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Measuring the Circular Economy at the Macro Level: Do Developed and Developing Countries Differ?

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ABSTRACT

This study develops a macro level circular economy index (CEI) to compare circular economy (CE) performance across 30 developed economies and 79 developing economies. Many existing indicators capture only one dimension of circularity and offer limited cross-country comparability. To address this problem, the study constructs a standardized index based on four core indicators: carbon efficiency (CAE), energy efficiency (EE), energy transition (ET), and material pressure (RE). The indicators are directionally aligned, normalized, and aggregated using Principal Component Analysis (PCA). The results show large differences in CE performance across countries. The 30 developed economies record a much higher average CEI than the 79 developing economies, with mean scores of 0.864 and 0.413, respectively. The gap is large and statistically significant. It remains robust across Levene's test, Welch's t test, and the Mann Whitney test. At the country level, the ranking and classification results reveal a clear global hierarchy. High-performing countries are concentrated mainly among developed economies, while low-performing countries are concentrated mainly among developing economies. These findings suggest that CE development remains highly uneven across the world. The gap is associated with structural differences in technology, institutions, energy systems, and resource use. The study provides a simple, transparent, and internationally comparable index that can support future research on macro level CE transition.

1. INTRODUCTION

Climate change, resource degradation, and the pressure for sustainable growth have made the circular economy (CE) a strategic priority for many countries [1]. The dominant linear model of extraction, production, and disposal still places heavy pressure on ecosystems. The global economy consumes more than 100 billion tons of materials each year, but only about 6.9% is recirculated into production, showing that global circularity remains far below sustainability targets [2]. WRI [3] further reports that the global material footprint averages about 12.6 tons per capita per year and should fall below 5 tons per capita to support long-term sustainability. These figures show that current growth patterns still depend heavily on virgin resources and that the shift toward circular systems remains slow (Figure 1).

The waste challenge reinforces this urgency. Municipal solid waste is projected to rise from 2.01 billion tons in 2016 to 3.40 billion tons by 2050, suggesting that material consumption is growing faster than the capacity of many economies to process and recycle waste [4]. Developed economies generate about 552 kilograms of municipal waste per capita each year, while recycled materials account for only about 12% of total production in the European Union [3, 5]. Cross-country differences are also large. Municipal waste recycling rates in the European Union average around 49-54%, with Germany exceeding 65%, and Japan also records rates above 50% [6]. By contrast, many developing countries have recycling rates below 2%, and low-income countries may fall below 10%. In parts of Africa, rates are estimated at about 1%, compared with roughly 40% in Europe for some waste streams [7]. These differences reflect unequal access to finance, technology, infrastructure, and governance capacity. At the same time, high material consumption in developed economies continues to weaken circular efficiency [8]. WRI [3] also notes that the wealthiest 25% of the global population consumes more than 50% of total resources, while lower-income groups account for only about 6%.

These differences also raise a measurement problem. Recycling rates, material consumption, and resource inequality each capture only part of the circular system. High recycling rates in developed economies may coexist with very high material consumption, while lower consumption in developing economies may reflect weaker industrial capacity rather than stronger circularity. Single indicators can therefore produce incomplete or misleading comparisons. The challenge is not only that countries differ in circular performance, but also that circularity is measured in different ways. A standardized and internationally comparable CE measure is therefore needed.

Existing measurement approaches vary across levels of analysis. Micro-level studies focus on products, firms, end-of-life management, and material recovery, using tools such as the Disassembly Effort Index (DEI), End-of-Life Index, Recycling Indicators (RI), circular business toolkits, value-based indicators, and the Material Circularity Indicator (MCI) [9-17]. Meso-level studies examine industrial parks, regions, and inter-organizational resource flows, including provincial indicator systems, eco-efficiency metrics, and recycling benefit indicators [18-22]. Macro level studies have advanced national and regional measures, but they remain largely context specific and often depend on harmonized regional data systems or material flow accounting [23-26].

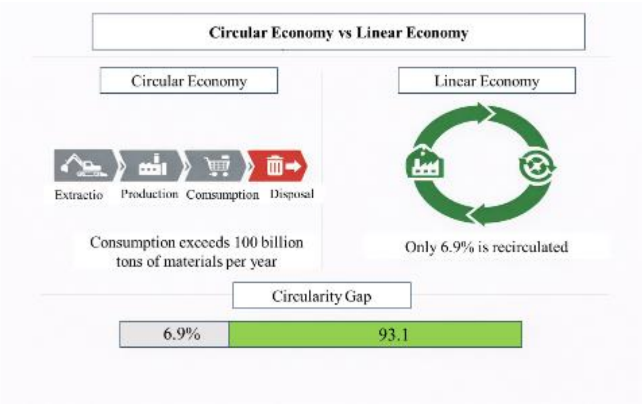

Figure 1. Comparison between the linear economy and the circular economy (CE) (circularity gap: 6.9% vs. 93.1%)
Source: Author (2025), based on data from Circle Economy [2].

The literature shows that CE measurement remains fragmented. Existing indicators range from disassembly effort and end-of-life metrics to recycling rates, material value retention, eco-efficiency measures, economy-wide material flow accounting, and multidimensional dashboards. Each measure captures a useful dimension, but no unified macro level index is designed to support standardized comparison between developed and developing economies. This gap motivates the construction of a composite macro level circular economy index (CEI) that improves international comparability while reflecting the multidimensional nature of circular transition.

To achieve this objective, the study compiles panel data for 30 developed and 79 developing countries over the period 2002 to 2024. The index is constructed using Principal Component Analysis (PCA), which allows the study to derive objective weights from the underlying data structure rather than imposing arbitrary weighting rules. Four macro level indicators are selected to represent the core dimensions of CE performance, namely carbon efficiency (CAE), energy efficiency (EE), energy transition (ET), and material pressure (RE). These indicators are first directionally aligned and normalized to ensure comparability, after which PCA is applied to extract the common variation that reflects overall CE performance across countries.

This study contributes to the literature in several important ways.

First, it advances the measurement literature on the CE by developing a standardized macro level index that enables consistent cross-country comparison between developed and developing economies. In doing so, it addresses the long-standing fragmentation in CE measurement and establishes a more systematic and transparent framework for empirical assessment. Moreover, the study provides a CE ranking based on the constructed index, offering a clear and policy relevant benchmark of relative performance across countries.

Second, the study centers on the rigorous construction and validation of the composite index. It integrates multiple dimensions of circular performance into a single standardized measure and evaluates its statistical properties, internal consistency, and cross-country applicability. The resulting index can serve as a foundational dataset for subsequent empirical analyses, enabling future studies to examine the determinants, dynamics, and consequences of CE performance using a consistent macro level benchmark.

The remainder of the study is structured as follows. Section 2 reviews the theoretical foundations and prior empirical approaches to CE measurement. Section 3 presents the data, variables, and methodological framework used to construct the composite index. Section 4 reports the empirical results, including the cross-country comparison and CE ranking. Section 5 discusses key findings and their implications. The final section concludes the study and outlines directions for future research.

2. LITERATURE REVIEW

2.1 Conceptual foundations of the circular economy

The CE provides a framework for rethinking production and consumption under resource, climate, and waste pressures. It challenges the linear model of extraction, production, consumption, and disposal, and promotes the retention of material, component, and product value for as long as possible. Despite its growing policy relevance, CE remains conceptually diverse because different academic, policy, and business communities emphasize different objectives and mechanisms [27-29].

A common conceptual foundation is that CE is not limited to recycling. Kirchherr et al. [8] showed that CE definitions usually combine reduce, reuse, and recycle strategies and are often linked to sustainable development. These strategies can slow resource loops by extending product lifetimes, close loops through recycling and recovery, and narrow loops by reducing material intensity. The hierarchy embedded in R frameworks also matters: reduction is usually preferred to reuse, and reuse is preferred to recycling. Recycling remains important, but it may be less circular when it leads to quality loss or downcycling [30].

The systems perspective is equally important. CE requires structural transformation rather than isolated efficiency improvements. It operates across micro, meso, and macro levels, involving changes in product design, firm practices, industrial networks, national infrastructure, and policy architecture [8, 31]. This multi-level nature means that circular performance must be measured in a way that matches the level of analysis.

CE is also closely connected to sustainable development. The sustainable development tradition emphasizes the integration of economic progress, social equity, and environmental protection [32-34]. CE can be viewed as an economic model for translating this ambition into resource and production systems. However, CE definitions often emphasize environmental and economic dimensions more strongly than social equity [8]. This creates a measurement challenge because a narrow resource-efficiency index may overlook wider distributional and welfare implications.

For this study, the relevant implication is clear. A macro level CEI should not be a simple recycling measure. It should capture system-level conditions that reflect resource efficiency, ET, carbon pressure, and material dependence. It should also be comparable across countries with different development levels. These conceptual foundations guide the choice of indicators and the construction of the index.

2.2 Existing approaches to measuring the circular economy

CE measurement is commonly organized across micro, meso, and macro levels [31, 35, 36]. Micro-level approaches examine products, firms, business models, and life-cycle stages. Meso-level approaches focus on industrial sectors, eco-industrial parks, supply chains, and regional systems. Macro level approaches assess national or regional circularity through resource productivity, waste intensity, recycling, emissions, EE, and material flow indicators.

Micro-level indicators provide detailed tools for product and firm assessment. Examples include the DEI, End-of-Life Index, Recycling Indicators (RI) for electronic products, the MCI, the Circular Economy Indicator Prototype (CEIP), and life-cycle based economic-environmental measures [9-12, 37-39]. These tools are useful for design, recovery, and firm level decision making, but they require detailed technical or corporate data and are difficult to scale to national comparison.

Meso-level indicators capture interactions among firms, sectors, and regions. Studies of chemical enterprises, eco-industrial parks, resource productivity, wastewater systems, agri-food systems, and value-chain circularity show how circular gains can emerge from coordination and industrial symbiosis rather than from isolated firms [13, 20, 40-44]. These approaches are policy relevant, but they remain sectoral or territorial and cannot directly answer how countries compare at the macro level.

Macro level measurement has developed through two main streams. The first stream constructs composite indicator systems for countries, provinces, or regions, as shown in the work of Qing et al. [18], Geng et al. [19], Claudio-Quiroga and Poza [23], and Drofenik et al. [24]. The second stream relies on economy-wide material flow accounting and related approaches to track domestic material consumption, processed outputs, stock accumulation, and circularity rates [25, 45-47]. These studies provide important foundations but are often tied to specific regions, data systems, or material flow accounting requirements.

Recent reviews confirm that CE indicators remain diverse and fragmented. Moraga et al. [48] showed that indicators differ by system function, product focus, material flow boundary, energy focus, and scenario design. Parchomenko et al. [49] identified separate clusters of resource-efficiency, material-flow, and product-oriented measures. De Pascale et al. [50] classified 61 indicators by spatial level and circular principles, while de Oliveira and Oliveira [51] found that many indicators do not fully reflect circular strategies or sustainability goals. These findings suggest that indicator choice strongly shapes what is understood as circular performance.

The literature therefore supports the need for a parsimonious macro level index that can be applied across countries with heterogeneous data systems. Table 1 summarizes key indicators and measurement systems from previous empirical studies. Rather than reproducing every prior approach, the present study builds on this literature by selecting a small set of internationally comparable indicators that capture systemic circular performance at the national level.

2.3 Measurement gaps in cross-country comparison

Table 1 shows that CE measurement has expanded rapidly, but the increase in indicators has not solved the problem of cross-country comparability. Many indicators are designed for products, firms, sectors, or regions. They are useful within their own contexts, but they are not designed to compare developed and developing economies under a common macro level framework.

At the micro and meso levels, tools such as the MCI, the DEI, and life-cycle based assessment methods help identify improvement opportunities within firms and products [9, 14, 37]. Evidence from Vietnam also shows that such tools can diagnose firm level material flows [16]. However, they cannot show where a national economy stands in circular transition or how it compares with other countries.

At the macro level, existing approaches are often region specific or data intensive. European studies benefit from Eurostat and harmonized monitoring frameworks [23]. Material flow accounting studies provide rich information on inputs, outputs, stocks, and recycling [25, 46, 47]. Yet these approaches are difficult to convert into a simple, standardized benchmark for countries with different development levels and uneven data quality.

A further problem is inconsistency in measurement logic. CE indicators may represent resource productivity, material flows, product design, recycling, waste treatment, innovation, or social sustainability [48-50]. Without a clear objective and comparable data structure, composite indices may become mechanical aggregations rather than analytically meaningful measures.

This review reveals a clear gap. There is no macro level CEI explicitly designed to compare developed and developing countries within a unified framework. Such an index must balance conceptual relevance and data feasibility. It must capture the essence of circularity, standardize indicator direction and scale, use transparent weighting, and recognize structural differences in technology, infrastructure, finance, and institutional capacity.

2.4 Structural differences between developed and developing economies

A comparison between developed and developing economies must account for structural heterogeneity. Circular transition reflects economic structure, institutional capacity, technology, infrastructure, and resource management systems. It is not only a matter of recycling or waste treatment [8, 47]. Ignoring these differences may distort cross-country interpretation.

Developed economies generally have more diversified industries, stronger environmental regulation, formal waste management systems, better secondary material markets, and more reliable statistical systems [23, 46, 52]. These conditions support higher circular performance and make national indicators easier to measure consistently.

Developing economies often depend more heavily on primary resource extraction, rapid infrastructure expansion, and informal recovery systems [25, 47]. Informal recycling may be important but poorly recorded. Financial constraints, weaker regulatory enforcement, and limited technological capacity can also reduce the effectiveness of material recovery systems [49].

These differences mean that the same indicator may carry different meanings across country groups. High material inflows in developing economies may reflect industrialization and urbanization, while high material consumption in developed economies may reflect saturated but resource-intensive lifestyles. For this reason, a macro level CEI must use broadly available indicators, apply common normalization and aggregation procedures, and remain conceptually aligned with CE principles [8, 47, 48, 50].

Recognizing structural heterogeneity is therefore central to the present study. The objective is not merely to generate a ranking, but to examine whether developed and developing economies display systematically different circular patterns when assessed under a unified and transparent macro level framework. By embedding the measurement design within an explicit understanding of development heterogeneity, this study aims to produce a more balanced and analytically meaningful comparison of CE performance across country groups.

Table 1. Summary of circular economy (CE) measurement indicators

No.	Level	Indicator / Measurement System	Refs.	Structure	Method
1	Micro	Disassembly Effort Index (DEI)	[9]	Single composite index	Multi factor weighted model
2	Micro	Circular Economy Toolkit	[14]	Life cycle questionnaire	Qualitative life cycle assessment
3	Micro	Reuse Potential Indicator (RPI)	[53]	Single index (0–1)	Technical potential quantification
4	Micro	End of Life Index (EoL)	[10]	Three components	Score normalization and weighting
5	Micro	Recycling Indicators (RI)	[11]	Four indicators	Standardization (0–1 scale)
6	Micro	Circular Economy Index (CEI)	[15]	Single material value index	Market value ratio
7	Micro	Material Circularity Indicator (MCI)	[37]	Single index (0–1)	Material flow analysis
8	Micro	Recycling Benefit Rate (RBR)	[21]	Single index	Life cycle assessment
9	Micro	Eco Cost Value Ratio (EVR)	[22]	Single index	LCA with economic conversion
10	Micro	Longevity Indicator	[54]	Three components	Material lifespan measurement
11	Micro	Material Reutilization Score (MRS)	[55]	Single index	Weighted average
12	Micro	Recycling Index (RI)	[12]	Two components	Metallurgical simulation
13	Micro	Circular Economy Indicator Prototype (CEIP)	[38]	Fifteen life cycle questions	Stage based scoring
14	Micro	Micro level CE Indicators Framework	[36]	Measurement framework	Theoretical synthesis
15	Micro	Integrated Environmental and Economic Index	[39]	Ten components	LCA and life cycle costing
16	Micro	Adapted Micro CE Indicators	[56]	Ten indicators	Survey and interviews
17	Micro	MCI Application in Vietnam	[16]	Single index	Empirical application
18	Micro	Corporate CE Practice Indicators	[17]	Group of indicators	Panel data analysis
19	Micro	CE Conceptual Framework for Enterprises	[57]	Conceptual framework	Theoretical analysis
20	Micro	CE Standards List in Vietnam	[58]	Sixty-five standards	Standards synthesis
21	Meso	CE Evaluation System for Chemical Industry	[13]	Eighteen indicators	Weighted model
22	Meso	Eco Efficiency Index	[20]	Four components	Integrated economic and environmental approach
23	Meso	Resource Productivity (RP)	[40]	Single index	Substance flow analysis
24	Meso	Wastewater CE Indicator	[41]	Single index	Quantitative model
25	Meso	Economic CE Indicators (ECEIs)	[43]	Thirteen indicators	Criteria based evaluation
26	Meso	Agro Food CE Dashboard	[42]	One hundred two indicators	Multidimensional dashboard
27	Meso	Olive Oil CE Indicators Review	[44]	Sector review	Systematic analysis
28	Meso	Regenerative Tourism CE Framework	[59]	Four pillars	SDG based framework
29	Macro	Provincial CE Evaluation Index	[18]	Twenty-six indicators	Weighted matrix
30	Macro	Integrated CE Assessment	[19]	Multiple parameters	Integrated analysis
31	Macro	CE Efficiency Index	[60]	Eight indicators	Data envelopment analysis
32	Macro	CE Efficiency Index	[61]	Three subsystems	Data envelopment analysis
33	Macro	Multi Regional Waste Input Output Model (MRIO)	[45]	MRIO model	Regression and correlation analysis
34	Macro	Macro Material Flow Tools	[46]	Six indicator pairs	Economy wide material flow analysis
35	Macro	Global Circularity Indicators	[47]	MFA based indicator group	Material flow analysis
36	Macro	CE Indicator Review	[50]	Sixty-one indicators	Classification by 3R principles
37	Macro	European Circular Economy Index	[23]	Fifteen variables	Second order factor analysis
38	Macro	ASEAN Economy Wide MFA	[25]	Economy wide MFA	Domestic material consumption and circularity rate
39	Macro	MICRON Indicator Framework	[24]	National and firm level indicators	Sensitivity analysis

Source: Author's compilation

3. METHODOLOGY

3.1 Data and country classification

The CEI is calculated by the authors using PCA based on four indicators. CAE is measured by the carbon intensity of GDP, expressed as kg CO_2 per unit of GDP, and is obtained from the World Development Indicators. EE is measured by GDP per unit of energy use, expressed as USD per kg of oil equivalent, and is also obtained from the World Development Indicators. ET is measured by the share of renewable energy in total primary energy consumption, expressed as a percentage, and is obtained from Our World in Data. RE is measured by domestic material consumption per GDP, expressed as tons per GDP, and is obtained from the Global Material Flows Database.

Missing observations are treated using Bayesian imputation. This approach is used to preserve the country-year structure of the panel and reduce potential bias caused by incomplete data. Bayesian imputation is appropriate because it allows missing values to be estimated from the observed distribution of the data while incorporating uncertainty in the imputation process. After imputation, the final dataset is organized as a balanced panel covering 109 countries over the period 2002-2024, including 30 developed economies and 79 developing economies.

The distinction between developed and developing economies is central to the analysis. Developed economies usually have stronger regulation, better infrastructure, higher technological readiness, and more stable reporting systems. Developing economies often face greater constraints in finance, institutions, infrastructure, and formal resource recovery. Comparing these two groups helps assess whether CE performance remains closely linked to development level.

3.2 Indicator selection and theoretical justification

To measure the CE at the macro level, this study uses four core indicators: CAE, EE, ET, and RE. These indicators capture four important aspects of circular transition: reducing environmental pressure, improving resource productivity, shifting toward cleaner energy, and lowering dependence on material inputs. Together, they provide a simple but comprehensive framework for comparing CE performance across countries.

3.2.1 Carbon efficiency

CAE is measured by the carbon intensity of GDP, expressed as kg CO_2e per 2021 PPP USD of GDP. It shows how much carbon emission is generated for each unit of economic output. A lower carbon intensity means that an economy can produce output with less environmental pressure. This indicator is closely related to the decoupling principle in CE theory, where economic growth should be achieved with lower environmental impact [8]. It also reflects cleaner technology, better energy management, and structural upgrading. Therefore, CAE is treated as a negative-direction indicator, meaning that lower values indicate better CE performance.

3.2.2 Energy efficiency

EE is measured by GDP per unit of energy use. It shows how much economic output is produced from a given amount of energy input. Higher EE means that an economy can generate more value while using less energy. This reflects the CE principle of resource optimization and is also consistent with the idea of decoupling economic growth from resource consumption [8]. Economies with higher energy productivity are usually more efficient, less energy intensive, and more technologically advanced. Therefore, EE is treated as a positive-direction indicator, meaning that higher values indicate better CE performance.

3.2.3 Energy transition

ET is measured by the share of renewable energy in total energy consumption. This indicator captures the shift from fossil-based energy systems toward renewable and sustainable energy sources. A higher renewable energy share suggests that an economy is reducing its dependence on finite resources and moving toward a cleaner energy structure. This is consistent with the regenerative logic of the CE, which emphasizes maintaining and restoring natural systems [37]. ET is also useful for cross-country comparison because developed and developing economies often differ in their financial, technological, and institutional capacity to adopt renewable energy. Therefore, ET is treated as a positive-direction indicator, where higher values indicate stronger circular performance.

3.2.4 Material pressure

RE is proxied by domestic material consumption per GDP. This indicator measures how much material input is required to produce economic output. It directly reflects the resource-use dimension of the CE. A lower level of RE means that an economy depends less on raw material extraction and uses resources more efficiently. This is consistent with the CE goal of reducing material throughput, extending product lifecycles, and increasing resource recirculation [47]. Compared with recycling rates, domestic material consumption per GDP is more suitable for cross-country analysis because it is broader and less affected by differences in national recycling statistics. Therefore, RE is treated as a negative-direction indicator, meaning that lower values indicate better CE performance.

3.3 Analytical strategy for constructing the circular economy index

One of the most critical issues in composite index construction is indicator directionality. As emphasized in prior studies [62, 63], all indicators must be consistently oriented so that higher values uniformly represent better performance. Without such alignment, the index may generate misleading comparisons, particularly when examining structural differences between developed and developing economies.

In this study, the CE is represented by a parsimonious set of four indicators that capture the core mechanisms of macro level circular performance: CAE, EE, ET, and RE. These indicators reflect how well an economy can reduce carbon emissions relative to output, improve energy productivity, shift toward renewable energy systems, and lower dependence on material inputs. This focused structure avoids unnecessary overlap among indicators while maintaining conceptual clarity. However, the indicators do not move in the same direction. EE and ET increase as circular performance improves, while carbon intensity and RE increase when environmental or resource pressure becomes stronger. This distinction is important for cross-country comparison, because differences in economic structure, technology, and resource use may otherwise bias the final index.

The following indicators are classified as negative-direction indicators, meaning that higher values imply weaker CE performance:

- Carbon intensity of GDP (CAE)
- Domestic Material Consumption per GDP (RE)

Higher values of these indicators indicate greater environmental and resource pressure, as they reflect higher carbon emissions per unit of output and stronger dependence on material inputs. This contradicts the decoupling principle at the core of CE theory, where economic growth should be achieved with reduced material use. If not properly adjusted, this variable could lead to biased results by favoring economies with high material throughput despite low circularity.

To ensure consistency, the negative direction indicators are reversed prior to normalization so that higher transformed values correspond to better circular performance. The transformation is defined as follows:

For each negative direction indicator:

$$X'_{ij} = \max(X_{ij}) - X_{i,j}$$

where,

$X_{i,j}$ is the original value for country i and indicator j;

$\max(X_{ij})$ is the maximum observed value of indicator j;

X'_{ij} is the reversed value.

This transformation ensures that higher values of $X'_{i,j}$ correspond to better circular performance.

The remaining indicators are classified as positive-direction indicators, meaning that higher values reflect better circular outcomes:

- Energy efficiency, measured by GDP per unit of energy use (EE)
- Renewable energy share in total energy consumption (ET)

Higher energy productivity indicates that the economy generates greater output with lower energy input, reflecting improvements in resource efficiency and technological capability. Similarly, a higher share of renewable energy signals a transition away from fossil-based systems toward more sustainable energy structures. Both indicators are therefore consistent with the core principles of CE development.

After directional alignment, all indicators are normalized to eliminate differences in measurement units. Given that the dataset includes heterogeneous variables expressed in ratios and percentages, direct aggregation would distort their relative contributions. Normalization ensures comparability across indicators and prevents unit-driven bias in the construction of the composite index [62, 63].

Following normalization, PCA is employed to derive objective weights and reduce arbitrariness in aggregation. PCA is widely applied in sustainability and environmental index construction because it extracts latent common structure from correlated variables while maximizing explained variance [62, 64]. Instead of assigning subjective weights, PCA allows the data structure to determine the relative importance of each indicator.

Let $Z_{i,j}$= $(Z_{i,1}, Z_{i,2} \dots Z_{i,4})$ denote the vector of normalized indicators for country i. The first principal component is defined as:

$$PC_{1,i} = \sum_{j=1}^{4} w_j Z_{i,j}$$

where,

w_j represents the loading coefficient of indicator j in the first principal component;

$PC_{1,i}$ is the composite CE score for country i.

The first principal component is retained because it captures the largest proportion of shared variation across the four indicators. It represents the underlying macro level circular performance factor. Indicators with higher absolute loadings contribute more strongly to overall circularity.

Importantly, PCA is conducted on the full pooled sample including both developed and developing economies. This unified estimation framework ensures that weights are derived from the same variance structure and avoids methodological fragmentation across country groups. Differences in index scores therefore reflect structural performance differences rather than estimation bias.

The choice of PCA is also appropriate for the purpose of this study because the objective is not to assign normative importance to each indicator, but to identify the common statistical structure underlying macro level CE performance. Alternative weighting approaches, such as equal weighting, are simple and transparent, but they assume that all indicators contribute equally to circularity. This assumption may be too strong because CAE, EE, ET, and RE do not necessarily vary with the same intensity across countries. Entropy weighting is another useful method, especially when the objective is to give greater weight to indicators with higher dispersion. However, entropy weights are driven mainly by information variability and may not fully capture the latent common dimension shared by the indicators.

PCA is therefore selected because it is more consistent with the aim of constructing a composite index from correlated indicators. It allows the weights to be derived from the covariance structure of the data and gives greater importance to indicators that contribute more strongly to the shared CE dimension. This reduces the arbitrariness associated with subjective weighting and avoids treating all indicators as equally informative.

4. EMPIRICAL RESULTS

4.1 Descriptive statistics and preliminary patterns

Table 2 reports the summary statistics of the four CE indicators for 109 countries. The results show considerable cross-country variation, suggesting that countries differ strongly in their level of CE performance.

Table 2. Summary statistics of circular economy (CE) indicators

Variable	Mean	Std. Dev	Max	Min
CAE	0.1940	0.1356	1.4950	0.0157
ET	0.0989	0.0548	0.5305	0.0207
EE	12.631	5.8574	48.2422	1.8850
RE	2.5178	2.1736	16.6011	0.1029

Source: Author's calculations.

Note: CAE = carbon efficiency, EE = energy efficiency, ET = energy transition, RE = material pressure.

EE has the highest mean value, at 12.631, and also the largest dispersion, with a standard deviation of 5.8574. Its values range from 1.8850 to 48.2422. This wide range indicates large differences in the ability of countries to generate economic output from energy inputs. Some economies use energy much more efficiently, while others remain highly energy intensive.

ET records a relatively low mean value of 0.0989, suggesting that renewable energy still accounts for a small share of total energy consumption in most countries. However, the maximum value of 0.5305 shows that some countries have made stronger progress in shifting toward renewable energy systems.

CAE has a mean value of 0.1940, with values ranging from 0.0157 to 1.4950. This variation indicates that carbon intensity differs substantially across countries. Economies with higher CAE values generate more carbon emissions per unit of output, while those with lower values show better CAE.

RE also shows strong variation across countries. Its mean value is 2.5178, with a standard deviation of 2.1736, and values ranging from 0.1029 to 16.6011. This suggests that the material intensity of production differs widely. Some economies depend heavily on material inputs to generate output, while others use materials more efficiently.

Figure 2 reports the pairwise correlations among the CE indicators. The results suggest moderate to strong associations between the variables, indicating that they capture related but distinct dimensions of CE performance.

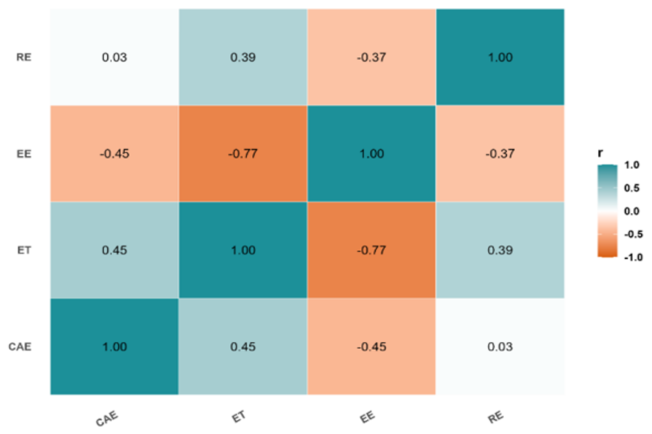

Figure 2. Correlation matrix
Source: Author's calculations.

A strong negative correlation is observed between EE and ET (r = -0.7722), suggesting that countries with higher energy productivity do not necessarily exhibit higher shares of renewable energy. This may reflect structural differences between economies, where improvements in EE are driven by technological optimization within existing energy systems rather than a transition toward renewables.

CAE is moderately positively correlated with ET (r = 0.4451), indicating that countries with higher renewable energy adoption tend to exhibit lower carbon intensity. This relationship is consistent with CE principles, as the shift toward cleaner energy sources contributes to reducing environmental pressure.

In contrast, CAE shows a moderate negative relationship with EE (r = -0.4519), suggesting that improvements in energy productivity may not always coincide with reductions in carbon intensity. This highlights the possibility that efficiency gains are achieved within carbon-intensive systems, particularly in developing economies.

RE exhibits relatively weak to moderate correlations with the other variables. Its near-zero correlation with CAE (r = 0.0300) suggests that material use intensity and carbon intensity may evolve independently across countries. Meanwhile, the moderate positive correlation between RE and ET (r = 0.3940) and the negative correlation with EE (r = -0.3743) indicate that material use patterns are partially linked to both ET and efficiency dynamics, but remain a distinct dimension of CE performance.

Table 3 reports the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. The overall KMO value is 0.762, indicating good sampling adequacy. Bartlett's test is also highly significant (chi-square = 3641.76, p < 0.001), rejecting the null hypothesis that the correlation matrix is an identity matrix. These results confirm that the variables are suitable for PCA.

Table 3. Kaiser-Meyer-Olkin (KMO) and Bartlett's test of sampling adequacy

Test	Statistic	Value	Interpretation
Kaiser-Meyer-Olkin (KMO)	Overall MSA	0.7620	Good
Bartlett's Test of Sphericity	Chi-square (χ^2)	3641.76	Significant
	p-value	0	Significant

Source: Author's calculations.

4.2 Principal Component Analysis results

Table 4 and Figure 3 report the PCA results. The first principal component (PC1) has an eigenvalue of 2.3149 and explains 57.87% of total variance. It is the only component with an eigenvalue greater than 1, and the scree plot shows a clear elbow after PC1. PC1 is therefore retained as the composite CEI.

Table 4. Principal Component Analysis (PCA) results

Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	2.3149	57.87	57.87
PC2	0.9706	24.27	82.14
PC3	0.4870	12.18	94.31
PC4	0.2275	5.69	100.00

Source: Author's calculations.

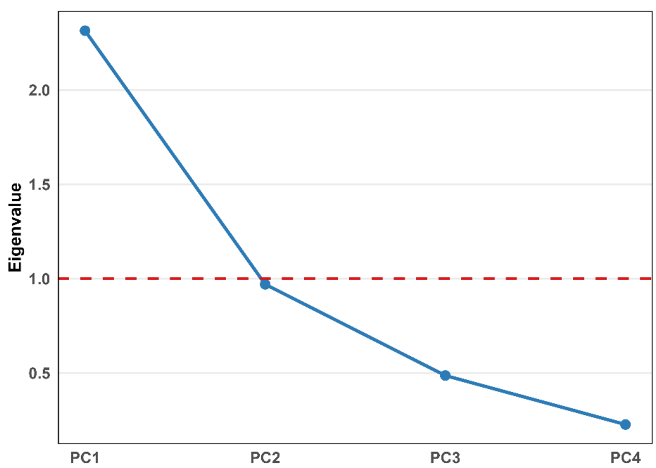

Figure 3. Scree plot of eigenvalues

Table 5 presents the factor loadings for PC1. All four indicators load positively on the retained component, confirming that PC1 captures a common CE dimension.

ET and EE have the highest loadings, at 0.5939 and 0.5919. CAE* and RE* also contribute positively, with loadings of 0.4126 and 0.3559. This means that the index is driven mainly by energy transition and energy productivity, while also capturing lower carbon intensity and lower material pressure.

Table 5. Factor loadings from Principal Component Analysis (PCA)

Variable	PC1	PC2	PC3	PC4
CAE*	0.4126	-0.6460	0.6422	-0.0004
ET	0.5939	-0.0088	0.3732	0.7127
EE	0.5919	-0.0174	-0.3973	0.7011
RE*	0.3559	0.7631	0.5390	0.0238

Source: Author's calculations.
Note: CAE* and RE* are reversed variables used in PCA to ensure that higher values indicate better circular economy (CE) performance.
CAE = carbon efficiency, EE = energy efficiency, ET = energy transition, RE = material pressure.

4.3 Classification of countries by circular economy performance

Figure 4 presents the CEI heatmap for 109 countries over 2002-2024. The index ranges from 0 to 1, with higher values indicating stronger circular performance. The color pattern shows a clear hierarchy across countries, with high-performing economies concentrated in the upper range and low-performing economies concentrated in the lower range.

The first thing the figure makes clear is that cross-country differences in CE development are large. The top part of the heatmap is dominated by advanced economies such as Sweden, Denmark, Norway, the United Kingdom, Switzerland, the Netherlands, Israel, Finland, France, Germany, Luxembourg, and Austria. These countries remain in dark green shades for most years. This suggests that their CE performance is not only high, but also stable over time. This pattern may be partly associated with stronger technological capacity, more developed environmental regulation, higher EE, and greater progress toward green growth in many developed economies.

The middle group looks more mixed. Countries such as Spain, Belgium, New Zealand, Ireland, Singapore, Slovenia, Italy, Hungary, Greece, Estonia, China, Poland, Croatia, Chile, Romania, Brazil, and Malaysia mostly appear in light green to pale yellow shades. This means they perform at moderate to fairly good levels, but they do not belong to the leading group. In practical terms, these countries seem to have made some progress in energy use, resource management, and environmental pressure reduction, but the transition is still less deep and less consistent than in the top tier.

Another useful insight from the figure is that it captures not only the level of CE performance, but also how it changes over time. In several countries, the colors gradually move from yellow or orange to lighter green in later years. This points to some improvement in the CEI. But the pace of improvement is uneven. A few countries improve only slightly, while many others keep roughly the same relative position throughout the sample period. This suggests that the shift toward a CE is likely to be a long-term structural process. Its pace may be influenced by underlying economic and institutional conditions.

At the lower end of the heatmap, countries such as Tanzania, Cameroon, Myanmar, Mozambique, Ethiopia, Zimbabwe, Mongolia, Uganda, Burkina Faso, and Madagascar remain in red or dark red shades for much of the study period. This indicates low CE performance and slow progress over time. From a practical point of view, this is not surprising. Many of these economies face common structural constraints, including weak technological capability, poor infrastructure, heavy dependence on raw material extraction, lower EE, and limited institutional capacity. In simple terms, these countries do not yet have the conditions needed to support a strong circular transition.

The figure also reveals some short run fluctuations in specific countries, shown by isolated color changes that differ from the overall pattern of a row. These shifts may reflect temporary changes in energy policy, economic shocks, changes in production structure, or adjustments in resource and CAE. Still, these short-term variations do not change the broader picture. Relative positions remain fairly stable. The leading group stays near the top, and the lagging group stays near the bottom for most of the period.

The figure offers three main insights. First, CE performance at the country-level is strongly stratified, with developed economies holding a clear advantage. Second, improvement does occur, but it is generally slow, which shows that circular transition depends on existing institutional quality, technological capability, and economic structure. Third, the gap between the leaders and the laggards remains wide, which suggests that the global transition toward a CE is still uneven and closely tied to differences in development levels.

Figure 5 presents the classification of 109 countries into three groups based on their CEI in 2024, namely high CE, medium CE, and low CE. The classification is based on tertiles of the 2024 CEI distribution. Countries in the top third of the distribution are classified as high CE economies, those in the middle third as medium CE economies, and those in the bottom third as low CE economies. This tertile-based approach provides a transparent and reproducible way to divide countries into relative performance groups. The figure shows a clear ranking pattern, with countries arranged from the highest to the lowest CE score. This visual structure makes it easy to observe both the distribution of countries across groups and the size of the gap between leading and lagging economies.

At the top of the ranking, the high CE group is dominated by advanced economies such as Sweden, Denmark, Norway, the United Kingdom, Switzerland, the Netherlands, Finland, France, Germany, and Austria. These countries record CE scores close to the upper bound of the index, indicating strong CE performance. Their position suggests that they have built more mature systems for resource efficiency, environmental governance, and green transition. In practical terms, these countries are better able to combine economic activity with lower resource pressure and stronger sustainability outcomes.

The medium CE group includes a broad set of countries with moderate but uneven performance. This group covers economies such as Latvia, Thailand, Mexico, the United Arab Emirates, Colombia, Viet Nam, South Africa, India, Uruguay, and Panama, among others. Their CE scores indicate that some progress has been made, but the transition remains incomplete. These countries are neither at the frontier nor at the bottom. Instead, they represent transitional cases where CE development is present but not yet deep, stable, or comprehensive.

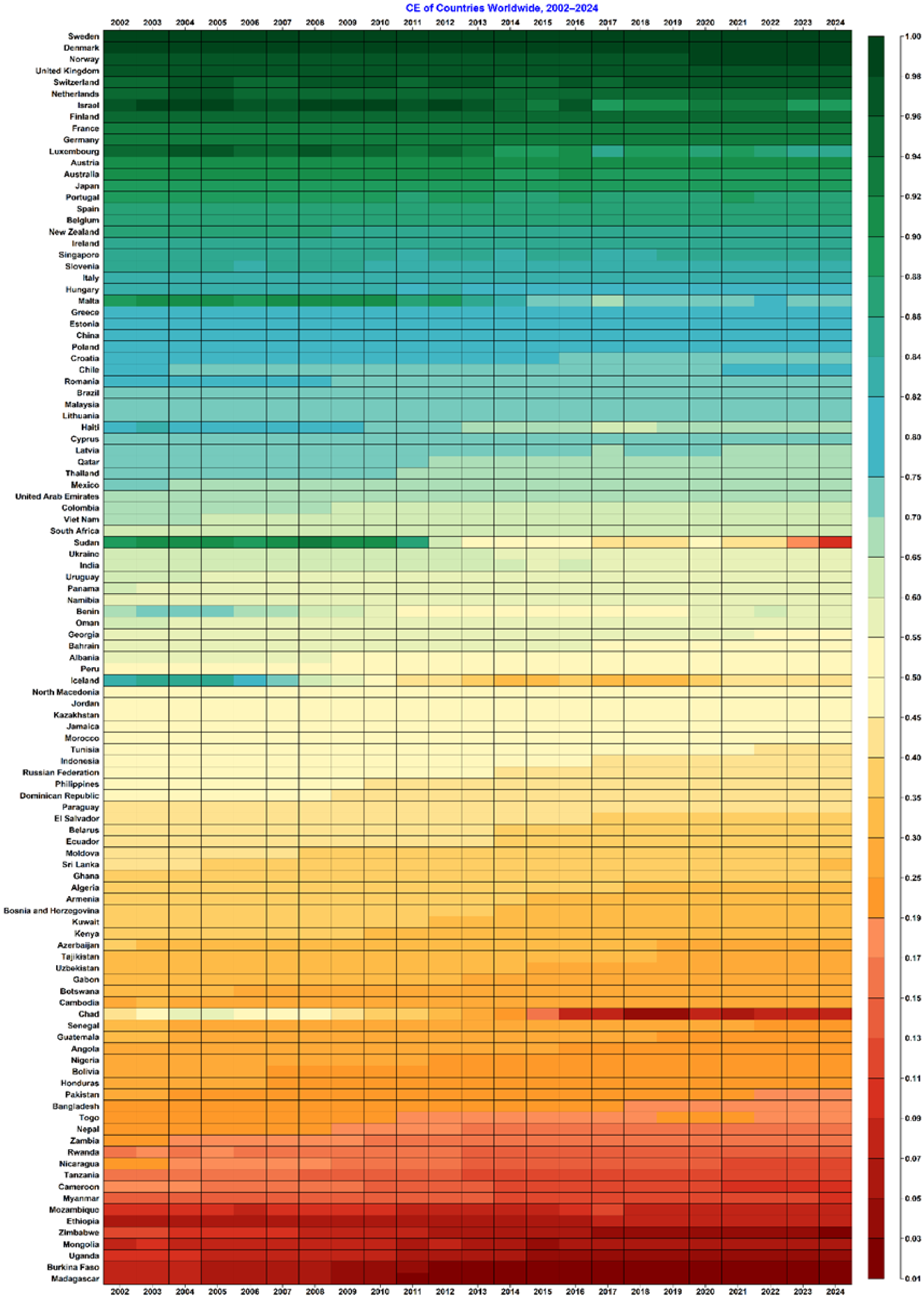

Figure 4. Heatmap of circular economy index (CEI) across 109 countries, 2002–2024

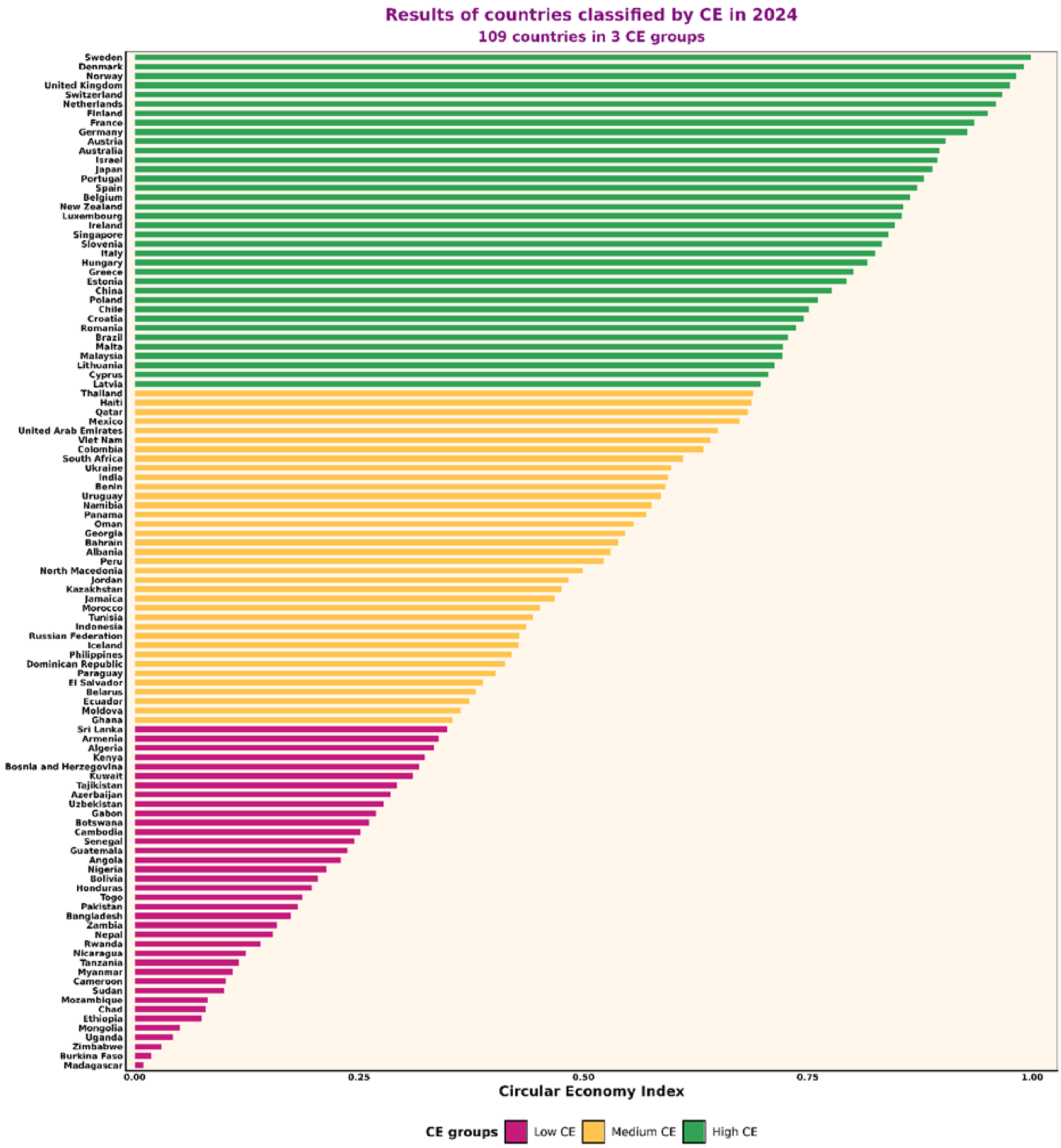

Figure 5. Distribution of 109 countries across three circular economy (CE) groups in 2024

At the bottom of the distribution, the low CE group consists mainly of developing and lower income economies such as Angola, Nigeria, Bolivia, Honduras, Pakistan, Bangladesh, Nepal, Rwanda, Tanzania, Cameroon, Mozambique, Ethiopia, Zimbabwe, Uganda, Burkina Faso, and Madagascar. Their low CE scores suggest limited progress in circular transition. This pattern may reflect structural constraints such as weak infrastructure, lower technological capability, heavy dependence on primary resource use, and weaker institutional capacity to support circular practices.

An important feature of the figure is the clear separation between groups. The high CE group occupies the upper part of the ranking with relatively compressed but high scores, while the medium CE group forms a broad middle layer. In contrast, the low CE group is concentrated at the lower end of the scale, with several countries recording very low index values. This indicates that CE performance across countries is not evenly distributed, but strongly stratified.

The figure suggests three main points. First, CE development remains highly uneven across countries. Second, advanced economies continue to dominate the top positions, indicating that economic development, institutional quality, and technological capability likely matter for CE performance. Third, the wide gap between the high and low groups implies that the global transition toward a CE is still incomplete and marked by substantial cross-country disparities.

Table 6. Descriptive statistics of the circular economy index (CEI) by development group

Country Group	Number of Countries	Mean	Standard Deviation	Minimum	Maximum
Developing	79	0.413	0.216	0.000	0.920
Developed	30	0.864	0.110	0.301	1.000

Source: Author's calculations.

4.4 Comparative analysis: Developed vs developing economies

Table 6 shows a clear difference in CE performance between developed and developing economies. The mean CEI is 0.864 for developed economies, compared with 0.413 for developing economies. The gap of about 0.45 points is large. This suggests that developed economies, on average, have moved further toward more resource-efficient and sustainable production systems.

The standard deviation also differs between the two groups. Developed economies have a lower standard deviation of 0.110, while developing economies record a higher standard deviation of 0.216. This means that developed economies are not only stronger on average, but also more consistent in their CE performance. By contrast, developing economies show wider variation. Some developing countries have made visible progress, while others remain at a much lower level of circular transition.

The minimum and maximum values further support this pattern. In the developing group, the CEI ranges from 0.000 to 0.920, showing a very wide spread in performance. This indicates that CE development within developing economies is highly uneven. In the developed group, the index ranges from 0.301 to 1.000. Although the weakest developed economy still records a relatively low score, the group as a whole remains much stronger, as shown by its higher mean and lower dispersion.

The table indicates that developed economies have achieved a higher and more stable level of CE performance, while developing economies remain more fragmented. One possible explanation is that developed countries generally have stronger institutions, better environmental regulation, more advanced technology, and greater financial capacity to support circular practices. Developing economies, by contrast, often face deeper constraints in infrastructure, governance, financing, and formal resource management, which may slow their transition toward a CE.

4.5 Robustness of group differences

The group comparison confirms a strong difference between developed and developing economies. Levene's test rejects equality of variances at the 1 percent level, indicating different dispersion across groups and supporting the use of Welch's t test (Table 7).

Table 7. Robustness tests for differences in the circular economy index (CEI) between developed and developing economies

Test	Statistic	*df*	p-Value
Levene's test for equality of variances	20.551	107	< 0.001
Welch's t-test	-14.111	94.756	< 0.001
Mann–Whitney U test	67		< 0.001

Source: Author's calculations.

Welch's t-test shows a highly significant mean difference, with a statistic of -14.111 and a *p*-value below 0.001. The average CEI is 0.413 for developing economies and 0.864 for developed economies, implying a gap from 0.466 to 0.451. This is both statistically significant and substantively large.

The Mann-Whitney U test gives the same conclusion, with a *p*-value below 0.001. The result is therefore robust even without relying on normality assumptions. CE performance is systematically higher in developed economies than in developing economies.

Figure 6 shows that developed economies remain ahead of developing economies throughout 2002-2024. The CEI for developed countries declines slightly from around 0.88 at the beginning of the period to nearly 0.85 in 2024, while the index for developing countries falls from about 0.44 to about 0.39. The gap remains large and shows no clear sign of narrowing.

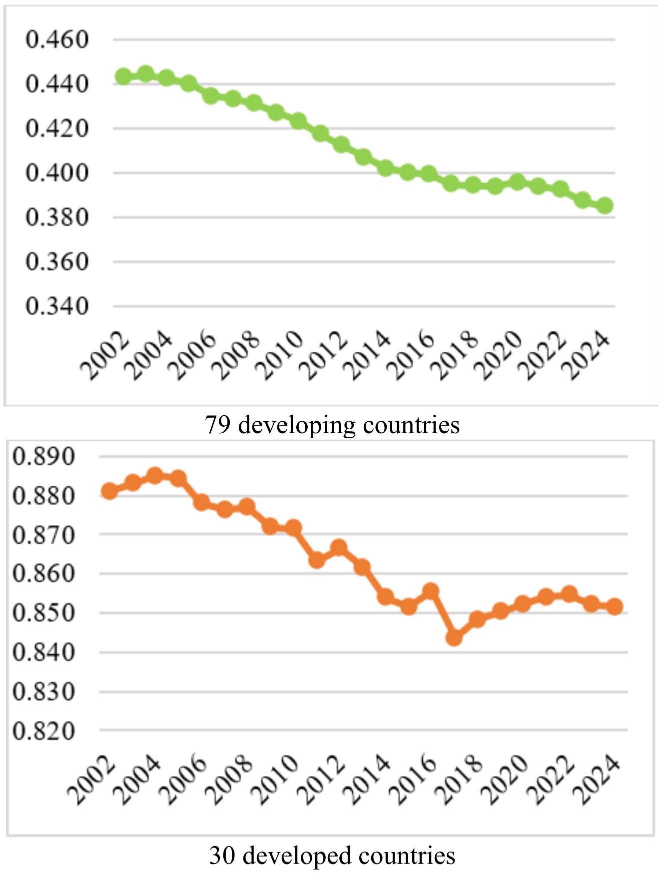

Figure 6. Circular economy index (CEI) over time, 2002–2024

4.6 Discussion

The findings support the central argument that CE performance differs substantially between developed and developing economies. This result is consistent with previous studies showing that circular transition is shaped by structural conditions rather than by recycling performance alone. For example, Kirchherr et al. [8] emphasized that CE requires systemic changes in production, consumption, reuse, and resource efficiency, while Haas et al. [47] showed that material flows and resource dependence remain central barriers to achieving a more circular global economy. In the same direction, Mayer et al. [46] argued that economy-wide circularity depends on the ability to close material loops, reduce input pressure, and improve resource productivity. The present study extends these insights by showing that such structural differences are not only visible in individual indicators, but also appear clearly in a composite macro level CEI.

The higher CEI scores of developed economies are broadly consistent with studies on CE measurement in Europe and other advanced economies. Claudio-Quiroga and Poza [23] found large differences in CE performance among European countries, reflecting differences in institutional capacity, technology, and policy implementation. Similarly, Drofenik et al. [24] showed that national CE progress depends on the alignment between policy targets and implementation capacity. The results of the present study support this view, but they also add a wider comparative perspective by showing that the gap is even more visible when developed and developing economies are assessed under the same measurement framework. Developed economies tend to perform better, possibly because they often have stronger technological capacity, more advanced environmental regulation, better data systems, and stronger institutional support for circular transition.

At the same time, the results should not be read as a simple success story for developed economies. Many developed countries still have high levels of material consumption. This point is consistent with previous research arguing that high-income economies may perform well on recycling, EE or environmental regulation while still maintaining resource-intensive consumption patterns. In this sense, stronger CEI scores reflect relative advantages in efficiency and transition capacity rather than a complete circular transformation. The index developed in this study helps reveal this tension by combining CAE, EE, ET, and RE in one framework. This is important because a country can perform well in one circular dimension while remaining weak in another.

For developing economies, the findings are also consistent with prior studies suggesting that CE implementation may be constrained by infrastructure, finance, technology, and institutional quality. Emami et al. [25], in the ASEAN context, showed that CE progress remains uneven because material consumption, waste systems, and circularity rates differ strongly across countries. Parchomenko et al. [49] and De Pascale et al. [50] also noted that CE indicators often fail to capture informal recovery systems and local circular practices. This is particularly relevant for developing economies, where informal reuse, repair, and recycling may be significant but poorly recorded in official statistics. Therefore, lower CE scores do not necessarily mean that these economies lack circular practices. Rather, they indicate that informal practices have not yet been transformed into formal, scalable, and measurable circular systems.

Compared with previous studies, the main contribution of this study is that it provides a unified macro level comparison between developed and developing economies using the same indicators, the same normalization procedure, and the same PCA-based weighting structure. Earlier studies have often focused on specific regions, specific material flows, firm-level indicators, or European data systems. This study moves the discussion forward by offering a simple and internationally comparable index that can identify broad development gaps in CE performance. The evidence suggests that developing economies need stronger circular infrastructure, better environmental data systems, targeted green finance, cleaner technology transfer, and institutional reforms that can transform informal circular practices into more efficient and scalable circular systems.

5. CONCLUSION AND POLICY IMPLICATIONS

This study develops a standardized macro level CEI for 109 countries over the period 2002 to 2024, including 30 developed economies and 79 developing economies. The index is constructed from four dimensions: CAE, EE, ET, and RE. By aligning indicator direction, normalizing heterogeneous variables, and applying PCA to the pooled sample, the study provides a transparent and internationally comparable measure of CE performance.

The results show that the index captures meaningful cross-country differences. The PCA results support the use of a single composite dimension, with the first principal component explaining 57.87% of the total variance. This suggests that the four indicators share a common underlying structure and can be used to represent macro level CE performance.

The main finding is that developed and developing economies differ sharply. Developed economies record an average CEI of 0.864, compared with 0.413 for developing economies. The gap of about 0.451 points is substantial. This difference is also robust across Levene's test, Welch's t-test, and the Mann-Whitney U test. The ranking, classification results, and visual evidence further suggest that circular transition remains uneven and is closely associated with development level.

These findings have clear policy implications. CE progress cannot be reduced to recycling alone. It also requires higher energy productivity, faster renewable ET, lower carbon intensity, and lower RE. Developed economies should focus on reducing excessive material consumption and strengthening circular production systems. Developing economies need greater investment in circular infrastructure, clean technology, institutional capacity, and environmental data systems.

The study contributes to the literature by offering a parsimonious macro level index that is feasible for a heterogeneous country sample and broad enough to avoid reducing circularity to waste management alone. It also suggests that CE development may be closely associated with differences in technology, institutions, energy systems, and production structures. Future research can use this index to examine the determinants of CE performance, including the role of finance, institutions, innovation, and policy capacity.

The study also has limitations. The index uses four macro level indicators, which improves comparability but cannot capture all dimensions of the CE. Data availability may also affect consistency, especially for developing economies. In addition, the index focuses on national-level outcomes and does not fully capture informal circular practices, sectoral dynamics, or firm-level behavior. Future studies should expand the indicator set, improve data coverage, and connect macro level measurement with sectoral and firm-level evidence.

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