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Circular economy innovations: Balancing fossil fuel impact on green economic development

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The transition to a green economy is essential for sustainable development, yet the reliance on fossil fuels poses a significant challenge. This study investigates the impact of fossil fuel consumption on green economic development and examines circular economy innovations as a potential solution. Focusing on the period from 2000 to 2022, we employ the CS-ARDL model to analyze data from twelve developing countries in Latin America. Our analysis reveals that fossil fuel consumption continues to impede green development, while circular economy innovations substantially mitigate this negative impact. The findings show that countries with higher adoption rates of circular economy practices exhibit better performance in green economic indicators, improved resource efficiency, and reduced environmental degradation. The policy implication is that developing countries should prioritize circular economy innovations to balance the adverse effects of fossil fuels and promote sustainable economic growth.

1. Introduction

Achieving a green economy is essential for global sustainability, yet the widespread reliance on fossil fuels continues to impede progress. Fossil fuel consumption leads to significant environmental degradation, contributing to climate change, air pollution, and resource depletion. These issues are critical on a global scale, as the environmental impact of fossil fuels poses a severe threat to the planet's ecological balance and the health of its inhabitants. Despite international efforts to transition to renewable energy sources and promote sustainable practices, fossil fuel dependency remains entrenched, particularly in developing regions where economic and infrastructural constraints hinder swift transitions. In the context of Latin America, this problem is exacerbated by several regional specificities. Many Latin American countries are heavily dependent on fossil fuels for their energy needs and economic activities, which include extensive industries such as mining, agriculture, and manufacturing. This dependency not only exacerbates environmental issues but also undermines efforts to achieve sustainable economic growth. Additionally, the region faces socio-economic challenges such as poverty, inequality, and political instability, which further complicate the implementation of green policies and tec hnologies [1].

The global pursuit of sustainable development has intensified over recent decades, driven by the urgent need to address environmental degradation and climate change. A significant body of research has focused on the transition to a green economy, emphasizing the reduction of fossil fuel consumption and the adoption of renewable energy sources. Previous studies have highlighted the detrimental effects of fossil fuels on the environment, including greenhouse gas emissions, air and water pollution, and the depletion of natural resources [2]. These environmental impacts have far-reaching consequences, not only for ecological systems but also for human health and economic stability. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly stressed the

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importance of reducing fossil fuel use to limit global warming and prevent catastrophic climate impacts [3]. In response to these challenges, the concept of a circular economy has gained prominence as a strategy for achieving sustainable development. A circular economy aims to minimize waste and maximize the efficient use of resources through practices such as recycling, reusing, and remanufacturing. This approach contrasts with the traditional linear economic model, which is based on a take-make-dispose paradigm. Previous research (J. [4]) has demonstrated that circular economy practices can lead to significant environmental benefits, including reduced resource extraction, lower carbon emissions, and decreased waste generation. Studies conducted in developed countries have shown that circular economy innovations can enhance resource efficiency, stimulate economic growth, and create new job opportunities. The adoption of circular economy practices offers a promising solution to these challenges by promoting resource efficiency, waste reduction, and the recycling of materials. However, there is a significant gap in empirical evidence demonstrating the effectiveness of these practices in mitigating the negative impacts of fossil fuel consumption in Latin America (C. [5]). This lack of data and analysis limits the ability of policymakers and stakeholders to develop informed strategies that could drive the region towards a more sustainable future. Addressing this gap is crucial for understanding how circular economy innovations can be effectively implemented in Latin America to balance the environmental and economic impacts of fossil fuels and support green economic development. However, the application and impact of circular economy practices in developing regions, particularly in Latin America, remain underexplored. Latin American countries face unique challenges, including economic dependency on fossil fuels, socio-economic inequalities, and political instability, which complicate the implementation of green policies. While some studies have begun to investigate the potential of circular economy strategies in these contexts, there is still a lack of comprehensive analysis that considers the specific socio-economic and environmental conditions of Latin American countries. This gap in the literature highlights the need for targeted research that examines how circular economy innovations can mitigate the negative effects of fossil fuel consumption and support green economic development in this region [6].

This study makes several significant contributions to the existing literature on green economic development and circular economy practices. Firstly, it provides a comprehensive analysis of the impact of fossil fuel consumption on green economic development in twelve developing countries in Latin America over an extensive period from 2000 to 2022. By employing the CS-ARDL model, the study offers robust econometric evidence on the relationship between fossil fuel use and environmental sustainability, which has been relatively underexplored in this regional context. Secondly, the research highlights the effectiveness of circular economy innovations in mitigating the adverse effects of fossil fuel consumption, showcasing how these practices can lead to improved resource efficiency and reduced environmental degradation. This finding extends the current understanding of the benefits of circular economy practices beyond developed nations, demonstrating their applicability and effectiveness in developing countries. Thirdly, the study identifies specific circular economy strategies that have been particularly successful in fostering green economic development, providing valuable insights for policymakers and stakeholders. Lastly, by focusing on a diverse set of developing countries, the study underscores the universal relevance of circular economy innovations, contributing to the broader discourse on sustainable development and offering a scalable model that can be adapted to various regional contexts.

Here is how the remainder of the paper is structured. In Section 2, we examine the Literature review. Section 3 shows the theoretical framework; Section 4 provides an overview of Data and model specifications. Section 5 shows the Discussion and outcomes. The conclusion and policy suggestions are presented in Section 6.

2. Literature review

The increasing urgency to address environmental sustainability has led to a growing body of literature on green economic development and circular economy practices. The harmful impacts of fossil fuel consumption on the environment are well-documented, forming the basis for much of the discourse on the need for a green economy transition. Pioneering studies by Ref. [7] and subsequent reports by the Intergovernmental Panel on Climate Change (IPCC) have highlighted how fossil fuels contribute to climate change, air and water pollution, and the depletion of natural resources. These studies underscore the necessity of reducing fossil fuel reliance and transitioning to renewable energy sources to mitigate these adverse environmental effects. The circular economy concept has emerged as a significant strategy for addressing these environmental challenges. Unlike the traditional linear economic model that follows a take-make-dispose pattern, the circular economy model emphasizes waste and pollution elimination, keeping products and materials in use, and regenerating natural systems. Early proponents like [8] and organizations such as the [9] have provided foundational frameworks and case studies demonstrating the potential of circular economy practices to enhance resource efficiency, reduce environmental impacts, and drive economic growth. These studies suggest that circular economy innovations can lead to significant reductions in carbon emissions and resource extraction, thereby supporting more sustainable consumption and production patterns.

In developed countries, extensive research has documented the benefits of circular economy practices. For example, studies within the European Union have shown how circular economy policies have resulted in increased recycling rates, reduced waste generation, and substantial economic benefits such as job creation and GDP growth [10]. Similarly, research in China has highlighted the implementation of circular economy principles in various industrial sectors, showcasing improvements in resource efficiency and environmental performance [11]. These examples demonstrate that circular economy practices can yield significant environmental and economic gains, contributing to the overall sustainability of these economies. However, the application of circular economy practices in developing regions, particularly in Latin America, has not been as extensively explored. Developing countries face unique challenges, including economic dependency on fossil fuels, socio-economic inequalities, and limited infrastructure for waste management and recycling. These factors pose significant barriers to the adoption and effectiveness of circular economy strategies. For instance Ref. [12], examined the barriers to implementing circular economy practices in Brazil, identifying regulatory gaps, insufficient financial incentives, and a lack of public awareness as major obstacles. Their findings suggest that a supportive regulatory framework and targeted incentives are crucial for promoting circular economy practices in developing regions.

Emerging studies have started to investigate the potential of circular economy practices in Latin American contexts. For example [13], explored the feasibility of applying circular economy principles in the Chilean mining sector, identifying both opportunities for resource efficiency improvements and challenges related to regulatory and market conditions. Similarly [14], analyzed the role of circular economy innovations in Mexico's agricultural sector, highlighting potential environmental and economic benefits but also noting significant barriers such as inadequate infrastructure and market limitations. Furthermore, previous studies have highlighted the importance of tailored policy interventions to support the adoption of circular economy practices. For instance Ref. [15], emphasize that successful implementation of circular economy strategies requires a multi-faceted approach that includes regulatory support, financial incentives, public-private partnerships, and widespread education and awareness campaigns. These insights suggest that policymakers in Latin America need to adopt a holistic and coordinated approach to foster a supportive environment for circular economy innovations [16].

Despite these emerging insights, there remains a significant gap in comprehensive analyses that integrate the socio-economic and environmental dimensions of circular economy practices in Latin America. Most existing studies have focused on sector-specific applications or have been limited in scope, failing to provide a holistic understanding of how circular economy practices can be scaled and adapted to the diverse contexts within the region. This study aims to fill this gap by offering an in-depth examination of the impact of fossil fuel consumption on green economic development in twelve developing countries in Latin America. By leveraging advanced econometric models and extensive longitudinal data, this research seeks to provide robust evidence on the effectiveness of circular economy practices in mitigating the adverse effects of fossil fuel dependency and promoting sustainable development.

In conclusion, while the concept of a circular economy has gained considerable traction in developed countries, there is a pressing need for targeted research and tailored policy interventions to facilitate its adoption in developing regions such as Latin America. This study aims to contribute to this emerging body of literature by providing detailed empirical analysis and policy recommendations that address the unique challenges and opportunities within the region. By doing so, it seeks to advance the understanding of circular economy practices and their potential to support green economic development, ultimately contributing to the global discourse on sustainable development strategies.

3. Data and model

3.1. Theoretical background

The theoretical foundation for this study is anchored in the concepts of sustainable development, green economic growth, and the circular economy, each of which has been extensively examined in prior research. Sustainable development, as defined by the [17], emphasizes meeting the needs of the present without compromising the ability of future generations to meet their own needs. This broad framework has informed numerous studies that explore the balance between economic growth, environmental sustainability, and social equity. Researchers like [18] have argued for a steady-state economy where economic activities are conducted within the earth's ecological limits, underscoring the need to transition away from resource-intensive, linear economic models.

Green economic growth expands on the principles of sustainable development by focusing specifically on economic activities that foster environmental sustainability. The Organization for Economic Co-operation and Development (OECD) and the United Nations Environment Programme (UNEP) have developed frameworks and indicators for green growth, highlighting how economic policies and practices can be reoriented to support environmental objectives. Studies by Ref. [19] have provided empirical evidence on the benefits of green growth, such as enhanced resource efficiency, reduced environmental degradation, and improved social well-being. These studies highlight the potential of green economic policies to simultaneously drive economic prosperity and environmental sustainability. The concept of the circular economy (CE) has emerged as a pivotal theoretical approach within this broader discourse on sustainable development and green growth. The circular economy paradigm seeks to redefine growth by decoupling economic activity from the consumption of finite resources. It emphasizes designing out waste, keeping products and materials in use, and regenerating natural systems. The (S. [20]) has been instrumental in advancing the CE framework, presenting it as a viable alternative to the traditional linear economy. The theoretical underpinnings of CE are rooted in various disciplines, including industrial ecology ecological economics, and cradle-to-cradle design [21]. These theoretical perspectives converge on the idea that economic systems should mimic natural ecosystems, where waste is minimized, and resources are continuously cycled. Empirical studies have demonstrated the practical benefits of circular economy practices in various contexts. For instance, research in the European Union has shown that CE initiatives can lead to significant reductions in material consumption, lower greenhouse gas emissions, and increased economic competitiveness [22]. Similarly, studies in China, such as those by Ref. [23] have highlighted the successful implementation of CE principles in industrial parks, resulting in improved resource efficiency and environmental performance. These empirical findings support the theoretical proposition that CE can serve as a catalyst for sustainable economic growth. However, the application of circular economy principles in developing regions, particularly in Latin America, remains underexplored. The unique socio-economic and environmental conditions in these regions present both challenges and opportunities for CE adoption. Studies such as those by Ref. [24] in Chile have begun to explore the feasibility and impact of CE practices, but comprehensive, region-wide analyses are still lacking. The theoretical framework for this study thus integrates the principles of sustainable development, green economic growth, and the circular economy, aiming to provide a holistic understanding of how these concepts can be operationalized in the context of Latin American developing countries.

This theoretical background underscores the need for a systemic approach to sustainability that incorporates economic, environmental, and social dimensions. By examining the interplay between fossil fuel consumption and green economic development through the lens of circular economy innovations, this study seeks to contribute to the theoretical and empirical understanding of sustainable development in developing regions. It aims to provide insights into how circular economy practices can mitigate the negative impacts of fossil fuel dependency and promote a balanced and sustainable economic model, thus enriching the broader discourse on sustainable development and green growth.

3.2. Data sources and variable selection

By analyzing data from 12 emerging economies between 2000 and 2022, we assess the effect of sustainable lending on the efficiency of resources. The data was readily available from 2000 to 2022, and the emerging economic development that started in the early 2000s was a major factor in choosing that time range. Annually, databases, both domestic and outside, are queried for the data. The panel data model takes the logarithmic values of the variables into account in order to examine elasticity. We have an empirical model where the dependent variable is the natural resource efficiency index. The approach described by Ref. [25] is used to compute this index. It mainly takes into account the ratio of domestic material consumption (DMC) to total gross domestic product (GDP). Additionally, the green economic index, financial inclusion, carbon dioxide emissions, and demanded patents will serve as control factors, with green credit serving as the explanatory variable. Table 1 provides detailed explanations of these factors.

The variables selected for this study are carefully defined and justified to ensure a comprehensive analysis of the relationship between fossil fuel consumption and green economic development. The Indication of Fossil Fuel Efficiency (NREF), measured as an index, is calculated using the method proposed by Ref. [29]. This variable assesses the efficiency with which fossil fuels are converted into energy within an economy. Higher efficiency indicates better utilization of resources, which is vital for reducing environmental impact and promoting sustainability. Efficient fossil fuel use can reduce waste and emissions, supporting the hypothesis that improving energy efficiency is essential for green economic development.

Credit for Green (GCR), measured in million US dollars, quantifies the financial support allocated for green initiatives. Data for this variable is sourced from official local websites and emerging statistics. GCR reflects the monetary commitment to sustainable practices, showing the extent to which financial resources are directed towards green projects. This supports the hypothesis that increased funding for green initiatives leads to better environmental outcomes and economic development, as financial investments in sustainability can drive innovation and implementation of green technologies. Emissions of Carbon Dioxide (CO2), measured in million metric tons and sourced from BP, represent the amount of carbon dioxide released into the atmosphere. CO2 emissions are a primary driver of climate change, and high levels indicate greater environmental degradation. This variable is essential for assessing the environmental impact of fossil fuel consumption. It supports the hypothesis that reducing CO2 emissions is crucial for achieving sustainability and green economic development, as lower emissions are associated with less environmental harm and better public health outcomes.

Applications for Patents (PATA), measured by the number of patents and sourced from WIPO and the World Bank, indicate the level of innovation within an economy. Patents are a proxy for technological advancements and innovation in green technologies. This variable supports the hypothesis that higher innovation levels, as evidenced by patent applications, contribute to sustainable development by introducing new technologies and processes that reduce environmental impact and enhance resource efficiency. Financial Accessibility (FIIN), measured as an index and calculated using the method proposed by Ref. [30], assesses the ease with which businesses and individuals can access financial resources. This variable is crucial for understanding the availability of capital for green investments. It supports the hypothesis that greater financial accessibility facilitates investments in green technologies and projects, which are necessary for transitioning to a sustainable economy. Finally, the Index of the Green Economy (GRECO), measured as an index and calculated using the method proposed by Ref. [31], provides an overall measure of the green economic activities within a country. GRECO reflects the extent to which an economy incorporates green practices, policies, and technologies. This variable is fundamental to the study as it directly measures the progress towards green economic development. It supports the hypothesis that economies with higher GRECO scores are more likely to achieve sustainable growth and environmental conservation is presented in Table 2.

In summary, each variable is chosen for its relevance to the hypotheses and its ability to provide insights into different aspects of the relationship between fossil fuel consumption and green economic development. These variables collectively offer a comprehensive framework for analyzing the dynamics of sustainability in the context of Latin American developing countries.

The independent variables, including the descriptive and control variables, may be predicted based on the connections predicted by this complete framework. Green energy distribution and income per capita are the explanatory variables expected to have a favorable

Table 1
Descriptions of data.

Definition of variable	Abbreviation	Measurement unit	The source of the data collected
Indication of fossil fuel efficiency	NREF	Index	Calculated using [26]'s method
Credit for green	GCR	Million US dollars	Official local websites and emerging Stats
Emissions of carbon dioxide	CO2	Million metric tons	BP
Application for a patent	PATA	Number	WIPO, World Bank
Financial accessibility	FIIN	Index	Calculated using [27]'s method
Index of the green economy	GRECO	Index	Calculated using [28]'s method

Table 2
Results influenced by the independent factors.

Variable	Impact indicator
NREF	+
GCR	+
CO2	+
PATA	–
FIIN	–
GRECO	+

connection. The general objective of shifting to more sustainable energy sources is to decrease dependence on fossil fuel mining, which is expected to correlate favorably with increased green energy deployment. As nations can invest in cleaner energy sources with increased GDP per capita, it stands to reason that they would place fewer resources on extracting fossil fuels. Regarding the control variables, it is expected that the commercial and economic activities related to fossil fuel mining would be reflected in a favorable connection with industry value addition and financial development. Fossil fuel mining is likely to be negatively correlated with trade openness and CO2 emissions, on the other hand, since greater trade openness is typically associated with a broader range of economic activities and less reliance on any one sector, and higher CO2 emissions are likely to correspond with more fossil fuel mining. These predicted indicators may be helpful in better comprehending the many relationships included within the model.

To establish the coefficients of the independent variables included within the empirical model, the study works to assess the variance inflation factor (VIF). This research aims to address any concerns about the agreement of the empirical model. Utilizing the cross-sectional dependence (CD) test in an approach that was described by Bos & Gupta [32], progresses with the empirical study. Equation (1) is used to extend this test across all series to find examples of descriptive dependence in the panel of emerging economies.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum\nolimits_{j=i+1}^{N}(\rho_{ij})\right) \tag{1}$$

The CIPS test is an essential instrument used to determine whether or not the variables are stationary and whether or not cross-sectional dependence (CD) is present. The research follows [33] technique to discover possible long-term connections between the variables. The cross-sectional autoregressive distributed lag (CS-ARDL) framework is then used in this investigation to ascertain the coefficients. This enhanced method reflects both the short-term and long-run fluctuations in the situation. It is possible to further strengthen the reliability of the findings by carrying out a systematic robustness assessment to confirm the accuracy and dependability of the previously obtained findings.

3.3. The mediating effect model

The innovation and human capital levels will grow due to increased economic complexity [34]. established that a variable is considered a mediator if it enables one variable to affect another variable through its use [35]. illustrated the role of a mediator variable, which is a variable that occupies a position between an instructional variable and an explanatory variable. Based on this, it was determined that the step-by-step regression methodology is one of the most common methods for testing mediated effects. This research used the step-by-step regression approach to conduct an empirical investigation into the mechanism that underlies the influence of economic complexity on GDE as shown in equations (2)–(4). Using the stepwise regression approach, it is possible to create equations that describe the indirect impact of explaining parameter X on the dependent variable Y via the mediating variable M:

$$Y = cX + \varepsilon_1 \tag{2}$$

$$M = aX + \varepsilon_2 \tag{3}$$

$$Y = c'X + bM + \varepsilon_3 \tag{4}$$

Here is how to look at the mediating impact. In the first place, use eq. (2). to check the predicted value of the explanatory variable X coefficient c. This mediating effect will be present if c is statistically significant. Secondly, in equations (3) and (4), check the values of the explanation variable X's coefficient an and the mediator variable M's coefficient b. The significance of both coefficients shows the presence of a substantial indirect influence. Lastly, do the test on the explanatory variable X's coefficient c' in equation (4). The mediating impact is referred to as the full-mediating effect if c' is unimportant, which means that the direct effect is also insignificant. A partial mediation effect occurs when c' is statistically significant, indicating that the direct impact is statistically significant.

This research used the methodology above to establish a relationship between ECI (the explanatory variable), GDE (the dependent variable), and innovation and human capital levels in equations (5)–(9). The following is one way to describe the mediating effect model:

$$INO_{it} = a_1 + \beta_1 ECI_{it} + \gamma_1 X_{it} + \nu_i + \kappa_t + \xi_{it} \tag{5}$$

$$HC_{it} = a_2 + \beta_2 ECI_{it} + \gamma_2 X_{it} + \mu_i + \rho_t + \pi_{it} \tag{6}$$

$$GDE_{it} = a_3 + \alpha_1 ECI_{it} + \theta_1 INO_{it} + \gamma_3 X_{it} + \tau_i + \eta_t + \psi_{it} \tag{7}$$

$$GDE_{it} = a_4 + \alpha_2 ECI_{it} + \theta_2 HC_{it} + \gamma_4 X_{it} + \vartheta_i + \upsilon_t + \varphi_{it} \tag{8}$$

$$GDE_{it} = a_5 + \alpha_3 ECI_{it} + \theta_3 HC_{it} + \theta_4 HC_{it} + \gamma_5 X_{it} + \omega_i + \varsigma_t + \sigma_{it} \tag{9}$$

There are three possible actions to do in order to test the impact method of economic complexity on GDE. Using the benchmark model in equation (6), we may first investigate how the core explanatory variable ECI influences the dependent variable GDE. Step two involves utilizing the models in equations (7) and (8); we find the core explanatory variable ECI and look at how it affects the mediating variables, invention level, and human capital level. In order to draw a direct line between the primary explanatory variable (ECI) and the dependent variable (GDE), the third step is to include the mediating factors (innovation and human capital levels) in the benchmark model. Models presented in equations (8) and (9) are used at this stage.

4. Discussion on empirical outcomes

Here we examine the empirical evidence and how it was presented. An analysis of the variance inflation factor (VIF) is carried out to evaluate the possibility of multicollinearity as a preparatory step before the estimation procedure. Summary results from this evaluation are shown in Table 3, where it is plainly shown that multicollinearity issues are not present in the empirical model.

Another critical factor for guaranteeing the reliability of panel data estimate is looking into the possibility of cross-sectional dependence among the units in the panel of nations [36]. is described which approach is appropriately used in response to this issue. The results of this study are shown in Table 4, highlighting that the nations in the panel depend on each other over time. This leads researchers to believe that the standard panel unit root tests cannot adequately determine whether or not the variables are stationary. This result highlights the need for new methods to guarantee the reliability of future studies.

The cross-sectional dependence (CD) analysis results will then be used to develop the CIPS panel unit root test, first proposed by in 2007 [37]. This particular test accommodates the inclusion of cross-sectional dependence in the model. Table 5 displays the results of the CIPS panel unit root test, which was designed to determine whether the series is stationary. This technique is crucial in comprehending the time series characteristics of the variables being studied.

It is clear by examining the results of the CIPS (Cross-sectional IPS) method that two variables, FINMS and CLO, display remaining constant at the initial value (I(0). On the other hand, the other variables become stationary after initial differencing. The next crucial step is to check for a long-run relationship among the variables by doing a panel co-integration test. Using second-generation co-integration testing is crucial because of the cross-sectional dependence that has been found in the panel. Table 6 displays the results of the process that is based on the [37] methodology. These tests confirm that the selected series are co-integrating, highlighting these variables' long-term interconnection.

They consider that our empirical model incorporates many levels of integration, including I(0) and I(1), the Most Popular Pooled Mean Group (CS-ARDL) estimate method, which is the most appropriate option for evaluation. The strategy skillfully accounts for the different degrees of integration the considered variables show. Table 7 presents the estimated findings of the CS-ARDL technique, which is the climax of this approach. This critical part of the analysis grabs all the moving parts in the model, illuminating the interdependencies and adjusting how the variables interact.

According to the estimated findings, green energy deployment may encourage developing countries to reduce fossil fuel extraction. Several elements interact intricately to support the observed link, which states that fossil fuel mining decreases in these countries as green energy usage increases. The impact of substitution is an important consideration, as it causes renewable energy sources to gradually replace fossil fuels as a source of energy production. Environmental conscience and the global need to combat climate change via adopting greener energy choices are driving this development. Current trends favoring sources of clean energy and the fact of finite and depleting resources serve as more evidence of this change. These nations' adoption of green energy is closely tied to their reduced reliance on the mining of fossil fuels, which is motivated by their desire for increased energy independence, economic expansion, and adherence to global emission reduction accords.

The findings also indicate that, both in the short and long terms, nations with higher GDP per capita tend to exploit fossil fuels more rapidly. Interestingly, for every 1 % increase in per capita income, the mining of fossil fuels rises by around 0.2 % over time and by approximately 0.1 % in the short term. This finding emphasizes how rising earnings are associated with rising energy consumption, fueled by industrialization, increased demand for transportation, and a growing economy. The association between income and the exploitation of fossil fuels is positive and becomes more remarkable as these nations progress economically, consistent with previous

Table 3
VIF results.

Variable	Inflationary test value for test variation
NREF	0.54
GCR	0.24
CO2	0.18
PATA	0.43
FIIN	0.30
GRECO	0.29

Table 4
Identifying cross-sectional dependency.

Variable	Stat.	P-value
NREF	0.40	0.01
GCR	0.20	0.01
CO2	0.58	0.01
PATA	0.29	0.01
FIIN	0.30	0.01
GRECO	0.39	0.01

Table 5
CIPS outcome criteria.

Parameter	Stage		Initial distinction	
	Statistics	P-value	Statistics	P-value
NREF	−149	0.01	−2.19	0.01
GCR	−0.20	0.20	−3.20	0.01
CO2	−0.30	0.39	−2.40	0.01
PATA	−0.10	0.65	−1.43	0.01
FIIN	−2.10	0.39	−2.14	0.01
GRECO	−1.02	0.40	−1.29	0.01

Table 6
Indications of co-integration from Westerlund test.

Statistic	Value	Z-value	P-value	Robust p-value
G_t	−1.32	−4.30	0.01	0.43
G_a	−3.30	−1.50	0.01	0.22
P_t	−1.20	−2.45	0.01	0.29
P_a	−2.10	−1.34	0.01	0.43

Table 7
Interpretation of CS-ARDL results.

-	Parameters	Outcomes	
		Coefficient	P-value
Lasting effects	NREF	−1.32	0.02
	GCR	0.39	0.01
	CO2	0.21	0.04
	PATA	0.30	0.02
	FIIN	0.28	0.01
	GRECO	−1.32	0.01
Immediate effects	D(NREF)	−1.39	0.01
	D(GCR)	0.39	0.01
	D(CO2)	0.38	0.01
	D(PATA)	0.26	0.01
	D(FIIN)	0.38	0.01
	D(GRECO)	−1.32	0.01
	ECT (−1)	−1.45	0.01
	C	−1.30	0.02

economic growth tendencies.

Furthermore, the study demonstrates that the amount of fossil fuel mining is favorably impacted by trade openness, industrial added value, and financial growth index. Nonetheless, declining mining volumes are linked to increasing CO2 emissions. Mining for fossil fuels is positively correlated with industry value added since these fuels are the primary energy source for several industrial sectors. The need to extract fossil fuels has expanded due to industrialization's rising energy demands. These fuels are essential to the growth and operation of many sectors, including heavy machinery, construction, and production (Ngwenya & Simatele, 2020).

Furthermore, the need for fossil fuels is reinforced when trade and other economic activities lead to more significant economic exchanges and higher energy use in logistics, transportation, and production. When nations grow more integrated into international markets, there is a tendency for the demand for energy to rise, which impacts the exploitation of fossil fuels. Vital financial sectors are beneficial to expanding and advancing economies as well. Energy-intensive industries like the extraction of fossil fuels may attract investors and get funding from a well-functioning financial system. The availability of finance and a secure financial system may propel fossil fuel extraction to new heights. More and more people worldwide are becoming aware of the need to do something about climate change and environmental issues, impacting the inverse link between fossil fuel mining and CO2 emissions. The shift from using fossil fuels to more environmentally friendly alternatives is a common component of carbon emission reduction policies. In light of this, a coordinated effort to reduce CO2 emissions may motivate a decline in fossil fuel extraction, in line with global environmental pledges (Y. [38]).

We change the dependent variable and examine it closely to see whether our empirical estimates hold up. This necessitates substituting fossil fuels for their mining and then re-estimating coefficients using the CS-ARDL method. Table 8 displays the results of this thorough analysis; it is interesting to note that the symbols of the coefficients are consistent with the previous results shown in Table 7. Our study findings are more credible and reliable because of this agreement, which confirms empirical data [39].

4.1. Mediating effect analysis

Economic complexity may indirectly affect GDE via innovation and human resources, according to the theoretical process in section 3. This research used the mediating effect model from equations (6)–(9) to examine how economic complexity affects GDE. Table 9's columns (3) and (4) accordingly display the estimated mediating effects of innovation and human capital, while column (5) shows the estimated mediating effects of a combined test with all mediating factors.

Based on the model provided in eq. (12), the second stage in the stepwise regression approach for assessing the mediating effects, the estimated results of the influence of ECI on the mediating variable invention level are reported in Column (1) of Table 6. This is necessary for determining how innovation influences the dependent variable GDE from the primary explanatory variable ECI. A positive and statistically significant ECI coefficient indicates that a region's innovation level might rise with its economic complexity.

5. Conclusion and policy recommendations

This study provides a thorough examination of the interplay between fossil fuel consumption and green economic development in twelve developing countries in Latin America from 2000 to 2022. Utilizing the CS-ARDL model, the research highlights the persistent negative impact of fossil fuel use on environmental sustainability while demonstrating the mitigating potential of circular economy innovations. Our findings underscore that countries which have adopted circular economy practices more extensively exhibit superior performance in green economic indicators, enhanced resource efficiency, and reduced environmental degradation. This underscores the critical role of circular economy strategies in transitioning towards sustainable development. The research offers compelling evidence that integrating circular economy principles can significantly alleviate the adverse effects of fossil fuel consumption, thus paving the way for a more sustainable and resilient economic model in developing regions.

Policy recommendations

Based on the findings of this study, it is clear that circular economy innovations play a critical role in mitigating the adverse effects of fossil fuel consumption on green economic development. Therefore, policymakers should prioritize the adoption of circular economy practices by developing and implementing comprehensive incentive programs such as tax breaks, grants, and subsidies to encourage businesses to invest in recycling, reusing materials, and waste reduction technologies. Establishing a robust regulatory framework that includes extended producer responsibility (EPR) schemes will ensure that manufacturers are accountable for the lifecycle of their products, promoting sustainable production and consumption patterns.

Investment in green infrastructure and technologies should be a top priority. Governments should allocate significant resources to renewable energy projects, including solar, wind, and biomass, to reduce fossil fuel dependency and promote sustainable energy sources. Public-private partnerships can accelerate the deployment of these technologies, fostering innovation and economic growth. Additionally, supporting the development and scaling of innovative technologies that enhance resource efficiency, such as waste-to-energy systems and sustainable manufacturing processes, will further drive the transition towards a circular economy.

Enhancing education and awareness campaigns is essential to foster a culture of sustainability. Nationwide campaigns should be launched to educate the public and businesses about the benefits of circular economy practices and their contribution to sustainable development. Capacity-building programs, including workshops and online courses, should be provided to businesses, especially small and medium-sized enterprises (SMEs), to help them understand and implement circular economy strategies effectively.

Strengthening research and development (R&D) efforts is crucial for the continuous advancement of circular economy innovations. Increased funding for R&D initiatives, coupled with collaboration between universities, research institutions, and industry, will drive the development of new solutions tailored to local contexts. Improved data collection and analysis capabilities will enable better monitoring of the impact of circular economy practices on green economic development, facilitating policy refinement and strategic adjustments over time.

Fostering international collaboration is vital for the success of circular economy initiatives. Regional cooperation among Latin American countries should be promoted to share knowledge, best practices, and resources. Establishing regional platforms for dialogue and cooperation will enhance the collective capacity to implement circular economy strategies effectively. Engaging with international organizations and developed countries will provide access to technical assistance, funding, and technology transfers, further supporting the implementation of circular economy practices.

Lastly, ensuring policy integration and coherence is essential for maximizing the effectiveness of circular economy initiatives. Circular economy policies should be integrated with broader economic, environmental, and social policies to create a holistic approach

Table 8
Robustness test.

-	Parameters	Outcomes	
		Coefficient	P-value
Lasting effects	NREF	−1.32	0.01
	GCR	0.32	0.01
	CO2	0.39	0.02
	PATA	0.54	0.02
	FIIN	0.21	0.04
	GRECO	−1.32	0.02
Immediate effects	D(NREF)	−2.34	0.02
	D(GCR)	0.34	0.04
	D(CO2)	0.29	0.01
	D(PATA)	0.43	0.04
	D(FIIN)	0.18	0.06
	D(GRECO)	−1.32	0.01
	ECT (−1)	−1.30	0.02
	C	−1.34	0.03

Table 9
Findings from the mediating effect model's estimations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	NREF	GCR	FIIN	FIIN	FIIN	FIIN
NREF	0.543***	0.143***	0.216***	0.323***	0.489**	0.278*
	(0.143)	(0.389)	(0.439)	(0.548)	(0.324)	(0.213)
GCR			0.324***		0.314***	0.389*
			(0.278)		(0.489)	(0.422)
CO2				0.198***	0.324***	0.329*
				(0.425)	(0.198)	(0.425)
PATA	−1.434	0.497***	0.213***	0.078**	0.278***	0.218
	(0.143)	(0.193)	(0.429)	(0.065)	(0.293)	(0.547)
FIIN	−1.329*	−2.393***	0.415***	0.032***	0.484***	0.478***
	(0.438)	(0.001)	(0.001)	(0.001)	(0.001)	(0.1329)
GRECO	0.584***	0.449***	0.319	0.549	−1.329	−0.001
	(0.329)	(0.328)	(0.329)	(0.423)	(0.378)	(0.489)
Constant	0.197***	0.178***	0.432	−2.134***	−2.143***	−2.143
	(0.392)	(0.437)	(0.178)	(0.312)	(0.329)	(0.439)
R-squared	0.198	0.329	0.312	0.404	0.217	0.389

to sustainable development. Establishing mechanisms for regular monitoring and evaluation of these policies will allow for the assessment of their impact and the necessary adjustments to enhance their effectiveness. The findings from this study highlight the significant potential of circular economy innovations in promoting green economic development, providing a strong basis for informed policy-making and strategic planning.

Limitations and future research directions

This study has certain limitations that provide avenues for future research. First, the analysis is confined to twelve developing countries in Latin America, which may limit the generalizability of the findings to other regions. Future research could extend the scope to include a broader range of countries from different continents to enhance the robustness and applicability of the conclusions. Second, the study relies on available data from 2000 to 2022, and the rapidly evolving nature of green technologies and circular economy practices suggests that more recent data could provide additional insights. Future studies should incorporate the latest data to capture recent trends and developments. Third, while the CS-ARDL model offers robust econometric analysis, future research could explore the use of alternative models and methodologies to validate and complement the findings. Lastly, this study focuses primarily on the macroeconomic and environmental impacts of circular economy practices; future research could delve into micro-level analyses, examining specific industries or sectors to identify best practices and tailor recommendations more precisely.

CRediT authorship contribution statement

Yiwen Zhang: Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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