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Critical Materials Import and Environmental Preferences: Evidence From G20 and N11 Economies

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ABSTRACT

Critical materials such as lithium and cobalt are indispensable for achieving the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). While these materials enable the deployment of low-carbon technologies, including electric vehicle batteries and renewable energy systems, they also present environmental, socio-economic, and geopolitical challenges due to their carbon-intensive extraction and global trade dynamics. This study employs a 20-year panel dataset from G20 and N-11 countries to investigate the relationship between critical material imports and national environmental performance, focusing on CO₂ emissions, GHG emissions, and embodied carbon in exports. Grounded in the dynamic capabilities framework, the research examines how countries reconfigure institutional arrangements, deploy circular economy strategies, and leverage innovation to balance sustainability goals with critical material dependencies. The findings reveal that lithium and cobalt imports contribute to improved environmental outcomes when accompanied by strong national-level dynamic capabilities, highlighting the importance of policy integration, technological adaptation, and resource efficiency in advancing national sustainability strategies.

1 | Introduction

In modern times, the strategic importance of critical materials such as lithium and cobalt has surged in global sustainability discussions, as they allow the energy transition and help achieve Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). These materials are essential to the manufacture of clean technologies such as EV batteries, wind turbines, and solar panels, which are central to decarbonizing national economies. However, their extraction, processing, and trade have raised significant environmental and social concerns, including carbon emissions, resource depletion, and labor exploitation (Agrawal et al., 2021; Chabowski et al. 2025; Bhatia and Jakhar 2021).

National governments are under growing pressure to balance the rising demand for critical materials with environmental sustainability imperatives. In response, there is increasing emphasis on policy frameworks that promote circular economy practices, green technology adoption, and regulatory reforms to minimize ecological damage (Cainelli et al. 2020; Yu et al. 2023; Abbass et al. 2022). Furthermore, integrated approaches that combine public-private partnerships (PPPs), foreign direct investment, and technological innovation have been emphasized in emerging economies to achieve environmental sustainability (Abbass et al. 2024).

To address this complexity, we have highlighted recent debates on the environmental trade-offs of critical material dependency and positioned national-level dynamic capabilities as a suitable

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conceptual lens to address adaptation, institutional transformation, and environmental performance (Teece 2007; Cuervo-Cazurra et al. 2022; Benito et al. 2022; Malik and Terzidis 2025a, 2026). This framework emphasizes a nation's ability to sense sustainability-related challenges, seize policy and technological opportunities, reconfigure institutional arrangements, and foster continuous learning to enhance adaptive capacity (Teece et al. 1997; Eisenhardt and Martin, 2000; Zahra and George 2002). These national-level dynamic capabilities are critical for designing and implementing sustainable development strategies involving essential imports of material. The importance of such transdisciplinary and agile policy approaches is further stressed in the literature on sustainable transitions (Bühning et al. 2024).

While previous research has investigated the environmental consequences of resource extraction, the interplay between critical material imports and national ecological goals achievement has received limited attention, particularly through a dynamic capabilities lens. This study addresses this gap by examining how nations shape their policy, industrial, and innovation ecosystem in response to critical material imports. We found that national capabilities arbitrate the relationship between critical material imports and environmental outcomes, using empirical data from G20 and Next-11 countries.

We contribute to the literature by proposing and empirically testing a conceptual model that links critical material imports to environmental indicators, such as CO₂ emissions, GHG emissions, and embodied carbon in trade, accounting for the moderating influence of national dynamic capabilities. By doing so, the study advances our understanding of how countries can transform critical material dependency into sustainable development opportunities, reinforcing their commitments to SDG 13 and broader environmental goals. In particular, this study draws on recent empirical and conceptual work addressing zero-waste strategies, sustainable production chains, and crisis-induced adaptations to environmental governance (Begum et al. 2022; Mehrotra et al. 2025).

This investigation is particularly timely, as countries seek to develop resilient, green economies amid the urgency of the climate crisis, resource scarcity, and geopolitical uncertainty. Our findings offer theoretical insights into sustainability governance and practical implications for policymakers aiming to align national economic strategies with global environmental mandates.

The paper is structured as follows: Section 2 outlines the theoretical framework and hypothesis development. Section 3 describes the research methodology. Section 4 presents the empirical findings, and the final section concludes with policy implications and directions for future research.

2 | Theory, Context, and Hypothesis Development

2.1 | SDG Commitment to the National Level

SDG commitment at the national level functions as a strategic blueprint that aligns domestic institutional frameworks, industrial strategies, and legislative instruments with the United Nations' Agenda 2030. Among the 17 Sustainable Development

Goals, SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) stand out as critical levers for national climate resilience and global decarbonization. These goals directly target reducing carbon emissions and transforming energy systems through innovation and infrastructure reform (Antonioli et al. 2022; Cuervo-Cazurra et al. 2022; Erin Bass and Grøgaard 2021). Countries increasingly embed these targets into regulatory frameworks, fiscal policies, and technology deployment strategies to drive low-carbon transitions (Montiel et al. 2021; Yu et al. 2023).

The dynamic capabilities framework offers a refined lens for analyzing how states develop and deploy these sustainability strategies. In particular, four national-level dynamic capabilities—sensing, seizing, reconfiguring, and learning, serve as institutional mechanisms for implementing SDG commitments. Sensing capabilities enable governments to monitor climate risks and global resource dependencies, while seizing capabilities activate climate financing, regulatory interventions, and technology investments (Teece 2007; Teece et al. 1997). Reconfiguring capabilities refers to the adaptive governance required to restructure industrial ecosystems and develop circular economy pathways, whereas learning capabilities institutionalize policy feedback loops, foster cross-sectoral knowledge diffusion, and improve climate governance over time (Robertson et al. 2023; Yu et al. 2023).

Multinational enterprises (MNEs) play a catalytic role in reinforcing national SDG commitments by operationalizing sustainability standards across global supply chains. Through PPPs and transnational sustainability coalitions, MNEs contribute to the diffusion of green technologies, institutional learning, and regulatory alignment (Van Tulder et al. 2021; Janetschek et al. 2019). Governments that embed SDG commitments into cross-sectoral collaborations and institutional infrastructures are more likely to enhance policy coherence, strengthen environmental outcomes, and improve their positioning in the global sustainability governance landscape (Chabowski et al. 2025; Wrålsén et al. 2021).

National SDG commitment mediated by dynamic capabilities provides a strategic foundation for balancing critical material dependencies with climate action mandates. This integrated approach enables countries to better align economic competitiveness with environmental stewardship, thereby strengthening the global regulatory framework for sustainable development (Benito et al. 2022).

2.2 | Critical Materials Significance at the National Level

Critical materials, including lithium, cobalt, nickel, graphite, and rare earth elements, are foundational to green technologies such as electric vehicles, solar photovoltaics, and wind turbines, making them essential enablers of SDG 7 and SDG 13 (Agrawal et al. 2021; McLellan et al. 2012). Their strategic role in the energy transition is linked to the decarbonization of the transport and energy sectors. However, their extraction and processing remain carbon-intensive and environmentally damaging, raising significant concerns about their alignment with sustainability objectives (Erin Bass and Grøgaard 2021; Chabowski et al. 2025).

From a dynamic capabilities perspective, national institutions must develop sensing capabilities to identify material vulnerabilities and sustainability trade-offs; seizing capabilities to invest in green extraction technologies, ethical sourcing, and resilient supply chains; reconfiguring capabilities to mainstream recycling, recovery, and reuse pathways; and learning capabilities to evaluate and adapt critical material governance frameworks (Teece 2007; Eisenhardt and Martin, 2000; Robertson et al. 2023).

These capabilities are especially urgent given the ethical and social risks associated with critical material supply chains, such as child labor and unsafe mining practices in cobalt-rich regions (Bhatia and Jakhar 2021). National governments must implement responsible sourcing policies, strengthen environmental regulations, and collaborate internationally to enhance supply chain transparency and security (Soberón Bravo 2023). Furthermore, we draw on insights from Lunde Seefeldt (2022), who analyzes the divergent policy frameworks across Chile, Argentina, and Bolivia, collectively known as the “Lithium Triangle” to highlight how institutional design and regulatory capacity significantly influence the environmental and developmental outcomes of lithium resource governance. Advanced recycling and circular economy principles can serve as complementary levers to reduce material dependency and mitigate environmental harm (Cainelli et al. 2020; Long et al. 2023).

The governance of critical materials is both a technical and institutional challenge. When embedded within national dynamic capabilities, policy efforts can reconcile material demand with sustainability imperatives by promoting cleaner production technologies, enforcing supply chain standards, and incentivizing cross-sectoral innovation (Boiral et al. 2012; Yu et al. 2023). These national-level interventions lay the groundwork for realizing the dual goal of economic competitiveness and environmental performance in the global transition toward sustainability.

2.3 | Conceptual Framework: Dynamic Capabilities at a National Level

The dynamic capabilities framework provides the conceptual foundation for analyzing how countries develop adaptive institutional systems to manage the environmental and economic complexities of critical material usage. National-level dynamic capabilities encompass a state's ability to sense global sustainability trends, seize opportunities for technological and regulatory innovation, reconfigure institutional arrangements, and foster continuous learning to align with evolving environmental goals (Teece et al. 1997; Winter 2003; Ambrosini and Bowman 2009).

Applied to the context of lithium and cobalt imports, the framework emphasizes how governments can identify environmental risks (sensing), scale responsible extraction practices and green technologies (seizing), implement systemic regulatory changes (reconfiguring), and institutionalize policy feedback loops (learning) (Eisenhardt and Martin, 2000; Robertson et al. 2023). These capabilities function within a broader policy architecture

that balances industrial development with climate imperatives and SDG alignment.

As illustrated in the conceptual model, national dynamic capabilities mediate the relationship between critical material imports and environmental performance. Countries with high dynamic capabilities are better positioned to mitigate the adverse impacts of resource extraction while leveraging critical materials to meet sustainability targets. This mediating role enables a nuanced understanding of how institutional adaptation, policy innovation, and collaborative governance can transform resource dependencies into pathways for sustainable development (Benito et al. 2022; Chabowski et al. 2025).

This framework also acknowledges the co-evolution of state capacity and sustainability challenges (see Figure 1). It highlights that national capabilities are not static but evolve in response to exogenous shocks (e.g., supply disruptions, climate disasters) and endogenous learning processes (e.g., regulatory experimentation, PPPs). Thus, dynamic capabilities provide a robust lens for assessing how states strategically reconfigure their economic systems to foster green transitions, reinforcing the relevance of this study to international business and policy debates.

2.4 | Critical Materials and SDG 13

Critical materials such as lithium and cobalt are central to the low-carbon technological transformation underpinning Sustainable Development Goal 13 (Climate Action). These materials are indispensable for the deployment of electric vehicle batteries, energy storage systems, and other renewable energy technologies aimed at decarbonizing the power and mobility sectors (Agrawal et al. 2021; Antonioli et al. 2022). However, their supply chains are environmentally burdensome, involving carbon-intensive extraction, hazardous waste, and complex global logistics, thereby presenting a paradox in the sustainability transition (Chabowski et al. 2025; Cuervo-Cazurra et al. 2022).

To address this paradox, countries must deploy dynamic capabilities that enable strategic realignment of their institutional and industrial responses. Sensing capabilities allow for continuous monitoring of the environmental costs and benefits associated with critical material usage. Seizing capabilities facilitate the adoption of climate-mitigating technologies and policy interventions that encourage resource efficiency, while reconfiguring capabilities support the transformation of linear material flows into circular systems. Learning capabilities close the policy feedback loop and enhance the governance of material-intensive sectors through adaptive experimentation and collaborative governance (Robertson et al. 2023; Wrålsen et al. 2021).

The conceptual model situates critical material imports as both enablers and stressors of environmental performance, depending on the maturity of national dynamic capabilities. When embedded in coherent institutional frameworks, imports of lithium and cobalt can support SDG 13 objectives by enabling clean energy infrastructure and emission reductions. Yet without robust governance mechanisms, these same imports may exacerbate CO₂ emissions, ecological degradation,

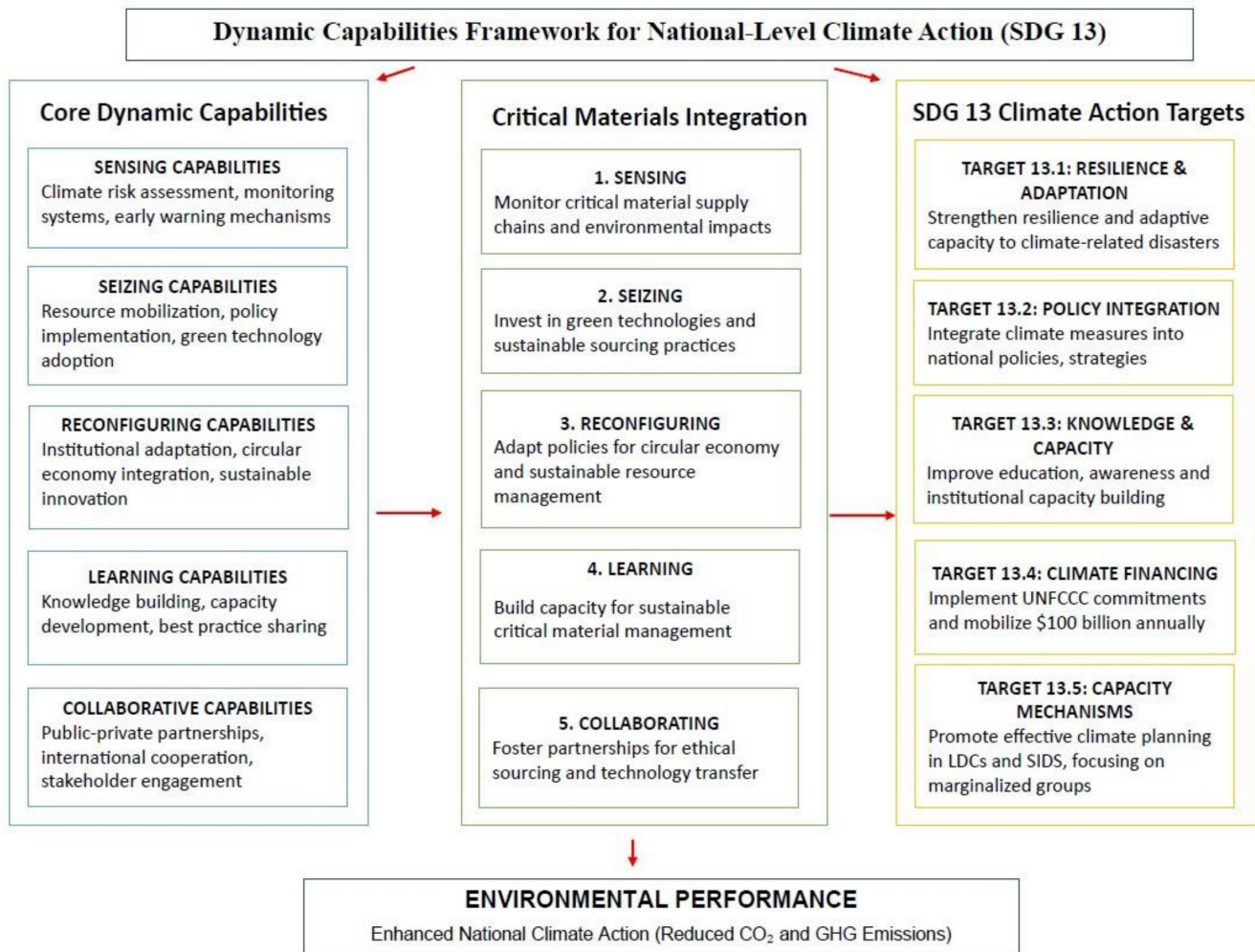


FIGURE 1 | Conceptual model: Dynamic capability at national level.

and geopolitical vulnerabilities (Buzzao and Rizzi 2021; Benito and Meyer 2024).

This duality is reflected in this study's hypotheses. Hypothesis 1a and Hypothesis 1b posit that lithium and cobalt imports enhance environmental performance through their role in clean energy systems. Hypothesis 2a and Hypothesis 2b recognize their potential to worsen CO₂ emissions due to unsustainable extraction practices. Hypothesis 3a and Hypothesis 3b extend this logic to GHG emissions, while Hypothesis 4a and Hypothesis 4b examine indirect emissions linked to fossil fuel exports. Collectively, these hypotheses underscore the importance of policy coherence, institutional agility, and cross-sectoral innovation in ensuring that critical material strategies align with national and global climate commitments (Gasbarro et al. 2016; Helfat et al. 2009).

By integrating dynamic capabilities with SDG-aligned policy design, national governments can navigate the environmental trade-offs of critical material use and reinforce their contributions to international climate governance. This framework offers a robust pathway for transforming material dependencies into sustainable development outcomes. Thus, we propose the following hypotheses:

Hypothesis 1a. *Lithium imports have a positive impact on National-level environmental performance.*

Hypothesis 1b. *Cobalt imports have a positive impact on National-level environmental performance.*

Hypothesis 2a. *Lithium imports have a negative impact on CO₂ emissions.*

Hypothesis 2b. *Cobalt imports have a negative impact on CO₂ emissions.*

Hypothesis 3a. *Lithium imports have a negative impact on GHG emissions.*

Hypothesis 3b. *Cobalt imports have a negative impact on GHG emissions embodied in imports.*

Hypothesis 4a. *Lithium imports have a negative impact on CO₂ emissions embodied in fossil fuel exports.*

Hypothesis 4b. *Cobalt imports have a negative impact on CO₂ emissions embodied in fossil fuel exports.*

3 | Research Methods

3.1 | Data and Sample

In this study, we use data from three databases as used in relevant studies in environmental research (e.g., Murshed et al. 2021; Abbass et al. 2022). First, we use data from the SDG dashboard site for country-level SDG performance.¹ Additionally, we use the CEPII (Centre d'études prospectives et d'informations internationales) database to collect data on lithium and cobalt imports.² Lastly, we use the World Bank database for other related variables. We fetch data from the above-mentioned sources from 2002 to 2021. In our primary analysis, we use G20 and N11 economies, as they are among the most influential economies, with significant contributions to carbon emissions and critical resource consumption.³ Our final sample comprises 546 country-year observations from 26 countries for a 21-year period.

3.2 | Dependent Variable

The dependent variable in this study is country-level environmental performance. We measure this environmental performance by utilizing data on SDG 13 from sdgindex.org (UN 2022). This database calculates the country-level achievement of all UN SDGs individually and collectively. Specifically, the SDG 13 index is based on three dimensions (CO₂ emission, GHG emission, and CO₂ export). Our analysis uses overall SDG 13 and individual dimensions as our main dependent variables.

3.3 | Independent Variable

In this study, we are using two main independent variables. To measure these variables, we utilize lithium (Li) and cobalt (Co) import data from the CEPII database (Chai and Wang 2023). CEPII provides data on different metal imports and exports at the country level on a transaction basis. Further, to use this data, we sum up all the import transactions within a year for Li and Co separately. Primarily, we collect data on imports of these two metals in quantity in metric tons and import value in USD. We utilize the natural log of quantity in metric tons as our main independent variable.

3.4 | Control Variable

Furthermore, we also added several control variables that influenced the country-level environmental targets. First, we add the GDP per capita to the right side of our model. Safi et al. (2021) stress that GDP significantly enhances environmental pollution. Next, we use renewable energy sources to control environmental performance (Erin Bass and Grøgaard 2021). Zafar et al. (2020) show that using renewable energy resources improves the environmental quality in OECD countries. Further, we utilize the lending interest rate (Zhang et al. 2021). Our sample period is also accompanied by two important events that directly influence the environmental quality of a country (the financial crisis and the Paris Agreement). We control their impact by adding a dummy variable for the period of these events. Moreover, we also fix the impact at the country and year level.

3.5 | Model Specification

We test our hypotheses using the fixed effect ordinary least squares (FEOLS) method in the following section. We employ the following regression equations:

$$SDG-13_{i,t} = \beta_0 + \beta_1 Li - IMP_{i,t} + \beta_2 GDP_{i,t} + \beta_3 REN_E_{i,t} + \beta_4 INT_R_{i,t} + \beta_5 FIN_C_{i,t} + \beta_6 PAR_A_{i,t} + \sum_{k=1}^{21} Year + \sum_{k=1}^{26} Country + \epsilon_{i,t} \quad (1)$$

$$SDG-13_{i,t} = \beta_0 + \beta_1 Co - IMP_{i,t} + \beta_2 GDP_{i,t} + \beta_3 REN_E_{i,t} + \beta_4 INT_R_{i,t} + \beta_5 FIN_C_{i,t} + \beta_6 PAR_A_{i,t} + \sum_{k=1}^{21} Year + \sum_{k=1}^{26} Country + \epsilon_{i,t} \quad (2)$$

Appendix A presents the definitions and data sources of all regression variables. All continuous variables are winsorized at 1% level.

4 | Results and Discussion

4.1 | Descriptive Statistics

Table 1 reports the sample distribution over the 26 countries. Our sample consists of two main groups of countries: G20 and N11. On average, Japan imports 11,913 metric tons of processed lithium and 12,585 metric tons of processed cobalt, making it the top importer of these critical materials in our sample. This table also reveals that South Korea, China, and the US actively participate in this competitive pursuit.⁴ The N11 economies want to replace gray energy consumption with more sophisticated green energy options (like EVs and Solar, see Figure 2). In this vein, Bangladesh is on top of the average growth of 242% in lithium imports and 447% in cobalt imports. Other N11 economies (such as Nigeria, Vietnam, and Pakistan) are also concerned about increasing imports of these critical materials to reduce their carbon footprints by promoting green technologies in their countries (Benito and Meyer 2024; Nathaniel et al. 2021). Figure 2 presents the critical materials used to produce the clean energy technologies.

Table 2 presents the descriptive statistics of all key variables used in our main regression. Using our final sample, the dependent variable *SDG_13* (Environmental performance) has a mean value of 77.76 with a maximum value of 98.73. These numbers show the commitment of these countries to achieve the UN climate action goal. Further, the mean values of sub-components of *SDG_13* also show a high average normalized score of 66 for *CO2_EM*, 80 for *GHG_EM*, and 88 for *CO2_EX*. Seemingly, the average of *SDG_ALL* is 68, showing the overall significant efforts of these countries to UN SDGs. On average, the lithium import is 6.49 (658.5 metric tons), and the maximum value is 10.6 (40,134.8 metric tons). Moreover, the cobalt mean value is 5.45 (232.8 metric tons), and the maximum value is 12.3 (219,695.9 metric tons).

TABLE 1 | Country-wise summary.

No.	Country	G20	N11	Li_IMT	Co_IMT	Li_GRT	Co_GRT
1	ARG	1	0	362.560	49.519	12.110%	0.854%
2	AUS	1	0	578.212	232.806	13.390%	17.256%
3	BGD	0	1	166.477	2.725	241.502%	447.056%
4	BRA	1	0	378.742	645.218	41.987%	12.626%
5	CAN	1	0	1891.418	2570.634	18.085%	10.631%
6	CHN	1	0	9687.156	123154.500	134.741%	61.401%
7	DEU	1	0	5845.236	2872.523	19.420%	2.661%
8	EGY	0	1	157.314	13.272	25.630%	100.691%
9	FRA	1	0	2458.455	2158.702	35.433%	8.316%
10	GBR	1	0	1852.504	4261.187	19.887%	4.570%
11	IDN	1	1	539.583	98.009	20.469%	12.038%
12	IND	1	0	3147.447	1035.582	51.893%	12.951%
13	IRN	0	1	279.099	39.336	35.573%	28.438%
14	ITA	1	0	1078.559	616.578	14.031%	2.258%
15	JPN	1	0	11913.450	12585.190	22.601%	2.506%
16	KOR	1	1	11972.550	3300.925	32.519%	18.108%
17	MEX	1	1	3272.596	63.203	145.688%	5.170%
18	NGA	0	1	361.078	5.165	136.335%	287.939%
19	PAK	0	1	334.890	100.494	208.944%	49.630%
20	PHL	0	1	520.121	97.347	78.852%	70.518%
21	RUS	1	0	829.302	99.271	14.783%	8.644%
22	SAU	1	0	531.311	36.289	80.435%	74.409%
23	TUR	1	1	630.663	285.705	13.604%	21.977%
24	USA	1	0	6072.321	11043.300	49.506%	4.628%
25	VNM	0	1	396.660	53.246	112.131%	235.150%
26	ZAF	1	0	640.226	1255.164	18.298%	89.195%
	Total			2534.536	6469.810	61.460%	61.140%

4.2 | Correlation Matrix

Table 3 presents the Pearson correlation matrix and variance inflation factor (VIF) for all independent side variables. Our key independent variables (*Li_IMP*, *Co_IMP*, *Li_USD*, and *Co_USD*) are highly correlated, and the maximum correlation among these variables is 0.962. Because of this high correlation (multicollinearity), we have added these variables one by one to our regression models (Friberg and Seiler 2017). The maximum correlation between the main independent and control variables is 0.595. To further confirm the issue of multicollinearity, we also utilize VIF, and the maximum value of VIF is 4.66. This value is under the defined rule of thumb (VIF < 10) in economics and finance.

4.3 | Main Regression

Table 4 presents the results to support our main hypothesis. We use Equations (1) and (2) for all the mentioned hypotheses in this context. We test the association between lithium/cobalt imports and national-level environmental performance by using the fixed-effect ordinary least squares (FEOLS) technique. We adjusted our models for two differences at the period and country levels to mitigate the issue of heterogeneity (Friberg and Seiler 2017; Nathaniel et al. 2021).

Models 1 and 2 regress environmental performance (SDG_13) on the key independent variables, that is, *Li_IMP* and *Co_IMP*, one by one, excluding the year and country fixed effects. In

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	●	○	●	●	●	○	●
Hydro	○	○	○	○	○	○	○	○	○
CSP	○	○	○	○	○	●	○	○	●
Bioenergy	●	○	○	○	○	○	○	○	○
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	○	○	○	○	○	○	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	○	○	○	●	○

FIGURE 2 | Critical materials' contribution to green energy technology. *Note:* Shading indicates the relative importance of minerals for a particular clean energy technology (● = high; ● = moderate; ○ = low). *Source:* International Energy Agency (May 2021), The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions.

TABLE 2 | Summary statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
Dependent variable					
<i>SDG_13</i>	546	77.763	20.235	13.629	98.732
<i>CO2_EM</i>	546	66.037	27.139	0.195	98.795
<i>GHG_EM</i>	546	79.451	18.708	28.912	98.975
<i>CO2_EX</i>	441	88.096	24.632	2.194	99.999
<i>SDG_ALL</i>	546	67.911	8.556	47.448	83.354
Independent variable					
<i>Li_IMP</i>	546	6.487	1.539	2.961	10.599
<i>Co_IMP</i>	546	5.452	2.888	-2.154	12.345
<i>Li_USD</i>	546	9.801	1.750	3.915	15.085
<i>Co_USD</i>	541	9.060	2.814	-3.540	15.620
Control variable					
<i>GDP</i>	546	9.056	1.376	6.109	11.091
<i>REN_E</i>	546	22.621	2.140	17.990	25.754
<i>INT_R</i>	546	2.069	0.844	-0.693	4.054
<i>FIN_C</i>	546	0.095	0.294	0.000	1.000
<i>PAR_A</i>	546	0.333	0.472	0.000	1.000

both models, lithium and cobalt imports significantly improve the country's performance of the country. In Models 3 and 4, we re-estimate Equations (1) and (2) with fixed effects. For Hypothesis 1a, the results shown in Models 1 and 3 continue to be positive and statistically significant at 1%, implying that countries with high lithium imports are committed to climate

action. For Hypothesis 1b, the results report the positive and high significance at a 1% level in Models 2 and 4, implying that if a country has more cobalt imports, it will increase its overall environmental performance. In this respect, Table 4 results support the expected Hypothesis 1a and Hypothesis 1b and chime with a few prior studies (Antonioli et al. 2022; Agrawal et al. 2021; Janetschek et al. 2019).

Table 4 also presents the coefficients of control variables. The *GDP* has a statistically significant negative relationship with *SDG_13* (Shahbaz et al. 2021). Conversely, renewable energy production, interest rates, the financial crisis period, and the Paris Agreement dummy positively impact the country's environmental performance (Long et al. 2023). These relationships are largely consistent with the extant literature on environmental performance. On average, our models predict 59% (*Adj R-sqr* 58.6) variations in our key dependent variable.

4.4 | SDG_13 Dimensions

Table 5 further tests our central hypothesis with the SDG13 main pillars. Following the sdgindex.org, the UN SDG_13 goal is divided into three main parts (CO₂ emission, GHG emission, and CO₂ exports). By following the European Commission Report 2022,⁵ the European countries have significantly reduced fossil CO₂ emissions in the power industry, other industrial combustion, buildings, transport, and other sectors compared to global CO₂ emissions.⁶ This report also reveals that other emerging countries, along with China, substantially enhanced the natural greenhouse effect and critically harmed life on Earth. This anecdotal evidence highlights the need to further explore this association with SDG_13's main pillars.

In Models 1, 3, and 5, we check the impact of lithium import on the *CO2_EM*, *GHG_EM*, and *CO2_EX*, respectively. Using the

TABLE 3 | Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	VIF
(1) <i>Li_IMP</i>	1.000									2.33
(2) <i>Co_IMP</i>	0.744*	1.000								2.09
(3) <i>Li_USD</i>	0.867*	0.767*	1.000							—
(4) <i>Co_USD</i>	0.757*	0.962*	0.796*	1.000						—
(5) <i>GDP</i>	0.538*	0.595*	0.527*	0.451*	1.000					1.85
(6) <i>REN_E</i>	0.469*	0.523*	0.548*	0.508*	0.326*	1.000				1.32
(7) <i>INT_R</i>	−0.542*	−0.510*	−0.524*	−0.497*	−0.503*	−0.367*	1.000			1.56
(8) <i>FIN_C</i>	−0.068	−0.051	−0.041	−0.015	−0.010	−0.022	0.041	1.000		3.65
(9) <i>PAR_A</i>	0.248*	0.070	0.252*	0.103	0.120*	0.104	−0.095	−0.229*	1.000	4.66

*Is showing the significance at 1% level.

TABLE 4 | Main results.

Variables	SDG_13			
	(1)	(2)	(3)	(4)
<i>Li_IMP</i>	1.737*** (3.24)		1.714*** (3.09)	
<i>Co_IMP</i>		0.806*** (2.93)		0.959*** (3.47)
<i>GDP</i>	−12.497*** (−22.98)	−12.328*** (−23.24)	−12.795*** (−23.19)	−12.809*** (−23.74)
<i>REN_E</i>	1.931*** (6.47)	1.863*** (6.00)	1.874*** (6.25)	1.724*** (5.54)
<i>INT_R</i>	1.616** (1.97)	1.435* (1.77)	1.572* (1.90)	1.493* (1.84)
<i>FIN_C</i>	1.018 (0.52)	1.204 (0.61)	5.663 (1.56)	6.907* (1.91)
<i>PAR_A</i>	3.481*** (2.78)	4.506*** (3.66)	9.987*** (2.72)	12.187*** (3.35)
Constant	131.393*** (16.29)	138.282*** (16.14)	130.978*** (15.70)	139.350*** (15.82)
Observations	546	546	546	546
Fixed Effects	No	No	Year & Country	Year & Country
Adj R^2	0.586	0.584	0.586	0.588

Note: Robust t statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

normalized score for CO₂_EM, GHG_EM, and CO₂_EX, the higher value shows the lower emission in this area. The lithium imports in the G20 and N11 economies are significantly associated with the SDG_13 dimensions. The association is observed with the cobalt imports. The results in Table 5 are comparable to our main findings in Table 4. Our findings align with the preceding evidence that critical materials are important for coping with the CO₂ and GHG emission problems (Pavel et al. 2024).

4.5 | Alternate Proxies

Additionally, to confirm the robustness of our findings, we replace our main variables with alternate proxies. We use SDG_13 as our primary dependent variable to show the environmental preferences at the national level. UN SDGs consist of 17 sustainable development goals, and the collective performance of a country on all these goals is also very important to achieve this global agenda

TABLE 5 | SDG-13 dimensions.

Variables	CO2_EM		GHG_EM		CO2_EX	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Li_IMP</i>	0.517*		1.508***		9.673***	
	(1.71)		(4.30)		(8.46)	
<i>Co_IMP</i>		0.142**		1.059***		6.433***
		(2.39)		(6.14)		(11.08)
<i>GDP</i>	-16.849***	-16.971***	-12.469***	-12.667***	-16.163***	-18.692***
	(-23.32)	(-23.95)	(-35.68)	(-37.62)	(-13.42)	(-15.50)
<i>REN_E</i>	3.275***	3.254***	0.259	0.031	3.406***	2.657***
	(8.34)	(7.97)	(1.36)	(0.16)	(5.99)	(4.82)
<i>INT_R</i>	1.791*	1.912*	3.503***	3.576***	0.209	-0.365
	(1.65)	(1.79)	(6.69)	(7.05)	(0.15)	(-0.29)
<i>FIN_C</i>	9.829**	9.574**	5.773**	7.043***	2.157	11.849*
	(2.07)	(2.01)	(2.51)	(3.11)	(0.34)	(1.93)
<i>PAR_A</i>	18.221***	17.667***	11.735***	13.832***	-1.644	10.387*
	(3.78)	(3.69)	(5.04)	(6.09)	(-0.25)	(1.69)
Constant	132.787***	131.828***	163.476***	173.132***	97.283***	159.878***
	(12.15)	(11.40)	(30.93)	(31.50)	(6.40)	(10.19)
Observations	546	546	546	546	441	441
Fixed Effects	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country
Adj R^2	0.631	0.631	0.805	0.812	0.293	0.360

Note: Robust t statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

(Benito et al. 2022; Chabowski et al. 2025). In Table 6, Columns 1 and 2, we use the country's overall SDG performance (SDG_ALL) as our main dependent variable. Both of our independent variables show a positive association with SDG_ALL. In sum, our results show that critical material import effectively mitigates environmental issues and supports the country's overall sustainability.

In addition, we also replaced our independent variables. In the former analysis, we used lithium and cobalt imports in metric tons, but in Columns 3 and 4, we use lithium and cobalt imports in USD. Our results are consistent with our main findings and show that critical materials (like lithium and cobalt) will remain necessary for environmental goals even if we measure them in metric tons or USD (Bahini et al. 2024; Yu et al. 2023).

To further validate the robustness of our findings, we replaced the key independent variables in our primary regressions—lithium and cobalt—with alternative critical materials: copper (Cu_PRO) and aluminum (Al_PRO) (Acquaviva et al. 2021). As illustrated in Figure 2, both copper and aluminum are extensively utilized in major green energy technologies, including solar panels, wind turbines, and electricity networks.⁷ In Models 5 and 6, we examine the effects of copper and aluminum on environmental performance. The results remain

consistent with our main findings, reinforcing the significant role of these critical materials in achieving environmental sustainability.

4.6 | Tackling Endogeneity

Our main analysis is based on FEOLS, which might be subject to potential endogeneity concerns due to reverse causality or dynamic panel endogeneity. Our findings imply that lithium and cobalt imports improved the national-level environmental performance (Yu et al. 2023). There is a possibility that this relationship is impacted by omitted variable bias, unobservable heterogeneity, and reverse causality. Indeed, we employ 2SLS and dynamic system GMM estimation that control reverse causality and omitted variable bias (Saeed et al. 2024).

In Table 7, we first employ Two-Stage Least Squares (2SLS) to address potential omitted variable bias and reverse causality. The selection of valid instruments is critical, particularly given the limited number of studies examining critical material imports in panel data settings (Feng and Wei 2023). We use two instruments in our first-stage regression: the total imports-to-GDP ratio (*IMP_PL*) and trade openness (*TRD_OP*). Columns (1) and (3) present the first-stage regression results. Columns (2) and (4) show that the instrumented variables—lithium and cobalt imports—retain a positive

TABLE 6 | Alternate proxies.

Variables	SDG_ALL		SDG_13		SDG_13	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Li_IMP</i>	0.325** (2.51)					
<i>Co_IMP</i>		0.522*** (4.97)				
<i>Li_USD</i>			0.000* (1.83)			
<i>Co_USD</i>				0.000* (1.71)		
<i>Cu_PRO</i>					1.120*** (6.20)	
<i>Al_PRO</i>						1.053*** (2.84)
<i>GDP</i>	4.408*** (20.64)	4.112*** (20.06)	-12.035*** (-24.39)	-11.998*** (-24.27)	-5.057*** (-9.90)	-5.481*** (-10.36)
<i>REN_E</i>	0.249** (2.15)	0.068 (0.58)	2.120*** (7.27)	2.208*** (7.39)	-0.406*** (-3.26)	-0.643*** (-3.14)
<i>INT_R</i>	-0.537* (-1.68)	-0.327 (-1.06)	0.954 (1.18)	0.800 (0.98)	-2.663*** (-5.46)	-2.292*** (-6.10)
<i>FIN_C</i>	-1.717 (-1.22)	-1.204 (-0.87)	6.142* (1.68)	6.128* (1.67)	2.071** (2.55)	3.472*** (4.32)
<i>PAR_A</i>	0.733 (0.51)	1.403 (1.01)	10.883*** (2.91)	11.715*** (3.16)	4.691*** (4.99)	7.150*** (7.39)
Constant	22.246*** (6.89)	27.458*** (8.20)	130.070*** (15.36)	128.240*** (15.05)	139.704*** (26.43)	148.104*** (19.90)
Observations	546	546	546	546	345	359
Fixed Effects	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country
Adj R^2	0.653	0.667	0.579	0.575	0.992	0.991

Note: Robust t statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

and statistically significant association with environmental performance. Additionally, the Sargan test statistic ($p > 0.1$) confirms the validity of our instruments, supporting their exogeneity.

Moreover, we introduce the lag of SDG_13 as an independent variable to apply the GMM technique. This new right-side variable shows a positive, significant relationship with the key dependent variable in both models (Nguyen et al. 2023). These results indicate that the national-level environmental performance is associated with its lag term, and the rest of the variables show the same relationship. AR1 is significant and shows that the first difference residuals are serially correlated. However, AR2 is insignificant, indicating that the second-difference residuals are not serially correlated (Nguyen et al. 2023). Other diagnostics

also confirm that the model is statistically well-fitted. Hence, our main findings are supported by the dynamic system GMM.

4.7 | Additional Analysis

Table 8 segregates our sample based on the percentage of forest area. We fetch this data from the World Bank database and normalize it by taking the natural logarithm. In our sample, Japan has the highest forest area, around 68%, and the United Kingdom has the lowest green area, around 13%. We divide our sample into two groups based on the mean: below the mean ($\text{Forest_A} < \text{mean}$) and above the mean ($\text{Forest_A} \geq \text{mean}$). Our main results are consistent only when greener countries

TABLE 7 | Endogeneity concerns.

Variables	Two-stage least squares				Generalized method of movement	
	1st stage (1)	2nd stage (2)	1st stage (3)	2nd stage (4)	Dynamic system GMM	
					(5)	(6)
<i>IMP_PL</i>	3.583*** (5.39)		5.359*** (3.91)			
<i>TRD_OP</i>	-0.069 (-0.30)		-0.650 (-1.35)			
<i>Lag (SDG_13)</i>					0.995*** (39.81)	0.987*** (34.83)
<i>Li_IMP</i>		23.188*** (6.23)			0.131*** (4.54)	
<i>Co_IMP</i>				7.523*** (8.26)		0.070** (2.33)
<i>GDP</i>	0.430*** (9.37)	-22.943*** (-11.26)	0.799*** (8.43)	-18.327*** (-17.08)	-0.061 (-0.51)	0.022 (0.18)
<i>REN_E</i>	0.121*** (4.89)	-1.626** (-1.96)	0.338*** (6.64)	-1.076* (-1.87)	0.149 (1.22)	0.093 (0.76)
<i>INT_R</i>	-0.363*** (-5.35)	10.339*** (4.65)	-0.710*** (-5.07)	6.611*** (4.70)	-0.150 (-0.37)	-0.360 (-1.03)
<i>FIN_C</i>	-0.221 (-1.46)	-0.153 (-0.02)	-0.611* (-1.96)	12.222** (2.36)	0.721*** (7.65)	0.792*** (8.34)
<i>PAR_A</i>	0.312*** (2.64)	-4.446 (-0.62)	-0.471* (-1.94)	11.665** (2.26)	0.337*** (5.47)	0.327*** (9.27)
Constant	-1.622** (-2.37)	13.926*** (8.79)	-1.720*** (-7.60)	23.135*** (13.09)	-1.404 (-0.29)	0.001 (0.03)
Observations	468	468	468	468	546	546
Number of cnid					26	26
Fixed effects	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country	Year & Country
Adj <i>R</i> ² /Cent <i>R</i> ²	0.563	0.436	0.498	0.199		
Sargan <i>p</i>		0.653		0.272		
Chi2 <i>p</i>					0.000	0.000
AR1 <i>p</i>					0.025	0.027
AR2 <i>p</i>					0.472	0.524

Note: Robust *t* statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

increase lithium and cobalt imports. The UN Environment Program highlights that forests have significant mitigation potential to help meet climate goals.⁸

Further, we extend our analysis to check the consistency of findings with more females in the national parliament. A recent study finds that a higher presence of women in national parliaments is more effective at ratifying environmental legislation and addressing climate change (Pierli et al. 2022). According to the World Economic Forum's gender gap report 2023, only 22.9% of

parliament members are female, which has increased by 4% since 2013.⁹ This increased number of women parliamentarians significantly influences the national-level strategies in diverse directions. To check this impact, we divided our sample into two groups by using the mean value of female parliamentarian percentage (World Bank database) within our sample in Table 9. Our main results are consistent with those of female-dominated parliaments within our sample. These results elaborate that a significant female presence in the national parliament promotes green energy solutions to achieve climate goals (Benito and Meyer 2024).

TABLE 8 | Forest area proportion.

Variables	Forest_A < mean		Forest_A ≥ mean	
	(1)	(2)	(3)	(4)
<i>Li_IMP</i>	-0.122 (-0.60)		3.571*** (3.98)	
<i>Co_IMP</i>		0.039 (0.23)		0.352* (1.83)
<i>GDP</i>	-3.034*** (-4.65)	-3.061*** (-4.67)	-14.935*** (-18.34)	-13.955*** (-17.24)
<i>REN_E</i>	0.105 (0.89)	0.116 (0.98)	1.720*** (3.28)	2.302*** (4.13)
<i>INT_R</i>	-4.592*** (-5.53)	-4.506*** (-5.52)	6.188*** (5.72)	4.904*** (4.62)
<i>FIN_C</i>	0.581 (0.57)	2.746 (1.20)	6.718 (1.35)	7.183 (1.40)
<i>PAR_A</i>	0.874 (0.72)	2.965 (1.23)	5.450 (1.07)	-2.074 (-0.14)
Constant	128.086*** (20.09)	125.163*** (19.35)	135.660*** (11.68)	136.168*** (10.75)
Observations	226	226	320	320
Fixed effects	Year & Country	Year & Country	Year & Country	Year & Country
Adj R^2	0.788	0.788	0.593	0.573

Note: Robust t statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

In the last, we segregated our sample into two parts. Our main sample consists of two unique groups, the G20 (Group of Twenty) and N11 (Next Eleven). The G20 economies are the main contributors to the global GDP, international trade, and technological development. Similarly, the N11 emerging economies and the BRICs are also in this race to become the largest economies in the 21st century. First, we run our main regression model with the G20 countries in Table 10, Models 1 and 2. Lithium and cobalt independent variables show a significant positive association with environmental preferences (Yu et al. 2023). However, with the N11 countries sample, only cobalt has a positive and significant relationship with Model 4. Results in Table 10 show that G20 countries are more concerned about adopting the latest renewable solutions to mitigate climate change concerns than N11 economies. However, the N11 economies are now focusing on investing more in renewable energy products.¹⁰

5 | Conclusion and Recommendation

This study advances a dynamic capabilities-based framework to explain how nations can strategically manage the environmental complexities associated with critical material imports, particularly in the pursuit of SDG 13 (Climate Action). National-level dynamic capabilities, defined as the capacity to sense, seize,

reconfigure, and learn in response to sustainability imperatives, provide a robust institutional lens for interpreting how governments adapt policy, industrial systems, and regulatory architecture under conditions of global ecological and economic volatility (Teece 2007; Ambrosini and Bowman 2009; Riviere et al. 2021). By embedding these capabilities into national policy systems, countries can transform material dependencies, such as those on lithium and cobalt, into leverage points for climate resilience, innovation, and sustainable development (Cuervo-Cazurra et al. 2022; Yu et al. 2023; Abbass et al. 2022). We are contributing to the literature by extending the national-level dynamic capabilities perspective to environmental governance in the context of critical materials (Malik et al. 2025). Our findings show that these capabilities not only involve the reconfiguration of institutions but also the integration of the circular economy, digital technologies, and international trade dependencies, elements that have not been addressed collectively in prior research.

A key insight from this research is the strategic relevance of circular economy integration. Circular economy principles, including recycling, reuse, repair, and eco-design, act as critical levers to decouple economic growth from environmental degradation (Cainelli et al. 2020; Barreiro-Gen and Lozano 2020; Ferasso et al. 2020). By institutionalizing closed-loop systems, especially for lithium-ion batteries, countries can reduce virgin extraction

TABLE 9 | Female parliamentarian proportion.

Variables	Female_P < mean		Female_P ≥ mean	
	(1)	(2)	(3)	(4)
<i>Li_IMP</i>	0.163 (1.16)		3.814*** (4.62)	
<i>Co_IMP</i>		0.092 (0.77)		0.966** (2.30)
<i>GDP</i>	-1.496*** (-3.25)	-1.589*** (-3.45)	-16.592*** (-20.82)	-15.104*** (-20.96)
<i>REN_E</i>	-0.762*** (-4.07)	-0.740*** (-3.95)	2.170*** (4.83)	2.278*** (4.54)
<i>INT_R</i>	-2.633*** (-5.00)	-2.780*** (-5.43)	0.605 (0.51)	0.404 (0.33)
<i>FIN_C</i>	0.333 (0.49)	1.931 (1.43)	8.816 (1.63)	10.576* (1.90)
<i>PAR_A</i>	-0.149 (-0.17)	0.518 (0.30)	15.188*** (2.87)	19.675*** (3.67)
Constant	132.355*** (22.38)	131.945*** (21.59)	142.570*** (11.99)	143.807*** (11.18)
Observations	201	201	345	345
Fixed Effects	Year & Country	Year & Country	Year & Country	Year & Country
Adj <i>R</i> ²	0.991	0.991	0.610	0.591

Note: Robust *t* statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

pressures, improve resource efficiency, and meet both SDG 12 (Responsible Consumption and Production) and SDG 13 mandates (Antonioli et al. 2022; Long et al. 2023). Recent research underscores how alignment of technologies and agile practices, as seen in zero-waste innovations in the hospitality sector, can serve as templates for embedding circularity across industries (Mehrotra et al. 2025).

Furthermore, this study highlights the importance of digital innovation in operationalizing national sustainability strategies. Technologies such as artificial intelligence, blockchain, and big data analytics enhance transparency, traceability, and responsiveness across critical material supply chains (Buzzao and Rizzi 2021; Gasbarro et al. 2016). AI-powered tools, for instance, enable predictive environmental risk modeling and optimal resource allocation, supporting proactive rather than reactive sustainability governance (Chen and Chang 2013; Robertson et al. 2023). These technologies are increasingly essential in building resilience against external shocks such as pandemics or geopolitical disruptions, as highlighted by Begum et al. (2022) in their work on sustainable production chains.

Policy recommendations emerging from this research underscore the necessity of robust institutional design. Governments must enact binding regulatory frameworks to govern resource-intensive sectors while incentivizing responsible sourcing,

environmental stewardship, and innovation in green technologies (Wenzel et al. 2021; Chabowski et al. 2025). As shown by Abbass et al. (2024), factors such as FDI, technological innovation, and trade openness must be coordinated to advance environmental sustainability across emerging economies, especially within the N-11 countries. Moreover, transdisciplinary approaches are required to mobilize systemic transitions across sectors and policy domains, as emphasized by Bühring et al. (2024).

Finally, national education systems must embed sustainability curricula to cultivate environmental literacy and foster the behavioral and cognitive capabilities needed to sustain long-term climate action (Van Tulder et al. 2021; Cuervo-Cazurra et al. 2022). These multi-level interventions—spanning policy, technology, and education—position nations to become frontrunners in the global sustainability transition (Benito et al. 2022).

5.1 | Policy Implications

A central policy implication of this study is the urgent need to develop and institutionalize PPPs that promote sustainable supply chain management and responsible resource governance. National governments, in collaboration with industry stakeholders, must co-create regulatory and operational frameworks that ensure ethical sourcing (discourage child labor, gender pay

TABLE 10 | G20 v/s N11 economies.

Variables	G20		N11	
	(1)	(2)	(3)	(4)
<i>Li_IMP</i>	1.308** (2.47)		0.187 (0.44)	
<i>Co_IMP</i>		1.097** (2.26)		0.629*** (3.17)
<i>GDP</i>	-12.883*** (-16.52)	-12.899*** (-16.61)	-8.191*** (-14.28)	-7.184*** (-14.50)
<i>REN_E</i>	2.975*** (6.22)	2.521*** (4.63)	1.025*** (5.59)	1.026*** (5.80)
<i>INT_R</i>	2.029* (1.92)	2.136** (2.10)	-0.079 (-0.07)	-1.093 (-1.04)
<i>FIN_C</i>	4.425 (0.91)	5.699 (1.18)	4.122* (1.81)	7.645 (1.41)
<i>PAR_A</i>	7.083 (1.42)	9.267* (1.89)	7.071*** (3.06)	7.107 (0.97)
Constant	110.252*** (8.34)	121.340*** (8.95)	128.471*** (18.24)	122.353*** (13.86)
Observations	399	399	231	231
Fixed Effects	Year & Country	Year & Country	Year & Country	Year & Country
Adj R2	0.475	0.479	0.699	0.712

Note: Robust *t* statistics are shown in brackets. *, **, and *** are showing the significance at 10%, 5%, and 1% level, respectively.

gap, among others), reduce environmental degradation, and enhance traceability across the life cycle of critical materials such as lithium and cobalt (Benito and Meyer 2024; Bhatia and Jakhar 2021; Janetschek et al. 2019). This collaborative approach not only diffuses environmental risk but also accelerates innovation in green extraction and processing technologies.

Moreover, policymakers must take a systems-oriented perspective that integrates transdisciplinary knowledge across sectors and governance levels. This is particularly relevant for crafting long-term sustainability pathways, where fragmented regulatory silos undermine coherent responses to planetary boundaries (Bühning et al. 2024). Establishing cross-sectoral councils and innovation platforms can facilitate the convergence of technological, regulatory, and behavioral expertise, thereby catalyzing systemic change. In the context of sustainable hospitality and waste reduction, for example, Mehrotra et al. (2025) illustrate how technology alignment and agile management practices can generate scalable models for responsible production, insights that are transferable to the governance of critical materials.

Fiscal and regulatory instruments, such as subsidies, tax credits, and green procurement policies, can incentivize firms to invest in low-emission technologies and adopt circular economy principles (Boiral et al. 2012; Yu et al. 2023). These mechanisms foster alignment between corporate strategies and national climate objectives

(SDG 13), supporting transitions to cleaner industrial practices. As emphasized in the recent sustainability discourse, such alignment generates dual dividends: environmental improvement (climate action) and reputational enhancement for firms operating in high-risk sectors (Chabowski et al. 2025; Falk and Hagsten 2020).

Finally, policy coherence must be ensured across international trade, foreign direct investment, and environmental regulation. As Abbass et al. (2024) argue, in the context of COP28 and the N-11 emerging economies, sustainability transitions depend not only on domestic reforms but also on global coordination of climate finance, technology transfer, and trade liberalization. National policymakers should thus advocate for harmonized environmental standards across global value chains and support multilateral efforts to strengthen institutional accountability in mineral resource governance. At the national level, there is a need to change policy on green production practices aligned with climate action, supported by institutional reforms, to achieve environmental targets and support resilient economic and ecological goals.

5.2 | Future Research Directions

While this study offers valuable insights into the mediating role of national-level dynamic capabilities in shaping the relationship between critical material imports and environmental

performance under SDG 13, it also highlights several promising avenues for future research.

First, deeper investigations into the enabling role of emerging technologies, such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT), are necessary to advance the implementation of the circular economy (Malik et al. 2025). These technologies can enhance supply chain transparency, facilitate closed-loop systems, and improve predictive modeling for resource optimization (Buzzao and Rizzi 2021; Cainelli et al. 2020; Chen and Chang 2013). Studies examining how digital infrastructures can be systematically embedded within sustainability policies at both national and regional levels would significantly enrich the discourse.

Second, comparative studies across high-income and emerging economies could uncover divergent institutional capacities, innovation ecosystems, and policy coordination mechanisms. As highlighted by Abbass et al. (2024), the ability of N-11 countries to leverage foreign direct investment and trade openness for environmental sustainability is context-dependent, necessitating tailored governance approaches. Understanding such variations can guide the diffusion of best practices and institutional benchmarking in sustainable resource management.

Third, future research must delve into the socio-ethical dimensions of critical material extraction, especially concerning human rights, community resilience, and occupational safety. The literature has already emphasized exploitative labor practices in mineral supply chains, particularly in cobalt mining (Bhatia and Jakhar 2021; Long et al. 2023). Integrating perspectives from social justice and feminist environmentalism would allow researchers to capture the multidimensional impacts of sustainability transitions better.

Fourth, longitudinal and multi-method studies are needed to assess the long-term effectiveness of regulatory instruments, sectoral differences, and capacity-building initiatives. Building on the work of Antonioli et al. (2022) and Montiel et al. (2021), future research could track how policy interventions evolve and interact with dynamic capability formation across time and sectors.

Fifth, understanding consumer behavior is critical to fostering sustainable demand and facilitating downstream circularity. Behavioral studies exploring consumers' willingness to pay for ethically sourced products, their preferences for clean technologies, and their responsiveness to eco-labeling schemes could complement upstream-focused policy analysis (Boiral et al. 2012; Wrålsén et al. 2021).

Finally, the cascading effects of global crises, such as the COVID-19 pandemic and climate-induced disasters, should be further explored as exogenous shocks that influence sustainability trajectories and reconfigure institutional priorities (Abbas et al. 2022; Begum et al. 2022). Such work could inform more adaptive and shock-resilient models of sustainable development (Malik and Terzidis 2025a, 2026).

By addressing these gaps, future research can deepen the conceptual and empirical understanding of how national dynamic capabilities mediate sustainability transitions in the age of

critical material dependency. These scholarly efforts will not only sharpen the analytical tools for policy design but also contribute to the broader global agenda of achieving a just, inclusive, and environmentally resilient future (Yu et al. 2023; Benito et al. 2022). Furthermore, there are other concrete streams for exploration: (i) role of AI and blockchain in supply chain transparency, (ii) social dimensions of critical material dependency, and (iii) comparative institutional analyses.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be available on request.

Endnotes

¹ Please see: <https://dashboards.sdindex.org/>.

² Please see: <http://www.cepii.fr/>.

³ Detail country list is available in Table 2.

⁴ <https://elements.visualcapitalist.com/ranked-the-top-lithium-ion-battery-producing-countries-by-2030/>.

⁵ Please see: https://commission.europa.eu/publications/annual-management-and-performance-report-2022-0_en.

⁶ Please see: https://edgar.jrc.ec.europa.eu/report_2022.

⁷ A recent article titled “Copper and Aluminium in the Service of Sustainable Development” highlights the critical role of copper and aluminium in the production of green energy technologies, including electric vehicles, renewable power infrastructure, and energy storage systems. See: https://www.electrispower.com/blog/copper-and-aluminium-in-the-service-of-sustainable-development?utm_source=chatgpt.com.

We focus on copper and aluminium production because most of the sample countries have reserves of these materials. In contrast, lithium and cobalt are found in only 3 to 4 countries within our sample, so their major demand is primarily met through imports.

⁸ Please see: <https://www.unep.org/topics/forests/why-do-forests-matter>.

⁹ Please see: <https://www.weforum.org/publications/global-gender-gap-report-2023/digest/>.

¹⁰ Please see: <https://www.weforum.org/impact/clean-energy-in-emerging-markets/>.

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Appendix A

Variable Definitions and Data Sources

Variable	Definition	Source
Dependent variable		
<i>GDG_13</i>	The <i>SDG_13</i> measures the total progress towards achieving the climate action goal. The score can be interpreted as a percentage of <i>SDG_13</i> achievement (0–100%).	https://dashboards.sdgindex.org
<i>CO2_EM</i>	Normalized score of CO ₂ emissions from fossil fuel combustion and cement production (tCO ₂ /capita)	Same
<i>GHG_EM</i>	Normalized score of GHG emissions embodied in imports (tCO ₂ /capita)	Same
<i>CO2_EX</i>	Normalized score of CO ₂ emissions embodied in fossil fuel exports (kg/capita)	Same
<i>SDG_ALL</i>	The overall <i>SDG</i> measures the total progress towards achieving all 17 <i>SDGs</i> . The score can be interpreted as a percentage of <i>SDG</i> achievement (0%–100%).	Same
Independent variable		
<i>Li_IMP</i>	Natural log of Lithium imports (quantities in metric tons) by country in the current year.	CEPII
<i>Co_IMP</i>	Natural log of Cobalt imports (quantities in metric tons) by country in the current year.	Same
<i>Li_USD</i>	Natural log of Lithium imports (value in US\$) by country in the current year.	Same
<i>Co_USD</i>	Natural log of Cobalt imports (value in US\$) by country in the current year.	Same
Control variable		
<i>GDP</i>	Natural log of GDP per capita (current US\$).	World Bank data
<i>REN_E</i>	Natural log of electricity production from renewable sources.	Same
<i>INT_R</i>	Natural log of lending interest rate (%)	Same
<i>FIN_C</i>	Dummy value 1 if the year is 2008 or 2009 (financial crisis period), otherwise 0.	—
<i>PAR_A</i>	Dummy value 1 if year is equal to or greater than 2016 (Paris Agreement), otherwise 0.	—
Other variable		
<i>Forest_A</i>	Forest area (% of land area)	World Bank data
<i>Female_P</i>	Proportion of seats held by women in national parliaments (%)	Same
<i>Cu_PRO</i>	Natural log of Copper production (quantities in metric tons) by country in the current year.	www.ourworldindata.org
<i>Al_PRO</i>	Natural log of Aluminium production (quantities in metric tons) by country in the current year.	Same
<i>IMP_PL</i>	Total imports scaled by GDP in the current year.	World Bank data
<i>TRD_OP</i>	Total imports plus total exports divided by GDP in the current year.	Same