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Research Article

Assessing the role of circular economy and green innovation in mitigating carbon emissions in the Visegrad countries

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Abstract. The shift towards a circular economy is an essential measure in achieving sustainable development because it seeks to separate economic expansion from resource use and environmental deterioration. To meet the European Union green deal, waste management, and the net zero emissions targets various countries are developing and adopting prudent strategies. This study investigates the dynamic affiliation between circular economy (CIR), green innovation (INV), renewable energy (REE), economic progress (GDP), and urbanisation (URB) on carbon emissions (CO2) in the Visegrad (V4) countries, comprising the Czech Republic, Hungary, Poland, and Slovakia. Using the CS-ARDL technique and quantile regression, data curation from 1990-2022 was analysed after checking for cross-sectional, unit root, and cointegration. The outcome demonstrates that circular economy, green innovation, and renewable energy had a negative effect on carbon emissions. In addition, GDP and URB had an immaterially positive influence on carbon emissions. Lastly, the quantile regression confirmed that the study provides useful information for policymakers and stakeholders in the Visegrad countries. It emphasised how important it is to take a broad approach to circular economy initiatives, support eco-friendly innovations, carry out renewable energy projects, and manage the urbanisation process well to achieve long-term economic growth and environmental health.

Keywords: Circular Economy, Green Innovation, Renewable Energy, Urbanization, CS-ARDL, Visegrad Region.

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1. Introduction

Climate challenges and ecological principles have made waste management a priority for EU communities, with the aim of extending the life cycle of products (Figge & Thorpe, 2023; Rahothan et al., 2023). The European Union's ultimate objective is to establish a society that is both carbon neutral and focused on recycling. This entails minimising trash and utilising any unavoidable garbage as a valuable resource to reduce greenhouse gas emissions. Issues associated with linear economies and increased urbanisation have caused many nations to transition to a circular economy (Akhimien *et al.,* 2021; Yang *et al.,* 2023). Previous investigations have demonstrated a link between environmental degradation and urbanisation, economic progress, and non-renewable energies (Chen *et al.,* 2023; D. Liu, 2023; Yao *et al.,* 2023). As the population grows, businesses and industries consume non-renewable energy more. This leads to high carbon emissions (Adebayo *et al.,* 2023; Voumik, Mimi, *et al.,* 2023). The Visegrad is a group of four communities (Poland, Slovakia, Hungary, and Czech Republic). The Visegrad nations accounted for about fourteen percent of the total EU population. With the free movement between nations, the unprecedented problem of growing supply to meet increasing demand has arisen since the world population topped 8 billion in late 2022, and the demand for natural resources continues to rise. During the Budapest 2021 forum, all the nations agreed to nine principles to meet the 2050 net zero carbon neutrality, with the circular economy included.

As documented by Sasmoko et al. (2022), the transition from linear to circular economy illustrated the 6R of reducing, reusing, recycling, repurposing, remanufacturing, and rethinking. There is a pressing concern about shifting from linear to circular to address waste management and energy challenges. The shift serves as a significant step towards a sustainable planet (Cainelli *et al.,* 2020a; Corvellec *et al.,* 2022). Industrial areas in the Visegrad Group can transition to more sustainable and resilient development models by adopting circular economy practices. This shift is crucial to mitigating the negative effects of urbanisation, such as increased energy consumption, pollution, and strain on natural resources. Dutta & Hazarika (2023) demonstrated that urbanisation and economic progress appreciate carbon emissions in 68 countries based on panel data from 2000-2019. Xie *et al.* (2023) empirically selected 42 counties under the BRI and evaluated the link between urbanisation and carbon emissions. The

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findings illustrated that restructuring industrial activities through ICT initiatives reduced environmental calamities. Additionally, Lv *et al.* (2023) employed the STIRPAT model in China to examine the relationship between URB and environmental deterioration. According to the empirical analysis, a 1% increase in urbanisation rate leads to 47.04% in carbon emissions. To address the issue of urbanisation and its externality effect, urban green space and management have recently been seen to answer it. (Baxevani *et al.,* 2024) examined citizen concern about green space in the city of Thessaloniki in Greece through a questionnaire. The empirical findings demonstrated that citizen awareness of urban green was limited and that policy initiatives on urban green space campaigns should be increased.

Next, circular economy, as a regenerative alternative to the traditional linear "take-make-dispose" model, necessitates a comprehensive rethinking of production and consumption patterns (Cainelli *et al.,* 2020; Velenturf & Purnell, 2021). Embracing green innovations involves the development and integration of technologies that minimise environmental impact, enhance resource efficiency, and contribute to the sustainable management of materials throughout their life cycles (Shah *et al.,* 2023; Yang *et al.,* 2023). This transformative approach not only addresses environmental challenges but also presents economic opportunities and societal benefits (Chen *et al.,* 2022). On the principle of mitigating waste and smart city development in China, Liu *et al.* (2022) examined China's 30 province policies of employing green innovation to mitigate carbon emissions. The findings show that provinces' adoption of green innovation resulted in a reduction in high carbon intensity, with the effects spreading to neighbouring provinces. Safi *et al.* (2023) conducted a study in Central and Eastern Europe, exploring various approaches to carbon pricing in both the long and short term. The study found a greater causality between carbon policy, emissions, and green innovation, both unidirectionally and bidirectionally. Huang & Guo's (2023) investigation of the MENA community identified a similar outcome. According to the panel data analysis from the MMQR model assessment, green innovation has a bidirectional nexus with carbon emissions.

Again, as the world grapples with escalating environmental concerns, ranging from climate change to resource depletion, the imperative for patent application becomes more pronounced (Passaro *et al.,* 2023; Zhu *et al.,* 2023). The challenges posed by a linear economy are apparent, and the urgency to adopt circular practices has become a global imperative. Dai *et al.* (2023) delves into the material role of enabling technological innovations in the realisation of a circular economy, exploring the key drivers, barriers, and emerging trends that shaped the discourse. The CIR concept has emerged as a material strategy that promotes resource efficiency, waste reduction, and the ongoing reuse of materials within a closed-loop system. At the heart of this paradigm shift lies the imperative to foster technological innovation that enables the transition towards circularity (Liu *et al.,* 2023; Sun *et al.,* 2023). Assessing the adoption of innovative technologies for waste sorting, recycling, and treatment is crucial. Smart waste management solutions, such as sensor-based bins and data analytics, can optimise collection routes and resource utilization. Investigating the technological landscape can highlight opportunities for efficiency gains. Saqib *et al.* (2023) evaluated the relationship between different income-level technologies and carbon emissions. Their findings show that carbon patents have different effects across countries, with research and development having an immaterial association with carbon emissions depreciation.

The evaluation of this investigation will close the gaps on the interplay between urbanisation, green innovation, renewable energy, and the circular economy, which is insufficient, despite the increasing emphasis on sustainability in the Visegrad region. There is a lack of substantial evidence regarding the Visegrad countries' implementation of green urbanization and the circular economy, despite the increasing global prominence of these concepts. This oversight has left concerns about practicality, barriers to adoption, and region-specific challenges unresolved. Moreover, studies often examine renewable energy and circular economy efforts in isolation, overlooking the potential synergies

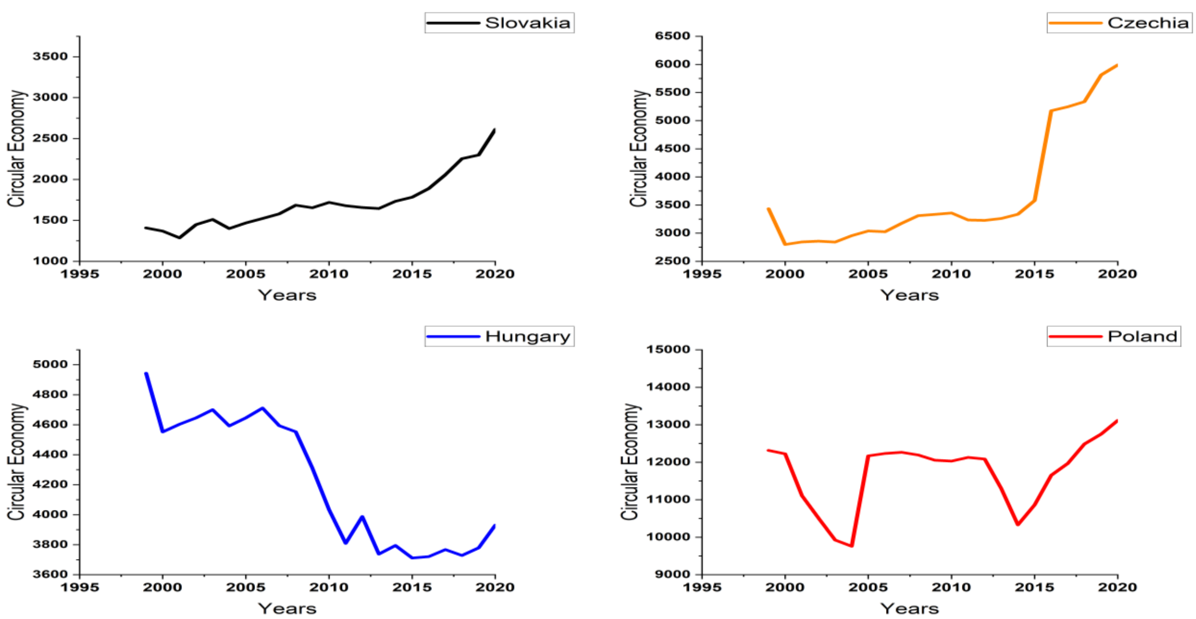

Fig 1. Trend of variables in Visegrad regions

that may arise from their integration with green innovation and urbanisation. This compartmentalised strategy overlooks the broader benefits of a comprehensive sustainability paradigm in a context characterised by unique socio-economic and political conditions. The lack of longitudinal data regarding the impact of these sustainability programs on the social equity, environmental outcomes, and economic resilience of urban areas over time represents a significant deficiency. Most studies solely focus on short-term effects, constraining our understanding of how these strategies can facilitate long-term sustainable growth. There is a lack of comprehensive policy research in the Visegrad region regarding the role of governance in facilitating or constraining green innovation and circular economy practices. A comprehensive examination of how legislative frameworks, economic incentives, and stakeholder engagement influence sustainability outcomes is essential for the region's transition to a sustainable economy.

Therefore, the Visegrad group is being considered for this research as they encompass a wide variety of economic structures and phases of growth, which adds to the uniqueness of this investigation. As encapsulated in Figure 1, the trend displayed the co-movement of the variables in the period 1999–2022. The regions collaborate to develop circular economy models and principles to meet the EU's green sustainability and green deal agenda. Exploring the interplay between these elements of carbon emissions, circular economy, urbanisation, green innovation, renewable energy, and economic progress within the groups, the investigation will provide a significant step towards circular economy. The STRIPAT model first explores these elements in the Visegrad group of communities through a thorough evaluation. The evaluation closes literary gaps and contributes to a causal affiliation between carbon emissions, circular economy, urbanisation, green innovation, renewable energy, and economic growth within the Visegrad groups. We adopt robust econometric approaches such as the CS-ARDL, as empirical inspection has confirmed their ability to withstand cross-sectional dependency. We employ the quantile regress to analyse the various long and shortchanges at different stages.

The following is the structure of the paper, which is based on Part 1 introduction; Part 2 delves into the existing literature, while Part 3 centres on the research methods, data, and empirical model. Part 4 presents the empirical findings and discusses them, and Part 5 shows the conclusion and policy implications.

2. Literature review

With the scarcity of resources and the efficient utilisation to improve the economy and reduce impact on the environment, the decision to move from linear to circular has become the material policy for institutions, governments, and pressure groups. Recent inspections have demonstrated that environmental quality and the road to zero carbon neutrality are possible through circular economy (Safi *et al.*, 2023; Zhang *et al.,* 2023). Urbanisation, green innovation, patent application, digitalisation, and environmental tax are material in depreciating carbon emissions (Njie *et al.,* 2024; Prempeh *et al.,* 2024).

2.1 Circular economy and carbon emission nexus

Moving toward a circular economy means reducing the amount of waste produced, increasing the efficiency with which resources are used and encouraging people to reuse, recycle, and repurpose items. Reduced utilisation of energy and raw materials is one way these principles help reduce carbon emissions from industry and resource extraction (Vogiantzi & Tserpes, 2023). There are significant obstacles that must be overcome as Visegrad communities keep pushing toward the limits of the circular economy. A major obstacle to the broad use of environmentally friendly technology is the enormous financial outlay required to finance necessary infrastructure upgrades and capacity-building programs. In the context of Saudi Arabia, Almulhim (2024) evaluated the different circular economy approaches to mitigate environmental damages associated with the SDGs 1 and 2. The outcome demonstrated that a holistic strategy is required to meet Saudi Arabia's 2030 projects. From the BRICS perspective, Tauseef et al. (2023) employed an econometric model of the CUP-FM and CUP-BC approaches to investigate the elements of nuclear and renewable energy utilization.

The findings illustrated that the abatement of environmental damage was mitigated through environmental innovation. (Thapa *et al.,* 2024) explored the EU and Vietnam waste trade affiliation. The European communities export about fifty percent of their waste. The findings predicted that without proper waste governance, soon the world will enter a waste curse in less emerging communities. In China, Yu *et al.* (2023) investigated waste trade within the mining sector between 1980 and 2021. The empirical inspection established that 0.15 and 0.07 percent were identified in the short and long term, respectively, from mining waste trade. In addition, the literature study has shed light on the pros and cons of the connection between carbon emission reduction and the circular economy (Figge & Thorpe, 2023; Sauvé *et al.,* 2021).

2.2 Green innovation and carbon emissions nexus

Governments and pressure groups are requesting sustainable means to cure carbon emissions and other climate-related changes, with environmental sustainability debate increasing recently (Safi *et al.,* 2023; Skordoulis *et al.,* 2020). Zafeiriou *et al.* (2022) employed resource base growth in the analysis of Greece energy and mineral exploitation. Their research findings show that Megalopoli and West Macedonia, with high-lignite industries, are transitioning to renewable energy. In China, Chau *et al.* (2023) explored environmental degradation and eco-innovation partners for the years 1988-2020. The nonlinear regression analysis shows that innovation influences carbon emissions negatively, according to the evaluation. To curb carbon footprint in MENA regions, Vu et al. (2023) employed CS-ARDL and the robust CCEMG to analyse panel data sets between 1990 and 2017. The results demonstrate that while factors like financial inclusion and economic progress appreciate carbon footprints, eco-innovation has a reducing effect on emissions. Zhu et al. (2023) identified additional outcomes in E7 communities. Their investigation revealed that ecological innovation and improved agricultural land development can enhance ecological quality. Mehmood *et al.* (2024) identified various perspectives on how eco-innovation impacts climate change to achieve net zero mitigation in the context of South Asian states. The econometric analysis depicted a favourable link between eco-innovation and carbon emissions. We conducted a systemic review of SMEs (Passaro *et al.,* 2023) and assessed articles that identified the various eco-innovation methods employed by SMEs. The article's analysis illustrates the key eco-innovation areas, including research and development, incentives, networking, culture, regulation, and technology factors. In Lithuania, Peyravi *et al.* (2023) explored the pathways to European ecological policy. Their evaluation results indicated that Lithuania is low in eco-innovation; influence from the EU regions has led to improvements in their emissions patterns. Employing the EKC model in India, Wang *et al.* (2023) examined the affiliation between eco-innovation and carbon emissions. The econometric analysis derived from the ARDL regression estimation indicates a decrease in ecological footprint due to eco-innovation between the years 1975 and 2017. Recently, Fatma & Haleem (2023) conducted a bibliometric investigation into eco-innovation of 723 articles from top published journals. Their results demonstrated that the trend toward mitigating ecological footprints, sustainable communities, and zero emissions is the development and implementation of eco-innovation by governments and industries.

2.3 Urbanization and carbon emissions nexus

The issues of urbanisation and pollution appreciation within the region are unthinkable (Kyriakopoulos et al., 2018). Urban green space management and planning involve the design, maintenance, and regulation of green areas in cities to promote environmental sustainability, public health, and urban life quality. These verdant areas encompass parks, gardens, urban trees, and green roofs. Dutta & Hazarika (2023) delve into the STIRPAT model on the affiliation between urbanisation and emissions among 168 economics. For the period 2000-2019, FMOL was employed to investigate Asian, African, Middle Eastern, and Southern American nations. The findings demonstrated that urbanisation and per capita had an appreciation relationship with carbon emissions. On a dual-carbon framework based, Tan *et al.* (2023) evaluated the mechanism of depreciating carbon emissions with urbanisation through coupling and coordination. The results show that prompting regional urbanisation within the construction areas leads to a carbon depreciation between 0.1538 and 0.4809. L. Xie *et al.* (2023) selected 42 BRI nations to study the effect of urbanisation and carbon emissions. The study used Driscoll-Kraay panel regression and panel moment quantile regression. The results illustrated that urbanisation had an unfavourable effect on carbon emissions. However, economies with high ICT exhibited a reduction in carbon emissions. In the case of H. Liu *et al.* (2023), they investigated carbon emissions from the variables of economic growth, energy consumption, and urbanization. Utilising the ARDL approach as an empirical evaluation of data from the period 1995-2020. The findings demonstrated no affiliation between urbanisation and carbon emissions.

On the global perspective, Chen et al. (2023) studied 125 economics urbanisation spillovers on carbon emissions. The bivariate spatial analysis established that urbanisation and carbon emissions had an invested U shape. Yao et al. (2023) studied urbanisation in China provincial regions for the period 200-2019. The empirical results show that urbanisation and carbon emissions had an N shape different from the literary U shape. This finding was attributed to local urbanisation and regional environmental policy. The ARIMA approach evaluated a recent zero carbon study in China (Xiaomin & Chuanglin, 2023). From a provincial perspective panel data, the kernel density and quantile estimated indicated that increasing urbanisation in the south had a favourable nexus with carbon emissions. However, the northern provinces had low carbon emissions with quality environmental policies. Similarly, Lv *et al.* (2023) tested the heterogeneity of the threshold STIRPAT model. Panel data set from 2003-2015 on China provincial urbanisation and carbon emissions. The results indicate that forty-seven percent of the increase in urbanisation leads to twenty-three percent contribution to carbon emissions. However, additional increases in urbanisation appreciate carbon emissions by seventy-eight percent.

2.4 Economic progress and carbon emissions nexus

The development of nations comes with its environmental externalities as resources are depleted, such as energies, raw materials, and urban expansion. When the world witnessed the COVID-19 pandemic, industrial activities were shut down, leading to a reduction in the carbon footprint levels (Papadogiannaki *et al.,* 2023; Yassine & Sebos, 2024). In Sub-Saharan Africa, Li *et al.* (2023) examined economic progress within thirty low-income nations for the period 1995-2016. The evaluation depicted energy consumption within rural communities that appreciated economic progress with no effect on carbon footprint. They suggested that a decrease in energy consumption reduced pollution. Khan *et al.* (2023) explored economic progress among the Belt and Road initiative communities. Employing the GMM econometric approach, the findings illustrated that appreciation in carbon emissions is associated with economic growth, foreign investment, and income inequality. Panel data from 1985 to 2019 from 35 Belt and Road Initiative nations yielded similar results (Khan *et al.,* 2023). They stated that natural resources and economic development had materially increased environmental deterioration. In terms of Southeastern Europe, Mitić et al. (2023) delve on the affiliation between economic progress, employment, and carbon emissions between 1995 and 2019. The causality illustrated a long-run unidirectional nexus between the indicators. However, Shen *et al.* (2023) reveal an inverted U-shaped affiliation between economic progress and carbon emissions across the various regions of China. The illustration based on impulse responses reveals that both the western and eastern regions of China have reduced their pollution levels. Between 2001-2020, Wang *et al.* (2023a) explored 24 countries with high energy consumption from various sources like oil, natural gas, coal, and nuclear. The empirical analysis demonstrated that Canada, South Korea, Finland, the UK, and Slovenia consumption of nuclear energy had a positive link to economic progress with a reducing effect on carbon emissions. Exiting literary investigations have demonstrated a link between economic progress and carbon emissions. Razzaq *et al.* (2023) inspected 10 countries with the highest GDP (Xie *et al.,* 2023) as drivers of carbon emissions in China for the period 1978-2020, and on global regional analysis (Huang & Guo, 2023) explored SSA, MENA, SA, ECA, AC, and EAP.

2.5 Renewable energy and carbon emissions affiliation

The demand for renewable energy is increasing due to the threats posed by climate change to both mankind and natural resources. The V4 group is the leader in the consumption of non-renewable energies in Europe. Renewable energies come with high costs in their implementation, as governments need funding for research and development into the projects. Hosan *et al.*'s (2024) exploitation on energy innovation and social equity within 23 developed countries highlighted that proper allocation and utilisation of public energy innovation investments are essential to promote clean energy technologies, advance the just energy transition, and improve social equity, inclusion, and community engagement. Following the EU's three policies on competitiveness, sustainability, and energy security to achieve a clean energy region, Arabatzis *et al.* (2017) investigated various renewable energies within Greece. Their studies on clustering of renewable energy plants help to reduce consumption of fossil fuels. On a panel data evaluation of 24 countries, Wang *et al.* (2023b) delve into the nuclear and REE utilisation effects on carbon emissions. The results showed that the combination of nuclear and renewable energies significantly reduces carbon emissions. Adebayo et al. (2023) explored technological innovation and renewable energies to decrease emissions within the BRICS economics for the period 1990-2019. The causality and robustness empirical results depicted that there exists unidirectional and decreasing effect affiliation between REE and C02. In Kenya, Chandra et al. (2023) adopted the STIRPAT approach to inspect the influence of renewable energy on carbon emissions. The ARDL estimator illustrated an inverse nexus between REE and carbon emissions in the long run, according to the findings. Likewise in China, Chen et al. (2023) investigated China's five-year policy agenda of depreciating carbon emissions by 2025. The greater causality empirically shows that China's economy relies on no renewable energies, leading to an increase in air pollution. With a void in literary investigations (Li *et al.,* 2023) highlighted policies to adopt in renewable energy to mitigate carbon emissions within the BRICS communities. The quantile and CCEMG estimates demonstrated that renewable energy reduced carbon emissions through eco-friendly taxes and subsidies. Crucial to the zero-emission target, Erdogan *et al.* (2023) evaluated G7 states investments in renewable energies. Their assessment empirically identified that G7 states investment in renewable energies is the cause of low emissions evidence.

2.6 Research gap.

While the discourse on economic progress, circular economy, green innovation, renewable energy, and urbanisation is gaining momentum in mitigating carbon emissions, there exist notable gaps in the existing literature, particularly concerning the Visegrad Group of communities. Firstly, there is a need for comprehensive studies that specifically explore the unique challenges and opportunities associated with elements in these nations. Factors such as urbanisation, green innovation, digitalisation, renewable energies, environmental taxes, and natural resource rent to transform from linear to circular. Secondly, the integration of circular economy principles into green innovation, economic progress, renewable energy, and urbanisation planning and policymaking remains an underexplored area in the literature. Research that examines the efficacy of circular economy strategies in addressing the complexities of these variables and their adaptability to the diverse contexts within the Visegrad Group is lacking. Additionally, the social dimension of sustainable development in the Visegrad countries requires further attention. Understanding the impacts of these elements on community dynamics, social equity, and the well-being of diverse populations is crucial for formulating inclusive and effective policies. The investigation employs robust methods and analytical techniques of the CSD, CIPS, CADF, CS-ARDL, and QR models.

3. Theoretical model

The STIRPAT model is a commonly employed paradigm for examining the influence of different factors on environmental outcomes. The concept is derived from the IPAT identity, which posits that environmental impact (I) is determined by the combined influence of population (P), affluence (A), and technology (T). The IPAT model ($\mathrm{I} = \mathrm{aP^b\,A^c\,T^d}\epsilon$) provides a sophisticated foundation for discerning the drivers of environmental changes (Dutta & Hazarika, 2023; Saqib et al., 2023). Its primary strength lies in its ecological grounding and its materiality to elucidate how alterations in driving forces are likely to impact environmental outcomes. However, a notable limitation of the IPAT model is its technique of fixed proportionality variations between effects and factors, overlooking the potential for non-proportional and non-monotonic effects. To address these limitations, the IPAT model underwent reformulation, resulting in the development of a stochastic model known as STIRPAT. This stochastic model captures the stochastic impacts through regression analysis on affluence, population, and technology. Scholars have expanded the STIRPAT model by integrating additional proxy variables to explore the multifaceted influences on the environment. Kihombo *et al.* (2021) utilized the STIRPAT model to investigate the impact of innovation on green total factor efficiency. In another instance, Dutta & Hazarika, (2023) applied the STIRPAT model to explore 68 communities with low to middle income on the affiliation between urbanization and carbon emissions. Additionally, Tan *et al.,* (2023) inspected the STIRPAT model to examine the relationship between environmental outcomes, wealth, population, and technology across 27 Chinese provinces. Therefore, this study leverages the STIRPAT model to scrutinize the impact of technological innovation on eco-efficiency in China. The utilization of the STIRPAT model allows for a comprehensive analysis that considers the stochastic nature of environmental impacts and incorporates a range of influencing factors beyond the traditional variables of affluence, population, and technology. By doing so, this research contributes to the evolving body of knowledge on the complex interactions between technological innovation and environmental efficiency, utilizing a well-established theoretical framework with demonstrated applicability in diverse contexts. The empirical equation was inspected on the variables as follows,

$$CO2 = f(CIR, INV, GDP, REE, URB) \quad (1)$$

Literary evaluation suggests that transformation of elements to the natural logarithm depreciates the issues of econometric bias (Sampene et al., 2023, 2024).

$$InCO2_{i,t} = \delta_0 + \delta_1 InCIR_{i,t} + \delta_2 InINV_{i,t} + \delta_3 InGDP_{i,t} + \delta_4 InREE_{i,t} + \delta_5 InURB_{i,t} + \varepsilon_{i,t} \quad (2)$$

Emerge from the above equation, In depicted the log function, the elements proxied by CO2 - carbon emission, CIR - circular economy, INV - green innovation, economic progress – GDP, REE - renewable energy, URB – urbanization. $\lambda_1 - \lambda_6$ denoted the coefficients of the elements. The slop is derived as λ_0 with the error calculated with $\varepsilon_{i,t}$. (t) the data curation period 1999 – 2022 and (i) Visegrad communities. Table 1 encapsules the evaluation of construct measurements.

3.1 Method and material

This section illustrates the research econometric models leading to circular economy, urbanization, green innovation, economic progress, and renewable energy on carbon emission depreciation in the Vise grad regions (Czech Republic, Hungary, Poland, and Slovakia). Panel data covering the period of 1999-2022. With surge in environmental damages and the demand for net zero emissions, empirical assessment had shown that carbon emission is appreciating with incremental in

Table 1
Expound variables

Determinants	Source	Acronyms	Measurement Unit
Carbon emission	(WDI, 2023)	CO2	Kilotons (kt)
Renewable energy	(OECD, 2022)	REE	(% of total final energy use)
Green innovation	(OECD, 2022)	INV	Patent application (non-resident + resident)
Circular economy	(WDI, 2023)	CIR	Waste recycling technologies, industry value addition.
Urbanization	(WDI, 2023)	URB	Percentage of urban total population
Economic progress	(WDI, 2023)	GDP	GDP (constant USD -2015)

Table 2
Descriptive statistics of variables

	InCO2	InCIR	InINV	InGDP	InREE	InURB
Mean	4.7876	3.5014	2.1119	4.1533	0.3747	0.6782
Median	4.6860	3.5231	1.9518	4.1721	0.3510	0.6708
Maximum	5.4970	4.1639	3.7290	4.4039	0.5356	0.7401
Minimum	4.0961	2.8715	0.7781	3.8420	0.2502	0.6123
Std. Dev.	0.4480	0.3776	0.8033	0.1321	0.0820	0.0404
Skewness	0.2230	0.1321	0.7645	-0.2988	0.6117	0.0986
Kurtosis	1.9262	1.9325	2.5228	2.3248	2.0914	1.9159
Jarque-Bera	6.7602	6.0462	12.8279	4.0647	11.6121	6.0699
Probability	0.0340	0.04864	0.0016	0.1310	0.0030	0.0480
Sum	574.5163	420.1686	253.4284	498.4042	44.9732	81.3895
Sum Sq. Dev.	23.8882	16.9691	76.8028	2.0794	0.8014	0.1950

infrastructure and industrial utilization of energy for productivity.

The empirical descriptive outcome presented the variables parameters of InCO2, InCIR, InINV, InGDP, InREE, and InURB within the Visegrad communities. Table 2 displayed the mean average values of InCO2 4.7876, InCIR 3.5014, InINV 2.119, InGDP 4.1533, InREE 0.3747, and InURB 0.6782. These averages mean findings demonstrate Visegrad communities' sustainability and environmental quality. Likewise, the variance

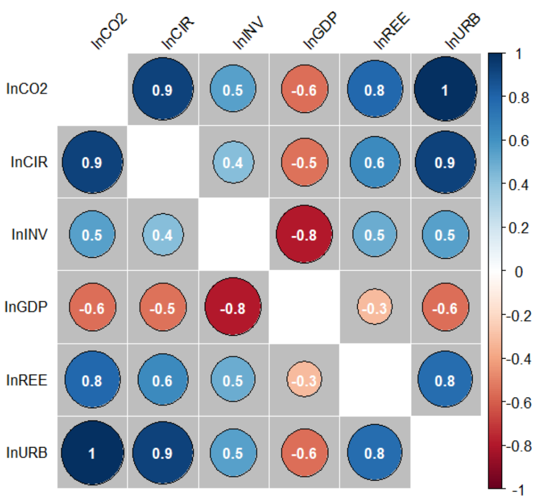

Fig 2. Correlation matrix

of the variables are as follows, InCO2 0.448, InCIR 0.3776, InINV 0.8033, InGDP 0.1321, InREE 0.0820, and InURB 0.0404. The normality of the constructs was estimated with the Jarque Bera approach. Which established that the variables of carbon emission, circular economy, green innovation, renewable energy, and urbanization are dispersed and abnormally distributed. However, economic progress had a normal distribution above 5%. Also, the variance inflation factor was employed to test the collinearity of the variables. The inspection indicates that the variables are not collinear and are independent. The correlation matrix of the constructs was presented in Figure 2 demonstrating the affiliation between the constructs. The inspection established a positive nexus between circular economy, green innovation, renewable energy, and urbanization within the Visegrad communities. The implication of the findings implies that a one additional upsurge in these constructs will produce 90% in circular economy, 50% in green innovation, 80% in renewable energy, and 100% in urbanization. However, economic progress had a depreciation of 60% with carbon emission. Following the empirical literary works of (Zhu *et al.*, 2023). the outcome of the results will be tested through an econometric model to verify the affiliations.

3.2 Econometric synopsis

In this part of the article, the methodology used to examine the relationship between the regressors, and CO2 is detailed. To guarantee that the research results were stable and trustworthy, the study used several econometric tests and estimate techniques. The cross-sectional dependence (CSD) and the slop heterogeneity were employed to test the panel data curation to avoid data bias over time and correlation among the elements. Equation 3-6 presented (Breusch & Pagan, 1980) Lagrange multiplier (LM) CDLM, (Pesaran, 2004)-Bia-Corrected approach and (Pesaran, 2007) -CD test.

$$LM = T\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sigma_{ij}^{t}\right) \quad (3)$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sigma_{ij}^{t}\right) \quad (4)$$

$$\tilde{\Delta}\mathrm{HS} = (N)^{\frac{1}{2}}(2K)^{\frac{-1}{2}}\left(\frac{1}{N}\tilde{S} - K\right) \quad (5)$$

$$\tilde{\Delta}\mathrm{AHS} = (N)^{\frac{1}{2}}\left(\left(\frac{2k(T-k-1}{T+1}\right)^{\frac{-1}{2}}\right)\left(\frac{1}{N}\tilde{S} - K\right) \quad (6)$$

Where, $\tilde{\Delta}$HS denotes the delta of the slant and $\tilde{\Delta}$AHS estimates the adjusted SH.

3.3 Evaluation of unit root and cointegration checks.

Furthermore, the data was put to check on the stationary approaches of two robust test proposed by (Pesaran, 2007) Cross-sectional Augmented (CIPS) and the Cross-sectional Augmented Dickey-Fuller (CADF). This was presented in equations 7 and 8.

$$\Delta Y_{it} = \alpha_i + \beta_i Y_{it-1} + \delta_0 \bar{Y}_{t-1} + \delta_1 \Delta\bar{Y}_t + \mu_{it} \quad (7)$$

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \quad (8)$$

Also, the panel cointegration of (Westerlund 2007) was employed as it served to determine the elements long run affiliations. The group G_a and G_t and panel group means P_a and P_t illustrated in Eq 8a-8d established that there is a long run affiliation between the elements which call for further empirical investigations.

$$G_\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\eta_i}{S.E(\widehat{\eta_i}} \quad (8a)$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\eta_i}{1-\sum_{j=1}^{k}\widehat{\eta_{ij}}} \quad (8b)$$

$$P_\tau = \frac{\widehat{\eta_i}}{S.E(\widehat{\eta_i})} \quad (8c)$$

$$P_a = T\eta_i \quad (8d)$$

Here, Equations 8a-8b use group tests to inspect the presence or absence of cointegration in the computational framework. The panel tests in equations 8c-8d indicate that at least one unit is cointegrated.

3.4 Long-run inspection

To establish the affiliation between carbon emission, circular economy, patent application, green finance, and renewable energy in the Visegrad regions, the investigation employed the CS-ARDL technique by (Chudik & Pesaran, 2015). Different econometric approaches have been utilized to calculate the panel estimation in the long term. The CS-ARDL model was used to calculate long term nexus due to its superiority over the Pool Mean Group - PMG, Augmented Mean Group - AMG, and Common Correlated Effect Mean Group – CCEMG.

The CS-ARDL model was chosen because it effectively addresses both cross-sectional dependence and dynamic heterogeneity. Unlike PMG, which assumes homogeneous long-run affiliation across units. CS-ARDL allows for heterogeneous short-run and long-run dynamics, making it more flexible in capturing unit-specific adjustments. Additionally, CS-ARDL incorporates cross-sectional averages to account for unobserved common factors. Though the Pool mean model offers a long-term effect of nexus among variables when there exists a homogeneity, it is not able to account for cross-sectional and slop heterogeneity. By exploring the affiliation between the variables with CS-ARDL, the estimator provides strong answers for econometric modelling is lacking or bias in OLS, PM, and AMG, making parameter estimations more accurate and reliable (Sampene *et al.*, 2024). By synthesizing and critically evaluating the models, we follow empirical literary works of (Deka *et al.*, 2023; Voumik *et al.*, 2023) and estimated the function as.

$$\Delta CO2_{it} = \varphi_{it} + \sum_{j=1}^{n}\varphi_{it}\, CO2_{i,t=j} + \sum_{j=0}^{n}`\varphi_{it}\, X_{i,t=j} + \sum_{j=0}^{1}`\varphi_{it}\, \bar{Z}_{i,t=j} + \mu_{it} \quad (9)$$

$\bar{Z}_t = (\Delta CO2_{it}, \bar{Z}_t)$ Constitutes the CST mean average and components X_{it} display the uniqueness individual independent variables CIR, INV, GDP, REE, URB.

3.5 Robustness check

Quantile regression provides a more comprehensive understanding of the distribution of the response variable and how the relationships between variables vary across different quantiles (Koenker & Bassett, 1978). It apprehends the least squares regression by estimating the conditional quantiles of a response variable, rather than focusing solely on the mean. To estimate the model, we assumed that y and x are the dependent and independent elements. To develop the conditional affiliation of the linearity, it is derived as follows; $y\, I\, x$

$$Y_q = X_i^{\iota}\beta_q \quad (10)$$

β_q denotes the coefficient of q quantiles, $q \in [0,1]$. β_q is minimized to estimate the panel quantile shown in EQ (11).

$$\beta_q \sum i \in \left\{y_i \geq X_{i\beta_q}^{\iota}\right\} q\left|y_i - X_i^{\iota}\beta_q\right| + \sum i \in \left\{y_i < X_i^{\iota}\beta_q\right\}(1 - q)\left|y_i - X_i^{\iota}\beta_q\right| \quad (11)$$

Alotaibi and Alajlan, (2021) indicated that to obtain the quantile plots for each independent contrast on the dependent element q moves incrementally from 0 to 1 to evaluate β_q.

Table 3
CSD and SHT evaluation

Series	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM
InC02	99.674***	18.933***	18.825***
InCIR	73.051***	12.981***	12.872***
InINV	173.882***	35.527***	35.418***
InGDP	222.269***	46.347***	46.238***
InREE	84.733***	15.593***	15.484***
InURB	99.964***	18.997***	18.890***
SHT Analysis	Δ statistic	*P* value	
$\tilde{\Delta}$SHT	9.766***	0.000	
$\tilde{\Delta}$ASHT	11.603***	0.000	

Table 4
The inspection outcomes

	Value	Z-Statis	Probability outcome
Gt	-3.674	4.933	0.034
Ga	-8.603***	5.754	0.000
Pt	-5.592	-0.264	0.240
Pa	-11.07***	0.066	0.000
Variance ratio	146.548***		0.000
Note: *** Meaning at 1%.			

4. Empirical results

4.1 Result of CSD and SHT

The initial diagnosis evaluation is encapsule in Table 3 with the CSD and SHT outcomes. The slope analysis rejected the null approach of homogeneity within the variables of circular economy, green innovation, economic progress, renewable energy, and urbanization among the Visegrad regions. The CSD inspection are consist with literary investigation of one percentage change in CIR, INV, GDP, REE, and URB will have a spill effect from state to another. (Fatma & Haleem, 2023; Safi *et al*., 2023).

4.2 CADF and CIPS evaluation

In the next step, the variable was assessed to identify the stationarity movements. To avoid and certified the threshold requirement of regression model second generation unit root are employed. As displayed in Table 4, the findings demonstrated that the variable were stationary at level I (0) of at first difference I (1).

4.3 Panel co-integration test

After confirming the stationarity of the variables, the (Westerlund, 2007) panel cointegration to employed to identify the long run affiliation between exogenous and endogenous constructs (Table 5). The evaluation affirms a cointegration presence and rejected the null technique of no cointegration among the variables. The variance statistics was adopted to confirm the long-term movement of the variables together. The Gτ and Pτ established that there is no unit root among the variable's investigation in the Visegrad communities.

4.4 Results of long-run estimation models and discussions

This section inspected the regression affiliation between CO2, CIR, INV, REE, URB employing the CS-ARDL approach. As illustrated in Table 6, in the long-run circular economy, green innovation, and renewable energy deployment had an inverse nexus with carbon emissions in Visegrad regions. With a Coeff values of -0.570 -CIR, -0.381- INV, and -0.404 REE indicates that a 1% shift in these variables cause a depreciation in carbon emission in the Visegrad region by 57%, 38.1% and 40.4% in the long term respectively. However, in the short-term renewable energy had not effect. Therefore, policies decisions can be inferred from this on which areas government should invest or put more research and development fundings. On the affiliation between economic progress and urbanization the results produced a favourable link with carbon emission. The estimation shows a Coeff values of 0.177 GDP and 0.879 URB in the long term, implying that 1% change in the variables will lead to appreciation in the emissions levels in the Visegrad region at 17.7% and 87.9% respectively. Similar results were found in the short term. The high emission in the urban areas is linked with the many industrial plants located in the urban communities. Urban green space management and planning could be the solution to limit this impact. The significance of the Coeff statis overall will be explained in the discussion step with further robustness checks. The ECT (-1) expound the affiliation between the variable adjustment speed from the short run to long run taken into consideration the cross-sectional dependence test. The Visegrad communities can adjust to their normal when there are changes in carbon emission over time at 20.8%. Therefore, policy on environmental damages is curial for these regions.

Table 5
Cointegration evaluation

	CIPS		CIPS	
	Level	1st diff	Level	1st diff
InC02	-2.138	-4.460***	-1.469	-3.490***
InCIR	-1.384	-4.304***	-2.287	-3.318***
InINV	-3.284***	-5.161***	-2.484	-4.008***
InGDP	-1.586	-3.814***	-2.514	-4.252***
InREE	-1.704	-5.014***	-3.430***	-4.650***
InURB	-2.107	-5.622***	-1.530	-3.550***

Note: *** Meaning at 1%,

Table 6
CS-ARDL evaluation

	Long-run evaluation		Short-run evaluation	
	Coeff	Standards err.	Coeff	Standards err.
InCIR	-0.570***	0.242	-0.256	0.313
InINV	-0.381***	0.074	-0.049	0.003
InGDP	0.177***	0.013	0.098	0.164
InREE	-0.404**	0.211	0.233	0.198
InURB	0.879*	0.521	0.583	0.185
ECT0(-1)			-0.208	0.056

Note: *** Meaning at 1%,

5. Discussions

The investigation results revealed that CIR had a material affiliation with carbon emissions depreciation in Visegrad communities. With a 1% appreciation in circular economy activities by Visegrad regions they will be able to depreciate their environmental externalities by 57%. According to the recent EU green deal report 2022, several European communities have implemented waste management and reuse of products for more than ones. The results affirm literary works of (Almulhim, (2024) evaluated the different circular economy approaches to mitigate environmental damages associated with the SDGs 1 and 2. The outcome demonstrated that a holistic strategy is required to meet the Saudi Arabia's 2030 projects. Employing the Eu circular economy framework between 2015-2023, De Pascale *et al.,* (2023) examined industrial sectors in Europe. They indicated that the most efficient circular economy practise is recycling 24.2% and reduce raw material use was 18.9%. According to the findings the food and beverage make good use of circular strategies. From the BRICS perspective, (Sampene *et al.,* 2024) employed econometric model of the CUP-FM and CUP-BC approach to investigate the elements of nuclear and renewable energy utilization. The findings illustrated that the abatement of environmental damage was mitigated through environmental circularity. However, as recommended in the article of Thapa *et al.,* (2024) explored the EU and Vietnam waste trade affiliation. The European communities export about fifty of its waste. The findings predicted that without proper waste governance, soon the world will enter a waste curse in less emerging communities. Similarly, in China, Yu *et al.,* (2023) investigated waste trade within the mining sector between 1980-2021. The empirical inspection established that 0.15 and 0.07 percent were identified in the short and long term respectively from mining waste trade.

With reference to the association between green innovation and carbon emission within the Visegrad States, the econometric established an inverse significance. An upsurge in green innovation by a unit percentage decrease environmental deterioration, ecological damages, by 38.1% and improves the ecosystem quality. The need to adopt and implement greener methodologies in production has become the debate of government and environmental pressure groups. The result from the investigation supports earlier inspection in E7 nation by Zhu et al., (2023). According to their analysis, ecological quality can be enhanced by means of ecological innovation and enhanced agricultural land development. Likewise, Peyravi *et al.*, (2023) investigated the approaches to European ecological policy in Lithuania. The evaluation results revealed that Lithuania, compared to other EU regions, has a relatively low effect in eco-innovation. However, efforts have been made to alter their emissions through green innovation practices by industries. Again, Wang *et al.,* (2023) used the EKC model to investigate the relationship between eco-innovation and carbon emissions in India. The econometric research using ARDL regression estimation reveals that eco-innovation leads to a reduction in ecological footprint from 1975 to 2017. Additionally, the recent reduction in China ecological footprint has been attributed to the region deployment of green innovation technologies and governmental.

Economic progress had a positive material association with carbon emission within both the long and short run estimation from the CS-ARDL outcome. The findings imply that a 1% change in economic progress among the Visegrad region will lead to a spill effect increase in carbon emission by an amount of 17.7%. All the Visegrad communities are considered in the Eu emerging markets with Poland been the 6th economy with the largest GDP. According to the Eu ecological footprint markings, the Visegrad communities emit a lot of carbon emission from fossil fuels. Poland and Hungry amin energy are coal. The examined relationship corroborates with (Mitić *et al.,* 2023) investigation in Southeastern Europe. The affiliation

Table 7
Quantile evaluation

	0.05	0.25	0.50	0.75	0.95
InCIR	0.002	0.020***	0.030***	0.031***	0.032***
	(0.010)	(0.007)	(3.996)	(0.009)	(0.012)
InINV	-0.003	-0.013***	-0.015***	-0.013***	-0.002
	(0.004)	(0.003)	(0.003)	(0.003)	(0.004)
InGDP	-0.013	-0.073***	-0.071***	-0.053***	0.036
	(0.027)	(0.018)	(0.017)	(0.017)	(0.024)
InREE	0.098	0.406***	0.415***	0.377***	0.324***
	(0.057)	(0.026)	(0.023)	(0.023)	(0.024)
InURB	10.929	10.269***	10.165***	10.259***	10.381***
	(0.193)	(0.078)	(0.076)	(0.100)	(0.144)

between economic progress, employment, and carbon emissions was explored between 1995-2019. The causality illustrated a long run unidirectional nexus between the indicators. However, Shen *et al.,* (2023) reveal an invert U shape affiliation between economic progress and carbon emissions across the various regions of China. Again, Li *et al.,* (2023) conducted a study on economic development in thirty low-income countries in Sub-Saharan Africa from 1995 to 2016. The assessment illustrated the energy usage in rural communities, appreciating the economic advancement without any impact on the carbon emissions.

Furthermore, the findings show an efficacious affiliation between renewable energy and carbon emission. With a negative correlation and a Coeff value of -0.404 indicates that, renewable energy depreciates emissions levels approximately 40.4%. Though renewable energy has been confirmed in empirical research to reduced emissions its was material so in the Visegrad regions. The study by Li *et al.,* (2023) emphasizes the need for specific measures to be taken in the BRICS communities to reduce carbon emissions in renewable energy. The quantile and CCEMG estimations indicated that the implementation of eco-friendly taxes and subsidies for REE resulted in a reduction of carbon emissions. In Kenya, a study conducted by Chandra Voumik *et al.,* (2023) utilized the STIRPAT technique to examine the impact of renewable energy on carbon emissions. The results demonstrated a negative relationship between REE and carbon emissions over a lengthy period using the ARDL estimator. As the Visegrad regions are most dependent on coal and fossil energy, Erdogan *et al.,* (2023) evaluated G7 states investments in renewable energies. Their assessment empirically identified that G7 states investment in renewable energies are the cause of low emissions which are crucial to the zero-emission target.

Finally, urbanization assert a positive nexus with carbon emission. Having the highest Coeff value in the long run of 87.9% with a percentage change in urbanization to promote environmental damages. Though Visegrad urban infrastructure is on a slow pace, urban activities and use of non-renewable energies has polluted the regions ecological footprint. Progiou et al., (2023) research on air quality technique in Thessaloniki city in Greece developed six methodological steps to follow to reduce PM^{10} levels. These encompass: (i) acknowledgement of the existing circumstances; (ii) determination of pollution source emission contributions and their correlation with particulate concentrations; (iii) utilisation of atmospheric models to elucidate the current conditions; (iv) assessment of strategies to mitigate particulate levels and the formulation and appraisal of alternative scenarios; (v) employment of atmospheric models for the prevailing alternative scenarios and evaluation of anticipated reductions in PM10 concentrations; and (vi) completion and preparation of the action plan. The inspection supports the previous investigation employing a bivariate spatial analysis established that urbanization and carbon emissions had an invested U shape (Chen et al., 2023). Additionally, Yao et al., (2023) studied on urbanization in China provincial regions for the period 200-2019. The empirical results show that urbanization and carbon emissions had an N shape different from the literary U shape. This finding was attributed to the local urbanization and regional environmental policy. Again, Dutta & Hazarika, (2023) delve into the STIRPAT model on the affiliation between urbanization and emission among 168 economics. For the period 2000-2019, FMOL was employed to investigate Asia, Africa, Middle East, and Southern America nation. The data revealed a positive nexus between urbanization and per capita income and carbon emissions.

6. Robustness check - Quantile regression.

The quantile regression was employed to inspect the robustness of the variables of circular economy, green innovation, economic progress, renewable energy, and urbanisation on carbon emissions among Visegrad communities. As encapsulated in Table 7 and illustrated in Figure 3, circular economy had a material influence on carbon emissions from the 25th to the 95th quantile. The findings established that CIR promotes environmental externalities among Visegrad regions. According to Yu *et al.* (2023) whose investigation in China mining provinces indicated that these reduced their waste through trading it. Similarly, EU plastic trade with Vietnam has raised concern for waste governance among governments and institutions on the long effects Thapa et al. (2024). As a result, Visegrad communities reduced their impact on the ecosystem through continued waste separation and reuse. The inspection produced a negative influence on green innovation and co-movement of the quantile regression affiliation with carbon emission in 25th, 50th, 75th, and 95th. The outcome of the research is affirmed in the investigation of Peyravi *et al.* (2023) in Lithuania following the EU green deal policy. However, the economic progress quantiles were different from the long-run estimation of the CS-ARDL approach. The quantiles are significant at all levels, with a negative effect on the carbon emission quantities produced in these Visegrad communities.

7. Conclusion and policy suggestions

The journey towards a circular economy is an intricate and diverse undertaking that necessitates the incorporation of different elements, such as eco-friendly innovation, sustainable financing, and urban development. To successfully navigate this paradigm change, it is crucial to have a thorough grasp of the fundamental factors that propel this transformation. These

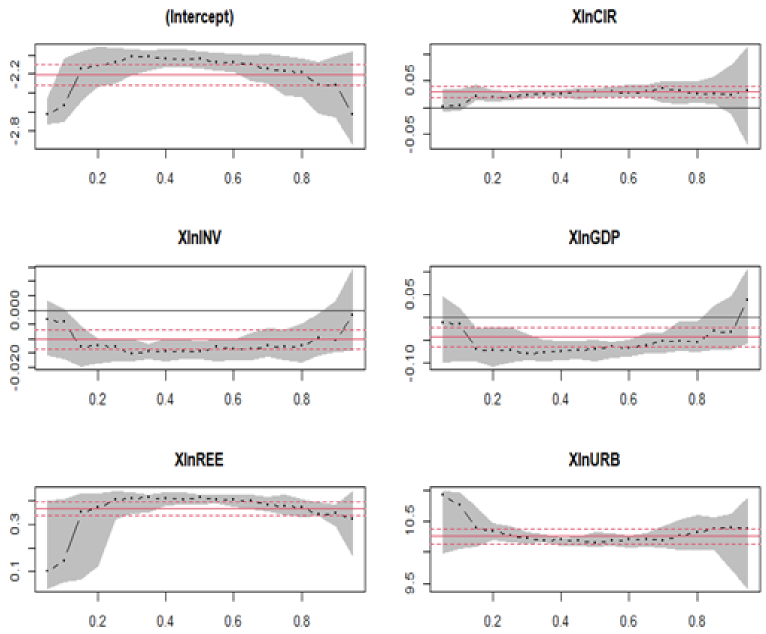

Fig 3. Quantile regression

factors encompass circular economy, green innovation, green finance, and urbanization (Bimonte et al., 2021; Cordes & Morrison, 2023). The investigation seeks to explore the affiliation between circular economy, green innovation, renewable energy, economic progress, and urbanization on carbon emission within the Visegrad communities. The Visegrad Group, consisting of the Czech Republic, Hungary, Poland, and Slovakia, has been actively investigating the possibilities of a circular economy to tackle environmental and economic difficulties. The research employed panel data curation from 1990-2022. The findings are as follows: (a) The preliminary evaluations established that the variables are stationary and co-operated in the long run. (b) The econometric evaluation from the CS-ARDL approach indicated that CIR, INV, and REE depreciate CO2 levels in the Visegrad regions. (c) Again, on the other hand URB and GDP revealed an appreciation nexus with CO2. (d) The results were then tested with the quantile regression model to identify the effects of variables at different quantiles. However, the outcome was affirmed to the CS-ARDL long run estimations.

The findings revealed that Visegrad regions can depreciate their environmental externalities and carbon emissions through deployment of circular economy methodologies and green innovation practices. Efficient exploitation of resources, elimination of waste, and implementation of closed-loop production systems have the potential to provide new economic opportunities and improve resource productivity. Efficient exploitation of resources, elimination of waste, and implementation of closed-loop production systems have the potential to provide new economic opportunities and improve resource productivity. Again, these can be effective when renewable energy that are economically friendly to the environment adopted by Visegrad communities in stand of dependent on fossil fuels. Finally, urbanization had a causal link to increasing the emissions levels in the Visegrad regions. This implies the need for a sustainable urban community where resources are circularly used and adoption of renewable energies.

The outcome from the empirical investigation has significant relevance for policy strategic decisions. The estimation findings indicated that CIR lessens carbon emissions. Hence, it is crucial for governments to give priority to the establishment of comprehensive policy frameworks that encourage the implementation of circular economy practices within the Visegrad communities. For example, the EU green deal is a policy to reduce waste within municipalities and recycle this waste into byproducts for other industries. Likewise, green innovation exited a significant relationship with carbon reduction. Implementing strict environmental rules and setting ambitious emissions-reduction targets can effectively incentivize the business sector to engage in environmentally friendly technologies. Authorities should contemplate the adoption of carbon pricing systems, such as emissions trading schemes or carbon taxes, to motivate enterprises to diminish their carbon emissions and foster the development of low-carbon technologies.

Again, renewable energy has recently been seen as a significant way to decarbonize emissions, environmental externalities, and environmental deteriorations. Governments should give priority to strategic investments in research and development for ecologically conscious renewable energies (wind, solar, ocean energy, and bioenergy). To expedite the rate of technological advancements and the successful implementation of ecological energies, the Visegrad nations should allocate public financing and resources to universities, research institutions, and private sector research and development. The Visegrad countries should establish collaborative platforms and networks that unite academia, industry, and policymakers to ease the exchange of knowledge, transfer of technology, and joint production of innovative renewable energy initiatives. These measures can effectively address the obstacles to the spread of renewable energies and facilitate cooperation between countries in the Visegrad region.

Furthermore, urbanization was found to increase the Visegrad region's carbon emissions and environmental externalities. To achieve a sustainable urbanization, the Visegrad countries should give top priority to the advancement of sustainable and compact urban planning that fosters the effective utilization of resources, diminishes urban sprawl, and promotes the utilization of public transportation, walking, and cycling. Policymakers ought to enforce more stringent restrictions regarding urban planning and land-use, as well as facilitate the growth of rural communities by providing the essential public social amenities. It is imperative for governments to provide incentives for the use of environmentally friendly building standards and energy-efficient technologies in both the construction and operation of buildings. An example of green urban rooting of buildings can be adopted from China.

Finally, this inspection is subject to several limitations that provide avenues for future research. This investigation specifically examines the Visegrad Group countries. However, future research could broaden the analysis to include a wider range of countries or areas to improve the applicability of the results. The analysis focuses solely on macroeconomic-level factors. Future studies could investigate the mechanisms and connections at the firm or industry level to provide a more detailed knowledge of the dynamics involved. The limited availability of data resulted in a rather brief study period. Further investigation using extended time series data has the potential to offer supplementary understanding of the enduring connections among the variables. In addition, future research might integrate additional pertinent variables, such as the influence of institutional quality, political stability, and international trade, to enhance the examination of the elements that contribute to economic growth within the framework of the circular economy and sustainability. Additionally, conducting a comprehensive qualitative inquiry, such as case studies or expert interviews, would enhance the quantitative research and provide a more profound comprehension of the contextual elements and policy ramifications in the Visegrad countries.

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References

Almulhim, A. I. (2024). Toward a Greener Future: Applying Circular Economy Principles to Saudi Arabia's Food Sector for Environmental Sustainability. *Sustainability (Switzerland)*, *16*(2). https://doi.org/10.3390/su16020786.

Bimonte, G., Romano, M. G., & Russolillo, M. (2021). Green innovation and competition: R&d incentives in a circular economy. *Games*, *12*(3). https://doi.org/10.3390/g12030068.

Breusch, T., & Pagan, A. (1980). The Lagrange multiplier test and its applications for the error components model with incomplete panels. *Review of Economic Studies*, *47*(1), 239–253.

Chandra, V. L., Ridwan, M., Hasanur Rahman, M., & Raihan, A. (2023). An investigation into the primary causes of carbon dioxide releases in Kenya: Does renewable energy matter to reduce carbon emission? *Renewable Energy Focus* , *47*. https://doi.org/10.1016/j.ref.2023.100491.

Chen, W., Wang, G., Yang, L., Huang, C., Xu, N., Gu, T., & Zeng, J. (2023). Spillover effects of urbanization on carbon emissions: A global view from 2000 to 2019. *Environmental Impact Assessment Review*, *102*. https://doi.org/10.1016/j.eiar.2023.107182.

Chudik, A., & Pesaran, M. H. (2015). Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. *Journal of Econometrics*, *188*(2), 393–420. https://doi.org/10.1016/J.JECONOM.2015.03.007.

Cordes, D. L., & Morrison, G. (2023). The Circular Economy, Big Data Analytics, and the Transformation of Urban Slums in Sub-Saharan Africa. *International Journal of Smart Sensor Technologies and Applications*, *2*(1), 1–27. https://doi.org/10.4018/ijssta.319720.

De Pascale, A., Di Vita, G., Giannetto, C., Ioppolo, G., Lanfranchi, M., Limosani, M., & Szopik-Depczyńska, K. (2023). The circular economy implementation at the European Union level. Past, present and future. In *Journal of Cleaner Production* (Vol. 423). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2023.138658.

Deka, A., Ozdeser, H., Seraj, M., & Kadir, M. O. (2023). Does energy efficiency, renewable energy and effective capital promote economic growth in the emerging 7 economies? New evidence from CS-ARDL model. *Future Business Journal*, *9*(1). https://doi.org/10.1186/s43093-023-00235-y.

Dutta, U. P., & Hazarika, N. (2023). Urbanization and carbon emissions: Panel evidence from 68 low-income and lower-middle-income countries. *Journal of Urban Affairs*. https://doi.org/10.1080/07352166.2023.2174871.

Erdogan, S., Pata, U. K., & Solarin, S. A. (2023). Towards carbon-neutral world: The effect of renewable energy investments and technologies in G7 countries. *Renewable and Sustainable Energy Reviews*, *186*. https://doi.org/10.1016/j.rser.2023.113683.

Fatma, N., & Haleem, A. (2023). Exploring the Nexus of Eco-Innovation and Sustainable Development: A Bibliometric Review and Analysis. *Sustainability (Switzerland)*, *15*(16). https://doi.org/10.3390/su151612281.

Kihombo, S., Ahmed, Z., Chen, S., Tomiwa, &, Adebayo, S., & Kirikkaleli, D. (2021). Linking financial development, economic growth, and ecological footprint: what is the role of technological innovation? *Environmental Science and Pollution Research*, *28*, 61235–61245. https://doi.org/10.1007/s11356-021-14993-1.

Koenker, R., & Bassett, G. (1978). Regression Quantiles REGRESSION QUANTILES'. *Econometrica*, *46*(1), 33–50.

Li, D., Bae, J. H., & Rishi, M. (2023). Sustainable Development and SDG-7 in Sub-Saharan Africa: Balancing Energy Access, Economic Growth, and Carbon Emissions. *European Journal of Development Research*, *35*(1), 112–137. https://doi.org/10.1057/s41287-021-00502-0.

Li, S., Samour, A., Irfan, M., & Ali, M. (2023). Role of renewable energy and fiscal policy on trade adjusted carbon emissions: Evaluating the role of environmental policy stringency. *Renewable Energy*, *205*, 156–165. https://doi.org/10.1016/j.renene.2023.01.047.

Mitić, P., Fedajev, A., Radulescu, M., & Rehman, A. (2023). The relationship between CO2 emissions, economic growth, available energy, and employment in SEE countries. *Environmental Science and Pollution Research*, *30*(6), 16140–16155. https://doi.org/10.1007/s11356-022-23356-3.

OECD. (2022). *Environmental policy - Patents on environment technologies* -. OECD.

Pesaran, M. H. (2004). General diagnostic tests for cross-sectional dependence in panels. In *CESifo Working Paper* (Vol. 1229). Springer.

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, *22*(2), 265–312.

Peyravi, B., Peleckis, K., & Jakubavičius, A. (2023). Eco-Innovation Performance of Lithuania in the Context of European Environmental Policy: Eco-Innovation Indicators and Efficiency. *Sustainability (Switzerland)*, *15*(4). https://doi.org/10.3390/su15043139.

Progiou, A., Liora, N., Sebos, I., Chatzimichail, C., & Melas, D. (2023). Measures and Policies for Reducing PM Exceedances through the Use of Air Quality Modeling: The Case of Thessaloniki, Greece. *Sustainability (Switzerland)*, *15*(2). https://doi.org/10.3390/su15020930.

Safi, N., Rashid, M., Shakoor, U., Khurshid, N., Safi, A., & Munir, F. (2023). Understanding the Role of Energy Productivity, Eco-Innovation and International Trade in Shaping Consumption-Based Carbon Emissions: A Study of BRICS Nations. *Environmental Science and Pollution Research*, *30*(43), 98338–98350. https://doi.org/10.1007/s11356-023-29358-z.

Sampene, A. K., Li, C., Khan, A., Agyeman, F. O., Brenya, R., & Wiredu, J. (2023). The dynamic nexus between biocapacity, renewable energy, green finance, and ecological footprint: evidence from South Asian economies. *International Journal of Environmental Science and Technology*, *20*(8), 8941–8962. https://doi.org/10.1007/s13762-022-04471-7.

Sampene, A. K., Li, C., & Nsiah, T. K. (2024). Catalyzing renewable energy deployment in the Mercosur economies: A synthesis of human capital, technological innovation and green finance. *Energy Strategy Reviews*, *53*. https://doi.org/10.1016/j.esr.2024.101388.

Shen, T., Hu, R., Hu, P., & Tao, Z. (2023). Decoupling between Economic Growth and Carbon Emissions: Based on Four Major Regions in China. *International Journal of Environmental Research and Public Health*, *20*(2). https://doi.org/10.3390/ijerph20021496.

Tan, F., Yang, S., & Niu, Z. (2023). The impact of urbanization on carbon emissions: both from heterogeneity and mechanism test. *Environment, Development and Sustainability*, *25*(6), 4813–4829. https://doi.org/10.1007/s10668-022-02246-1.

Thapa, K., Vermeulen, W. J. V., De Waal, M. M., Deutz, P., & Nguyễn, H. Q. (2024). Towards a Just Circular Economy Transition: The Case of European Plastic Waste Trade to Vietnam for Recycling. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-023-00330-w.

Voumik, L. C., Rahman, M. H., Islam, M. A., Chowdhury, M. A. S., & Zimon, G. (2023). The Impact of Female Education, Trade Openness, Per Capita GDP, and Urbanization on Women's Employment in South Asia: Application of CS-ARDL Model. *Systems*, *11*(2). https://doi.org/10.3390/systems11020097.

Wang, Y., Villanthenkodath, M. A., & Haseeb, M. (2023). The dynamic link between eco-innovation and ecological footprint in India: does the environmental Kuznets curve (EKC) hold? *Management of Environmental Quality: An International Journal*, *34*(5), 1225–1247. https://doi.org/10.1108/MEQ-05-2022-0136.

WDI. (2023). *World Development Indicator Database*. The World Bank.

Westerlund, J. (2007). Testing for Error Correction in Panel Data*. *Oxford Bulletin of Economics and Statistics*, *69*(6), 709–748. https://doi.org/10.1111/J.1468-0084.2007.00477.X.

Yao, Y., Shen, Y., & Liu, K. (2023). Investigation of resource utilization in urbanization development: An analysis based on the current situation of carbon emissions in China. *Resources Policy*, *82*. https://doi.org/10.1016/j.resourpol.2023.103442.

Yu, S., Wang, X., Liu, J., & Wei, F. (2023). Role of mining waste trade on green development in China: Policy implications for circular economy. *Resources Policy*, *86*. https://doi.org/10.1016/j.resourpol.2023.104147.

Zhu, P., Ahmed, Z., Pata, U. K., Khan, S., & Abbas, S. (2023). Analyzing economic growth, eco-innovation, and ecological quality nexus in E-7 countries: accounting for non-linear impacts of urbanization by using a new measure of ecological quality. *Environmental Science and Pollution Research*, *30*(41), 94242–94254. https://doi.org/10.1007/s11356-023-29017-3.