varsigma = \{\tilde{\psi}_{\varsigma 1}, \tilde{\psi}_{\varsigma 1}..., \psi_{\varsigma,T-1}\}$,for $\varsigma = 0,1...,\beth$ is gotten. WAMCC can be calculated as shown in Eqn. (4).

$$\hat{\zeta}m,\pi(\phi_\varsigma) = \frac{Corr\left(\tilde{\psi}_{\tau\varsigma t},\ \bar{\bar{\psi}}_{\tau\varsigma t+\pi}\right)Cov\left(\tilde{\psi}_{\tau\varsigma t},\ \bar{\bar{\psi}}_{\tau\varsigma t+\pi}\right)}{\left(Var(\tilde{\psi}_{\tau\varsigma t})Var\left(\bar{\bar{\psi}}_{\tau\varsigma t+\pi}\right)\right)^{\frac{1}{2}}} \tag{4}$$

Fernández-Macho (2012) uses the arctan $h(r)$ in formulating the WAMC confidence interval (CI), in place of the adverse overblown metric. The CI depends on the assumption of the grasp of $\mathfrak{X}$ in the estimate of WAMC and WAMCC and $\zeta\phi(\varrho_\varsigma)$ in equation (4), providing a broader thought of WAMC and WAMCC.

3.6. Descriptive Statistics

The significant differences and similarities in descriptive statistics across NAFTA nations in the analyzed variables are revealed in Table 2. For example, life expectancy (LNLEX) and urbanization (LNURB) exhibit less variation over the three countries, with similar mean and median values, suggesting relatively steady trends. In contrast, the contribution of renewable energy (LNRE) and CO_2 emissions ($LNCO_2$) exhibits increased variability, particularly noticeable in Mexico, presenting a peaked distribution associated with greater kurtosis for LNRE. Relatively lower variation is shown for economic growth (LNECOG) and technology innovation (LNTEI), which would incline to the left for Canada and the United States. In contrast, Mexico's data shows right-skewness for LNLEX and LNRE. The Jarque-Bera test result indicates the non-test of equality for most variables and more pronounced distributions that are normal in both instances, Mexico, the non-symmetry, and more peakedness. All this indicates demographic stability on the LEX index and URB and, parallel with it, variable environmental-economic dynamics, which would yield the complex interrelationships involving ECOG, RE, TEI, CO_2 emissions, and LEX in NAFTA countries. At the same time,

Table 2: Descriptive statistics

Canada	Variables	LNLEX	$LNCO_2$	LNECOG	LNRE	LNTEI	LNURB
	Mean	0.365308	0.524616	0.881046	0.245837	1.423815	1.423691
	Median	0.365734	0.528196	0.885283	0.245895	1.423824	1.423691
	Maximum	0.367498	0.534166	0.893812	0.257603	1.443781	1.443673
	Minimum	0.362405	0.505975	0.860342	0.234662	1.405511	1.405383
	Standard Deviation	0.001642	0.008249	0.010655	0.005255	0.01021	0.01021
	Skewness	−0.38482	−1.01525	−0.71755	−0.00647	−0.04112	−0.03991
	Kurtosis	1.638792	2.735046	2.075396	2.581406	1.919391	1.919683
	Jarque-Bera	41.56905	71.28273	49.54468	2.981604	19.96612	19.94876
	Probability	9.41E-10	3.32E-16	1.74E-11	0.225192	4.62E-05	4.66E-05
	Sum	149.0457	214.0434	359.4668	100.3015	580.9166	580.8661
	Sum Sq. Dev.	0.001097	0.027695	0.046208	0.011238	0.042424	0.042426
	Observations	408	408	408	408	408	408
Mexico	**Variables**	**LNLEX**	**$LNCO_2$**	**LNECOG**	**LNRE**	**LNTEI**	**LNURB**
	Mean	0.357978	0.50319	0.761834	0.088296	1.518425	1.518416
	Median	0.358801	0.508153	0.762952	0.088197	1.51945	1.51944
	Maximum	0.367794	0.519088	0.770491	0.107175	1.540292	1.540284
	Minimum	0.353388	0.46904	0.7481	0.058234	1.490352	1.490341
	Standard Deviation	0.002252	0.013819	0.006119	0.009915	0.014513	0.014514
	Skewness	0.427249	−0.74019	−0.71569	−0.60611	−0.2321	−0.23208
	Kurtosis	5.438901	2.243429	2.455614	3.493569	1.840033	1.840017
	Jarque-Bera	113.5329	46.98672	39.86894	29.1224	26.53697	26.53691
	Probability	2.22E-25	6.27E-11	2.20E-09	4.74E-07	1.73E-06	1.73E-06
	Sum	146.0549	205.3014	310.8282	36.02492	619.5175	619.5136
	Sum Sq. Dev.	0.002064	0.077728	0.015241	0.040009	0.085727	0.085739
	Observations	408	408	408	408	408	408
United States	**Variables**	**LNLEX**	**LNECOG**	**$LNCO_2$**	**LNRE**	**LNTEI**	**LNURB**
	Mean	0.362351	0.903229	0.714998	0.197542	1.606873	1.606855
	Median	0.362484	0.906153	0.7138	0.196429	1.608169	1.60815
	Maximum	0.365824	0.925585	0.724208	0.207406	1.620891	1.620871
	Minimum	0.359984	0.880034	0.699676	0.183146	1.586962	1.586945
	Standard Deviation	0.001338	0.0125	0.006195	0.005919	0.00967	0.00967
	Skewness	−0.14969	−0.31933	−0.13847	−0.17545	−0.37463	−0.37463
	Kurtosis	1.875423	2.138483	2.10399	1.837791	1.989925	1.989896
	Jarque-Bera	23.02306	19.5518	14.95197	25.05567	26.88765	26.88902
	Probability	1.00E-05	5.68E-05	0.000567	3.62E-06	1.45E-06	1.45E-06
	Sum	147.8391	368.5174	291.7193	80.59716	655.6041	655.5967
	Sum Sq. Dev.	0.000729	0.063591	0.015617	0.01426	0.03806	0.038055
	Observations	408	408	408	408	408	408

Figure 1 shows the correlation among the study variables for the countries under investigation.

The correlation plot in Figure 1 for Canada, Mexico, and the USA shows notably similar patterns, highlighting key regional nuances in the relations with CO_2 emissions, ECOG, life expectancy, RE, TEI, and URB. Across all countries, CO_2 emissions strongly correlate with economic growth, life expectancy, technological innovation, and urbanization, indicating that traditional growth pathways and urban development correspond with higher emissions. However, renewable energy consistently exhibits negative correlations with CO_2, ECOG, and LEX, underscoring its role in mitigating emissions and the challenges of integrating sustainability into growth and health services. Technological innovation and urbanization are closely correlated in each country, reflecting their mutual development as economic and social transformation drivers. While Canada and Mexico exhibit a more pronounced challenge in aligning renewable energy with urban and technological trends, the USA shows a broader agitation between renewable energy adoption and its traditional development pathways. These dynamics emphasize the shared complications of balancing growth, sustainability, and public health across economic contexts.

4. RESULTS AND DISCUSSION

Figure 2 shows the link between Life Expectancy (LEX) and CO_2 emissions in Canada, Mexico, and the USA. We observe a complex interplay shaped by time scales and regional dynamics. Across all three countries, short-term relationships are characterized by predominantly positive, non-directional coherence, reflecting a general alignment among life expectancy and carbon emissions trends. However, causality is weak, thus further proving that the link between CO_2 emissions and life expectancy (LEX) is complicated and multidimensional (Azam and Adeleye, 2023; Saidmamatov et al., 2024). Canada exhibits notable shifts, transitioning from positive to negative coherence over different periods. Mexico and the USA show more consistent positivity, with occasional negative phases signaling evolving environmental and health challenges, aligning with the divergent view of Mahalik et al. (2022), who found that in emerging countries, CO_2 hurts LEX, while in developing countries, CO_2

Figure 1: Correlation heatmap

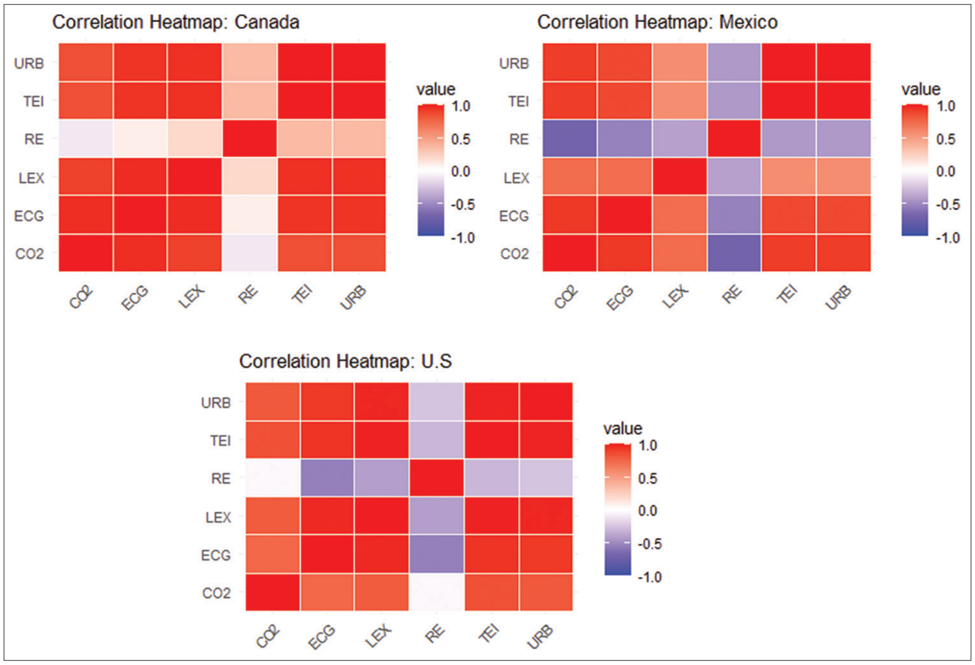
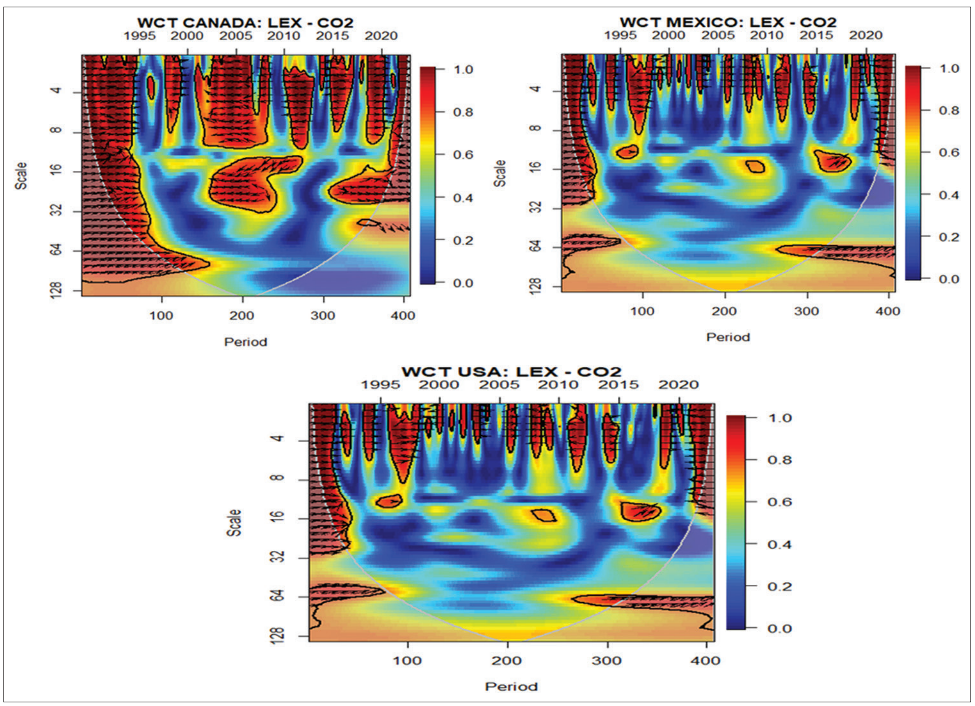


Figure 2: Co-movement between LEX and CO_2 emission in NAFTA



emissions increase LEX. In the medium term, all three countries highlight instances where LEX drives CO_2, indicating that health improvements may catalyze ecological progress, such as emissions reductions (Azam and Adeleye, 2023). The long-term analysis underscores a consistently positive coherence in Canada and Mexico, with LEX leading CO_2, suggesting that sustained health progress aligns with greater environmental awareness and action. This observation perfectly aligns with Matthew et al. (2020), who found that LEX responds positively for every 1% surge in the variable of CO_2 emissions, increasing by 0.123% in West Africa, proving that even though carbon is negative to agricultural output, it increases LEX through some routes. The USA follows a similar trajectory but has experienced negative long-term phases after 2011, reflecting the nuanced impact of emissions on health. These findings reveal that while regional differences exist, the interplay between life expectancy and CO_2 emissions is shaped by shared progress trends and environmental consciousness over time.

The dynamic interconnectedness between Life Expectancy (LEX) and Economic Growth (ECOG) in Canada, Mexico, and the USA is highlighted in Figure 3. This illustrates the intricate interplay

Figure 3: Co-movement between life expectancy and economic growth in NAFTA

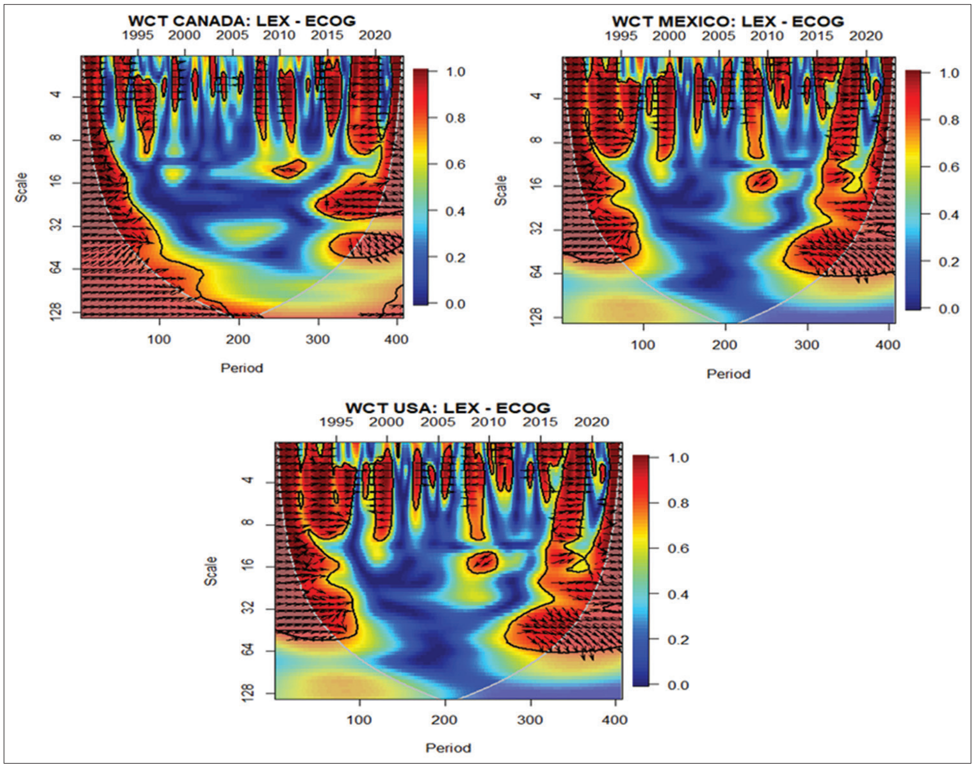
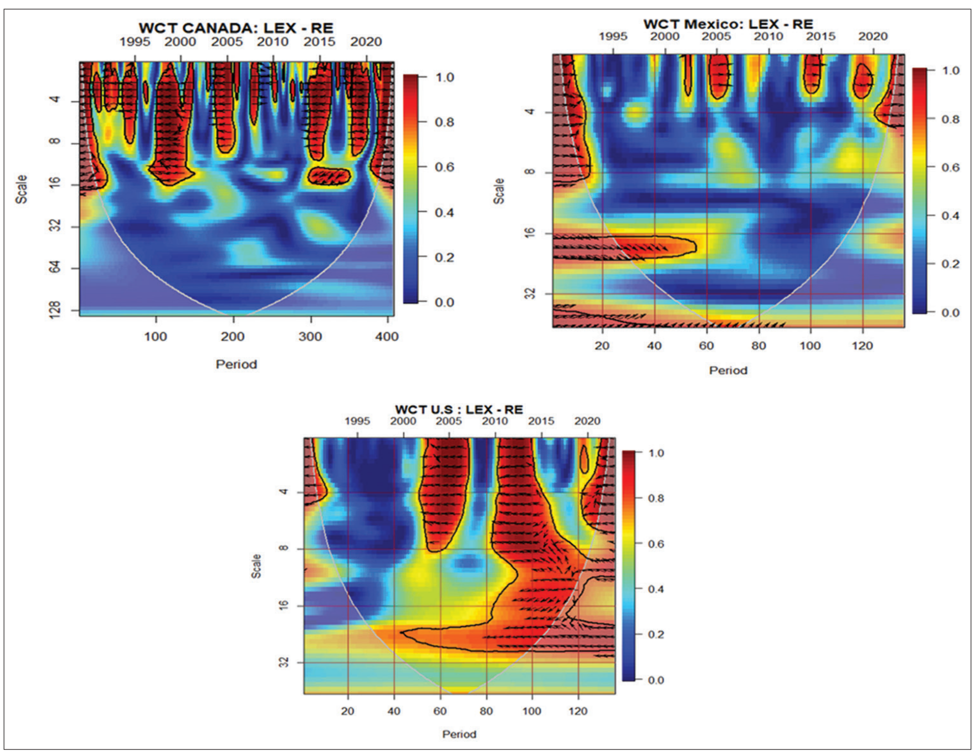


Figure 4: Co-movement between LEX and RE in NAFTA



between health and economic performance across different time scales. In the short term, all countries demonstrate predominantly positive, non-directional relationships, indicating general alignment but limited causality (Amin et al., 2024; Hendrawaty et al., 2022). Negative phases in Canada and Mexico highlight how economic fluctuations influence health outcomes during specific periods. Agrawal (2024), established the link among ECG, represented by the GDP per capita, and LEX; data for 20 countries were analyzed, and it found that LEX can be affected, although the influence of GDP growth might not be direct, while the USA shows consistent stability (Lawal et al., 2023). Medium-term dynamics show occasional negative coherence, with LEX leading ECOG in

Figure 5: Co-movement between LEX and TEI in NAFTA

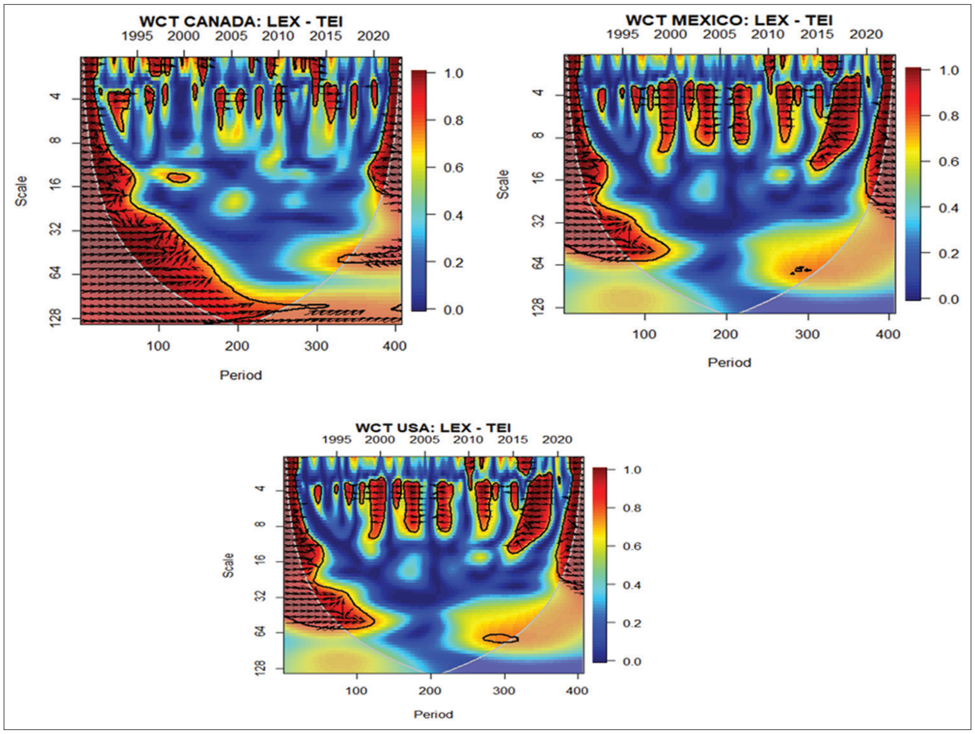
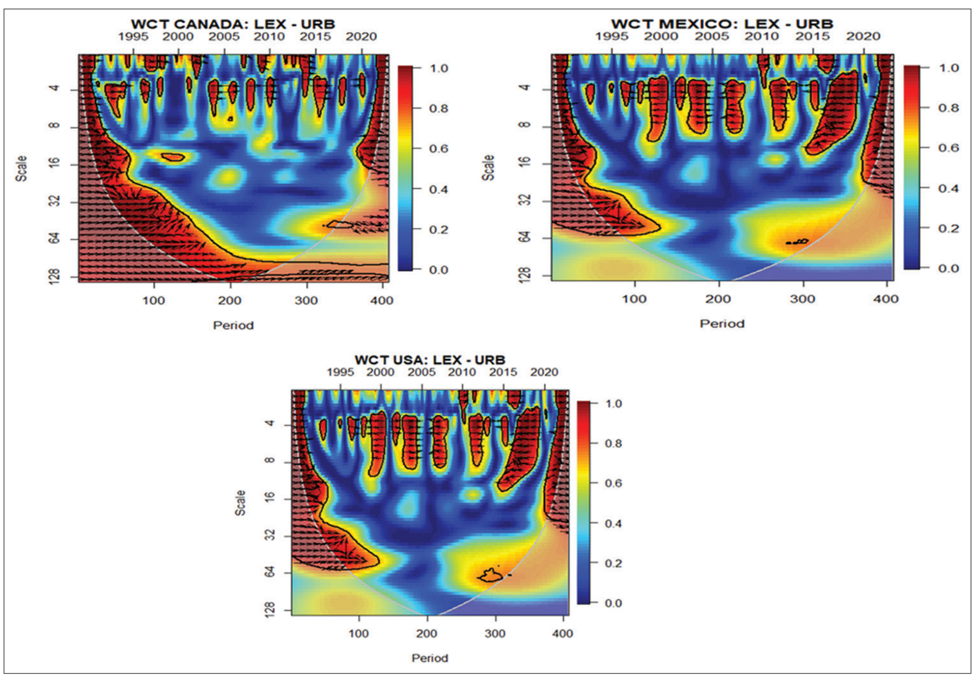


Figure 6: Co-movement between life expectancy and urbanization in NAFTA



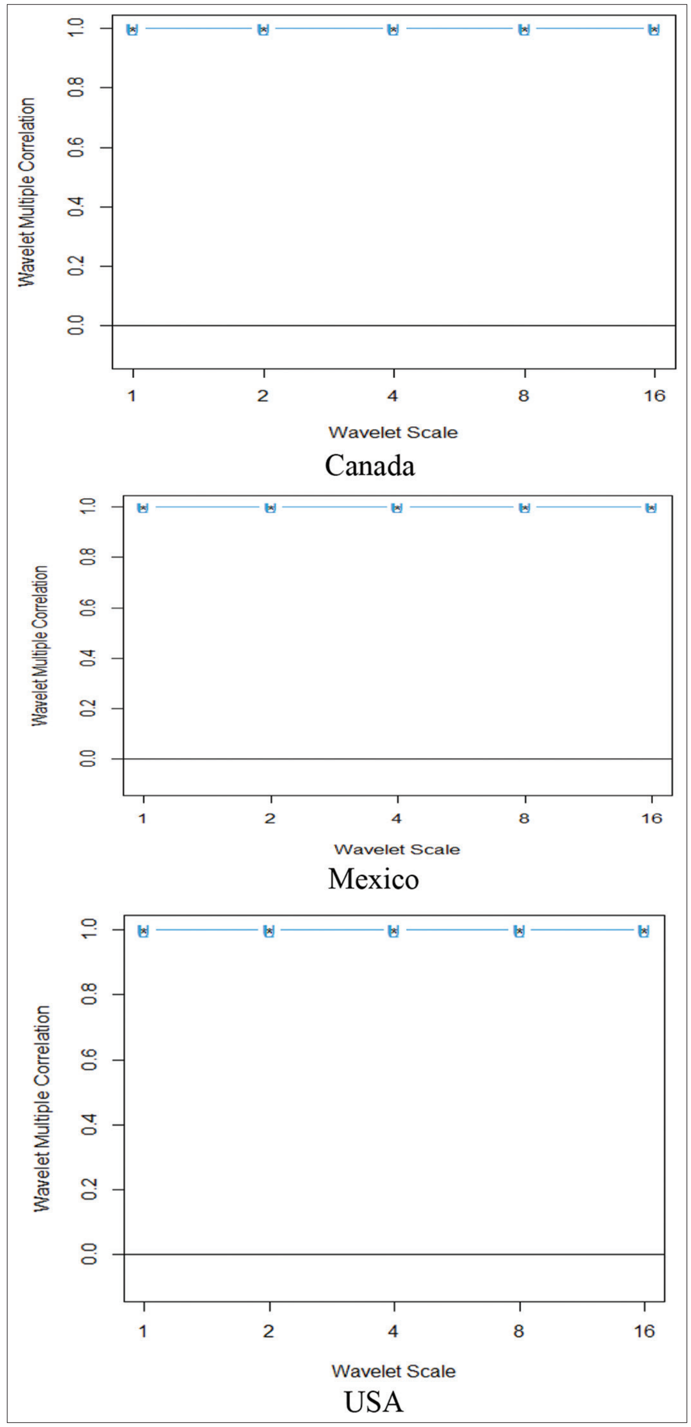
Mexico and the USA, suggesting that health improvements can act as a precursor to economic growth. Conversely, Canada displays sustained positive coherence, albeit non-directional, indicating persistent but unclear interactions. Over the long term, all countries exhibit positive coherence, with either ECOG leading or a bidirectional influence (Lawal et al., 2023). Canada and the USA emphasize the role of ECOG in supporting health advancements through improved living standards and healthcare. Thus, LEX is positively influenced by ECG, as represented by ECG, such that a 1% rise in ECG leads to a 0.014 upsurge in LEX (Bashir et al., 2022). At the same time, Mexico reflects mutual reinforcement, showcasing how economic and health progress can be intertwined over extended periods. These patterns underline the complex and evolving nexus between LEX and ECOG across diverse contexts.

Figure 4 highlights Life Expectancy (LEX) and Renewable Energy (RE) integration in Canada, Mexico, and the USA. The wavelet coherence highlights the complex interactions that evolve across time scales and periods. In Canada, the relationship is predominantly positive and non-directional across all scales, depicting a consistent alignment between renewable energy and life expectancy improvements; this discovery aligns with prior works that RE improves health outcomes through environmental quality, hence longevity (Yang et al., 2023). However, a shift to a negative phase suggests evolving dynamics, possibly influenced by changes in energy policies or the broader energy-health nexus. In Mexico, a positive, non-directional relationship exists at short-term scales. In contrast, medium- and long-term scales show RE-leading LEX, particularly post-2006, suggesting that renewable energy growth fosters better health outcomes through improved environmental quality; this also aligns with RE in the Nordic region correlates positively with LEX, showing that investment in RE is associated with sustainable economic growth, favoring good health and a longer LEX (Dai et al., 2024). Conversely, the USA presents a more complex picture, with a predominantly negative relationship in the short term, potentially indicating the challenges of energy transitions (Wiredu et al., 2023). Yet, a positive shift emerges in the medium term, where LEX drives RE, pointing to the role of health advancements in promoting RE investments. Across all countries, the interplay between LEX and RE underscores how renewable energy transitions and health outcomes are interdependent, with varying lead-lag dynamics reflecting country-specific contexts and temporal shifts (Ebhota et al., 2023).

Figure 5 presents the co-movement between Life Expectancy (LEX) and Technological Innovation (TEI) in Canada and Mexico. The USA, which reveals a consistent positive relationship across time scales, underscoring a robust synergy between technological advancements and public health improvements, further aligns with prior works. As all these linked issues suggest, TEI may produce health improvements that assure longer lives (Sampene et al., 2024; Zhang et al., 2021). In Canada, the relationship remains primarily positive and non-directional across all scales, with long-term coherence showing LEX leading TEI, suggesting that rising life expectancy may drive demand for technological advancements, particularly in health-related fields (Baldanzi et al., 2019). In like manner, Mexico exhibits a predominantly positive relationship. However, medium-term coherence reveals TEI leading LEX in recent periods, emphasizing the critical role of technology in driving health improvements despite occasional short-term negative phases reflecting transitional dynamics. In the USA, the relationship is mainly positive and non-directional across all scales and periods, indicating a stable alignment where technological innovation and life expectancy mutually reinforce each other in a dynamic balance. Considering all things, the findings across these nations highlight the integral role of technological progress in shaping public health while revealing feedback loops where improved health outcomes catalyze further innovation (Baldanzi et al., 2019; Gehringer and Prettner, 2017).

The multifaceted link between life expectancy (LEX) and urbanization (URB) in Canada, Mexico, and the USA is displayed in Figure 6. We observe a predominantly positive and non-directional relationship, reflecting a strong and consistent alignment between urbanization and public health improvements across most time scales and periods. In Canada, the relationship is marked by mutual reinforcement, with urbanization promoting better healthcare access, improved infrastructure, and enhanced standard of living,

Figure 7: WAMC results between LEX and (CO_2, ECOG, RE, TEI, and URB)



supporting long-term health improvements. Distinct from prior works, URB adversely influences the LEX in South Asia. However, health expenditure perhaps moderates the effects, suggesting that better health facilities are integral to improving LEX in urban areas (Ahmad et al., 2023). Also, in the ASEAN-5 countries, the URB hurts LEX and reflects health challenges associated with rapid urban development. Strategic urban planning and healthcare investment will be needed to reduce risks and improve LEX (Amin et al., 2024). Mexico exhibits a largely positive relationship, with urbanization fostering life expectancy gains, though occasional negative phases

Table 3: Summary results of WAMC between LEX and factors

Countries	Scales	WAMC
Canada	D1	0.9999
	D2	0.9999
	D3	0.9999
	D4	0.9999
	D5	1
Mexico	D1	0.9999
	D2	0.9999
	D3	0.9999
	D4	0.9999
	D5	1
USA	D1	0.9999
	D2	0.9999
	D3	0.9999
	D4	0.9999
	D5	1

at medium-term scales, suggesting potential challenges tied to urban development (Ebeling et al., 2022). In the USA, the relationship is also mostly positive, indicating that urban settings consistently provide socioeconomic and infrastructural benefits that promote life expectancy (Tripathi, 2021). However, short-term negative phases highlight potential disruptions or inequalities within urban growth, particularly in the medium term. Ultimately, the conclusions emphasize the crucial role of urbanization in driving public health advancements while acknowledging the complexities and transitional impacts in each nation.

4.1. Multiple Correlation Estimation Outcomes

The outcomes of the WAMC calculations for the synchronous amalgamation of the elements that influence LEX are shown in Figure 7. We observe a similar and strong integration between variables across all economies in NAFTA. The results highlight the uniformity of integration across various frequencies, with all individual countries showing the most significant (100%) and lowest (99.99%) values in the very long (intermediate) term. The chosen factors (CO_2, ECOG, RE, TEI, and URB) collectively justify the uppermost percentage values of the disparities in LEX when all other variables are held constant, according to a desultory analysis of these results. This indicates the significant influence these factors have on LEX in NAFTA. In contrast to the bivariate analysis's inconsistent (mix of weak, moderate, and vigorous) results, these data's constant near-perfect correlations across all frequencies demonstrate their synergistic nature. These nuanced findings indicate that these factors are essential drivers of LEX differences across all scenarios and should be prioritized when monitoring the factors impacting LEX changes in NAFTA nations. The second column of Table 3 offers an instance of these discoveries.

5. CONCLUSION AND POLICY DIRECTIONS

It has been shown that the timeframes and the regions of the countries of NAFTA become explicable solely through the dimensions of life expectancy (LEX), CO_2 emissions, economic growth (ECOG), renewable energy (RE), technological innovation (TEI), and urbanization (URB) in how they interact and relate to each other, and the relevance of this framework becomes visible by Sustainable Development Theory. Empirical findings revealed strong and vital relationships between timeframes and regions, emphasizing the contribution of RE and technology-based innovative resources to improving LEX and environmental quality. The effects of urbanization and ECOG are mixed, and their outcome varies from state to state and is contingent on the character of specific primary dynamics and infrastructure quality. WAMC analysis shows that in any case, one has to include them among the main synergistic factors; it thus might work as a perfect reason for different actions under policy and sustainability initiatives around what life expectancy at NAFTA can motivate. Achieving sustainable development in NAFTA countries requires coordinated and actionable policies that align environmental sustainability, economic growth, and social well-being. The study highlights the interconnected roles of RE, urbanization, technological innovation, and health outcomes, accenting the need for integrated and targeted policy interventions. Below are the key policy directions tailored to address these challenges and leverage the opportunities identified.

To begin with, policies allowing the governments in NAFTA countries to fill the gaps between public health, energy development, and environmental protection should come first. Targeted investment in renewables infrastructure and clean technologies simultaneously reduces carbon emissions and improves health outcomes by reducing pollution-related health risks. Create cross-sectoral task forces or committees that unite key health, energy, and environmental ministries to develop and align economic growth strategies with sustainability goals. It will also mean regional cooperation of policymakers under NAFTA to integrate regulations and best practices to tackle cross-border environmental issues jointly. Furthermore, technological advancement should be a priority to address ecological sustainability and improve public health. Governments must step up agricultural research and development funding, particularly for their green technologies and health innovations. They should provide tax credits, grants, and subsidies to private-sector companies as incentives to invest in developing clean energy and health technologies. It would allow the establishment of regional innovation hubs and knowledge-sharing platforms within NAFTA for university-industry-policymaker collaboration. These will magnify the contribution of technological innovations to life expectancy, environmental quality, and economic resilience. Further, by exporting green technologies, these countries could be positioned as global leaders in the green agenda.

Also, urbanization brings opportunities but also introduces challenges for public health and environmental sustainability. Urban planning should major in infrastructural development that benefits all people, particularly in energy-efficient public transport, green building codes, and affordable housing for countries like Mexico, due to their peculiar urban dynamics. Innovative solutions in cities, such as waste-to-energy systems and sustainable water management solutions, would make cities better living environments. All differences must be honestly addressed within urban areas, focusing on underserved areas so that all citizens can benefit from improved living conditions. Besides, policies for sustainable cities should also consider healthcare access and emergency response systems to avert possible health risks that could arise from accelerated urbanization. These targeted policy measures will provide a perfect win for NAFTA member countries in that trifecta balancing act: economic progress, environmental sustainability, and public health. Besides, these measures will address the problems and make this region well-positioned to be a global leader in sustainable development for future generations.

While the current study offers a ground-breaking novelty, future studies can be broken down into more specific and localized data that studies localized impacts or variations in the newly studied relationships; though currently constrained by data, additional factors that could potentially be looked at involve health infrastructure, environmental regulations, or education to understand their potential contribution to life expectancy. Also, future studies could explore the different sectors, like manufacturing, agriculture, or energy, and their contribution towards sustainability and health outcomes. These future research directions would allow for a richer understanding of the factors that achieve sustainable development and public health, and develop a finer scale and more nuanced understanding.

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