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EDITED BY
Hongjian Zhu,
Yanshan University, China

REVIEWED BY
Kunpeng Ge,
East China University of Technology, China
Guochang Xu,
National Institute for Environmental Studies (NIES), Japan
Xin Xiong,
Nanjing University, Nanjing, China, in collaboration with reviewer GX

*CORRESPONDENCE
Bo Wang,
zealotking@126.com

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Quantitative evaluation study of lithium sustainable development policies in China based on the PMC index model

Jie Gao[1], Wei Liu[2], Mao Xu[2] and Bo Wang[3]*

[1]Key Laboratory of Strategic Mineral Resources of the Upper Yellow River, Ministry of Natural Resources, Lanzhou, China, [2]School of Environment, Tsinghua University, Beijing, China, [3]Technical Center for Tailing Utilization, Chinese Academy of Geological Sciences, Beijing, China

The sustainable development of lithium is essential for facilitating the low-carbon energy transition and ensuring sustainable economic growth. Understanding the effectiveness of China's policies on lithium development is vital for advancing these goals. This study constructed a comprehensive policy evaluation system using content analysis and the PMC (Policy Modeling Consistency) index model. A total of 12 representative policies were analyzed, and their performance was visualized through PMC surface diagrams. The evaluation revealed that among the 12 policies, 2 were rated as "excellent," 9 as "good," 1 as "acceptable," and none as "poor." These results indicate that China's policies for lithium's sustainable development are generally well-designed and scientifically grounded. Despite their strengths, the policies exhibit areas for improvement, including low timeliness, insufficient long-term planning, and limited dynamic adjustment mechanisms. Regional policy coordination is also lacking, especially in non-major lithium-producing areas where policy quality tends to be lower. To address these issues, we recommend optimizing future policies by enhancing timeliness and flexibility, improving regional coordination, refining policy tools, and increasing public participation.

KEYWORDS

low-carbon energy transition, lithium, sustainable development policies, PMC index model, quantitative evaluation, China

1 Introduction

In recent years, the urgent need to address global climate change and promote sustainable development has led to a global consensus on accelerating the low-carbon green energy transition (IEA, 2021). Against this backdrop, the Chinese government has implemented a series of measures, including actively developing renewable energy, improving energy efficiency, and setting long-term carbon neutrality goals. Specifically, in the "14th Five-Year Plan" and the 2030 carbon peak target, China has outlined its strategic path for green development. Furthermore, the report of the 20th National Congress of the Communist Party of China further emphasized the necessity of accelerating energy transition and actively participating in global climate governance. China's strategic path for green development includes expanding the use of solar, wind, and hydropower, investing in smart grid technologies, and promoting electric vehicle adoption. A particular focus is placed on innovation in energy storage solutions, such as lithium-ion batteries, which are crucial for balancing renewable energy supply and demand.

The development of low-carbon energy transition technologies requires support from various critical metals, resulting in a rapid increase in demand. However, limited resource reserves and production capacity have led to supply shortages, particularly for lithium (Dong et al., 2020; Liu M. et al., 2023). Critical metals supporting industries like photovoltaic and wind power are in high demand and are unevenly distributed globally. China mainly relies on lithium imports from Australia and Chile, which account for 58% and 21% of the global supply, respectively (Shao and Lan, 2020). The U.S. Energy Information Administration (EIA) noted in its "World Energy Outlook 2019" that among global critical metals, tellurium and lithium are expected to have the highest demand growth rates from 2018 to 2050, at 6.9% and 6.2%, respectively (U.S. Energy Information Administration Office of Energy Analysis, 2019). Despite China's significant share of global lithium reserves, the quality of these reserves is relatively low. China's current strategy involves prioritizing the use of imported lithium ore while addressing technical challenges associated with domestic extraction. Research by Liang et al. indicates that China relies on imports for approximately 84%–99% of its nickel, cobalt, lithium, and manganese resources (Zhai et al., 2019). Notably, in 2019, China processed more than half of the world's lithium, underscoring the urgency of ensuring lithium security (Kim et al., 2021). The concentration of lithium supply among a few key countries and regions has led to significant price fluctuations. While political instability is a concern in some resource-rich areas, key lithium suppliers such as Australia and Chile are generally considered politically stable. Instead, the price volatility in lithium markets is more closely tied to the rapid development and increasing demand for power battery technology, which has driven substantial price increases (Aguilar Lopez et al., 2024). Predictions by Wang et al. suggest that to meet China's low-carbon energy transition needs, the demand for critical energy metals such as lithium, cobalt, and nickel will increase by 8.6–25 times between 2020 and 2040, while domestic resources can only support 10–30 years of consumption (Wang et al., 2021). Therefore, the supply-demand contradiction for lithium required for China's future low-carbon energy transition will become increasingly prominent, significantly impacting technological progress, market promotion, and international competitiveness. Meanwhile, studies have shown that recycling and cascading utilization of retired power batteries from electric vehicles, a major lithium consumption scenario, offer an innovative approach to achieving sustainable lithium development under the low-carbon energy transition (Baars et al., 2021; Dunn et al., 2021; Kamran et al., 2021; Thakur et al., 2022).

Given the strategic importance of lithium, its sustainable management is crucial. Sustainable lithium development involves ensuring long-term resource utilization across extraction, processing, use, and recycling stages. This approach meets current needs without compromising future generations' ability to meet their own, minimizes environmental impacts, and supports continuous economic and social development. With the growing demand for lithium from electric vehicles and renewable energy storage systems, sustainable lithium development is vital for transitioning to a low-carbon economy and energy structure (Xu et al., 2019). Current research on sustainable lithium development focuses on several key areas: (1) Assessing and mitigating environmental impacts during lithium extraction and processing (Wang et al., 2020; Thakur et al., 2022); (2) Enhancing lithium utilization efficiency and recycling (Swain, 2017; Bobba et al., 2019); (3) Understanding the social and economic impacts of lithium extraction and use (Sverdrup, 2016; Liu and Agusdinata, 2020); (4) Innovating with alternative materials to lithium (Ali et al., 2021; Roy et al., 2024). To promote sustainable lithium development in China, relevant policies must guide and support efforts within the low-carbon energy transition. However, there is limited research on China's sustainable lithium development policies, particularly from a policy text quantification perspective.

This paper develops a quantitative analysis framework to evaluate China's sustainable development policies for lithium using content analysis and text mining methods, incorporating the Policy Modeling Consistency (PMC) index model. The PMC index mode is a tool used to assess the coherence and effectiveness of policy measures. It integrates both qualitative and quantitative approaches for comprehensive policy evaluation. By analyzing representative policies, the study aims to gain an in-depth understanding of trends in China's sustainable lithium development, providing a scientific basis for formulating and improving future policies. The evaluation results are intended to offer insights for enhancing the normativity and operability of China's sustainable lithium development policies, thereby promoting the continuous advancement of lithium development in the country.

2 Methods and data

2.1 Data sources and sample selection

To systematically and comprehensively gather policy samples related to the sustainable development of lithium, this study used "sustainable development of lithium" as a keyword to collect relevant policy documents from the PKU Law legal database. To ensure data accuracy and authority, supplementary information was also sourced from provincial government portal websites. In selecting policy samples, we emphasized national and provincial policy documents to ensure comprehensive analysis and authoritative insights. Through a manual full-text review, we selected 75 policy documents highly relevant to China's sustainable development of lithium from the initially collected large volume of documents as the main subjects of analysis (detailed information is listed in the appendix). Furthermore, to evaluate regional differences and implementation effects of lithium policies comprehensively, we selected 7 lithium sustainable utilization policies from China's main lithium-producing regions and 5 from non-lithium-producing regions, totaling 12 policies as evaluation samples. These policies cover various aspects and regional characteristics of China's sustainable lithium development. An in-depth evaluation of these 12 policies was conducted using the PMC index model. This quantitative analysis tool assesses the content quality, implementation feasibility, and expected outcomes of policy documents, providing a scientific basis for policymakers. Through this method, we aim to reveal the

TABLE 1 China's representative policy for the sustainable development of China's lithium.

Policy code	Policy name	Issuing department	Date issued
P_1	Approval of the Overall Territorial Spatial Planning for the Ali Region (2021-2035)	Tibet Autonomous Region	2024-06-18
P_2	Notice of Adjustment of 2016 Municipal Key Projects	Henan	2016-07-28
P_3	Notice on the Issuance of Ten Measures on Promoting the Development of New Energy Battery Industry Chain	Henan	2023-03-06
P_4	Jiangxi Province 14th Five-Year Plan for the development of industrial technology innovation notice	Jiangxi	2021-11-19
P_5	Notice on a number of policy measures to optimize and strengthen the province's lithium new energy industry	Jiangxi	2022-10-11
P_6	Notice on the issuance of a number of policies to support the development of new energy battery industry	Gansu	2022-06-17
P_7	On the issuance of Qinghai to build a national clean energy industry highland action program	Qinghai	2021-08-12
P_8	Implementing Opinions on the Implementation of the National New Energy Vehicle Industry Development Plan (2021-2035) in Qinghai Province	Qinghai	2021-08-27
P_9	On the issuance of the "to promote the implementation of high-quality development of the lithium industry views" notice	Sichuan	2023-09-19
P_{10}	On the issuance of "Suining City" 14th Five-Year Plan "lithium industry development plan" notice	Sichuan	2022-03-10
P_{11}	On the issuance of Yichun City, "14th Five-Year Plan" manufacturing high-quality development plan notice	Jiangxi	2021-12-20
P_{12}	Notice on the Issuance of the Three-Year Action Plan for the Development of New Energy Battery Industry in Yunnan Province (2022-2024)	Yunnan	2022-04-06

implementation effects of China's lithium sustainable development policies and their adaptability and optimization directions across different regions.

Based on a comprehensive examination of central and local government policies, this study carefully selected 12 representative policies from the collected sample policy database for in-depth analysis. The specific policies are listed in Table 1. Given the close relationship between lithium distribution and the geographical environment, the core documents of China's lithium sustainable development policies are primarily concentrated in lithium-rich areas such as Jiangxi, Sichuan, and Qinghai. These regions have abundant lithium mineral resources and play crucial roles in the national lithium industry development strategy. Consequently, the research focused on selecting policy documents from these areas to explore their practical effects on lithium development, environmental protection, and economic growth. To gain a more comprehensive understanding of China's policy landscape for promoting the sustainable development of lithium nationwide, this study also examined relevant policy documents from non-lithium producing areas. Although these documents do not directly address lithium mining and processing, they provide essential support in technological innovation, industrial chain extension, market regulation, and environmental governance, enriching the research on China's lithium sustainable development strategies.

2.2 Content analysis methodology

The content analysis method identifies the overall and objective characteristics of subjects to propose qualitative hypotheses about issues. It then conducts systematic and objective quantitative statistical analysis based on these hypotheses. This method reveals the essence of the research content and draws qualitative conclusions supported by statistical data (Kolbe and Burnett, 1991). Compared to merely describing and observing research objects to obtain results, content analysis forms conclusions through objective data analysis, enhancing the research's objectivity and rigor.

In this study, we employ the content analysis method combined with text-mining techniques to extract key information from policy documents. We preprocess the document collection by extracting high-frequency words and eliminating irrelevant words to more accurately identify and analyze key parameter variables.

2.3 PMC index model

The PMC index model, proposed by Estrada et al., is specifically designed to evaluate policy texts (Ruiz Estrada, 2010). The operational process of this model mainly includes four key steps: (1) Identifying variable classifications and parameters; (2) Constructing a multi-input-output table; (3) Calculating the PMC index; (4) Drawing PMC surface graphs. These graphs can three-dimensionally display the evaluation results of lithium sustainable development policies, making them more intuitive.

The application scope of the PMC index model is also quite broad, encompassing various domains such as regional sustainable development policies (Liu et al., 2022), green development policies (Dai et al., 2021), new energy vehicle industry policies (Liu M. et al., 2023), carbon emission and carbon neutrality policies (Lu et al., 2022), manufacturing development policies (Nkoua Nkuika and Yiqun, 2022), and other aspects. It covers areas such as development, environmental protection, energy, industry, and ecology, primarily focusing on research related to policy timeliness, issuing institutions, target audience, types, intensity, social benefits, incentives, and constraints. The main contribution of the PMC index model lies in assessing the internal consistency of individual policies and revealing the overall characteristics of policies and their differences from other aspects by analyzing their strengths and weaknesses. Compared to other evaluation methods, a significant advantage of the PMC index model is its rich evaluation dimensions and its ability to effectively avoid index weight errors and subjective evaluation errors, ensuring the objectivity and accuracy of evaluation results.

2.3.1 Identify variable categorization and parameters

The 75 selected policy documents were imported into ROSTCM6.0 software for file merging, word segmentation processing, word frequency statistics, and other operations. The initial list of high-frequency words from the first run lacked practical significance for this study. Consequently, after manual screening, we eliminated irrelevant words such as "research," "service," and "improvement," ultimately identifying 83 effective high-frequency words. Subsequently, using NVivo 11, we coded the top 24 effective high-frequency words to create a coding table (see Table 1). From Table 2, it is evident that the core elements of China's sustainable development policies for lithium include resource management, renewable energy use, battery technology improvement, and environmental protection supervision, among other aspects.

In this study, based on the practice of China's lithium sustainable development policies in the context of low-carbon energy transition, and on the foundation of policy text mining, we set up 10 primary variables and 43 secondary variables. We reviewed several key studies and frameworks that have been widely recognized in the field of policy evaluation and sustainable development. The design of these variables and the corresponding evaluation criteria were developed with reference to existing literature and established frameworks in policy analysis (Yang et al., 2022; Liu F. et al., 2023). The primary variables are: Policy Nature (X1), Policy Domain (X2), Policy Focus (X3), Policy Duration (X4), Policy Target (X5), Policy Function (X6), Policy Measures (X7), Policy Guarantee (X8), Policy Evaluation (X9), and Policy Disclosure (X10). The specific variable design and evaluation criteria are shown in Table 3.

2.3.2 Construction of multi-input-output tables

The multi-input-output framework offers an innovative approach to data analysis, enabling the multidimensional quantification of individual variables. This methodological structure forms the foundation for computing 10 primary variables, each capable of accommodating an unlimited number of secondary variables. A key feature of this framework is the equal weighting of all variables, regardless of their hierarchical position. To implement this concept, we use a binary coding scheme: secondary variables are assigned a value of 1 if present in the policy text and 0 if absent (Yang et al., 2022). This egalitarian treatment of variables within the multi-input-output framework significantly mitigates potential subjectivity in policy evaluation. In the context of sustainable lithium resource development policies, we have constructed a customized multi-input-output table (Table 4). This tailored framework allows for a comprehensive and nuanced analysis of policy instruments, capturing the multifaceted nature of sustainability initiatives in the lithium sector.

2.3.3 Calculation of PMC index

Building upon Estrada's work, we construct a PMC index model for lithium sustainable development policies. Based on the secondary variables in Table 5, the PMC index is calculated according to the four basic steps of Equations 1–4 (Ruiz Estrada, 2010). Variables are set according to the lithium sustainable development policy text, including primary and secondary variables.

$$X{:}N[0,1] \tag{1}$$

Create a multi-input-output table, and based on text mining and binary methods, assign specific values to secondary variables, with each parameter encoded as binary "0" or "1".

$$X = \{XR{:}[0,1]\} \tag{2}$$

Combining the assignment of secondary variables from the previous step, calculate the values of primary variables according to Equation 3. In Equation 3, t represents the primary variable, j represents the number of secondary variables included in the corresponding primary variable, and n represents the number of secondary variable indicators.

$$X_t\left(\sum_{j=1}^{n}\frac{X_{ij}}{T(X_{ij})}\right), t = 1,2,3\cdots \tag{3}$$

Use the formula to sum up the values of all variables:

$$PMC = X_1\left(\sum_{a=1}^{6}\frac{X_{1a}}{6}\right) + X_2\left(\sum_{b=1}^{5}\frac{X_{1a}}{5}\right) + X_3\left(\sum_{b=1}^{7}\frac{X_{1a}}{7}\right) + X_4\left(\sum_{b=1}^{3}\frac{X_{1a}}{3}\right) + X_5\left(\sum_{b=1}^{5}\frac{X_{1a}}{5}\right) + X_6\left(\sum_{b=1}^{4}\frac{X_{1a}}{4}\right) + X_7\left(\sum_{b=1}^{5}\frac{X_{1a}}{5}\right) + X_8\left(\sum_{b=1}^{5}\frac{X_{1a}}{5}\right) + X_9\left(\sum_{b=1}^{3}\frac{X_{1a}}{3}\right) + X_{10} \tag{4}$$

Based on domestic and international scholars' research on PMC index ratings, the PMC index values are divided into 4 levels: 10-9 is considered excellent (perfect consistency), 8.99-7 is considered good (excellent consistency), 6.99-5 is considered acceptable (acceptable consistency), 4.00-0 is considered unacceptable (unacceptable consistency).

2.3.4 Constructing PMC surface diagrams

The PMC surface graph is a tool that visually displays the effectiveness of policy evaluation. In this study, we use the visualization of the PMC surface to characterize the strengths and

TABLE 2 High Frequency Words in China's lithium Sustainable Development Policy.

Sequence	High frequency words	Frequency	Sequence	High frequency words	Frequency
1	Resource	992	13	Clean energy	264
2	Production	980	14	Economy	218
3	lithium	764	15	Technological innovation	213
4	Energy	667	16	New material	202
5	New energy	618	17	Digitalisation	168
6	Ecological	590	18	Mineral resources	148
7	New energy battery	239	19	Natural resource	126
8	Industrial development	487	20	Comprehensive utilization	111
9	Battery	451	21	Environmental impact	85
10	Mines	332	22	Environmental protection	84
11	lithium battery	286	23	Key technology	80
12	Energy storage	276	24	Strategic resource	80

weaknesses of various policies. To construct the PMC matrix, 10 primary variables are set. However, the primary variable X10, which represents policy transparency, has no secondary variables, and all policies are publicly accessible, so this item scores 1 for all. Considering the symmetry of the matrix and the balance of the PMC surface, X10 is excluded, forming a third-order square matrix. The PMC surface is calculated according to Equation 5.

$$PMC - \text{Surface} = \begin{pmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{pmatrix} \tag{5}$$

3 Quantitative analysis of sustainable development policies for lithium in China in the context of low-carbon energy transition

3.1 PMC-index of 12 representative policies

The 12 representative policies were processed through a multi-input-output analysis framework, where text mining and content analysis techniques were employed to assign values to each secondary variable, as illustrated in Table 5. Subsequently, the PMC-Index values for China's lithium sustainable development policies were calculated, as presented in Table 6. The ranking of these policies, based on their PMC-Index values, is as follows: P11 > P10 > P4 > P7 > P12 > P9 > P8 > P5 > P3 > P6 > P2 > P1.

Among the 12 evaluated policies, two (P10, P11) are rated at the "excellent" level, nine (P2, P3, P4, P5, P6, P7, P8, P9, P12) are at the "good" level, and one (P1) is at the "acceptable" level, with no policies falling into the "unacceptable" category. The average PMC-Index value of these policies is 8.31, which places them in the "good" category. This indicates that China's lithium sustainable development policies generally exhibit strong effectiveness and implementation results, adequately supporting the healthy development of the lithium industry. Overall, the policies demonstrate a good level of scientific validity and feasibility. However, there are areas that require further improvement and optimization to enhance their comprehensive effectiveness and long-term impact.

Among the evaluated lithium recycling policies, those rated as "excellent" show a distinct regional distribution. Sichuan Province contributed one policy, while Jiangxi Province contributed the other, together constituting the two "excellent" policies. Notably, Qinghai Province, despite being rich in lithium resources, had both of its policy documents rated as "good," indicating a strong policy-making capability but also highlighting areas for potential improvement.

Specifically, Sichuan Province's two policy documents (P9, P10) performed excellently in the assessment, with PMC-Index scores of 8.79 and 9.13, respectively, resulting in an average score of 8.96. This underscores the province's leading position in formulating lithium recycling policies. Jiangxi Province's three policy documents (P4, P5, P11) also performed well in the Policy Matching Comprehensive Index (PMC-Index) assessment, with scores of 8.93, 8.22, and 9.47, respectively, averaging 8.87. This demonstrates Jiangxi's strong policy-making capabilities and emphasis on lithium recycling policy formulation. Qinghai Province's two policy documents (P7, P8) averaged a PMC-Index score of 8.61, reaching a "good" level. In summary, all three provinces demonstrated strong policy-making capabilities, with Sichuan and Jiangxi showing particularly high performance in lithium recycling policies.

10.3389/feart.2024.1488223

TABLE 3 Variable design and evaluation criteria.

Primary variables	Secondary variables	Evaluation criterion
Policy Nature (X1)	X1.1 Prediction	Whether it is predictive, Yes for 1, No for 0
	X1.2 Supervision	Whether supervision is involved, Yes for 1, No for 0
	X1.3 Suggestion	Whether countermeasures and suggestions are included, Yes for 1, No for 0
	X1.4 Orientate towards	Whether orientate towards are included, Yes for 1, No for 0., Yes for 1, No for 0
	X1.5 Stabilisation	Whether stable contents are included, Yes for 1, No for 0., Yes for 1, No for 0
	X1.6 Description	Whether there is descriptive content, Yes for 1, No for 0
Policy Field (X2)	X2.1 Politics	Whether it involves the political field, Yes for 1, No for 0
	X2.2 Economics	Whether the content involves the economic field, Yes for 1, No for 0
	X2.3 Technology	Whether the technical level is included, Yes for 1, No for 0
	X2.4 Society	Whether social services are involved, Yes for 1, No for 0
	X2.5 Environment	Whether the environmental aspect is included, Yes for 1, No for 0
Policy Focus (X3)	X3.1 Energy conservation and emission reduction	Whether energy conservation and carbon emission are included, Yes for 1, No for 0
	X3.2 Technological innovation	Whether technological innovation is involved, Yes for 1, No for 0
	X3.3 Economic benefit	Whether economic benefit is involved, Yes for 1, No for 0
	X3.4 Environmental management	Whether environmental management is involved, Yes for 1, No for 0
	X3.5 Eco-protection	Whether eco-protection is involved, Yes for 1, No for 0
	X3.6 Energy restructuring	Whether energy restructuring is involved, Yes for 1, No for 0
	X3.7 Adjustment of industrial chain	Whether it involves the adjustment of industrial chain, Yes for 1, No for 0
Policy Timeliness (X4)	X4.1 Long-term	Whether the content involves for more than 5 years, Yes for 1, No for 0
	X4.2 Medium-term	Whether the content involves for 3–5 years, Yes for 1, No for 0
	X4.3 Short-term	Whether the content involves for 1–3 years, Yes for 1, No for 0
Policy Object (X5)	X5.1 Government	Whether the target group is the government, Yes for 1, No for 0
	X5.2 Enterprise	Whether the target group is the enterprise, Yes for 1, No for 0
	X5.3 Society	Whether the target group is the society, Yes for 1, No for 0
	X5.4 Scientific researcher	Whether the target group is the scientific researcher, Yes for 1, No for 0
	X5.5 Public	Whether the target group is the public, Yes for 1, No for 0
Policy Impact (X6)	X6.1 Fill an industrial gap	Whether it can fill an industrial gap, Yes for 1, No for 0
	X6.2 Sustainable development	Whether it involves sustainable development, Yes for 1, No for 0
	X6.3 Robust mechanism	Whether it involves robust mechanism, Yes for 1, No for 0
	X6.4 Win-win cooperation	Whether it can fulfill win-win cooperation, Yes for 1, No for 0

(Continued on the following page)

TABLE 3 (*Continued*) Variable design and evaluation criteria.

Primary variables	Secondary variables	Evaluation criterion
Policy Tool (X7)	X7.1Physical incentive	Whether it involves physical incentive, Yes for 1, No for 0
	X7.2 Financial aid	Whether it involves financial aid, Yes for 1, No for 0
	X7.3 Technical Support	Whether it involves technical support, Yes for 1, No for 0
	X7.4 Policy restraint	Whether the policy involves mandatory regulations such as administrative orders,Yes for 1, No for 0
	X7.5 Investment promotion	Whether it involves investment initiatives, Yes for 1, No for 0
Policy Guarantee (X8)	X8.1 Social promotion	Whether social promotion is involved, Yes for 1, No for 0
	X8:2 Industrial estraint	Whether industrial estraint is involved, Yes for 1, No for 0
	X8.3 Government supervision	Whether government supervision is involved, Yes for 1, No for 0
	X8.4 Social supervision	Whether social supervision is involved, Yes for 1, No for 0
	X8.5 Talent Development	Whether talent development is involved, Yes for 1, No for 0
Policy Evaluation (X9)	X9.1 Clear goals	Whether the policy goals are clear, Yes for 1, No for 0
	X9.2 Reasonable Scheme	Whether the scheme involved is reasonable, Yes for 1, No for 0
	X9.3 Adequate planning	Whether the planning involved is adequate, Yes for 1, No for 0
Policy Publicity (X10)	—	—

TABLE 4 Multi-input–output table.

Primary variables	Secondary variables
X1	X1.1 X1.2 X1.3 X1.4 X1.5
X2	X2.1 X2.2 X2.3 X2.4 X2.5
X3	X3.1 X3.3 X3.3 X3.4 X3.5 X3.6 X3.7
X4	X4.1 X4.4 X4.3
X5	X5.1 X5.5 X5.3 X5.4 X5.5
X6	X6.1 X6.6 X6.3 X6.4
X7	X7.1 X7.7 X7.3 X7.4 X7.5
X8	X8.1 X8.8 X8.3 X8.4 X8.5
X9	X9.1 X9.9 X9.3
X10	—

Policy performance shows a clear gradient among provinces that are not major lithium producers. Yunnan Province leads with a PMC-Index of 8.62, closely followed by Gansu Province with a score of 8.38, both achieving "good" levels. Although Henan Province has formulated numerous policy documents, its two most representative policies (P2, P3) have relatively low PMC-Index scores of 7.49 and 7.81, averaging only 7.65. This indicates that while Henan Province places significant importance on sustainable lithium development, there is substantial potential for improvement in the professionalism and effectiveness of its policy-making. The Tibet Autonomous Region shows the weakest policy performance, with a PMC-Index of only 6.17. Although this is considered "acceptable," there is a noticeable gap compared to other regions. This result suggests that Tibet needs to improve its current situation by strengthening policy research and enhancing policy-making capabilities. The reasons for these differences may include variations in resource endowments, levels of economic development, and industrial structures among different regions, leading to disparities in the quality of lithium recycling policies across the country.

The Debra chart of China's lithium policies presents the average values of nine main variables across 12 policies, providing an intuitive overview of the policies' current strengths and weaknesses and highlighting areas for future improvement. As shown in Figure 1, the average score of these nine main variables is 0.81, indicating an overall good performance. The sub-figures a, b, and c in the figure title represent comparative charts of the Primary Variables scores for policy documents P1-P12 against the average scores of these policy documents.

Among the evaluated variables, X9 scores the highest at 0.97, suggesting that China's lithium policies have a solid foundation, clear objectives, scientific planning, detailed execution strategies, and a relatively complete overall framework. This is closely followed by X1 and X2, both scoring 0.92, indicating that the policies are accurately positioned in terms of nature and scope, with broad coverage

TABLE 5 Multi-input–output table of 12 representative policies.

Primary variables	Secondary variables	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
X1	X1.1	1	1	1	1	1	1	1	1	1	1	1	1
	X1.2	1	1	1	1	1	1	1	1	1	1	1	1
	X1.3	1	1	0	1	1	1	1	1	1	1	1	1
	X1.4	1	1	1	1	1	1	1	1	1	1	1	1
	X1.5	1	1	1	1	1	1	1	1	1	1	1	1
	X1.6	1	0	0	1	0	1	1	0	1	1	1	0
X2	X2:1	1	1	1	1	1	1	1	1	1	1	1	1
	X2:2	0	1	1	1	1	1	1	1	1	1	1	1
	X2:3	0	1	1	1	1	1	1	1	1	1	1	1
	X2:4	1	1	1	1	0	0	1	1	1	1	1	1
	X2:5	1	1	1	1	1	0	1	1	1	1	1	1
X3	X3:1	0	1	1	1	1	1	1	1	1	1	1	1
	X3:2	0	1	1	1	1	1	1	1	1	1	1	1
	X3:3	1	0	1	1	1	1	1	1	1	1	1	1
	X3:4	0	1	0	1	0	0	0	1	0	1	1	0
	X3:5	1	1	1	1	1	0	1	1	1	1	1	1
	X3:6	0	1	1	1	1	1	1	1	1	1	1	1
	X3:7	0	1	1	1	1	1	1	1	1	1	1	1
X4	X4:1	1	0	1	1	1	0	1	0	0	1	1	1
	X4:2	0	0	0	0	0	0	0	1	0	0	0	0
	X4:3	0	1	0	0	0	1	0	0	1	0	1	0
X5	X5:1	1	1	1	1	1	1	1	1	1	1	1	1
	X5:2	0	1	1	1	1	1	1	1	1	1	1	1
	X5:3	1	1	1	1	1	1	1	1	1	1	1	1
	X5:4	0	1	1	1	1	1	1	1	1	1	1	1
	X5:5	0	0	0	0	0	0	0	0	0	1	1	0
X6	X6:1	0	1	0	1	1	0	1	1	1	1	1	1
	X6:2	1	1	1	1	1	1	1	1	1	1	1	1
	X6:3	1	1	1	1	1	1	1	1	1	1	1	1
	X6:4	1	1	1	1	1	1	1	1	1	1	1	1

(Continued on the following page)

TABLE 5 (*Continued*) Multi-input–output table of 12 representative policies.

Primary variables	Secondary variables	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
X7	X7:1	0	1	1	1	1	1	1	1	1	1	1	1
	X7:2	0	0	1	1	1	1	1	1	1	1	1	1
	X7:3	0	0	0	0	0	0	0	0	0	0	0	0
	X7:4	0	1	1	1	1	1	1	1	1	1	1	1
	X7:5	1	1	1	1	1	1	1	1	1	1	1	1
X8	X8:1	0	0	0	1	1	0	1	1	1	1	1	1
	X8:2	0	1	1	1	1	1	1	1	1	1	1	1
	X8:3	1	1	1	1	1	1	1	1	1	1	1	1
	X8:4	1	0	0	1	0	0	1	1	1	1	1	1
	X8:5	1	0	1	1	1	1	1	1	1	1	1	1
X9	X9:1	1	1	1	1	1	1	1	1	1	1	1	1
	X9:2	1	0	1	1	1	1	1	1	1	1	1	1
	X9:3	1	1	1	1	1	1	1	1	1	1	1	1
X10	X10:1	1	1	1	1	1	1	1	1	1	1	1	1

TABLE 6 PMC-Index of 12 representative policies.

Policy	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	PMC-index	Rank	Level
P1	1	0.6	0.29	0.33	0.4	0.75	0.2	0.6	1	1	6.17	12	Acceptable
P2	0.83	1	0.86	0.33	0.8	1	0.6	0.4	0.67	1	7.49	11	Excellent
P3	0.67	1	0.86	0.33	0.8	0.75	0.8	0.6	1	1	7.81	9	Excellent
P4	1	1	1	0.33	0.8	1	0.8	1	1	1	8.93	3	Excellent
P5	0.83	0.8	0.86	0.33	0.8	1	0.8	0.8	1	1	8.22	8	Excellent
P6	1	0.6	0.71	0.33	0.8	0.75	0.8	0.6	1	1	7.59	10	Excellent
P7	1	1	0.86	0.33	0.8	1	0.8	1	1	1	8.79	4	Excellent
P8	0.83	1	1	0.33	0.8	1	0.8	1	1	1	8.76	6	Excellent
P9	1	1	0.86	0.33	0.8	1	0.8	1	1	1	8.79	5	Excellent
P10	1	1	1	0.33	1	1	0.8	1	1	1	9.13	2	Perfect
P11	1	1	1	0.67	1	1	0.8	1	1	1	9.47	1	Perfect
P12	0.83	1	0.86	0.33	0.8	1	0.8	1	1	1	8.62	7	Excellent
Average	0.92	0.92	0.85	0.36	0.8	0.94	0.73	0.83	0.97	1	8.31		

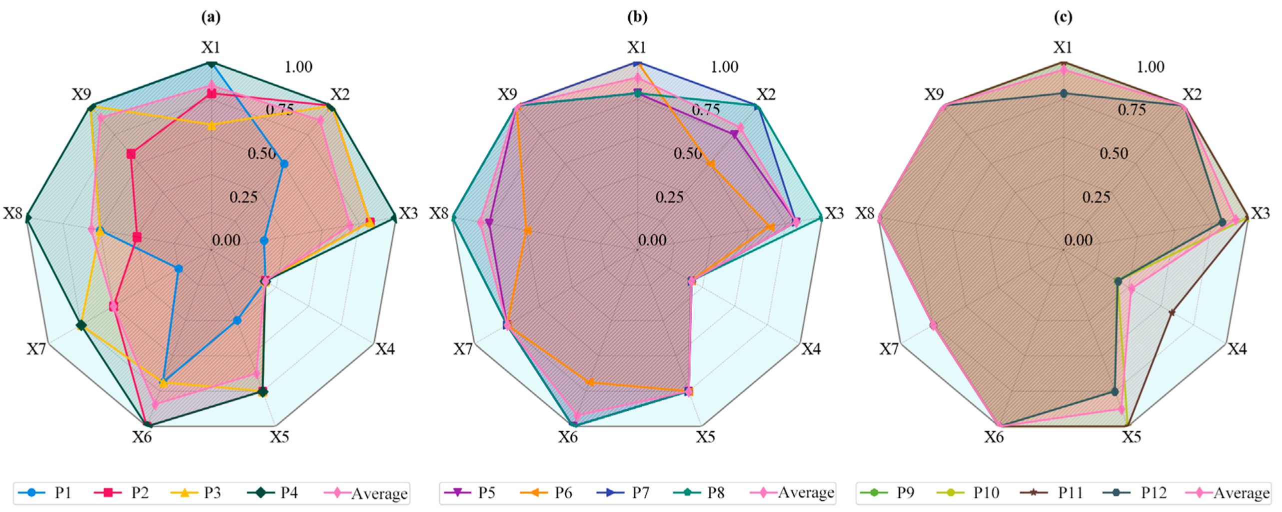

FIGURE 1
The Debra chart of China's lithium policies.

that effectively meets industry development needs. X6 scores 0.94, reflecting that policy formulation thoroughly considers the impact on industry and society, with clear expected outcomes. X5 scores 0.80, showing good performance in targeting and covering relevant interest groups. However, there are areas needing improvement. X4 scores the lowest at only 0.36, significantly below average, indicating a clear deficiency in the timeliness of current lithium policies, which may hinder their ability to respond quickly to industry changes and emerging challenges. Although above average, X7 scores 0.73, suggesting that there is still room for improvement in enriching and optimizing policy implementation methods. X3 and X8 score 0.85 and 0.83, respectively, performing well but still with room for enhancement. This suggests that policies can be further strengthened in focusing on key issues and providing necessary safeguard measures.

In conclusion, China's sustainable development policies for lithium exhibit a relatively complete overall framework, with outstanding performance in policy evaluation, nature, field, and impact. However, there is a notable shortcoming in policy timeliness, and there is room for improvement in policy tools, focus, and safeguard measures. Future policy-making should prioritize enhancing policy timeliness, strengthening multi-departmental collaboration, enriching policy tools, and further refining policy focus and safeguard measures. These improvements will better enable the policies to adapt to the rapid development and changes in the lithium industry.

3.2 Analysis of PMC-surface for 12 representative policies

The scores for each policy variable were input into data analysis software in a 3x3 matrix format, and a three-dimensional color surface plot was used to generate the PMC-Surface diagram for the 12 policy documents. The resulting PMC surface of China's sustainable development policies for lithium is shown in Figure 2. The X-axis corresponds to 1, 2, 3 in the figure, while the Y-axis corresponds to Series 1, Series 2, Series 3. The Z-axis represents the PMC index scores of the policies being evaluated. Different color blocks represent scores for different main variables. The protruding parts of the surface plot indicate higher scores, while the concave parts indicate lower scores.

Policy P1 has a PMC-Index of 6.17, rated as "acceptable" and ranked 12th. This policy serves as a guiding document for lithium development and utilization in Tibet. It excels in X1 and X9, indicating precise policy positioning and a robust assessment mechanism. It also scores well in X6 (0.75), demonstrating significant influence. However, it scores low in X3 (0.29) and X7 Policy Tool (0.2), suggesting inadequate attention to key issues and limited implementation methods. Future policy development should address these shortcomings to enhance overall effectiveness. The PMC surface of P1 is depicted in Figure 2A.

Policy P2 has a PMC-Index of 7.49, rated as "excellent" and ranked 11th. This policy primarily adjusts lithium-related projects, scoring full marks in X2 and X6, indicating comprehensive coverage and strong influence. High scores in X3 (0.86) reflect effective attention to key issues. However, it scores low in X4 (0.33) and X8 (0.4), indicating a lack of long-term planning and implementation safeguards. Enhancing these areas in future policies can improve sustainability and execution effectiveness. The PMC surface of P2 is shown in Figure 2B.

Policy P3 has a PMC-Index of 7.81, rated as "excellent" and ranked 9th. This policy primarily guides the development of the lithium battery industry chain. It scores full marks in X2 and X9, reflecting comprehensive coverage and a well-established assessment mechanism. High scores in X3 (0.86) show effective attention to key issues. However, it scores low in X4 (0.33) and X1 (0.67), suggesting a need for better long-term planning and policy positioning. Future policy formulation should strengthen these aspects to enhance overall effectiveness. The PMC surface of P3 is shown in Figure 2C.

Policy P4 has a PMC-Index of 8.93, rated as "excellent" and ranked 3rd. This policy proposes suggestions for lithium utilization and technological development, scoring full marks in multiple

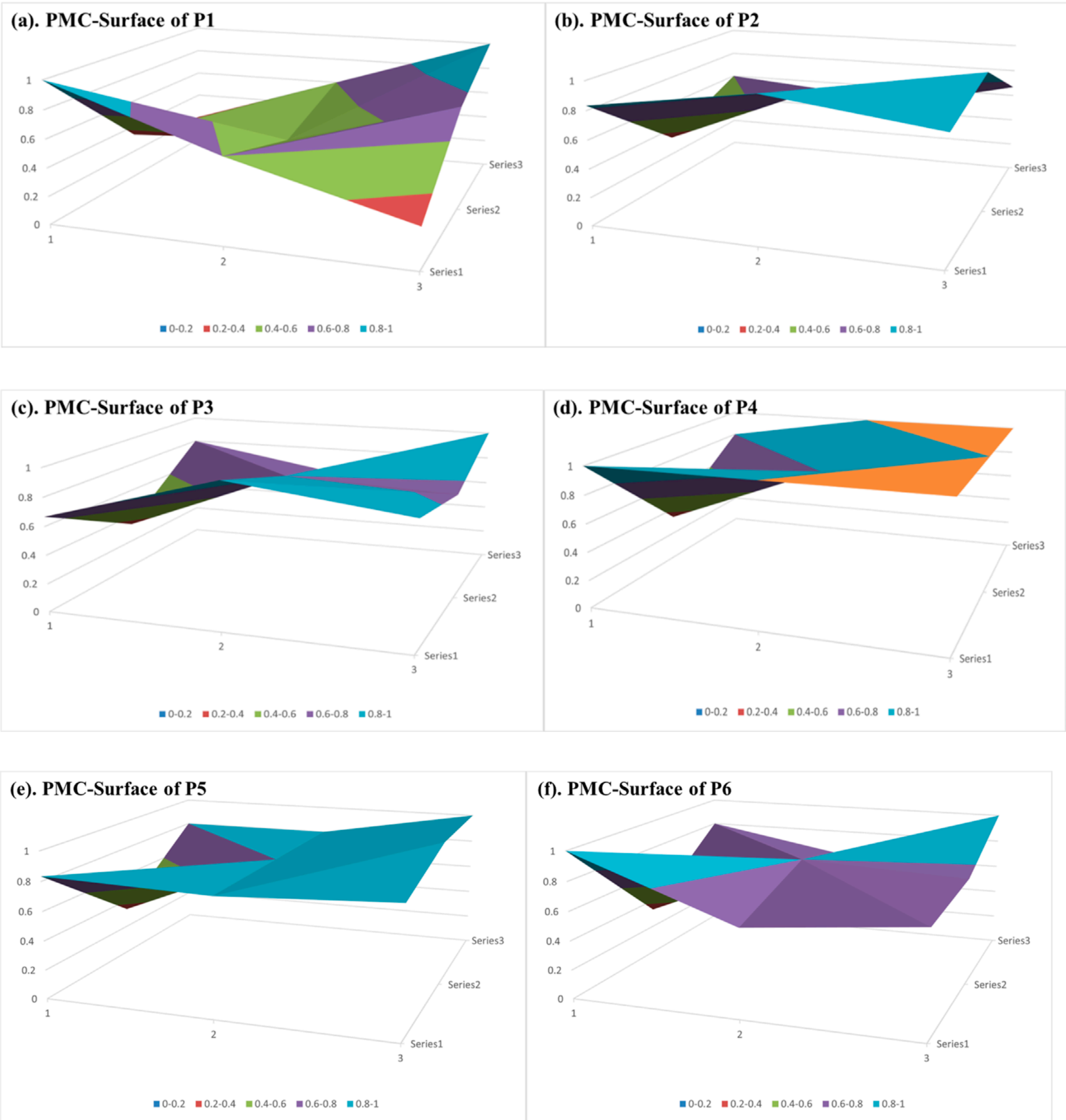

FIGURE 2
(Continued).

indicators including X1, X2, X3, X6, X8, and X9. This reflects its comprehensiveness and high quality. However, a low score in X4 (0.33) indicates insufficient consideration of rapidly changing environments. Future policies should introduce regular assessment and adjustment mechanisms to enhance adaptability. The PMC surface of P4 is shown in Figure 2D.

Policy P5 has a PMC-Index of 8.22, rated as "excellent" and ranked 8th. This policy proposes suggestions for the development of the lithium battery business. It excels in X6 Policy Impact and X9, scoring full marks. Other indicators such as X1, X3, X5, X7, and X8 are above average, reflecting its comprehensiveness. However, the low score in X4 (0.33) suggests a lack of adaptability. Future revisions should focus on improving timeliness and expanding field coverage. The PMC surface of P5 is shown in Figure 2E.

Policy P6 has a PMC-Index of 7.59, rated as "excellent" and ranked 10th. This policy discusses the development of the new energy battery industry, excelling in X1 and X9. Above-average scores in X5 and X7 reflect targeted nature and diverse tool application. However, low scores in X4 (0.33), X2 (0.6), and X6 (0.75) suggest a need for better coverage, influence, and flexibility. Future policies should focus on these areas to improve overall effectiveness. The PMC surface of P6 is shown in Figure 2F.

Policy P7 has a PMC-Index of 8.79, rated as "excellent" and ranked 4th. This policy guides the clean utilization of lithium, scoring full marks in X1, X2, X6, X8, and X9. High scores in X3

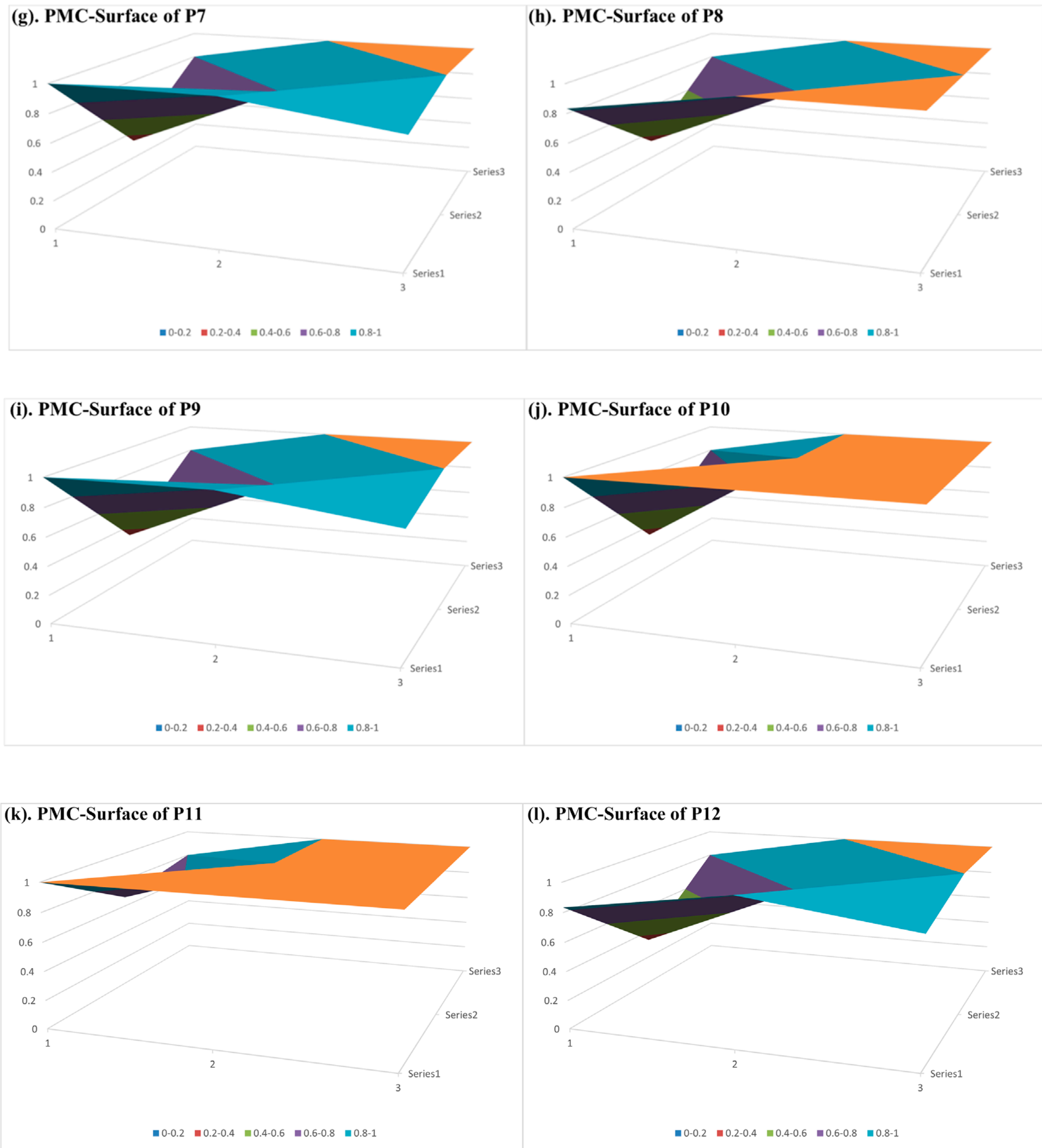

FIGURE 2
(Continued). The PMC-Surface of China's sustainable development policies for lithium.

(0.86) and X5 (0.8) reflect broad coverage. However, a low score in X4 (0.33) indicates a lack of adaptability. Future revisions should improve timeliness and establish flexible update mechanisms. The PMC surface of P7 is shown in Figure 2G.

Policy P8 has a PMC-Index of 8.76, rated as "excellent" and ranked 6th. This policy plans for the development of new energy vehicles, excelling in X2, X3, X6, X8, and X9. High scores in X1 (0.83), X5 (0.8), and X7 (0.8) reflect its comprehensiveness. However, a low score in X4 (0.33) indicates deficiencies in flexibility. Future revisions should enhance policy flexibility and response speed. The PMC surface of P8 is shown in Figure 2H.

Policy P9 has a PMC-Index of 8.79, rated as "excellent" and ranked 5th. This policy plans for the high-quality development of the lithium battery industry, excelling in X1, X2, X6, X8, and X9. High scores in X3, X5, and X7 reflect its effectiveness. However, a low score in X4 (0.33) suggests a need for better flexibility. Future revisions should focus on enhancing policy flexibility and response speed. The PMC surface of P9 is shown in Figure 2I.

Policy P10 has a PMC-Index of 9.13, rated as "perfect" and ranked 2nd. This policy provides guidance for the development planning of the lithium battery industry, scoring full marks in seven aspects including X1 Policy Nature, X2, X3, X5, X6, X8, and X9. A high score in X7 (0.8) reflects effective tool application. However, a low score in X4 (0.33) indicates a lack of flexibility. Future revisions should improve timeliness and consider further optimization of policy tools. The PMC surface of P10 is shown in Figure 2J.

Policy P11 has a PMC-Index of 9.47, rated as "perfect" and ranked 1st. This policy provides guidance for the high-quality development of the lithium manufacturing industry, excelling in multiple dimensions including X1 Policy Nature, X2, X3, X5, X6, X8, and X9. Although X4 scores 0.67, the highest among the 12 policies, it still lacks phased planning. Future revisions should enhance phased planning and flexibility. The PMC surface of P11 is shown in Figure 2K.

Policy P12 has a PMC-Index of 8.62, rated as "excellent" and ranked 7th. This policy plans to develop the new energy battery industry, excelling in X2, X6, X8, and X9. High scores in X1, X3, X5, and X7 reflect its comprehensiveness. However, a low score in X4 (0.33) indicates a lack of flexibility. Future revisions should enhance policy flexibility and response speed. The PMC surface of P12 is shown in Figure 2L.

4 Discussion

Building on the PMC index analysis of 12 representative lithium policies in China, detailed in Chapter 3, this section presents the key findings of the study. The analysis indicates that the selected policies are generally effective in achieving their intended outcomes, aligning with previous research that suggests practical implementation considerations have been adequately addressed. This underscores China's strategic focus on sustainable lithium development.

From a regional perspective, the effectiveness of lithium policies varies across different areas in China. For instance, in major lithium-producing regions, policies in Jiangxi and Sichuan provinces are notably effective, while those in Qinghai Province, though slightly less effective, still perform well. In non-major lithium-producing regions, policies in Yunnan and Gansu provinces show strong performance, whereas those in Henan Province and Tibet Autonomous Region are relatively weaker. These regional disparities can be attributed to differences in resource endowment, economic development levels, and industrial structures, influencing policy directions and objectives. Existing studies support this view, noting that resource distribution and regional development levels play significant roles in determining policy efficacy, especially in the lithium sector (Zhou et al., 2020). Effective policy formulation must account for these regional disparities to promote sustainable lithium development.

At the micro-policy level, notable variations exist in policy objectives and targets. Some policies focus on macroeconomic guidance, while others emphasize technological advancements or industrial growth (Kaya, 2022; Xiong et al., 2023). This study, in alignment with existing literature, underscores the need for greater flexibility and targeted objectives in policy design to respond to rapidly evolving market and technological conditions. Achieving sustainable development in the lithium industry requires synergy between policies that emphasize resource recycling, technological innovation, coordinated industrial development, and environmental protection.

The formulation and implementation of policies are influenced by factors such as resource endowment, economic development level, industrial base, policy execution, and public and enterprise involvement. For instance, regions with abundant lithium reserves, like Jiangxi and Sichuan, focus on resource development and efficient utilization, while non-major producing areas may prioritize downstream industry development or technological innovation. Economically developed regions might emphasize high-end industrial chains and innovation, whereas less developed areas might focus on resource development and basic industry growth. Regions with established lithium battery industrial chains tend to have more comprehensive policies, while those with weaker industrial foundations focus on attracting investment and nurturing emerging industries.

Policy implementation varies regionally due to differences in resources, economic conditions, and strategic goals, leading to diverse approaches in execution and effectiveness. Effective policy implementation also depends on public and enterprise engagement, which is often insufficiently emphasized in the policies examined. Factors such as public environmental awareness, corporate innovation capacity, and industry-academia-research collaboration significantly impact policy outcomes. The surge in demand for lithium mines in Yichun, Jiangxi, has encouraged unlicensed mining. A lithium battery company experienced water pollution, yet environmental management failed to adapt swiftly. This aligns with other resource studies, indicating that unrestrained resource extraction often leads to severe ecological damage without adequate environmental protection measures. To prevent similar situations, the following strategies can be implemented: (1) Enhance Environmental Regulation and Real-Time Monitoring; (2) Implement Dynamic Permitting and Penalty Mechanisms; (3) Involve Community Participation and Public Education; (4) Promote Technological Innovation and Resource Recycling; (5) Ensure Cross-Departmental Coordination and Regional Cooperation. These measures aim to manage lithium extraction sustainably and protect local ecosystems.

This study differs from previous research by expanding the scope to include both major and non-major lithium-producing areas in China and employing quantitative evaluations based on the PMC index model. This approach provides an objective assessment of policy effectiveness and considers regional differences in resource endowment, economic development, and industrial foundation. Consequently, this study offers a comprehensive understanding of the challenges in formulating and implementing sustainable lithium development policies and proposes targeted optimization strategies.

5 Conclusion

This study establishes an evaluation index system for China's lithium sustainable development policies, focusing on the themes of sustainable development and the circular economy. The research assesses 12 representative policies from both lithium-producing and non-producing regions in China using the PMC index model, highlighting the importance of these policies in promoting efficient resource utilization and industrial chain development. The evaluation reveals that most policies are effective, with two rated as "excellent," nine as "good," and one as "qualified," reflecting a high average PMC index score of 8.31. This indicates a robust governmental commitment to lithium sustainability, incorporating strategic planning, resource management, technological innovation, and environmental considerations.

However, the study identifies a significant need for improvement in policy timeliness and adaptability. Current policies lack dynamic adjustment mechanisms to respond promptly to industry shifts, technological advancements, and environmental changes. The low scores for policy timeliness suggest the necessity for more flexible and regularly updated policies to cope with market fluctuations and the rapid evolution of technology.

To enhance policy effectiveness, the study proposes the introduction of regular review and dynamic adjustment mechanisms within the policy cycle, supported by big data and artificial intelligence to predict market trends and evaluate policy performance. It also recommends fostering inter-departmental coordination for quicker policy updates and implementing specific financial incentives and regulatory frameworks to accelerate policy adoption and ensure environmental compliance. Additionally, establishing inter-provincial committees could facilitate regional cooperation, ensuring a unified approach to lithium policy across China.

These findings not only address the specific policies evaluated but also reflect broader issues in the formulation of lithium sustainable development policies. The study underscores the importance of addressing these challenges in future policy-making to support the sustainable development of the lithium sector, which is crucial for advancing the new energy industry. The limitations of the study include potential biases in indicator selection and design due to subjective judgments and a limited sample size, which may affect the depth and scope of policy evaluation. Future research should focus on optimizing these indicators and expanding the sample size to enhance the comprehensiveness and accuracy of policy evaluations. Additionally, future research should consider horizontal comparisons and evaluations between different dimensions and cross-sectoral policies to provide more comprehensive policy optimization suggestions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

JG: Conceptualization, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. WL: Conceptualization, Formal Analysis, Investigation, Visualization, Writing–review and editing. MX: Formal Analysis, Software, Visualization, Writing–review and editing. BW: Funding acquisition, Supervision, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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