



Circular resource efficiency through climatic governance and sustainable competitiveness interaction: Global policy insights for SDG 12

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ABSTRACT

SDG 12 is about responsible consumption and production, and this study is particularly designed for its attainment using circular practices as its instrument. However, it is assumed that the interaction of climatic governance and sustainable competitiveness can make this happen. Circular practices are important because they reduce waste and pressure on resource utilization and support cleaner production. This study is based on global data from 2017 to 2024. For empirical analysis, Panel Quantile Regression (PQR) supported by Markov Chain Monte Carlo (MCMC) simulation is used, this technique is robust for endogeneity and non-normality. Further, robustness is confirmed through Bayesian regression. According to the results, as determinants, competitiveness and governance are showing higher pressure on natural resources by increasing the material footprint from biomass. But their interaction is favorable for more circular and sustainable outcomes. This interaction is tested on the 25th, 50th, and 75th Quantiles, and interestingly, only the 50th Quantile depicts highly satisfactory results. Economic globalization, renewable energy, and digitalization are the model's controlling factors, and only economic globalization is favorable for circularity. Overall, this study provides valuable contributions for policymakers seeking to promote circular practices through sustainable competitiveness and climate governance.

1. Introduction

In a resource-constrained environment, the circular economy is important for sustainability [1]. Many resources can be reused multiple times with minimal energy input and limited environmental impact, allowing materials and energy to circulate within a closed-loop system. Reuse, recycling, remanufacturing, and sustainable design are among the circular practices linked to the production process that are most important for reducing pollution and increasing industry efficiency through sustainable practices [2]. In the present era, where economies are putting energy into winning the economic race, this puts more pressure on resource utilization. As a result, the concept of cleaner production is eliminated, and fossil-based energy use emerges [3]. It does not mean, the efforts are not taking place regarding this, United

Nations Environment Programme (UNEP)¹ is actively promoting the circular practices. Their efforts are putting the economies on the path of 12th Sustainable Development Goal, which is “responsible for consumption and production”.

The Biomass from Material Footprint, a sustainability metric that captures the total volume of biomass resources such as crops, wood, and other biological materials extracted globally to fulfill the consumption needs of a country is a suitable representative of circularization. It reflects the environmental pressure a nation places on natural biological resources regardless of where extraction occurs (UNEP, 2023; [4]). Simultaneous to economic growth a gradual decrease in footprint showing the lesser and lesser pressure on portraying efficiency in economic activities through optimal resources utilization and the existence of circularity [5]. However, the emergence of circular practices validates

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¹ UNEP. (2023). *Global Material Flows Database*. United Nations Environment Programme.

sustainable development through cleaner production [6].

To maintain the Biomass from Material Footprint lower, this study has established two pillars, and both of them are directly related to the production process. One is sustainable competitiveness, while the other is environmental governance. This study is based on a key hypothesis that the interaction of sustainable competitiveness and environmental governance assures circularity in the production process [7]. Considering sustainable competitiveness, it implies the economic activities while protecting natural resources and supporting social wellbeing. Its existence in the production process supports long-term transitions by enabling the industrial integration towards circular principles [8]. However, when short-term gains are preferred over competitiveness, it can weaken a sustainable growth path by hindering investment in green infrastructure. It implies that the technological innovation under the competitive behavior of firms does not support the circular practices. Considering the findings of Işık et al. [9] to tackle this, climatic governance has a dual role to play. One is the determining role, and the other is moderating (as a moderator of sustainable competitiveness). It complements the competitive behavior and eliminates its negative externality if it exists. As a determinant, it increases the efficient behavior of firms towards innovative productive capacities [10]. A climate governance framework can channel competitive strategies toward sustainable ends through clear regulatory institutions [11]. This is one side; alternatively, when there is a weak climatic governance framework, it not only determines circular practices adversely but also damages competitiveness [12]. Thus, in this study, climatic governance as a key determinant of the circular economy is examined.

Fig. 1, in the form of a world map, is presented to demonstrate the country-specific spread of climatic governance (GO). In this way, regional differences can be validated regarding institutional readiness within the economic, social, and governance grounds. Western Europe, North America, and Australia reflect higher GO values, suggesting stronger regulatory frameworks and better climate policy implementation. On these grounds, it is assumed that these economies can better handle sustainable competitive leading to assure the least Biomass from Material Footprint. The Figure is also pointing towards a reality that the western side of this world is more beneficiary than the east.

There are several aspects towards which this study is contributing to the literature, (i) literature exists on the circular economy, but in this study, it is measured through Biomass Material Footprint. Ul-Durar et al. [13] have instrumented it through the same indicator that is only for a firm level. While this study reflects a global analysis. (ii) As the dependent variable is novel, the impact of sustainable competitiveness and climatic governance is also a freshly tested phenomenon. (iii) This study is contributing to the literature through the interaction of sustainable competitiveness and climatic governance, and it is assumed that this interaction can bring sustainability and keep the Biomass Material Footprint lower and assure cleaner production. On the basis of this contribution to the literature, this study has several research objectives. Firstly, to test the determining impact of sustainable competitiveness and climatic governance, secondly, to test the interacting role of sustainable competitiveness and climatic governance towards a sustainable circular economy, and lastly, to propose suitable policy implications for a global-level circularity application. Based on these objectives and contributions, this study will answer these questions, (i) do sustainable competitiveness and climatic governance as a determinant enhances circularity and (ii) do the interaction of climatic governance and sustainable competitiveness useful for circular practices and (iii) do the controls (Globalization, Information communication Technology, and Renewable Energy) help reduce pressure on circular economy.

To successfully achieve the study's objectives, this study is divided into several parts. The first section was an introduction, which has already been done and consists of the theoretical relation between the interaction of sustainable competitiveness and climatic governance, and circular economy, and the objectives of the study. Later, the literature is discussed. It describes how different studies have tried to work on the

subject and on what grounds the present study is contributing to the literature. The third section consists of the description of data, the theoretical model, and the methodology. The estimations are being interpreted in the fourth section. The conclusions of the study are discussed in the fifth section, which are further complemented by the robust policy recommendations.

2. Literature review

To discuss the concept of circular economy there is a need to understand the concept of limitations to growth. This concept is rooted in earlier Malthusian ideas. On its beginning, this concept was articulated by Kenneth E. Boulding and later popularized by the Limits to Growth report in the 1970s [14,15]. Building on this, some academics and significant international organizations highlighted the social and environmental dimensions of growth. They asserted that a linear production framework is not enough to support ongoing expansion due to limited resources [16,17]. However, the meaning of circular economy is about using the resources again and again with zero waste, resulting in a controlled ecological footprint [18]. Regarding this, the findings of Pearce and Turner [19] are noticeable, who have highlighted the importance of circularity over linearity. De Sisto et al. [20] have endorsed a circular perspective to resource flow because it is the only way to transfer the resources from this generation to the next. Further, studies like Munaro et al. [21] and Barrie et al. [22] have declared that circularity is the only way to bring novelty in the monopolistic competitive markets and to effectively capture the market share. Moreover, circular practices enhance both sustainability and competitiveness within firms' production behavior [2]. Studies by Schroeder et al. [23] and Velenturf and Purnell [24] highlighted its relevance for achieving the SDGs.

The role of technological advancement cannot be neglected in waste reduction, enhancing resource effectiveness, and force chain effectiveness [25]. In this context, information communication technology helps in optimizing energy use and resource application, and are necessary in enhancing the circular practices [26]. Several studies argued that the structure of the circular economy can be enhanced by the support of exploration and development on ICT tools [27]. While studies including Chauhan et al. [28], Singh et al. [29] and European Commission, 2020 have taken it as a useful tool to maintain circular practices because it can effectively manage a product over its whole life cycle transparently and collaboratively using digital information. Further, it also helps to support and maintain circular economy practices by exercising a range of digital platforms and tools aligned with indirect frugality structures [30]. These all are the supportive discussion. Oppositely, Yu et al. [27] have discussed that there are still numerous challenges to promoting the circular economy by applying ICT. Barrie et al. [22] revealed that international trade significantly contributes to an increase in the circular economy inclusively. Yamaguchi [31] and Jánoš [32] confirmed the interaction of international trade with the shifting towards a circular economy. Accordingly, global trade policies provide help to support for the circular economy. Polyakov et al. [33] and Darázs & Šalgovičová [34] revealed that the circular economy helps to strengthen the balance of trade for countries, and international trade also helps to enhance the movement towards a circular economy. Despite support by many countries and international organizations, the circular economy is facing economic, social, and technological challenges, which often limit its implementation to a conceptual framework rather than widespread action [35].

Khan & Osinska [36] revealed that circular economy indicators cause a reduction in total energy consumption and a rise in renewable energy consumption. Empirical evidences by Malikova [37], Papież et al. [38], and Hailemariam and Erdiaw-Kwasie [39] have claimed that the circular economy helps to improve environmental quality. Khanna et al. [40] found that the transition towards the circular economy is a major cause of climate change. Laureti et al. [41] and Nunes et al. [42]

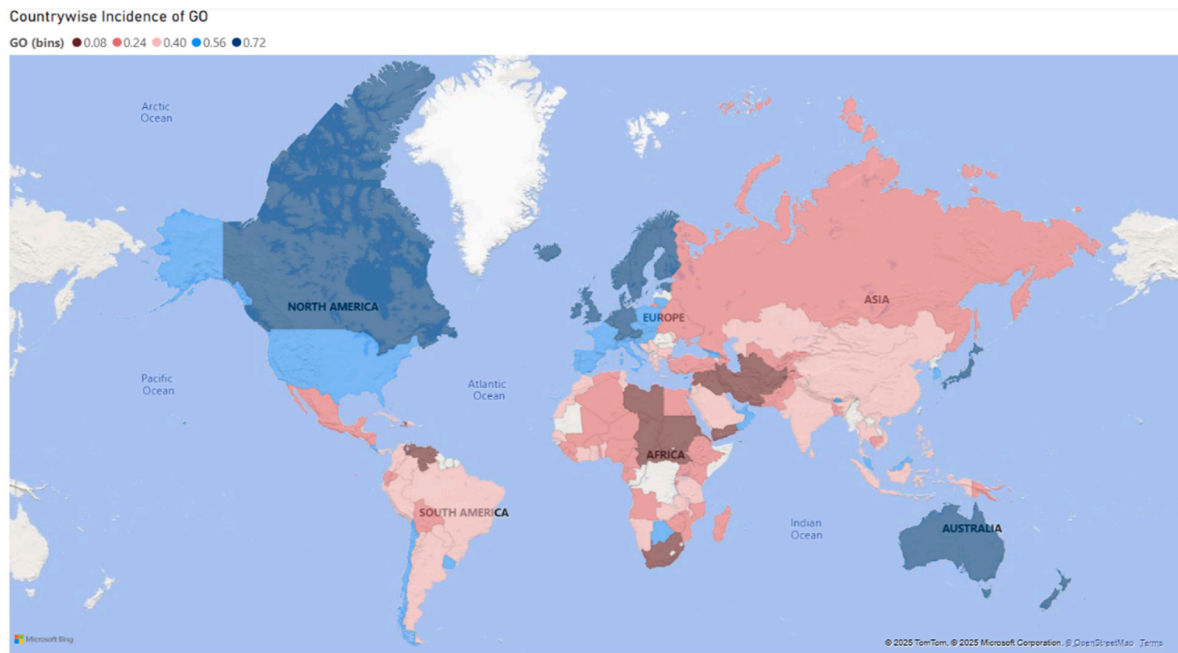


Fig. 1. Country wise Climatic Governance Performance.

emphasize the substantial beneficial effect that renewable energy experts on circular economic systems. Even though the circular economy causes an increase in carbon emissions, vigorous and effective use of institutions can help to sustain the environment [43]. Several studies revealed that indicators of institutional quality are the main tools of the effective conversion towards the circular economy [44]. Moreover, a recent study found that the circular economy is positively affected by the environmental performance and institutional quality [45]. Therefore, Cramer [46] highlighted the significance of the public and network governance for a circular economy.

Recent advancements in both theoretical and applied research are laying the groundwork for a profound shift in the global economy towards a circular economy. Several studies have examined the impact of the circular economy on renewable energy, but very few have explored how the energy transition affects the circular economy. Though some studies have presented the effect of institutional quality on the circular economy, none have explicitly estimated the impact of climate governance on the circular economy, despite the environmental sensitivity associated with the circular economy. Moreover, the impact of sustainable competitiveness on the circular economy has not been explored previously. The study has addressed this issue in the current work. From the critics of the above literature, the study has established that the circular economy is a multi-dimensional challenge having economic, technological, competitiveness, and environmental factors. This has led to a heightened call for creative and effective strategies to manage the intricate challenges related to the circular economy context by revisiting it through the lens of influencing and emerging factors. Thus, the paper pursues to address these breaches by examining the suitability of existing indicators for statistical analysis and by constructing a model to assess how competitiveness, technology, energy transition, and climate governance influence the circular economy.

3. Data, theoretical model, and research methods

This section is added to analyze the nature and transformation of the variables which are part of analysis. Further, the econometric approaches utilized to estimate the regression coefficients are also explained in this section. It is because, the suitability and the accurateness econometric approaches with the nature of data will make the

findings any study robust. The estimation approaches are also being discussed in this section, as this study is based on two regression techniques: one is the IV_PQR, and the other is Bayesian Regression. The suitability and the basic derivations is mainly discussed. The description of the visual effect of the integration term is also included here. This section is further strengthened through the theoretical model presented in sub-Section 3.3. This conceptual discussion provides a base for understanding the mechanism behind the impact of sustainable competitiveness on the circular economy and how climatic governance moderates this relationship.

3.1. Data

Data from the period 2017 to 2024 is considered from different secondary sources, and this period is selected based on data availability. However, it is a global data set for all the countries that exist in this time frame (a complete list of countries is presented in the appendix via Table 5). Circular Economy (CE) is calculated by using total biomass material footprint, reflecting pressure on natural resources. This variable is transformed into its natural logarithmic form to manage skewness, reduce outlier effects, and enhance the interpretability of coefficients in percentage terms [47]. While the remaining variables are in actual form. The main explanatory variable, Sustainable Competitiveness (SC), represents a country's capacity for economic growth while ensuring environmental and social sustainability, sourced from Sol-Ability. Climatic Governance (GO), taken from the ND-GAIN index, reflects institutional strength and climate policy effectiveness, and is applied both directly and as a moderator. Control variables include Economic Globalization (EG), Information Communication Technology (IT), and Renewable Energy Consumption (RE), all drawn from the World Development Indicators (WDI), and each contributing to the understanding of circular transitions. Table 1 presents an overview of the variables used to examine how sustainable competitiveness and climatic governance influence circular economy outcomes.

3.2. Estimation methods and model to be estimated

This section presents the research methodology adopted to estimate the impact of sustainable competitiveness on circular practices,

Table 1
Variables' description.

Variables	Symbol	Definition	Source
Circular Economy	CE	Total biomass resources consumed by an economy, reflecting pressure on circular economy practices.	UNEP
Sustainable Competitiveness	SC	Nation's capacity to attain long-term economic growth, ensuring social and environmental sustainability.	SOL
Economic Globalization	EG	The summation of a nation's imports and exports as a percentage of GDP.	WDI
Information Communication Technology	IT	People using the internet as a share of the total population.	WDI
Green Energy Use	RE	Total use of Renewable energy as a percentage of total energy consumption.	WDI
Climatic Governance	GO	Country's institutional capacity, stability, and policy effectiveness in tackling climate change.	ND-GAIN

considering the moderating role of climatic governance. Since the nature of the relationship is expected to vary across different points of the distribution, and there is also a possibility of endogeneity, this study applies two complementary techniques. First, instrumental variable quantile regression (IV_PQR) is employed to capture distributional effects and account for potential endogeneity in the regressors. The model is optimized using Markov Chain Monte Carlo (MCMC) simulation for better efficiency and convergence. To validate the estimated results of IV_PQR Bayesian regression method is incorporated. This method is an inference based and shows results through probability distributions rather than fixed coefficients.

3.2.1. Panel quantile regression

In this study, two techniques are being followed. Here, IV_PQR, optimized through Markov Chain Monte Carlo (MCMC) simulation, is a main technique, and further robustness is confirmed using Bayesian regression. Both methods are chosen to effectively handle endogeneity, because the cross-sections are greater than the time period. Particularly, IV_PQR is robust for cross-sectional heterogeneity and distributional variation across the conditional range of the dependent variable. Unlike other econometric approaches, IV_PQR is based on the median; therefore, it is robust when the dependent variable is non-normally distributed. This technique also provides a quantile process to analyze how explanatory variables affect different points in the distribution of the dependent variable. The general linear quantile regression model is expressed through Eq. (1). Where, $Q_Y(\tau|X)$ is the τ -th conditional quantile of the dependent variable Y , X is a vector of regressors, which may include endogenous components, and $\beta(\tau)$ is a vector of quantile-specific coefficients.

$$Q_Y(\tau|X) = X\beta(\tau) \tag{1}$$

To address endogeneity, the instrumental variable quantile regression (IVQR) framework proposed by Chernozhukov and Hansen [48] is employed. If X is endogenous and Z is a valid instrument, the IV quantile model satisfies the condition shown by Eq. (2). Here, $\psi_\tau(u) = \tau - I(u < 0)$ is the quantile score function. Given that the model remains linear in parameters, estimation involves solving a set of linear moment conditions specific to each quantile. This study enhances the estimation using MCMC simulation, which is employed not because the model is nonlinear, but to improve sampling efficiency and convergence diagnostics. MCMC is particularly useful for generating posterior distributions of parameters and drawing inference under complex panel settings.

$$E[\psi_\tau(Y - X\beta(\tau)) \cdot Z] = 0 \tag{2}$$

As the panel structure of this study consists of a relatively short time span (T) compared to a larger number of countries (N), the IV_PQR technique is particularly suitable [49]. This approach performs well in settings where $N > T$, allowing for robust estimation despite limited time-series observations. It also effectively accounts for country-specific heterogeneity across the panel.

3.2.2. Bayesian regression

Bayesian regression is employed to verify the consistency and robustness of the main findings. Unlike frequentist methods, Bayesian estimation considers prior beliefs and updates them with observed data to produce posterior distributions. The general Bayesian linear regression model is shown by Eq. (3). While the priors are shown through expression 4. Where, β_0 , and V_0 are the prior mean and variance of the coefficients, and $IG(a_0, b_0)$ is the Inverse-Gamma prior for the error variance.

$$Y = X\beta + \varepsilon, \varepsilon \sim N(0, \sigma^2 I) \tag{3}$$

$$\beta \sim N(\beta_0, V_0), \sigma^2 \sim IG(a_0, b_0) \tag{4}$$

The posterior distribution is obtained using Bayes' Theorem, shown by expression 5.

$$P(\beta, \sigma^2|X, Y) \propto P(Y|X, \beta, \sigma^2) \cdot P(\beta)P(\sigma^2) \tag{5}$$

Given that the posterior distribution is analytically difficult to solve, MCMC techniques (such as the Gibbs sampler) are used to draw samples from the posterior, allowing estimation of posterior means and credible intervals. In this study, this technique is included because it efficiently addresses parameter uncertainty, thereby appropriately validating the empirical results derived from IV_PQR.

3.2.3. Interaction visuals

In this study, the interaction of sustainable competitiveness and climatic governance is considered for sustainable circular practices. To visualize this effect, a method proposed by Dawson [50] is considered. This method incorporates the basic regression coefficients along with the mean and standard deviation of the independent and moderator variables. However, this study emphasizes that a moderator variable changes the strength or direction of the relationship between an independent and a dependent variable, which is being visualized through this method. The basic moderation model is expressed through Eq. (6).

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 Z_{it} + \beta_3 (X_{it} * Z_{it}) + \varepsilon_{it} \tag{6}$$

Here, Y is the outcome, X is the independent variable, Z is the moderator, and $X*Z$ is the interaction term. Dawson highlights that proper centering of variables is essential to avoid multicollinearity and improve interpretation. He also offers guidance on plotting interactions and testing the significance of moderation effects in both linear and logistic models.

3.2.4. Model to be estimated

This study is based on Eq. (7) where the left-hand side shows the outcome variable while right hand side contains the predictors and β s are the coefficients. Studies like Chenavaz et al. [51] and Ren [52] are the recent studies that have contributed significantly on the subject. In this study, sustainable competitiveness is considered a key determinant of circular practices and it is assumed as a positive contributor. So, considering the findings of Oliveira et al. [53] and Rehman et al. [54] this study added sustainable competitiveness to the model.

Apart from the main explanatory variable, the interaction term of sustainable competitiveness with climatic governance is also included to test how the influence of competitiveness on circular practices shifts under different levels of governance quality. The inclusion of this moderating term is justified by the arguments of Bocken et al. [12] and Lazarevic & Valve [11], who suggest that the transition towards

circularity is more effective when economic strategies are aligned with robust environmental governance frameworks.

This study captures not only the independent effects but also the combined influence of governance and competitiveness on circular transitions. Moreover, three important control variables are added to ensure a model's completeness. The first one is economic globalization, which has been found to enhance the movement toward a circular economy through trade openness and knowledge dispersion [22,33]. The second is information and communication technology (ICT). It is proxied through the usability of internet among the people. It is assumed that it supports the implementation of circular practices by improving tracking systems, transparency, and efficient allocation of the resource [25,29]. The third is renewable energy consumption. It is taken as the use of renewable energy percentage of total energy use. Numerous studies suggest that cleaner energy systems are fundamental to reducing the ecological footprint of production procedures and driving sustainable circular systems [38,41].

The error term (ε_{it}) in the model, capturing all unobserved factors that may affect circular economy practices but are not explicitly included in the model. The significance of this term cannot be ignored as it contains the measurement errors, missing variables (the variables that possibly determine the circular practices but are not present in the study), and country-specific shocks. The presence of this error component supports the application of strong estimation methods to produce consistent and unbiased results, particularly in the presence of endogeneity or distributional asymmetries.

$$CE_{it} = \beta_1 SC_{it} + \beta_2 EG_{it} + \beta_3 IT_{it} + \beta_4 RE_{it} + \beta_5 GO_{it} + \beta_6 SC_{it} * GO_{it} + \varepsilon_{it} \quad (7)$$

3.3. Theoretical model

Sustainable competitiveness might influence the extent to which circular practices are adopted and diffused within an economy, serving as the baseline theory of this study [51]. But the circular practices have three important components: first is innovation, second is institutions, and the third is resource efficiency [55]. This study has considered these components for innovative sustainable competitiveness, for institutional capacity climatic governance is taken. For resource efficiency, three controls (IT, RE, and GO) have been considered. But managing all these things, long-term planning grounded in robust policy implications is a must. The impact of sustainable competitiveness on circular economy in the presence of climatic governance can be better understood using the functional form presented in Eq. (8).

$$CE_{it} = f(SC_{it}, GO_{it}, SC_{it} * GO_{it}) \quad (8)$$

Eq. (8) shows that circular economy as a function of sustainable competitiveness, climatic governance and the interaction of sustainable competitiveness and climatic governance. It is directly related to the Transition Theory. It implies that, systemic change as a result of dynamic interactions between institutional innovation, socio technical structures, and governance mechanisms [56]. Here, circular practices are representing the systemic change. For firms it is not easy to transform into a circular mechanism. It requires a complete change of system. If we talk about the existing mode of output generation most of the firms are following fossil-based energy system and some sort of non-renewable, particularly in emerging economies. It is a difficult task to make it into happen [11]. Here the role of sustainable competitiveness is important, it represents the competition among the firms on sustainability ground. In other words, which firms using circular based production or is least harmful for climate. As a result of sustainable competitiveness circular means of production emerges [57]. Further the role of climatic governance is to compliment the role of sustainable competitiveness. This notion is aligned with Ecological Modernization

Theory (EMT). EMT describes how environmental regulation emerges, and firms' innovative capacities must bring resource efficiency and cleaner production [58]. To comprehend this phenomenon Fig. 2 is constructed. Basically, this structure describes systemic interlinkages within the circular economy transition through the interaction of sustainable competitiveness and climatic governance [35].

4. Estimated results and interpretations

This section contains the estimation analysis of this study and first of all the interpretations of descriptive statistics, presented in Table 2. The dependent variable, circular economy (CE_{it}), has a mean value of 17.65 and ranges from 13.20 to 22.22. Here, mean is the average while a high minimum and maximum value is confirming significant variation across countries. Sustainable competitiveness (SC_{it}) also shows a similar pattern with mean 44.546 and with range spanning from 30.13 to 62.09. Economic globalization (EG_{it}) has the highest variation among all variables, reflecting diverse trade openness levels globally. ICT (IT_{it}) access ranges widely too, from as low as 2 % to full coverage. Renewable energy consumption (RE_{it}) shows both negative and high positive values, indicating inconsistencies in reporting and policy across countries. Lastly, climatic governance (GO_{it}) remains relatively consistent but still varies enough to justify its inclusion as both a predictor and moderator in the model. Prominently, all the values of the mean are less than Std. dev. showing that these variables are under-dispersed and the values are not spread out too much around the mean.

The descriptive statistics of this study are further reinforced through the visual understandings provided in Figs. 3 and 4. Fig. 3 focuses on testing, whether the dependent variable normally distributed or not. Since the adopted econometric technique does not rely on normality, the figure helps confirm the departure from it. The histogram clearly illustrates non-normality in the overall distribution. This observation is further supported by the ridgeline plot, which captures time-specific deviations. Ideally, it should look bell-shaped, but it is not; from the right curve is losing its shape. Another illustration of this overall normality, the year-specific normality plot (ridgeline plot) is also losing its bell shape. Additionally, the outlier detection plots (both time-wise and country-wise) confirm the presence of extreme values in the dataset. The spread is going far from both the edges (upside and downside). In this situation, any traditional regression technique based on the mean is not suitable because it is affected by extreme values, while the median is not. As a result, together these visuals provide strong justification for using a distributionally robust method like IV_PQR.

Fig. 4 explores association patterns among variables. The heatmap and combined scatter matrix reveal weak correlation among regressors, validating the absence of multicollinearity. Following that, the scatter plot between sustainable competitiveness and circular economy illustrates how the strength of association shifts across values, underscoring the relevance of quantile-based analysis. Lastly, when the moderating effect of climatic governance is introduced, the scatter plot visibly transforms and demonstrating a change in the relationship pattern. This visual evidence clearly supports the significance of including the interaction term in the model.

Table 3 presents the quantile specific results obtained through the IV_PQR approach, which allows an evaluation of how the influence of core variables changes across different levels of circular economy performance. Sustainable competitiveness (SC_{it}) remains statistically significant across all quantiles, yet its consistently positive coefficient indicates that, when considered in isolation, more competitive economies tend to exert greater pressure on biomass resources. This outcome implies that economic performance, when not supported by sustainability driven policies, may lead to intensified material use, a concern also highlighted by Oliveira et al. [53] and Sadiq et al. [55].

The interaction between climatic governance and sustainable competitiveness yields a significantly negative coefficient across all quantiles, demonstrating that climatic governance as a moderator of

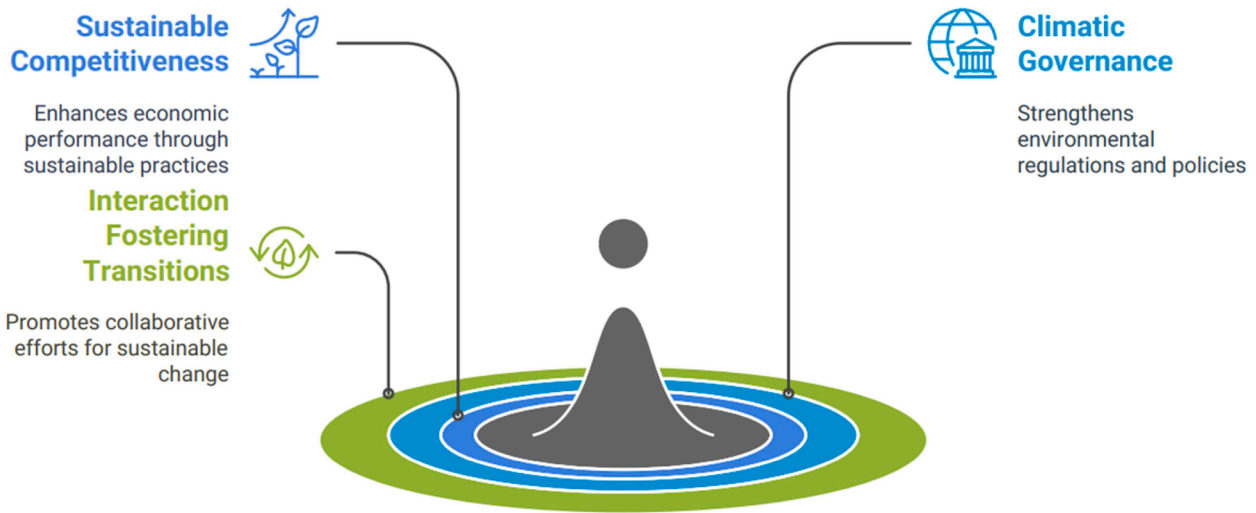


Fig. 2. Theoretical model.

Table 2
Descriptive statistics.

Variables	Mean	Std. dev.	Min	Max
CE	17.651	1.546	13.206	22.227
SC	44.546	6.634	30.133	62.099
EG	86.166	56.349	2.473	394.220
IT	62.470	28.830	2.004	100
RE	33.498	28.337	-1.859	95.5
GO	0.475	0.192	0.077	0.891

sustainable competitiveness has played its role, in reshaping sustainable competitiveness and circular economy relationship. This supports the core principle of Ecological Modernization Theory (EMT), which holds

that positive environmental regulatory systems can dissociate economic growth from ecological harm by directing market behavior towards cleaner production and efficiency. In this context, effective governance mechanisms do not hinder competitiveness but rather reform its orientation toward sustainability [11,12]. Figs. 5–7 further illustrate this moderating relationship. At the 25th quantile, the traditional Dawson [50] structure is evident, as the slope of SC_{it} reverses once GO_{it} is introduced, forming a cross shaped pattern resembling the demand and supply equilibrium. At the 50th quantile, although both slopes remain negative, the interaction curve shifts downward, weakening the adverse effect of SC_{it} . At the 75th quantile, both slopes are positive, yet the inclusion of the interaction term still induces a downward shift, suggesting that the moderating influence of GO_{it} remains relevant even in

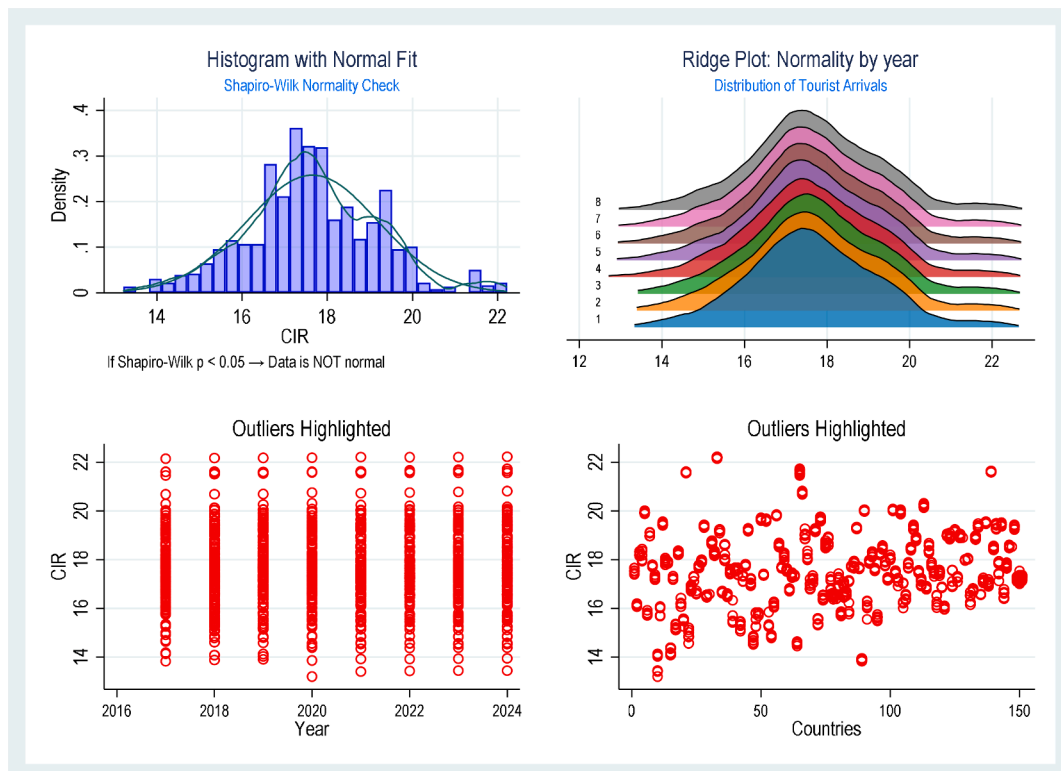


Fig. 3. Visual normality test.

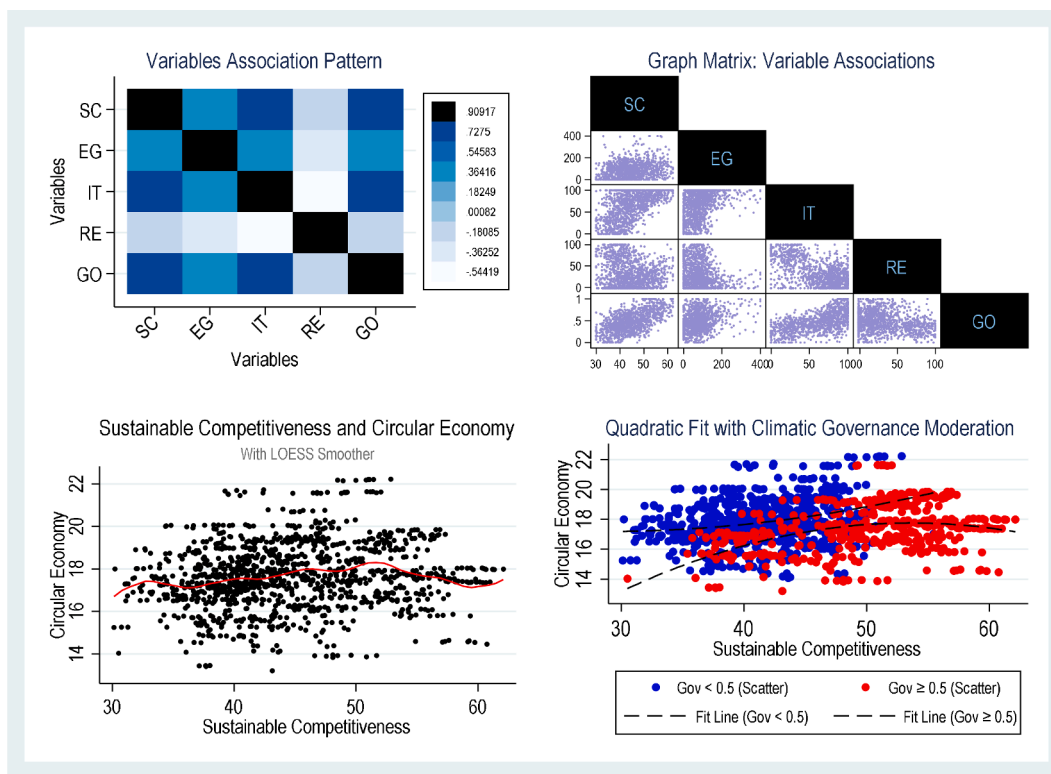


Fig. 4. Visual association patterns.

Table 3
IV_PQR estimated results.

Variables	25 th Quantile			50 th Quantile			75 th Quantile		
	Coeff.	SE	Prob	Coeff.	SE	Prob	Coeff.	SE	Prob
SC	0.080	0.013	0.000	0.051	0.002	0.000	0.075	0.003	0.000
EG	-0.002	0.0009	0.033	-0.006	0.0005	0.000	-0.011	9.39E-05	0.000
IT	0.001	0.001	0.248	0.002	0.002	0.205	-0.007	0.001	0.000
RE	0.001	0.001	0.343	-0.019	0.0002	0.000	-0.010	0.001	0.000
GO	7.541	0.546	0.000	2.087	0.680	0.002	1.549	0.619	0.012
SC*GO	-0.152	0.013	0.000	-0.084	0.015	0.000	-0.029	0.010	0.005

economies with relatively strong circular performance.

The interpretation becomes more robust when control variables are examined. Economic globalization (EG_{it}) shows a consistent and significant negative coefficient across all quantiles. This finding supports the argument that trade openness and global integration can help reduce pressure on natural resources by facilitating knowledge sharing, efficient resource use, and cleaner production methods [22,33]. Information and Communication Technology (IT_{it}) demonstrates a mixed pattern: at lower quantiles, its effect is insignificant, while at higher quantiles it turns significant and negative. This suggests that IT_{it} contributes to circular practices more effectively in countries already performing relatively better on circular economy measures, consistent with findings from Singh et al. [29]. Renewable energy consumption (RE_{it}) is also associated with a negative coefficient, particularly strong at the middle and upper quantiles, confirming its role in supporting sustainable production and reducing resource intensity [38].

Table 3 contains the regression output, and it only demonstrates the impact through the sign of the coefficient. However, Figs. 5–7 have been constructed to visually demonstrate whether the interaction term significantly transforms the impact of the regressor or not. This method to visualize the interaction is proposed by Dawson [50]. Fig. 5 contains the estimated results of the 25th quantile. As a determinant, sustainable competitiveness is destructive for circular practices (as reflected in a

positively sloped curve). The interaction term has transformed this into a negative. Though at early stages the impact of interaction is damaging circularity on a global scale, but gradually is responsible for reducing resource pressure and improving the circular economy. And gradually become on its lower levels.

The estimated results of the 50th quantile are presented in Fig. 6. Again, the sustainable competitiveness is responsible for increasing resource consumption pressure, and this function has a positively sloped curve. But interestingly, the interaction has completely transformed this relationship, and the interaction has completely shifted down the curve into a negative slope. It implies that the central countries where circular practices are not too high nor too low are highly beneficent from the interaction of sustainable competitiveness and climatic governance. Lastly, Fig. 7 is presented to visualize the 75th quantile results. Here, the interaction term is not responsible for transforming the main functional relationship but slightly shifts the positive relationship. It implies that the countries with high circular practices are not the significant beneficiaries of this interaction.

The key findings of this study are further validated with the help of Bayesian regression. Instead of probability values, this technique provides a 95 % credible interval. The outcomes of Bayesian regression are fully aligned with IV_PQR. It can be observed in Table 4 that the sustainable competitiveness and climatic governance are responsible for

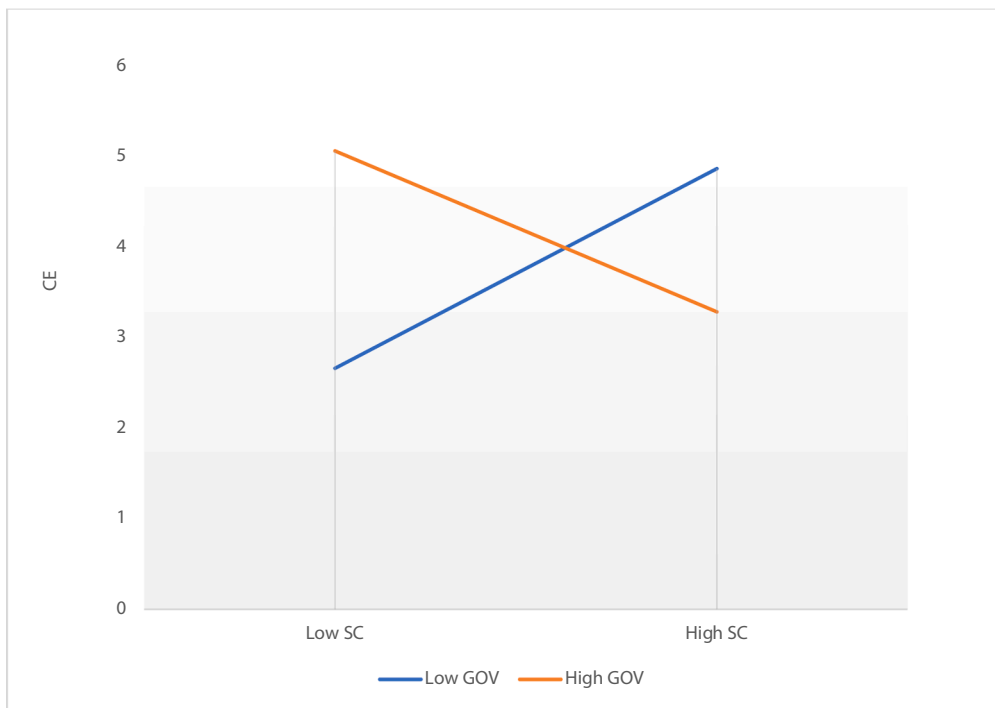


Fig. 5. Visual Moderating Effect with 25th Quantile.



Fig. 6. Visual Moderating Effect with 50th Quantile.

increasing pressure on the circular economy, while their interaction has a negative coefficient, indicating a reduction in resource consumption pressure. The negative coefficients of globalization, ICT, and renewable energy again support their favorable role in reducing environmental load. The robustness of these outcomes is supported by a 10,000 MCMC sample, and the average efficiency value of 0.042 confirms the reliability of posterior estimates. Overall, the Bayesian findings align well with the IV_PQR results, offering further support for the core argument

of this study.

5. Conclusions and policy recommendation

This research is designed to encourage circular behavior among firms' output-related behavior, and for this purpose, global data from 2017 to 2024 is considered. Circular economy is measured through Biomass from Material Footprint and sustainable competitiveness as its

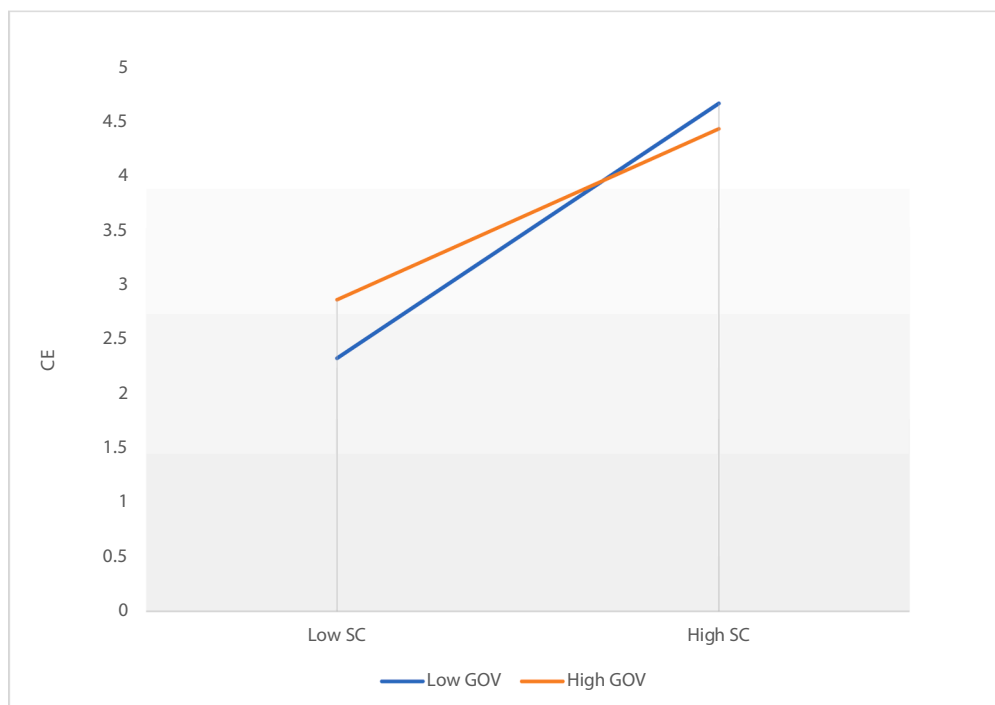


Fig. 7. Visual Moderating Effect with 75th Quantile.

Table 4
Bayesian regression estimated results (Robustness).

Variables	Coeff.	SE	95 % Credible Interval	
SC	0.409	0.007	0.393	0.424
EG	-0.009	0.00092	-0.010	-0.007
IT	-0.019	0.003	-0.026	-0.012
RE	-0.010	0.002	-0.015	-0.005
GO	20.013	0.829	18.359	21.621
SC*GO	-0.471	0.011	-0.492	-0.446
C	2.643	0.150	2.335	2.947
MCMC Sample	10,000	AVG Efficiency	0.042	—

key determinant. Sustainable competitiveness does not ideally determine the circular economy because it is responsible for increasing the Material Footprint. While the study has an assumption for sustainable competitiveness opposite to it. While one assumption is partially successfully tested, that is related to the moderating role of climatic governance. As a determinant, climatic governance is responsible for increasing material footprint, but when it interacts with sustainable competitiveness, the joint behavior becomes ideal. The moderating effect is also visualized through Figs. 5–7, particularly at the 50th Quantile.

Economic globalization, ICT, and renewable energy use are considered the control variables of the model. Among them, only economic globalization is revealing ideal results. In all quantiles, it is responsible for reducing resource pressure by reducing the Material Footprint. ICT

Table 5
Appendix (List of countries).

Afghanistan	Cambodia	France	Kuwait	Oman	Sweden
Albania	Cameroon	Gabon	Kyrgistan	Pakistan	Switzerland
Algeria	Canada	Gambia	Lebanon	Panama	Syria
Angola	Central African Republic	Georgia	Liberia	Papua New Guinea	Tajikistan
Argentina	Chad	Germany	Libya	Paraguay	Tanzania
Armenia	Chile	Ghana	Lithuania	Peru	Thailand
Australia	China	Greece	Luxembourg	Philippines	Togo
Austria	Colombia	Guatemala	Madagascar	Poland	Tunisia
Azerbaijan	Costa Rica	Guinea	Malawi	Portugal	Turkey
Bahamas	Cote d'Ivoire	Haiti	Malaysia	Qatar	Turkmenistan
Bahrain	Croatia	Honduras	Mali	Russia	USA
Bangladesh	Cuba	Hungary	Malta	Rwanda	Uganda
Belarus	Cyprus	Iceland	Mexico	Saudi Arabia	Ukraine
Belgium	Czech Republic	India	Moldova	Senegal	United Arab Emirates
Belize	Denmark	Indonesia	Mongolia	Serbia	United Kingdom
Benin	Djibouti	Iran	Morocco	Sierra Leone	Uruguay
Bhutan	Dominican Republic	Iraq	Mozambique	Singapore	Uzbekistan
Bolivia	Ecuador	Ireland	Namibia	Slovakia	Venezuela
Bosnia and Herzegovina	Egypt	Israel	Netherlands	Slovenia	Vietnam
Botswana	El Salvador	Italy	Netherlands	South Africa	Yemen
Brazil	Equatorial Guinea	Jamaica	New Zealand	South Korea	Zambia
Brunei	Eritrea	Japan	Nicaragua	South Sudan	Zimbabwe
Bulgaria	Estonia	Jordan	Niger	Spain	
Burkina Faso	Ethiopia	Kazakhstan	Nigeria	Sri Lanka	
Burundi	Finland	Kenya	Norway	Sudan	

and renewable energy use are conditionalized. ICT's impact is advantageous only at the 75th quantile. It implies that only those nations where the Material Footprint is high are the beneficiaries. While renewable energy use is beneficial in circular practices at the 50th and 75th quantiles.

Based on the findings, this study recommends that national governments, environmental regulatory bodies, and international institutions such as the United Nations Environment Programme (UNEP) work jointly to embed sustainability and circularity indicators within competitiveness frameworks. As results show that sustainable competitiveness, in isolation, increases pressure on circular resources, it becomes essential that growth strategies are not pursued in silos. Instead, they must be aligned with circular economy principles through regulatory guidance, environmental safeguards, and institutional discipline. The significant moderating role of climatic governance observed across all quantiles supports the need for reforms in governance systems to strengthen transparency, accountability, and climate policy enforcement. Private-sector actors, particularly those in industrial and technological sectors, should also integrate circularity into their competitive strategies to align with future policy and market directions. These policies are for long-term sustainability in circular practices. While short and midterm-enhancements must require an instant transformation of renewable sources. For this purpose, developing and emerging economies should learn from the developed countries. The governments should incentivize the transformation from non-renewable to renewables and assurance of subsidies.

In addition, the empirical support for economic globalization, ICT, and renewable energy consumption highlights specific areas for policy action. The negative association between globalization and circular pressure suggests that environmentally guided trade agreements, sustainable value chains, and responsible investment flows must be encouraged. Institutions such as the World Trade Organization (WTO) and regional trade blocs should promote incentives for green innovation and circular compliance in global markets. Similarly, since ICT was found to have a quantile-specific influence, especially at higher performance levels, investment in digital tools for waste tracking, resource monitoring, and supply chain optimization should be prioritized. Finally, given the positive role of renewable energy in reducing environmental strain, policymakers and energy ministries should collaborate to make green energy more accessible and affordable, particularly in countries with high material footprints. These policies are presented for a global perspective to maintain sustainable behavior of circular practices and for the attainment of SDG 12.

Additionally, In the short term, governments can improve data systems, support clean energy projects, and guide firms to adopt recycling and repair practices. In the medium term, stronger digital infrastructure, wider renewable energy access, and trade rules that support resource efficient production can help. In the long term, global institutions, national agencies, firms, and communities can work together to redesign value chains, shift trade toward low waste production, and build education systems that support a circular mindset.

Despite the study's valuable contribution regarding the attainment of circular practices, there are still some limitations that future researchers can consider. First of all, this study has considered sustainable competitiveness as a key determinant of the circular economy. But it cannot be only a key determinant; other researchers can consider financial development, R&D expenditures, carbon taxation, environmental performance, and technological innovations. The period from 2017 to 2024 was considered because of the sustainable competitiveness, as this variable is available for this span. In case of considering other determinants, researchers will get data for a longer period of time, and many advanced methods can be implemented for robust findings. This study has considered only global data, which might not provide a clear picture of the exact scenario. It can be split into groups like emerging economies, OECD economies, and particularly economies struggling against climate change. The analysis can also be further

strengthened using a disaggregated form of climatic governance. It comprises economic, social, and governance readiness to tackle the adverse impacts of climate change. Based on these specifications, three of four models can be formulated.

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Data availability

The data are publicly available and their sources are mentioned in [Section 3.1](#).

CRediT authorship contribution statement

Adnan Ali Shahzad: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Conceptualization. **Federica Cucchiella:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Formal analysis. **Mubasher Iqbal:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Judit Oláh:** Writing – review & editing, Validation, Resources, Project administration, Investigation, 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.

Data availability

Data will be made available on request.

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