*International Research Journal of Environmental Sciences*_____ ISSN 2319–1414
Vol. **15(4),** 35-45, October **(2026)** *Int. Res. J. Environmental Sci.*

Transitioning from Linear to Circular: Evaluating the Economic and Sustainability Potential of Circular Economy in India

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Available online at: www.isca.in, www.isca.me
Received 2nd August 2026, revised 16th September 2026, accepted 9th October 2026

Abstract

We examine various indicators of the circular economy in the Indian context. For this purpose, we have analyzed the relationship between material consumption (Direct Material Consumption, DMC and Material Footprints, MF), share of renewable energy in the energy basket, CO_2 emissions and economic growth (GDP) in India from 1990 to 2024. Using data extracted from international organizations databases (World Development Indicators, WDI and United Nation Environment program, (UNEP), the paper uses Johansen cointegration and VECM to understand the long-run and short-run relationship between variables. The paper found that GDP, material consumption, and renewable energy have a steady long-run equilibrium with GDP adjusting at a speed of 23-28% per year. But we find no cointegration between CO_2 emissions, material use, and renewable energy, suggesting that emissions are driven by factors outside this system. We observed that results pertaining to the short-run indicate that material consumption has a negative effect on GDP and renewable energy coefficients are insignificant.

Keywords: Renewable Energy, Indicators, Linear Production, Circularity, Transition, Ecological Economics.

Introduction

Green growth is recognized as an important part of future planning process and Indian policymakers have recognized it and it is included in the India's policy framework. The method of production being currently followed in India and most of the world economies is a linear production model which is popularly referred as 'take-make-and dispose' economy[1].

Its adverse impact due to misuse/overuse of resources is being increasingly questioned as this is making the current consumption pattern unsustainable.

Alternative models of production and consumption were explored so that the objective of sustainable growth with minimum adverse impact on environment and ecology can be achieved. The Circular Economy (hereafter CE) model is suggested as alternate because it ensures recycling and reusing the waste generated during the production consumption cycle. The main purpose is not to focus on 'manufacturing-use-disposal' but rather on 'reduce–reuse–recycle'. The CE model promotes resource-efficient and environmentally sustainable production. The idea is to attain circularity of inputs to avoid loss of inputs and minimize waste. The idea of CE was culminated from several schools of thought and the model is refined over a period of time. The definition and conceptual issue are dealt in detail in many previous studies[1-4].

India's demand for energy, minerals, construction materials and consumer goods has increased manifold owing to growth and population increase. Moreover, urbanization is happening at a fast rate. Together they give rise to a high level of material consumption and waste generation. CPCB, annual report 2021-22 showed that the total amount of waste generated in India was approximately 170,339 TPD during 2021–22[5]. Of this, about 92 percent is collected but only 54% is processed. Approximately 41,455 TPD (24%) was disposed of in landfills and 37,373 TPD (22%) remained unaccounted for. Recognizing these challenges, the Government's focus shifted on promoting resource efficiency and circularity in India.

The Government of India has integrated CE principles in the policy sphere. Basically CE is the central pillar to efficient energy transitions. The key aspect of sustainable development (green growth) is energy transition and the Government has recognized this by making budget provision for this. In the budget speech of Union Budget 2023–24, green growth featured among the seven key priorities (*Saptarishi*). The budget allocation of ₹35,000 crore for capital investments in support of the energy transition in 2023–24, underlines the emphasis on green growth and sustainable economic development (Government of India, 2023). The budget document 2023-24 is a testimony of the Indian government focus on green energy, sustainable agriculture, green mobility, energy-efficient technologies, and low-carbon intensity.

With the above background this paper made attempts to understand the current position of India in sustainability and circularity. The secondary data were extracted from online international databases for the period 1990-2024, keeping in view the availability of consistent data for this period only. We investigated the progress of CE and sustainable economic development in India by analyzing resource use, renewable energy consumption, economic growth and carbon emissions.

Literature review: The linear economic model is replaced by the CE model due to the inherent pressure on resources by the former. The concept of CE has its ideas rooted in Industrial ecologyand ecological economics. The main idea put forward by industrial ecology is that the by-products of one production system should be used as inputs in other production systems[6]. Whereas key idea of ecological economics is that economic growth must occur within environmental limits[7]. Efficient use of resources is the guiding principle of both industrial ecology and ecological economy.

The recent research defines and refines the concept of CE. The literature on the CE can be broadly classified into themes: conceptual development, drivers and enablers, policy and governance, implementation challenges, and the social dimension. Table 1 presents major studies and highlights the evolution of the CE from a resource-efficiency concept to a broader framework for sustainable development.

As evident from the above table, the concept of CE has progressed to a wider framework based on value retention, clean production methods and sustainable consumption/production systems[10-12]. The concept of CE is closely linked with sustainable development. The literature normally views the concept of CE distinct from sustainability but it does provide practical ways for achieving sustainability[13,14]. Scarcity of resources, environmental pressures, economic incentive, and improvement in technology, public policies, and collaboration among stakeholders are discussed as the factors important for adoption of CE practices[15-18].

India specific studies show challenges faced in implementing. The studies include factors such as policy and institutional gaps, role of the informal sector, financial constraints, technological constraints and supply chain constraints faced by MSMEs which impact CE implementation[20-24]. The literature suggests that transition to a CE necessitates coordinated efforts by stakeholders[1,25,26].

Material Flow Analysis (MFA) is widely used in evaluation of resource use and for identifying the ways for improving efficiency from a circular economy perspective[27,28]. The material flow analysis in case of plastic use and production in India has also been used[29]. MFA helps in guiding decision making for the industry and policy planning pertaining to the environment[30,31].

A study analyzing India's metabolic transition from biomass to fossil fuels found that DMC had quadrupled (1961–2008) to 4.3 t/capita[32] and this is confirmed by another study which found a 93% rise in per capita DMC (1978–2017) but low resource productivity[33].

The paper evaluates the economic and sustainability potential of CE in India with some specific objectives in mind. The paper focuses on four things: i. How have material use, renewable energy, growth, and emissions trended in India between 1990 and 2024?. ii. Is there a clear link between CE indicators and economic growth and if so, what does it look like? iii. Do CE practices actually reduce CO_2 emissions? (We use CO_2 as our proxy for sustainability) iv. What has the Indian government done so far to push the circular agenda.

Methodology

Data and Variables: The study uses time series data for 1990 to 2024 on GDP per capita (constant 2015 US dollars), carbon dioxide (CO_2) emissions per capita excluding land use, land-use change and forestry (LULUCF), renewable energy consumption as a percentage of total final energy consumption (*hereafter referred to as* RE), and total natural resource rents (*hereafter NRR*) as a percentage of GDP, that are extracted from the World Development Indicators (WDI) database. The data on material flow indicators namely Domestic Extraction (*hereafter DE*), Domestic Material Consumption (*hereafter DMC*), Domestic Material Input (*hereafter DMI*), and Material Footprint (*hereafter MF*) are taken from the UNEP IRP database.

The variables capture various dimensions of the circular economy, namely resource extraction, material consumption, material requirements, resource productivity, renewable energy utilization, economic growth and environmental sustainability. We use material flow and productivity data to see how efficiently India turns natural resources into economic value.

The study has taken material flow indicators - DE, DMC, DMI and MF. DE captures raw materials extracted domestically. DMC reflects total materials directly used and represents intensity of domestic resource use. DMI adds imports to domestic extraction, giving total material input available for economic production. And MF tracks the global resources behind India's final consumption — including materials embedded in trade.

Economic growth is captured by GDP per capita while environmental sustainability is measured through per capita carbon CO_2 emissions. Clean-energy transition is proxied by RE. Per-capita versions of the material indicators and productivity ratios are calculated for the purpose of description and they are not included in the econometric models as they are derived from GDP and the material flow variables. The variables are shown in Table-2.

Conceptual Framework: This paper is based on the presumption that efficient use of material resources and increasing share of RE are a reflection of a movement towards a circular economy. The changes in resource use efficiency are captured by material flow indicators (DE, DMC, DMI and MF). Renewable energy consumption reflects the transition towards cleaner sources of energy. The material flow indicators are expected to directly influence economic growth. The environment sustainability is measured through their effect on carbon emissions.

Table-1: Thematic Summary of Circular Economy Literature.

Theme	Key Studies
Conceptualization, Evolution & Scope	Industrial ecology introduced the concept of industrial ecosystems, in which waste generated by one method serves as an input for otherprocesses[6]; Ecological economics established the theoretical basis for a circular economic system as an alternate model[8]; Operational principles for sustainable resource use were articulated through ecological economics[7]; The concept of a "performance economy" laid early foundations for CE thinking[2]. CE definitions have been systematically analyzed to identify core principles and boundaries[4]. CE has inherent limitations related to thermodynamic constraints and rebound effects[9]. CE is an "umbrella term" encompassing resource-life-extension concepts [10]. Evolution of CE can be traced from industrial residues to value retention and sustainable systems[11]. Evolution from waste plans to support cleaner technologies and responsible consumption[12]. CE is a means to achieve sustainability, not synonymous with it[13]. CE, Green Economy, and Bioeconomy share common goals but differ in emphasis and scope[14].
Drivers, Barriers & Enablers	Motivations for CE adoption include resource scarcity, environmental impact, and cost-benefit analysis[15]; CE in supply chains enhances both environmental and economic performance[16]; Stakeholder collaboration is fundamental to CE implementation[13]; CE success depends on technology, government policies, governance, and stakeholder collaboration. Policy and governance are non-negotiable enablers[17]; CE requires integration of supply chains, institutions, and technological pathways; isolated interventions fail[18]; Technical aspects (reuse/recycling) are well-covered, but strategic adoption and business models are under-researched[15]; Business model innovation is critical for CE adoption[1,3].
Policy, Governance & Measurement	Public policies, technological capability, and industry participation are crucial, particularly in developing countries[19]. Absence of robust CE indicators in India is a major hurdle for evidence-based policymaking[20]. NITI Aayog identifies e-waste, batteries, construction materials, plastics, and agriculture as priority sectors; emphasizes recycling systems and stakeholder coordination for resource security. Indian waste management data provides context for CE policy implementation[5].
Implementation Challenges (India)	Coordinated policy, tech innovation, and collaboration is called for; notes informal sector as a major barrier[20]; MSMEs practice reuse/repair/recycling but informally and without strategy[21]; In e-waste, informal recycling dominates; recommends integrating informal collectors via modified EPR framework[22]. Identifies financial, institutional and implementation barriers, and highlights the necessity of supportive policies, financial incentives and practical implementation strategies[23]. Limited technical expertise, weak digital capabilities, and poor supply chain collaboration as key constraints—even when government initiatives exist[24].
Social Dimension	CE prioritizes economic and environmental goals; the social dimension is normally ignored[13]. Circular economy, green economy, and bioeconomy share the objective of balancing economic, environmental and social dimensions, although they differ in emphasis and scope[14]. Studies on e-waste and MSMEs underscore the imperative of formalizing, indicating that social inclusion is often overlooked[21-22].

Table-2: Description of Variables used in Models.

Variable	Definition	Unit
GDP	GDP per capita (constant 2015 US$)	US$
CO_2	CO_2 emissions excluding LULUCF per capita	Tonnes per capita
RE	Renewable energy consumption (% of total final energy consumption)	Percentage (%)
DMC	Domestic Material Consumption	Million tonnes
MF	Material Footprint (Raw Material Consumption)	Million tonnes
MPDMC	Material Productivity (DMC)	US$/kg

Analytical Framework: The paper employs descriptive statistics and trend analysis to examine changes in material use, RE consumption, economic growth and CO_2 emissions in India during 1990–2024. The relationships among these variables are applied using suitable packages in 'R'. Theoretically, progress in resource efficiency is expected to favorably affect economic growth and efficient use of natural resources. Simultaneously, efficient material use and greater reliance on RE are expected to reduce environmental pressure as they lower carbon emissions and improve environmental sustainability.

Among the material flow indicators, DMC and MF are included in the econometric analysis as they represent domestic resource use and consumption-based material use, respectively. Separate models using DMC and MF are estimated to test the robustness of the results. Four empirical models are specified. Models I and II examine the influence of CE indicators on economic growth, while Models III and IV analyze their impact on environmental sustainability, measured by per capita carbon dioxide (CO_2) emissions. All continuous variables, except RE were transformed into natural logarithms to enable the coefficients to be inferred as elasticity.

The models estimated in the study are as under.

Model – 1 (Economic Growth)

$$ln\ lnGDP_t = \beta_0 + \beta_1 lnDMC_t + \beta_2\, RE_t + \varepsilon_t \quad (1)$$

Model – I1 (Economic Growth- Robustness)

$$ln\ lnGDP_t = \beta_0 + \beta_1 lnMF_t + \beta_2\, RE_t + \varepsilon_t \quad (2)$$

Model – III (Environment Sustainability)

$$ln(CO_2)_t = \alpha_0 + lnDMC_t + \alpha_2\, RE_t + \mu_t \quad (3)$$

Model – IV (Environment Sustainability- Robustness)

$$ln(CO_2)_t = \alpha_0 + lnMF_t + \alpha_2\, RE_t + \mu_t \quad (4)$$

Augmented Dickey-Fuller (ADF), ADF-Generalized Least Squares (ADF-GLS) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests were applied. Then the Johansen (1988) cointegration approach was employed. Unlike single-equation methods, the Johansen framework treats all variables as potentially endogenous and allows for the identification of multiple long-run relationships among the variables. Before cointegration analysis, the optimal lag length for the Vector Autoregressive (VAR) system was determined using information criteria such as AIC(Akaike), SC(Schwarz) and HQ (Hannan–Quinn). All three criteria yielded different lag orders, the lag length suggested by the Schwarz Criterion (SC) was taken because it is generally preferred for relatively small samples. The co-integrating relationships were then examined using Johansen's trace (Initially we planned to use ARDL for analysis but the bound test failed (ARDL Bounds F-statistic ≈ 0.76 and p-value ≈ 0.91). As unit test indicated that all the variables are integrated of order one, Johansen's cointegration approach was adopted) and maximum eigenvalue statistics.

Based on the identified co-integration rank, Vector Error Correction Models (VECM) were estimated for the model specifications which have co-integrating variables. The VECM framework allows the separation of short-run dynamics from long-run adjustments. The Error Correction Term (ECT) reflects the rate at which the system returns to its long-run equilibrium after a disturbance.A statistically significant ECT term points to the long-run causality and confirms that short-run deviations converge towards the equilibrium. The diagnostic tests on the residuals were conducted for reliability. The Portmanteau test was used for examining the existence of serial correlation. Normality was evaluated using the multivariate Jarque–Bera test. The presence of conditional heteroskedasticity was assessed with the help of the multivariate ARCH test. These diagnostics were performed using the **urca** and **vars** packages in R.

Table-3 describes a summary of the variables and Figures 1–4 illustrate their long-term trends. Gross Domestic Product (GDP) per capita averaged approximately $1,188 over the period. It has increased from $532 to $2,367. But this growth has been resource intensive and emission intensive, as average per capita CO_2 has increased nearly threefold from its minimum. Notably, the share of RE has declined steadily dropping from 53.0% to 32.4%. This indicates a relative shift towards fossil fuel-based energy sourcing. Natural resource rents (NRR) exhibit high volatility, with a mean of 2.97% of GDP but a sharp spike to 7.11% in 2008. Despite the rise in absolute material use and emissions, resource productivity indicators show gradual improvement.

Results and Discussion

Table-3: Descriptive Statistics of the Variables (1990–2024).

	Mean	Median	Min	Max	SD	Skewness	Kurtosis
GDP per capita (US$)	1188	1069	532	2367	554	0.58	-0.91
CO_2 per capita (t)	1.29	1.19	0.69	2.17	0.45	0.35	-1.29
Renewable Energy (%)	41.3	41.5	32.4	53.0	7.19	0.14	-1.63
NRR (% of GDP)	2.97	2.51	1.75	7.11	1.18	1.68	3.68
DE (Mtonnes)	5106	5083	2901	8427	1627	0.33	-1.11
DMC (Mtonnes)	5290	5140	2906	8896	1793	0.36	-1.16
DMI (Mtonnes)	5474	5362	2952	9292	1906	0.35	-1.16
MF (Mtonnes)	4699	4698	2677	7808	1506	0.36	-1.03
GDP/DMC (USD/kg)	0.26	0.25	0.16	0.38	0.07	0.24	-1.27
GDP/MF (USD/kg)	0.30	0.28	0.18	0.44	0.09	0.27	-1.37
Per Capita DE (tones)	4.23	4.27	3.33	5.85	0.74	0.42	-1.03
Per Capita DMCb(tones)	4.37	4.32	3.34	6.17	0.86	0.42	-1.16
Per Capita DMI (tones)	4.52	4.51	3.39	6.45	0.93	0.40	-1.17
Per Capita MF (tones)	3.89	3.93	3.04	5.42	0.69	0.46	-0.91

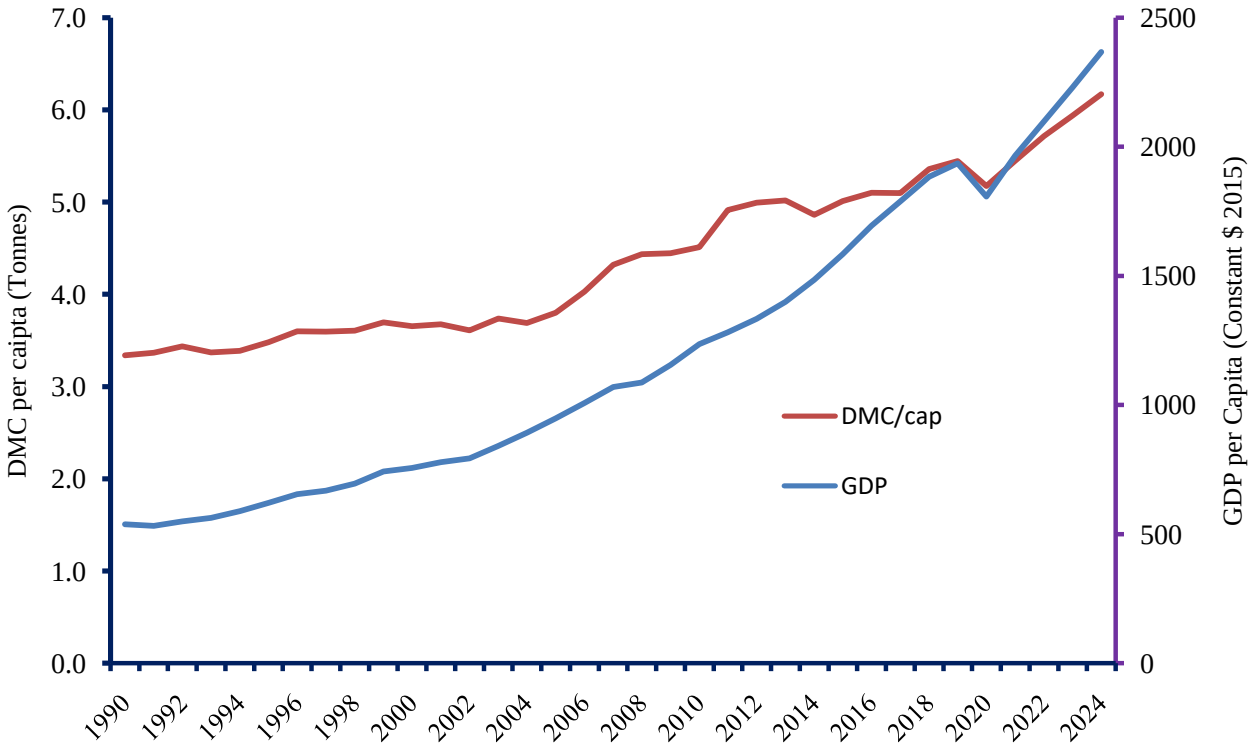


Figure-1: Per Capita GDP-Per Capita DMC.

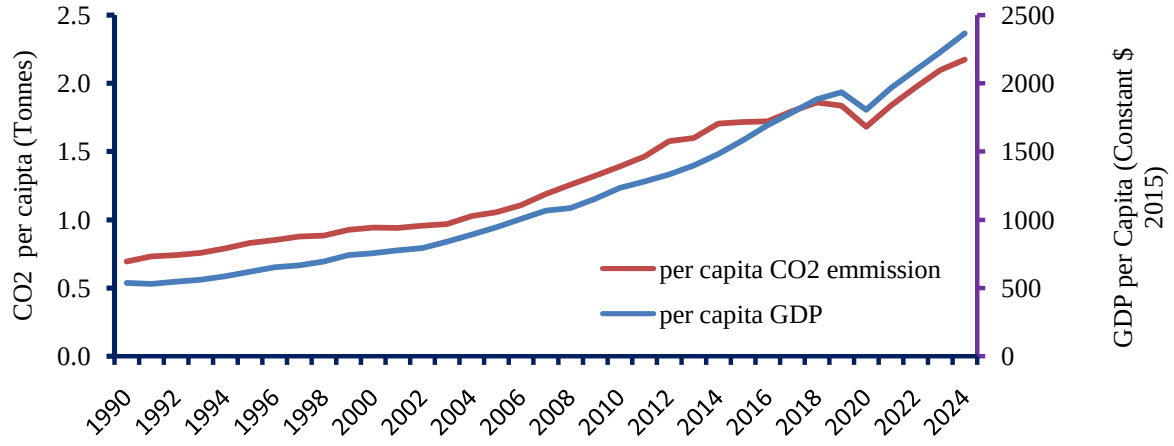


Figure-2: Per Capita GDP-Per Capita CO_2 Emission.

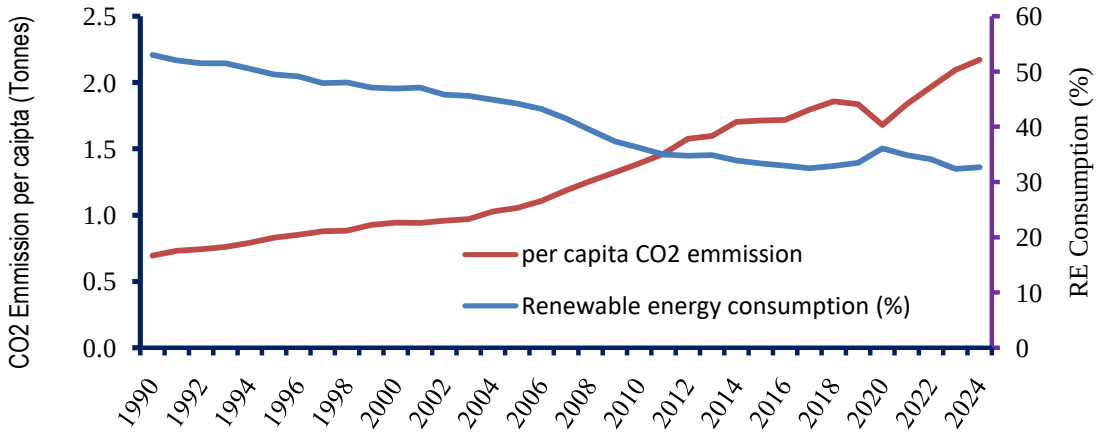


Figure-3: Per Capita CO_2 Emissions and RE Consumption (% of Total).

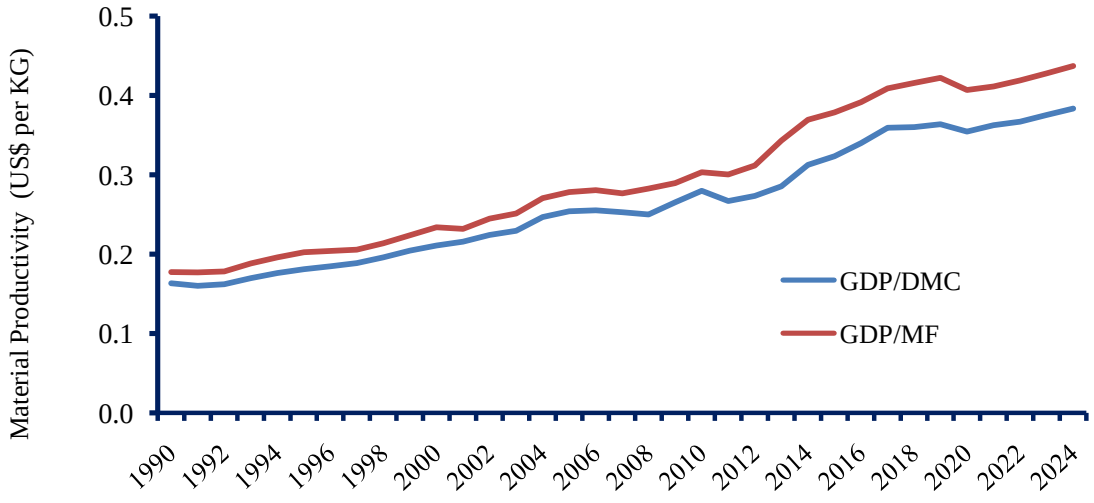


Figure-4: DMC Productivity (GDP/DMC) & MF Productivity (GDP/MF).

Material productivity (GDP/DMC) averaged 0.26 USD/kg and more than doubled from its minimum of 0.16 to 0.38 USD/kg. The GDP/MF also followed a similar upward path from 0.18 to 0.44 USD/kg suggesting an improvement in the efficiency of material use. Per capita material flows—DE, DMC, DMI, and MF—all increased steadily, with averages of 4.23, 4.37, 4.52, and 3.89 tonnes per capita, respectively. The distributional properties of these variables indicate smooth, long-term trends with low kurtosis (platykurtic) for most indicators, except for NRR, which is highly leptokurtic and right-skewed due to the 2008 outlier. This highlights the need for decoupling and for accelerating energy transition. The descriptive statistics indicate adequate variation across the variables while revealing stable long-term trends, providing a suitable basis for the subsequent time-series econometric analysis.

Stationarity Analysis: The stationarity of the variables was examined using the ADF, ADF-GLS and KPSS unit root tests. These tests provide evidence on the order of integration of the variables before proceeding with the cointegration analysis.

Table-4 reports the results of the ADF, ADF-GLS and KPSS unit root tests. The ADF and ADF-GLS results indicate that all variables are non-stationary at levels but become stationary after first differencing. The KPSS test supports these findings by failing to reject the null hypothesis of stationarity after first differencing. Accordingly, all variables are integrated of order one (I(1)), satisfying the prerequisite for examining long-run relationships.

Cointegration Analysis: Before testing for long-run relationships, we needed to choose the right lag length. Using both the AIC and SC, we settled on two lags for each of the four models. Table-5 presents the Johansen trace test results. For Models I and II, the trace statistics (52.82 and 48.81) exceed the 5% critical value (34.91), confirming the presence of one cointegrating vector (r = 1) in each specification. This indicates a stable long-run equilibrium relationship between GDP, material consumption, and renewable energy. However, for Models III and IV, the trace statistics (27.89 and 33.07, respectively) fell below the critical value, indicating no cointegration among the variables of interest. Consequently, VECM estimation is valid only for the GDP equations (Models I and II). For the CO_2 equations, we report short-run dynamics using first-difference OLS regressions.

Table-4: Unit Root Test Results.

Variable	ADF (Level)	ADF (First Difference)	ADF-GLS (Level)	ADF-GLS (First Difference)	KPSS (Level)	KPSS (First Difference)	Order of Integration
lnGDP	0.961	-5.702***	-2.576	-5.221***	0.144	0.081	I(1)
lnCO_2	-0.106	-5.109***	-1.890	-5.132***	0.098	0.076	I(1)
lnDMC	0.123	-5.528***	-2.352	-5.632***	0.092	0.072	I(1)
lnMF	0.209	-5.998***	-2.705	-6.016***	0.072	0.063	I(1)
RE	-1.243	-4.256***	-1.028	-2.845	0.133	0.101	I(1)

Source: Compiled from results obtained using R software based on the data collected as described above.
Notes: ADF and ADF-GLS entries report the test statistics, while KPSS entries report the LM test statistic. ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively. The null hypothesis of the ADF and ADF-GLS tests is that the series contains a unit root, whereas the null hypothesis of the KPSS test is trend stationarity. Lag lengths were selected using the AIC for the ADF test and the Modified AIC for the ADF-GLS test.

Table-5: Johansen Trace Test Results.

Model	Variables	Lag	Trace Statistic (r=0)	5% Critical Value	Cointegrating Rank
I	lnGDP, lnDMC, RE	2	52.82***	34.91	r = 1
II	lnGDP, lnMF, RE	2	48.81***	34.91	r = 1
III	lnCO_2, lnDMC, RE	2	27.89	34.91	r = 0
IV	lnCO_2, lnMF, RE	2	33.07	34.91	r = 0

Note: Trace statistics are compared with 5% critical values.***p < 0.01, All models include a constant term. Lag length based on AIC and SC.

Short run and Long run Adjustment Dynamics: Table-6 reports the ECT coefficients from the VECM for Models I and II. The coefficients are negative and statistically significant (-0.233 and -0.282, respectively; $p < 0.01$). This confirms that GDP adjusts to correct deviations from the long-run equilibrium. The speed of adjustment is modest—approximately 23.3% of disequilibrium is corrected within one period in Model I, and 28.2% in Model II—suggesting a gradual adjustment process. This implies that while GDP does respond to restore balance, the adjustment is not instantaneous, reflecting structural rigidities or policy lags in the Indian economy. In the short run, the coefficients of material consumption are negative (ΔlnDMC = -0.434, p = 0.053; ΔlnMF = -0.462, p = 0.057). The significance level falls just outside the 5% threshold but they provide weak evidence suggesting that rapid resource extraction does not immediately translate into higher output. On the other hand, the RE coefficients are small and statistically insignificant.

Results (Table-7) show that material consumption (DMC and MF) carries a positive coefficient in both specifications (0.341 and 0.108), suggesting that increased resource use is associated with higher emissions in the short run. However, these coefficients are statistically weak (p = 0.089 for DMC; p = 0.623 for MF). RE coefficients are negligible and statistically insignificant in both models (-0.005). The absence of cointegration implies that CO_2 emission, material use and RE do not have a long-run relationship. Since the Johansen trace test indicated no cointegration for these models (Table-4), VECM estimation is not appropriate and ECT coefficients are not reported.

Diagnostic Evaluation of VECM Models: To validate the reliability of our VECM estimates, we conducted a series of diagnostic tests on the residuals of Models I and II. Table 8 presents the results. The Breusch-Godfrey LM test confirms the absence of serial correlation in both models ($\rho = 0.989$ for both), indicating that the dynamic specification is adequate. The multivariate ARCH test indicates no heteroskedasticity in either model ($\rho = 0.730$ for both), confirming constant variance of the residuals. However, the multivariate Jarque-Bera test reveals significant deviation from normality in both models (JB = 159.4, $\rho < 0.001$ for both). This is a common issue in time series analysis with limited observations (n = 35) and does not undermine the robustness of the cointegration results. VECM estimates remain consistent and asymptotically normal even under non-normality conditions, provided that the other assumptions—no serial correlation and homoskedasticity—are satisfied[34]. Non-normality in small samples is not uncommon and does not invalidate cointegration inference[35].

Table-6: Estimated Error-Correction Coefficients from the VECM

Model	Cointegrating Equation	Dependent Variable	ECT	t-stat	Short Run Coefficients			
					ΔDMC/ ΔMF	t-stat	ΔRE	t-stat
I	lnGDP = 0.969 lnDMC + 0.020 lnRE + C	ΔlnGDP	-0.233***	-4.958	-0.434*	-1.94	0.013	0.21
II	lnGDP = 1.536 lnMF + 0.001 lnRE + C	ΔlnGDP	-0.282***	-4.064	-0.462*	-1.91	0.011	0.18

Note: *** significant at the 1% level and * significant at the 10% level.

Table-7: Short-Run Dynamics for CO_2 Equations

Model	Dependent Variable	ΔDMC/ΔMF	t-stat	ΔRE	t-stat
III	ΔlnCO_2	0.341†	1.762	-0.005	-0.495
IV	ΔlnCO_2	0.108	0.496	-0.005	-0.437

Note: † $\rho < 0.10$. Since the Johansen trace test indicated no cointegration (Table-5), a VECM could not be estimated. These are OLS estimates in first differences and should be interpreted as short-run associations only, not as error-correction.

Table-8: Diagnostic Tests for Residuals (VECM)

Test	Model I	Model II
Serial Correlation	$\chi^2 = 95.145$ ($\rho = 0.989$)	$\chi^2 = 95.145$ ($\rho = 0.989$)
Normality (JB)	JB = 159.39 ($\rho < 0.001$)	JB = 159.39 ($\rho < 0.001$)
Heteroskedasticity (ARCH)	$\chi^2 = 168$ ($\rho = 0.730$)	$\chi^2 = 168$ ($\rho = 0.730$)

Note: LM = Breusch-Godfrey Lagrange Multiplier test statistic; JB = Jarque-Bera test statistic; ARCH = Autoregressive Conditional Heteroskedasticity test.

Policy framework in India: India's CE transition is driven by a growing suite of sector-specific regulations rather than a single overarching law, with Extended Producer Responsibility (EPR) emerging as the central accountability mechanism. As detailed in Table-9, recent rules targeting plastics, e-waste, and batteries have established clear collection and recycling targets, while complementary initiatives like the Vehicle Scrappage Policy and NITI Aayog's Roadmaps aim to boost secondary material recovery.

Despite this robust policy architecture, implementation remains the critical bottleneck. Persistent challenges—including inadequate source segregation, insufficient recycling infrastructure, and the dominance of informal, unregulated players—continue to dilute policy effectiveness. Going forward, India's success will depend less on new regulations and more on bridging the execution gap. Priority actions include formalizing the informal sector, scaling investment in advanced recycling technologies, and strengthening state-level enforcement and digital monitoring to ensure compliance under the EPR framework.

Discussions: One important result we found is the asymmetry between GDP and CO_2emissions. GDP adjusts to correct imbalances—roughly 23–28% per year—but CO_2 emissions show no such tendency. This conforms to the weak decoupling narrative[43-44] as Indian economy responds to material constraints, but not to carbon constraints. If we want to cut CO_2 emissions, we cannot simply rely on growth. We also find that material extraction has a negative short-run effect on GDP. This aligns with the resource curse literature[45-46] suggesting that extraction brings frictions and delays before any growth payoff appears. Renewable energy share in total energy consumption is insignificant—not because it is unimportant, but because their current share is still too low to affect GDP or CO_2 emissions in any measurable way. This supports the earlier findings[47-48] that showed that renewable effects often only appear after a threshold is crossed. In India's case RE share fell from 53% in 1990 to 32.4% in 2023. Fossil fuels still form a major part of India's energy basket. We found that material productivity has risen but emissions haven't changed much. A plausible explanation of this could be a rebound effect[49] which states that the efficiency gains are offset by more consumption. The implications for policy are that the efficiency in itself is not enough. We need scale in renewables, direct instruments like carbon pricing and standards, and a shift in industrial policy toward value addition. The results are to be viewed in light of the following limitations: a small sample, omitted variables like fossil fuel intensity and industrial structure, and some residual non-normality. Future research with richer data, non-linear models, or sector-level focus could take this further.

Table-9: Major Circular Economy Policies and Government Initiatives in India[24,36-42].

Policy/Initiative	Year	Objective	Contribution
Plastic Waste Management Rules	2016 (Amended 2022)	Ensure scientific management of plastic waste	Enhances plastic recycling and reduces plastic leakage
Extended Producer Responsibility (EPR)	2022	Ensure producer responsibility for post-consumer waste	Strengthens collection, recycling and resource recovery
E-Waste Management Rules	2022	Promote formal collection and recycling of electronic waste	Facilitates recovery of valuable and critical metals while reducing hazardous waste
Battery Waste Management Rules	2022	Ensure environmentally sound collection and recycling of used batteries	Improves recovery of lithium, cobalt, nickel and lead
Vehicle Scrappage Policy	2021	Promote scientific dismantling of end-of-life vehicles	Enhances metal recovery and resource efficiency
Steel Scrap Recycling Policy	2019	Promote organized recycling of ferrous and non-ferrous metals	Reduces dependence on virgin raw materials and supports secondary metal production
Swachh Bharat Mission–Urban 2.0	2021	Promote scientific municipal solid waste management	Strengthens waste segregation, recycling and scientific waste processing
NITI Aayog CE Roadmaps	2023–present	Develop sector-specific CE strategies	Facilitates resource efficiency and circular production across priority sectors

Conclusion

This study examined the relationships among GDP, material consumption, renewable energy, and CO_2 emissions in India over 1990–2024. The key findings are: (i) GDP and material use share a stable long-run equilibrium, with GDP adjusting to correct imbalances at a moderate pace; (ii) RE has no significant effect on growth and/or emissions; and (iii) emissions do not adjust to correct disequilibrium meaning they are driven by factors outside the system. The policy implications are: (i) RE needs to reach critical mass—current levels are too low to influence macro outcomes; (ii) emissions require direct intervention; growth-led improvements alone will not suffice; (iii) material efficiency must be complemented by absolute reduction targets; and (iv) industrial policy should prioritize value addition over extraction volume to minimize short-run adjustment costs.

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