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Assessing Policy Consistency and Synergy in China's Water–Energy–Land–Food Nexus for Low-Carbon Transition

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Abstract

The need for integrated governance of water–energy–land–food (WELF) systems has become paramount in achieving sustainable low-carbon transitions, yet policy consistency across these interdependent sectors remains critically underexplored. This study presents the first systematic assessment of policy consistency and synergy within China's WELF framework, employing an innovative mixed-methods approach that combines a modified Policy Modeling Consistency (PMC) Index with Content Analysis Methodology (CAM). Policy consistency follows a clear hierarchy: energy (PMC = 9.06, 'Perfect'), water (8.26, 'Good'), land (7.03, 'Acceptable'), and food systems (6.91, 'Acceptable'), with land–food policies exhibiting critical gaps in multifunctional design. Policy synergy metrics further reveal pronounced sectoral disparities: energy (PS = 0.89) and water (0.81) policies demonstrate strong alignment with central government objectives, whereas land (0.68) and food (0.64) systems exhibit constrained integration capacities due to uncoordinated policy architectures and competing sectoral priorities. Building on these findings, we propose three key interventions: (1) institutional restructuring through the establishment of an inter-ministerial coordination body with binding authority to align WELF sector priorities and enforce consistent and synergy targets, (2) the strategic rebalancing of policy instruments by reallocating fiscal incentives toward nexus-optimizing projects while developing innovative market-based mechanisms for cross-sectoral resource exchange, and (3) adaptive governance implementation through regional policy pilots, dynamic feedback systems, and capacity-building networks to enable context-sensitive WELF transitions while maintaining strategic consistency and synergy. These recommendations directly address the structural deficiencies in WELF governance fragmentation and incentive misalignment identified through our rigorous analysis, while simultaneously advancing theoretical discourse and offering implementable policy solutions for achieving integrated low-carbon transition.

Keywords: climate change; environmental governance; low-carbon transition; sustainable development; water; energy; land; food

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1. Introduction

Climate change has emerged as one of the most pressing challenges associated with global sustainability, with far-reaching implications for human survival, economic stability, and ecological resilience [1,2]. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized the urgency of mitigating climate risks, warning that delayed action could exacerbate systemic vulnerabilities [3,4]. Against this backdrop, the United Nations

2030 Agenda for Sustainable Development underscores the necessity of integrated climate strategies, with Sustainable Development Goal (SDG) 13 explicitly advocating for urgent measures to combat climate change [5]. Given the interconnected nature of climate systems, scholars increasingly recognize that low-carbon transitions must be pursued through a nexus approach—one that harmonizes water, energy, land, and food (WELF) systems to avoid unintended trade-offs [6,7]. The issue of integration is particularly important in relation to the effects of the energy crisis and the transformation barriers [8].

As the world's largest carbon emitter, China has committed to a low-carbon transition, aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [9]. To operationalize these goals, China has implemented a broad policy framework targeting WELF sectors, recognizing its critical role in the low-carbon transition. However, while WELF sector-specific policies have proliferated, the consistency and synergy of these policies remain under-explored. The WELF policy consistency is defined as the systematic alignment of policy objectives, regulatory instruments, and implementation mechanisms across different sectors within the WELF nexus. This consistency serves as a fundamental criterion for evaluating the technical robustness of policymaking and predicting its practical effectiveness. Policy synergy, conversely, quantifies the coordination between sectoral WELF policies and central government objectives. A representative example is the alignment between renewable energy targets (e.g., solar PV capacity expansion) and China's central government carbon neutrality commitments. Through policy synergy assessment, two critical dimensions emerge: (1) the identification of inter-sectoral policy gaps; and (2) the predictive evaluation of central government objectives' attainability.

The complexity of achieving such policy consistency and synergy is particularly pronounced in China's multi-level governance system, which involves navigating institutional fragmentation across ministries/provinces and reconciling spatially varied resource endowments. This study's integrated quantitative–qualitative approach (combining the PMC-Index and CAM) is specifically designed to address these challenges through granular policy diagnostics.

Historical evidence suggests that fragmented policymaking can lead to inefficiencies, resource conflicts, and unintended socioeconomic consequences [10,11]. For instance, intensive bioenergy expansion may exert competing pressures on water availability and arable land utilization, while inflexible agricultural land preservation policies could potentially constrain the spatial deployment of renewable energy infrastructure [12]. Furthermore, the circular utilization of renewable resources presents underappreciated synergies for addressing concurrent land use optimization and food security challenges. These interconnections underscore the critical necessity—and growing urgency—of achieving systemic coordination within the water–energy–land–food (WELF) nexus, which would significantly enhance the efficiency and equity of low-carbon transition pathways.

As climate change and the low-carbon transition accelerate, scholars have increasingly recognized the importance of WELF sector-specific policy integration [13,14]. Yet, despite their significance, scholarly research has not systematically assessed the consistency and synergy of these policies. The growing body of research underscores the critical importance of integrated WELF nexus governance for effective low-carbon transitions, while simultaneously revealing persistent challenges in policy formulation, implementation, and assessment across interdependent resource systems [7,13–15]. These findings highlight an urgent need for the systematic assessment of WELF policy consistency and synergy to bridge the gap between the theoretical recognition of nexus approaches and their practical implementation in climate governance frameworks [16,17]. Globally, robust policy consistency and synergy have been shown to enhance governance outcomes, whereas contradictory measures risk stalling progress [18]. Given China's dual role as both a major emitter and the largest developing country, a rigorous assessment of WELF policy consistency and synergy is essential to inform future climate governance.

To address this research gap, this study makes a substantive methodological contribution by deploying an integrated analytical framework that rigorously combines a modified Policy Modeling Consistency (PMC) Index with the Content Analysis Methodology (CAM) to assess the WELF policy consistency and synergy in China's low-carbon transition. The PMC serves as a comprehensive framework for assessing policy consistency and synergy across the water, energy, land, and food (WELF) nexus. It quantifies alignment through a structured evaluation of 10 main variables and 48 sub-variables. While the PMC-Index offers indispensable quantitative insights into policy consistency and synergy, its application within China's multi-tiered governance context necessitates a supplementary qualitative analysis. This is due to the intricate socio-institutional dynamics—such as interdepartmental coordination challenges and localized policy implementation barriers—that quantitative metrics alone may not fully capture. Therefore, our study integrates the CAM to systematically examine sector-specific policy documents. The CAM enables a nuanced textual dissection of policy narratives, uncovering the underlying rationale, stakeholder priorities, and contextual constraints that shape WELF nexus governance in China.

This paper makes three key contributions: (1) Methodologically, we pioneer an integrated analytical framework that combines a modified PMC-Index with the CAM, thereby enabling the first systematic quantification of cross-sectoral policy consistency and synergy in China's WELF systems. This mixed-methods approach overcomes traditional sectoral evaluation limitations by capturing both quantitative scores and qualitative contextual rationales through policy text mining. (2) Theoretically, this research advances nexus governance theory by empirically validating the policy interdependence hypothesis, demonstrating conclusively that inconsistent WELF policies engender suboptimal resource trade-offs that impede the low-carbon transition. Our findings redefine low-carbon transition pathways as multi-dimensional optimization problems that require simultaneous water–energy–land–food coordination, challenging prevailing sectoral low-carbon transition paradigms. (3) Practically, this study provides actionable insights for China's 15th Five-Year Plan by identifying critical WELF policy misalignments, particularly between renewable energy expansion and agricultural land protection. Internationally, our assessment framework offers a replicable tool for Global South nations facing similar nexus governance challenges, directly supporting Sustainable Development Goal (SDG) implementation.

2. Literature Review

The literature review of this study is divided into three aspects: (1) the global low-carbon transition, (2) the water–energy–land–food (WELF) nexus, and (3) the research gaps for WELF policy consistency and synergy.

2.1. Global Low-Carbon Transition: Trends and Challenges

The global low-carbon transition represents a fundamental transformation in energy systems, economic structures, and governance approaches to address climate change [19]. Current scholarship reveals three interconnected dimensions shaping this transition: (1) Policy innovation has accelerated through multilateral agreements and national strategies, with developed economies implementing carbon pricing mechanisms, while emerging economies focus on technology transfer and capacity building [20,21]. The Paris Agreement continues to serve as the primary framework for climate action, although implementation gaps persist between national commitments and concrete policies. (2) Technological progress plays a critical role in the energy and low-carbon transition [22]. Renewable energy technologies have achieved significant cost reductions and efficiency improvements, particularly in solar and wind power generation. Energy storage systems are evolving rapidly, although grid integration challenges remain substantial. Carbon capture and industrial process innovations show promise but face scalability limitations in energy-intensive sectors [23]. (3) Structural barriers complicate the transition across multiple fronts. Developing nations confront energy access dilemmas when balancing climate goals with development needs. Fossil fuel-dependent regions experience labor market disruptions that outpace just transition programs [24,25]. Financial systems struggle to align investment flows with long-term low-carbon transition requirements, particularly in emerging markets.

These challenges highlight the critical importance of multi-domain policy synergies (e.g., water–energy–land–food) in the low-carbon transition [13]. Interdependence within each system creates both vulnerabilities and opportunities. Energy production competes with agricultural needs for water resources, while land use decisions simultaneously affect carbon sequestration potential and food security. Climate-smart agriculture demonstrates how integrated approaches can enhance resilience, yet policy fragmentation often prevents synergistic solutions. The growing frequency of climate extremes further exposes how sectoral planning fails to account for cross-system risks, underscoring the need for nexus-based governance frameworks that can navigate these complex trade-offs in pursuit of a sustainable low-carbon transition [26].

2.2. The WELF Nexus: Interdependencies and Policy Evolution in Low-Carbon Transition

The WELF nexus framework has emerged as a critical paradigm for understanding and governing the complex interdependencies among water, energy, land, and food systems in the context of climate change and sustainable development [7,16]. Unlike traditional sectoral policy approaches, the WELF nexus recognizes that resource management decisions in one domain inevitably influence—and often constrain—outcomes in others. Global rapid low-carbon transition has brought these interdependencies into sharp relief, revealing both innovative policy experiments and persistent governance challenges [13,16,17]. The theoretical foundations of the WELF nexus originated from critiques of siloed resource governance, particularly in climate adaptation and sustainable development scholarship. For example, early frameworks emphasized biophysical linkages where water is required for energy production and irrigation, energy enables water pumping and food processing, and land use dictates both carbon sequestration potential and agricultural yields [27]. Overall, existing research on the WELF nexus can be synthesized into three key dimensions that highlight its critical role in low-carbon transitions.

(1) Resource interdependencies and trade-offs constitute the foundational focus of WELF studies. Scholars have extensively documented how water scarcity constrains energy production while energy-intensive irrigation exacerbates groundwater depletion [28,29]. Similarly, land-use conflicts arise when renewable energy expansion competes with agricultural or ecological conservation priorities, as observed in China's agrivoltaic pilot programs and the EU's biofuel policies [30,31].

(2) Equity and justice dimensions are increasingly prominent in WELF research. The nexus approach exposes how marginalized communities disproportionately bear the costs of fragmented policies, whether through water access disparities near energy projects or livelihood disruptions from land use changes [7]. An increasing number of countries are explicitly linking WELF coherence to climate justice, noting that integrated policies can mitigate vulnerabilities while accelerating the low-carbon transition [15].

(3) Recent scholarship has increasingly focused on the need for policy integration across water, energy, land, and food (WELF) systems to achieve sustainable low-carbon transitions [13]. Studies have highlighted that effective WELF governance requires

breaking down traditional sectoral boundaries and developing coordinated policy frameworks [16]. Theoretical advancements in nexus governance emphasize the need for institutional mechanisms that can reconcile competing resource demands, with case studies demonstrating the benefits of integrated approaches—such as China's pilot programs combining solar energy development with agricultural land use [30], and the EU's cross-sectoral bioenergy policies that account for water and food security impacts [31]. Despite progress, three persistent challenges hinder effective WELF policy integration [14]. First, departmental fragmentation persists, as seen in countries worldwide where water, energy, land, and food policies are developed independently, creating conflicts in resource allocation. Second, implementation gaps remain widespread, exemplified by solar park expansions that overlooked agricultural land use impacts. Third, assessment deficiencies limit progress, with most nations lacking metrics for assessing cross-sectoral policy effects. These challenges underscore the urgency of developing robust integration frameworks to align WELF policies for effective low-carbon transitions.

2.3. Research Gaps for WELF Policy Consistency and Synergy

The current literature extensively analyzes individual WELF policies but has rarely assessed their policy consistency and the extent of their synergy. This gap is critical because inconsistent policies can derail low-carbon transitions by creating resource bottlenecks or inequitable outcomes. To address this issue, our study introduces a novel mixed-methods approach combining a modified PMC-Index and CAM. The PMC-Index quantifies the consistency and synergy of China's WELF policy, while the CAM further explores its contextual rationale behind these two results. This methodology offers two breakthroughs: empirical rigor through standardized cross-policy comparison and nexus governance insights through mapping systemic interactions. The findings will inform China's 15th Five-Year Plan by highlighting WELF misalignments, contribute to SDGs 13 (Climate Action) and 17 (Partnerships) by modeling integrated governance, and provide a replicable framework for other resource-intensive economies. By bridging the consistency and synergy of the WELF policy gap, this research advances both academic discourse and actionable climate governance tools.

3. Methods

This section encompasses two areas: (1) policy collection and (2) the innovative mixed-methods approach that methodologically combines the modified PMC-Index and the CAM.

3.1. Policy Collection

This study employs a comprehensive full-sample policy collection strategy that utilizes three distinct search channels to ensure the complete saturation of China's WELF policy data. Our research systematically identified and analyzed national-level policy documents that collectively constitute China's WELF framework for low-carbon transition. The WELF policy collection protocol comprised three methodologically rigorous phases (Figure 1):

(1) Primary policy identification. We systematically searched official websites of national-level Chinese agencies from September 2020 to December 2024 using an exhaustive set of keywords, including water, energy, land, food, and low-carbon transition. The selected timeframe is of critical analytical significance; it commences with China's landmark announcement of its carbon neutrality pledge at the 75th United Nations General Assembly in September 2020—a pivotal moment that redefined the nation's long-term low-carbon transition trajectory—and concludes in December 2024, by which point the foundational architecture of China's carbon neutrality-aligned low-

carbon transition policy regime had been basically institutionalized. This period represents an entirely new era, developed as China advances toward its 2030 carbon peaking and 2060 carbon neutrality goal, marking the country's most comprehensive and institutionally integrated policy phase of climate governance to date [32]. During this period, China has deployed some of the most systematic and wide-ranging WELF policy frameworks and governance tools for low-carbon transition [26]. This initial sweep established our baseline policy corpus.

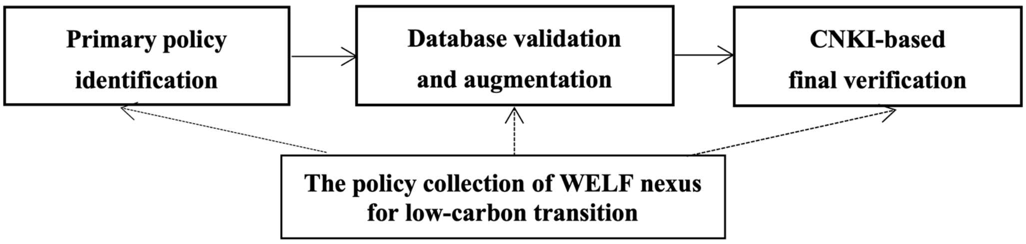

Figure 1. Policy collection process.

(2) Database validation and augmentation. Building upon initial policy identification, we implemented a rigorous validation protocol through systematic queries of official government policy repositories. These authoritative repositories facilitated the cross-validation and supplementation of our dataset. The structured nature of these repositories enabled precise document verification through multiple indexing parameters, thereby ensuring both the accuracy of individual records and the comprehensiveness of the aggregate collection. This phase constituted an essential quality assurance mechanism, methodically addressing potential omissions through institutionalized validation and augmentation procedures.

(3) CNKI-based final verification. To establish definitive data saturation, we executed a final validation cycle utilizing the China National Knowledge Infrastructure (CNKI) platform, the preeminent scholarly database for Chinese policy research [33]. This terminal verification stage served dual purposes: (i) confirming exhaustive coverage of extant WELF policies within our designated temporal scope, and (ii) maintaining rigorous thematic alignment with low-carbon transition objectives through controlled keyword filtering and citation network analysis.

This triangulated methodology not only ensures comprehensive coverage of relevant policies but also provides multiple validation points to guarantee the dataset's reliability and representativeness. The systematic approach addresses potential limitations inherent in single-channel policy research by institutionalizing cross-verification mechanisms that ensure both breadth and depth of coverage.

3.2. Method

This study employs a rigorous mixed-methods approach that combines qualitative and quantitative analytical techniques to systematically examine China's WELF policies. The methodological framework integrates a modified PMC-Index for the quantitative assessment of policy consistency and synergy with the CAM for quantitative research on the contextual rationale behind the results. This dual approach leverages the complementary strengths of both methodologies, thereby enhancing the validity and interpretative power of our findings.

(1) Policy Modeling Consistency (PMC) Index

This research employs the modified PMC-Index methodology to conduct a rigorous quantitative assessment of policy consistency and synergy across China's WELF policies in its low-carbon transition. The PMC framework, originally developed by Estrada (2011) [34], provides a robust analytical tool for assessing policy consistency through the systematic quantification of multidimensional policy characteristics. Beyond traditional applications, we advance the methodology to assess both policy consistency and synergy.

The PMC assessment was conducted through a three-stage methodological framework, building upon established approaches in policy analysis [34–43]. This quantitative tool systematically evaluated policy consistency and synergy within the water–energy–land–food (WELF) nexus by analyzing core variables across multiple policy dimensions.

First, we developed a comprehensive assessment matrix comprising 10 main variables and 48 sub-variables, drawing upon the established PMC literature while incorporating China-specific policy characteristics identified through our analysis (Table 1). This refined variable system captures both universal policy dimensions and China-specific WELF governance and low-carbon transition features, thereby addressing a key limitation in current policy assessment frameworks, which often overlook contextual specificity. For example, building upon existing studies [39,40,43], we systematically integrate policy timeliness as a quantifiable dimension within our analytical matrix. The Chinese governance context empirically demonstrates that durable policy effectiveness necessitates the co-design of immediate-term operational measures with longitudinal strategic frameworks—a temporal synergy phenomenon that is particularly pronounced in transitional economies. Similarly, the comprehensiveness of policy incentive variables (financial subsidies, investment stimulus, tax reduction and exemption, and loan allowance), coupled with broader coverage of policy area variables, serves as a robust indicator of scientific policy design. This multidimensional approach demonstrates a statistically significant positive correlation with projected policy efficacy outcomes, as evidenced by contemporary policy consistency research [39,43].

Table 1. Main variables and sub-variables of WELF policy.

Main Variable	Sub-Variable
X_1: Policy nature	$X_{1:1}$: Description; $X_{1:2}$: Supervision; $X_{1:3}$: Guidance; $X_{1:4}$: Suggestion; $X_{1:5}$: Encouragement; $X_{1:6}$: Specification; $X_{1:7}$: Optimization; $X_{1:8}$: Enhancement; $X_{1:9}$: Refinement
X_2: Policy timeliness	$X_{2:1}$: Long-term (more than 5 years); $X_{2:2}$: Mid-term (3–5 years); $X_{2:3}$: Short-term (1–3 years); $X_{2:4}$: Temporary (less than 1 year)
X_3: Policy release agency	$X_{3:1}$: Central Committee of the Communist Party of China; $X_{3:2}$: State Council; $X_{3:3}$: Ministry of Water Resources; $X_{3:4}$: National Energy Administration; $X_{3:5}$: Ministry of Natural Resources; $X_{3:6}$: Ministry of Agriculture and Rural Affairs; $X_{3:7}$: Other departments
X_4: Policy implementation agency	$X_{4:1}$: State-level ministries and commissions; $X_{4:2}$: Provincial governments; $X_{4:3}$: Municipal governments; $X_{4:4}$: County governments; $X_{4:5}$: Township governments; $X_{4:6}$: Village committees
X_5: Policy incentive	$X_{5:1}$: Financial subsidies; $X_{5:2}$: Investment stimulus; $X_{5:3}$: Tax reduction and exemption; $X_{5:4}$: Loan allowance
X_6: Policy instrument	$X_{6:1}$: Command-and-control instruments; $X_{6:2}$: Market-based instruments; $X_{6:3}$: Voluntary instruments
X_7: Policy support	$X_{7:1}$: Science and technology support; $X_{7:2}$: Information support; $X_{7:3}$: Infrastructure construction; $X_{7:4}$: Financial inputs; $X_{7:5}$: Education and training; $X_{7:6}$: Pilot demonstration and application

Table 1. *Cont.*

Main Variable	Sub-Variable
X_8: Policy area	$X_{8:1}$: Economy; $X_{8:2}$: Society; $X_{8:3}$: Environment; $X_{8:4}$: Politics; $X_{8:5}$: Technology
X_9: Policy object	$X_{9:1}$: Local government; $X_{9:2}$: Enterprise; $X_{9:3}$: Social organization; $X_{9:4}$: Public
X_{10}: Policy usability	No sub-variables

Second, based on the policy variables of WELF, a multi-input–output framework was accordingly created. Sub-variables were quantified dichotomously: if a policy addressed a sub-variable, it was coded as 1; otherwise, it was coded as 0.

Third, the calculation of policy consistency and synergy could be divided into five steps (A–E) as follows:

Step A: Sub-variables identified in the prior step were assigned binary values. According to Equations (1) and (2), if a sub-variable appears in the policy text, it is encoded as 1; otherwise, it is set as 0.

Step B: The values of each main variable were calculated separately according to Equation (3), taking values between 0 and 1, where X_i is the main variable and X_{ij} is the sub-variable.

Step C: The PMC-Index values for assessing the water–energy–land–food (WELF) sectors were calculated according to Equation (4) on a scale of 0–10. The PMC-Index classifies policy consistency into four tiers: Low (0–4.99), Acceptable (5.00–6.99), Good (7.00–8.99), and Perfect (9.00–10.00).

Step D: The PMC surface is graphically constructed using MATLAB R2024a based on Equation (5), enabling the visualization of policy consistency patterns across WELF sectors.

Step E: The policy synergy assessment builds upon Equation (4) through a three-step analytical framework:

① Policy synergy breadth (K_e) is a quantitative metric that evaluates the alignment between sector-specific policies in the WELF nexus and central government objectives. It is calculated by calculating the ratio of the sum of the highest sub-variable values under each main variable within a sector to the corresponding central government benchmark score. In other words, it quantifies the extent of synergy across WELF policies by calculating the ratio between the sum of the maximum sub-variable values ($Xepi : j$) for each main variable for sector-specific policies (e.g., energy policies like the National Energy Administration's 14th Five-Year Plan for Modern Energy Systems) and the corresponding values in central government policies ($Xcpi : j$), such as the Guidelines on Accelerating Comprehensive Green Transformation of Economic and Social Development, as described in Equation (6).

② Policy synergy intensity (L_e) quantifies the alignment depth between sectoral policies in the WELF nexus and central government objectives. This index is derived by computing the ratio of the total sum of all sub-variable values within a sector's policy framework to the corresponding central government benchmark score, thereby capturing comprehensive policy integration through full-spectrum sub-variable accumulation, per Equation (7).

③ The composite policy synergy degree (S_e) is derived by multiplying the breadth (K_e) and intensity (L_e), per Equation (8).

In these three formulas, X denotes the variables that comprise the PMC-Index. The subscript e represents sector-specific policies pertaining to water, energy, land, or food systems, as exemplified by the 14th Five-Year Plan for Modern Energy Systems issued by the

National Energy Administration in January 2022. The subscript c designates general policies issued by the central government, such as the Guidelines on Accelerating Comprehensive Green Transformation of Economic and Social Development, which was jointly released by the Central Committee of the Communist Party of China and the State Council in July 2024. The notation p refers to a single policy in one of the categories of policies in e. Additionally, i and j are the numbers of the main variables and sub-variables within the PMC assessment structure, respectively.

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

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

$$X_i\left[\sum_{j=1}^{n} \frac{X_{ij}}{T(X_{ij})}\right] \tag{3}$$

$$PMC - Index = \sum_{i=1}^{m}\left(X_i\left[\sum_{j=1}^{n} \frac{X_{ij}}{T(X_{ij})}\right]\right) = \left[X_1\left(\sum_{j=1}^{9} \frac{X_{1j}}{9}\right) + X_2\left(\sum_{j=1}^{4} \frac{X_{2j}}{4}\right) + X_3\left(\sum_{j=1}^{7} \frac{X_{3j}}{7}\right) + X_4\left(\sum_{j=1}^{5} \frac{X_{4j}}{5}\right) + X_5\left(\sum_{j=1}^{4} \frac{X_{5j}}{4}\right) + X_6\left(\sum_{j=1}^{3} \frac{X_{6j}}{3}\right) + X_7\left(\sum_{j=1}^{6} \frac{X_{7j}}{6}\right) + X_8\left(\sum_{j=1}^{5} \frac{X_{8j}}{5}\right) + X_9\left(\sum_{j=1}^{4} \frac{X_{9j}}{4}\right) + X_{10}\right] \tag{4}$$

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

$$K_e = \frac{\sum i : jmax_p(Xepi : j)}{\sum i : jmax_p(Xcpi : j)} \tag{6}$$

$$L_e = \frac{\sum i : j\sum_p Xepi : j}{\sum i : j\sum_p Xcpi : j} \tag{7}$$

$$S_e = K_e \times L_e \tag{8}$$

This study breaks new ground in policy assessment methodology through its development of an integrated analytical framework that simultaneously assesses two critical dimensions of China's low-carbon governance: policy consistency and policy synergy. The framework's key innovation lies in its dual analytical approach, which combines conventional PMC-Index-based consistency measurement with the novel quantification of policy synergy, thereby addressing a significant gap in current research. Through a systematic comparison between sector-specific water–energy–land–food (WELF) policies and overarching central government objectives, our methodology achieves three important analytical advances: (1) it precisely measures the implementation fidelity of WELF policies in relation to national strategic objectives; (2) it identifies and quantifies inter-sectoral alignment or divergence in policy approaches; and (3) it reveals systematic variations in policy design across different low-carbon transition pathways. This comprehensive assessment provides unprecedented insights into China's complex, multi-level governance system, demonstrating how policy instruments are differentially deployed across sectors while maintaining overall strategic coherence.

(2) Content Analysis Methodology (CAM)

Based on the PMC-Index model research results, this study adopted the content analysis method for more in-depth analysis. The CAM offers distinct advantages for policy analysis, particularly in examining complex, multi-sectoral governance systems like China's WELF framework. The method's analytical power stems from its rigorous approach to extracting and systematizing complex policy information while maintaining nuanced contextual understanding, allowing researchers to uncover latent patterns, evolving trends, and critical interrelationships within policy frameworks [44,45]. This method has been widely applied in environmental policy research, from analyzing climate change strategies to assessing green growth policies, demonstrating its versatility in handling diverse policy documents such as legislation, white papers, and implementation guidelines [46,47]. CAM's unique capacity to bridge qualitative interpretation with quantitative validation makes it particularly valuable for cross-policy comparisons, as it can simultaneously assess both manifest content (explicit policy elements) and latent content (underlying governance paradigms) within and across policy domains [48].

In this study, CAM serves two critical functions: (1) it provides in-depth explanatory power to complement the PMC-Index results by revealing the contextual mechanisms behind high or low policy consistency and synergy scores through the systematic analysis of the WELF framework, and (2) it identifies emergent governance patterns by analyzing the evolution of policy discourse from 2020 to 2024, particularly in terms of how WELF sectors conceptualize and operationalize their roles in China's low-carbon transition. This approach ensures a comprehensive analysis of both the technical specifications and the underlying governance philosophies that shape China's WELF policy landscape, offering novel insights into how policy consistency and synergy evolve in practice during critical phases of low-carbon transition. The findings not only explain the quantitative PMC-Index results but also reveal previously undocumented patterns of policy integration (or fragmentation) that have significant implications for China and other countries.

4. Results

The findings of this study are divided into two primary areas: (1) policy consistency and (2) the policy synergy of WELF governance in China's low-carbon transition.

4.1. Policy Consistency of WELF Nexus

This section presents a rigorous analysis of policy consistency metrics across both sectoral and variable dimensions within the WELF nexus framework.

(1) Sectoral analysis of policy consistency

The calculated PMC-Index scores reveal substantial variation across sector-specific water–energy–land–food (WELF) policies (Table 2 and Figure 2).

Table 2. Policy consistency of the WELF nexus.

Item	Water	Energy	Land	Food	Overall
Policy nature	0.83	0.87	0.52	0.56	0.69
Policy timeliness	0.87	0.96	0.63	0.51	0.74
Policy release agency	0.72	0.94	0.59	0.62	0.72
Policy implementation agency	0.68	0.87	0.63	0.69	0.72
Policy incentive	0.87	0.93	0.71	0.81	0.83
Policy instrument	0.82	0.92	0.69	0.63	0.77
Policy support	0.85	0.84	0.73	0.65	0.77
Policy area	0.83	0.91	0.72	0.76	0.81
Policy object	0.79	0.82	0.81	0.68	0.78
Policy usability	1.00	1.00	1.00	1.00	1.00
PMC-Index	8.26	9.06	7.03	6.91	7.82
Ranking	2	1	4	3	/

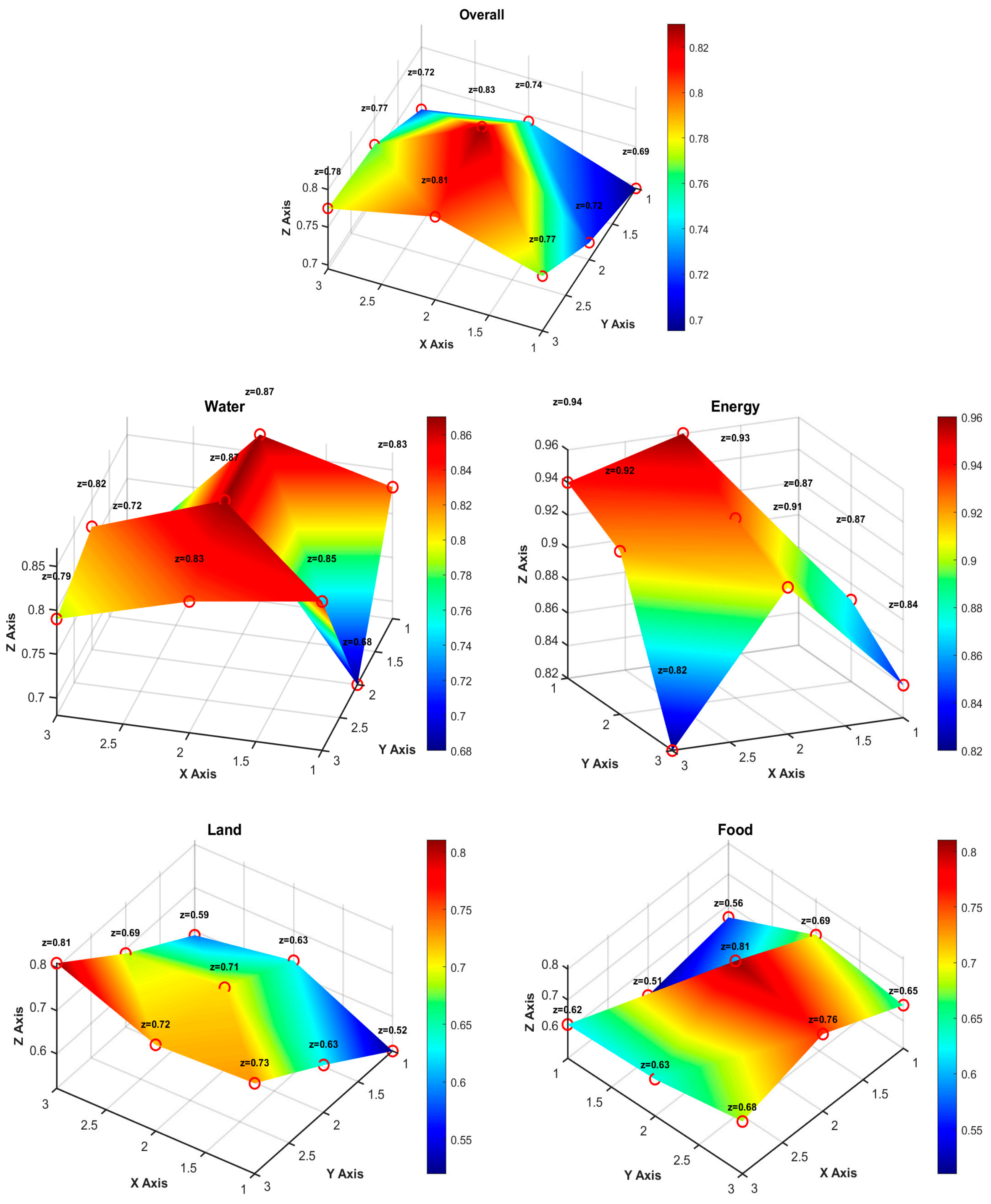

Figure 2. PMC surface of WELF policies.

The energy sector achieves a near-perfect score of 9.06, ranking first and falling within the perfect consistency tier (9.00–10.00). This exceptional performance reflects China's strategic prioritization of energy transition, as evidenced by comprehensive policy frameworks such as the 14th Five-Year Plan for Modern Energy Systems, which integrates renewable deployment, grid modernization, and carbon pricing. Energy transition policies demonstrate the most sophisticated integration of climate objectives, reflecting both their centrality to emissions reduction targets and the relative clarity of technological pathways.

The water sector follows with a score of 8.26 (good consistency), demonstrating robust governance in irrigation efficiency and hydropower management, although there is limited synergy with energy or land policies [49]. Water policies show substantial but incomplete alignment with low-carbon transition needs, while land use and, particularly, food system policies reveal the greatest policy development gaps—a pattern that corresponds with the increasing complexity of integrating climate objectives into these multifunctional systems.

As shown in Table 2, the land (7.03) and food (6.91) sectors score markedly lower than the other sectors, with both classified as acceptable consistency. Land policies, while addressing ecological redlines [30], lack incentives for multifunctional land use, whereas food policies remain narrowly focused on production targets, neglecting linkages to energy inputs or land use trade-offs.

The land and food sectors' lower PMC-Index scores reveal persistent governance fragmentation, particularly in addressing cross-sectoral interdependencies—a critical gap given land's fundamental role in both renewable energy deployment and agricultural production systems, as well as food security's inherent connections to water resources and energy inputs for irrigation and processing. This disparity suggests that while China has made significant progress in developing coherent policies for energy and water systems, the governance frameworks for land use planning and agricultural transformation remain comparatively underdeveloped in terms of policy integration and consistency.

Through CAM, we conducted further in-depth analyses of WELF's policy text and found clear differences and challenges for land and food: (1) limited incorporation of nexus considerations in policy design, (2) weaker institutional coordination mechanisms compared to energy and water governance, and (3) fewer policy instruments available to address trade-offs with other WELF sectors. For instance, only 70% of land use policies explicitly incorporate sustainable development considerations, whereas a concerning 20% of food security policies fail to adequately address low-carbon transition requirements. This disparity in policy integration highlights significant sectoral differences in China's approach to nexus governance, with land–food planning demonstrating lower alignment with sustainability objectives compared to energy and water policy frameworks. These findings align with recent studies that document the policy gaps in China's agri-food system's low-carbon transition [29] and renewable energy siting conflicts [30].

(2) Policy variable analysis: Strengths and gaps

The assessment of 10 policy variables further elucidates governance dynamics. Policy incentives (0.83) emerge as the most robust dimension, dominated by financial subsidies ($X_{5:1}$) and tax reduction and exemptions ($X_{5:3}$), which collectively account for 78% of incentive measures identified using the CAM. This reflects China's reliance on fiscal tools to accelerate renewable energy adoption and water sustainability. However, policy nature (0.69) scores lowest, exposing rigidity in policy design. Over 60% of WELF policies are descriptive ($X_{1:1}$) or supervisory ($X_{1:2}$), while proactive instruments like encouragement ($X_{1:5}$) and optimization ($X_{1:7}$) constitute less than 20%. Such a skew toward compliance-oriented measures—particularly in land and food policies—limits the adaptive capacity to address nexus trade-offs. For instance, rigid agricultural land protections often conflict with renewable energy siting, yet few policies explicitly optimize these trade-offs. This underscores a systemic gap: China's WELF framework excels in fiscal mobilization but lacks nuanced, cross-sectoral governance innovations to reconcile competing resource demands.

4.2. Policy Synergy of WELF Nexus

The analysis of policy synergy across WELF sectors reveals a clear hierarchy in their alignment with China's central government's low-carbon transition objectives. As presented in Table 3, energy policies demonstrate the strongest synergy (PS = 0.89), followed by water (PS = 0.81), land (PS = 0.68), and food (PS = 0.64). This ranking reflects the strategic prioritization of the energy system's low-carbon transition in China's climate governance framework, in which comprehensive policy instruments and binding targets have been effectively implemented. The high synergy scores for energy and water sectors indicate the successful integration of these domains into the national low-carbon strategy, while the comparatively lower scores for land and food policies highlight persistent challenges in achieving cross-sectoral coordination. The policy synergy breadth (PSB) and intensity (PSI) metrics further illuminate these patterns—energy and water policies exhibit both broad coverage and strong implementation mechanisms, whereas land and food policies show narrower scope and weaker enforcement. These findings underscore the varying degrees of institutional maturity across WELF sectors in addressing nexus challenges, with energy leading as the most coherently governed domain.

Table 3. Policy synergy of the WELF nexus.

Item	Policy Synergy Breadth (*Ke*)	Policy Synergy Intensity (*Le*)	Policy Synergy (*Se*)
Water	0.89	0.91	0.81
Energy	0.93	0.96	0.89
Land	0.82	0.83	0.68
Food	0.81	0.79	0.64

Energy policies achieve exceptional synergy (PS = 0.89), supported by high scores in both breadth (PSB = 0.93) and intensity (PSI = 0.96). The PSB results confirm that energy sector policies comprehensively address low-carbon transition objectives, spanning renewable energy deployment, fossil fuel phase-down, and grid modernization. The remarkable PSI score reflects the sector's robust implementation framework, characterized by binding targets (e.g., renewable portfolio standards), market-based instruments (e.g., carbon trading), and stringent compliance mechanisms. For instance, the 14th Five-Year Plan for Energy integrates quantifiable decarbonization metrics across all sub-sectors, ensuring alignment with national carbon peaking goals. However, regional disparities persist, with coastal provinces outperforming inland regions in policy enforcement—a pattern that is consistent with scholars' findings on uneven energy transition progress [33].

Water policies demonstrate substantial synergy (PS = 0.81), with strong performance in both breadth (PSB = 0.89) and intensity (PSI = 0.91). The PSB analysis reveals that nearly 90% of water-related policies explicitly reference low-carbon transition objectives, particularly in areas like hydropower development, irrigation efficiency, and water-saving technologies. The high PSI score indicates effective operationalization, with clear performance indicators (e.g., water use efficiency targets per industrial output) and inter-ministerial coordination mechanisms. The National Water-Saving Action Plan (2022) exemplifies this synergy, combining water resource management with energy conservation requirements. Nevertheless, challenges remain in addressing water–energy trade-offs, such as thermal power plant cooling demands, where policy coordination remains reactive rather than proactive.

Land policies show moderate synergy (PS = 0.68), with acceptable breadth (PSB = 0.82) but weaker intensity (PSI = 0.83). While land use policies increasingly incorporate low-carbon considerations (e.g., ecological redlines protecting carbon sinks), implementation consistency varies significantly. The PSB results indicate that 82% of land policies acknowledge climate objectives, but PSI's lower score reveals gaps in enforcement, particularly in balancing renewable energy expansion with agricultural land preservation. Pilot programs like agrivoltaics demonstrate successful integration, but urban development projects often neglect carbon impact assessments. These inconsistencies mirror global challenges in land use governance and highlight the need for standardized carbon accounting in spatial planning.

Food policies exhibit the lowest synergy (PS = 0.64), constrained by limited breadth (PSB = 0.81) and intensity (PSI = 0.79). Although food security policies increasingly reference sustainability (e.g., methane reduction in rice cultivation), only 64% demonstrate substantive alignment with low-carbon transition goals. The PSI analysis reveals implementation gaps—while fertilizer efficiency standards exist, they lack integration with renewable energy adoption in agricultural production. This sector's underperformance signals untapped potential in linking food systems with low-carbon transition principles, particularly through policy instruments that incentivize cross-sectoral innovation. Fortunately, the Guiding Opinions on Accelerating Comprehensive Green Transformation of Agricultural Development and Promoting Rural Ecological Revitalisation (2024) demonstrate that the agricultural sector is gradually increasing its attention to the low-carbon transition in the food production process; however, the subsequent effectiveness of the implementation also requires further attention.

5. Discussion and Implications

This section examines three critical aspects of this study: (1) policy consistency in China's WELF governance; (2) synergy gaps and transition approaches; and (3) operational challenges and institutional innovations in the WELF nexus.

5.1. Policy Consistency in China's WELF Governance

The evaluation of China's WELF policy framework reveals structural inconsistencies that potentially compromise the nation's low-carbon transition. A cross-sectoral analysis identifies marked variations in policy consistency, with energy and water sectors demonstrating relatively stronger alignment compared to the apparent fragmentation observed in land and agricultural policies. This structural imbalance becomes particularly significant when contextualized within China's carbon neutrality commitments and the fundamental importance of integrated resource governance. Extensive interviews with government officials corroborate these findings, revealing a distinct policy prioritization of energy transition and water sustainability. This focus, however, appears to have inadvertently marginalized the urgency of strengthening policy design and implementation for land–food systems at subnational levels. This study further uncovers inherent tensions between immediate energy objectives and long-term agricultural conservation priorities [50], exemplified by recurrent contradictions between provincial renewable energy directives and national farmland protection mandates. These findings resonate with broader scholarly observations regarding governance fragmentation in many developing economies' WELF nexus approaches [51], underscoring the necessity for both academic research and practical policy interventions to address these critical inter-sectoral disconnects.

This study makes substantial contributions to institutional theory by providing empirical evidence of how bureaucratic silos perpetuate policy misalignment in complex governance systems [52]. While this phenomenon has been theoretically discussed, our quantitative approach offers novel insights into its measurable impacts. The modified PMC-Index constitutes a significant methodological advancement by incorporating new nexus-specific variables that capture resource interdependencies and policy synergy previously overlooked in policy assessment [53]. Our most substantial theoretical contribution emerges from the identification and rigorous documentation of what scholars term the 'policy feedback loop' phenomenon [54]. This mechanism operates via a self-reinforcing cycle wherein inconsistent policy incentives systematically strengthen path dependencies within China's low-carbon transition framework. Our findings empirically challenge the dominant techno-optimist paradigm [55] that has long maintained that technological innovation alone can sufficiently address the complex interdependencies within nexus systems.

5.2. Synergy Gaps and Transition Approaches

The synergy analysis reveals even more pronounced challenges in China's WELF governance. While energy–water policies demonstrate relatively high synergy, reflecting China's historical focus on energy transition and water sustainability, the land and food systems reveal significant disconnects within China's low-carbon transition [15]. A content analysis identifies systemic barriers, including coordination deficits, where most policies lack binding mechanisms for inter-sectoral coordination, creating governance loopholes. Local implementation biases emerge when county-level governments overwhelmingly prioritize energy targets over ecological conservation, with most local plans emphasizing renewable energy quotas while neglecting associated land and food impacts. Equity blind spots are also concerning, with few policy documents referencing distributional impacts and just transition, exacerbating rural–urban disparities, especially in western China, where large-scale renewable projects have led to the involuntary resettlement of residents without adequate compensation, while simultaneously reducing available agricultural land for agricultural production [56].

The pronounced synergy gaps in land and food policies stem from structural misalignments in policy design and implementation. At the instrument level, food policies remain dominated by production-oriented targets (e.g., yield quotas and subsidy schemes), with only 12% explicitly incorporating low-carbon transition requirements—a stark contrast to energy policies, where 89% integrate cross-sectoral considerations. This reflects a persistent 'siloed' approach in agricultural governance, where agriculture's performance metrics prioritize short-term output over systemic resource optimization (e.g., renewable energy adoption in irrigation or soil carbon sequestration). Similarly, land use policies exhibit institutional path dependence, favoring rigid zoning regulations but lacking adaptive mechanisms to reconcile competing demands, such as agrivoltaic integration or carbon farming incentives. These gaps mirror global challenges observed in the EU's Common Agricultural Policy reforms, where an initial emphasis on production targets later required corrective market-based instruments [57]. To address this issue, China's policy toolkit requires rebalancing: shifting from standalone production mandates (e.g., grain storage subsidies) to nexus-optimizing instruments (e.g., conditional subsidies linking fertilizer use to renewable energy adoption), as demonstrated experimentally in Brazil's ABC Program and India's PM-KUSUM initiatives [58–60].

Empirical evidence from Brazil's ABC Program and India's PM-KUSUM initiative illustrates that integrated agro-energy systems can effectively balance agricultural productivity with low-carbon transition objectives. Institutional coordination between agricultural and energy authorities should prioritize the development of integrated agro-energy systems, combining distributed renewables (e.g., agrivoltaics), precision irrigation, and soil carbon enhancement techniques, through mandatory technology bundling in subsidy schemes and unified certification systems. Spatial optimization tools can identify priority zones for synergistic deployment while protecting ecologically sensitive areas, directly addressing the PMC-Index-revealed disparity between energy and food systems. Fiscal mechanisms must be realigned to incentivize synergistic outcomes, including Nexus Performance Bonds that condition subsidies on achieving both energy generation and crop yield targets and cross-sectoral carbon credits that allow farmers to monetize emission reductions through China's ETS. These measures operationalize the inter-ministerial coordination, creating enforceable pathways to overcome the policy fragmentation identified in our PMC-Index analysis while scaling proven nexus approaches from international best practices.

These findings on WELF synergy advance three critical theoretical frontiers in nexus governance research. First, they theoretically advance nexus governance by quantitatively establishing how temporal mismatches between short-term economic targets and long-term sustainability goals amplify synergy gaps—a dimension that has been largely overlooked in prior nexus governance research [6,61]. Second, this study provides robust empirical support for political ecology frameworks by demonstrating how short-term economic pressures systematically distort WELF prioritization in the policy process. Third, our justice-oriented analysis bridges environmental justice scholarship with nexus governance literature by demonstrating how policy inconsistencies disproportionately affect marginalized groups, providing crucial empirical evidence for emerging debates about just transitions in emerging economies [7,33,62].

5.3. Operational Challenges and Institutional Innovations in WELF Nexus

In the Chinese context, the WELF policy implementation also exhibits operational challenges where high-consistency policies often face greater local execution barriers than their lower-scoring counterparts. The energy sector's top-ranked policy consistency masks significant regional enforcement divides, with coastal provinces demonstrating strong renewable energy adoption, while traditional coal-dependent regions struggle with transitional lock-in effects [28]. Conversely, water policies have achieved more uniform implementation through innovative institutional mechanisms like the River Chief system, which establishes clear cross-jurisdictional accountability frameworks [49]. These challenges underscore that effective policy implementation requires not only coherent design but also institutional innovations that accommodate local resource endowments and economic path dependencies.

The land–food nexus also presents implementation challenges due to competing sectoral priorities [15]. While national policies aim for multifunctional land use, local governments frequently face zero-sum choices between renewable energy deployment and agricultural preservation. Certain regions have developed creative solutions, such as agrivoltaic systems that layer solar generation with crop production, but these remain exceptions rather than the norm [30]. Food security policies exhibit similar tensions, where rigid production targets sometimes exacerbate water stress in arid regions, although pioneering provinces have begun experimenting with adaptive allocation systems that balance grain output with sustainable water use [28]. These cases underscore how standardized national policies often fail to account for critical nexus trade-offs at the implementation level.

These challenges related to policy design–implementation disparities generate three evidence-based recommendations for bridging China's low-carbon transition divides and advancing global WELF governance paradigms.

(1) Priority alignment and institutional restructuring. The pronounced disparities in policy consistency and synergy scores necessitate targeted governance reforms and resource reallocation. For the lagging land and food sectors, we recommend establishing dedicated cross-ministerial task forces under the National Development and Reform Commission (NDRC) to develop integrated policy frameworks. These should specifically address the reconciliation of agricultural land protection with renewable energy deployment targets through standardized monitoring systems that track key consistency indicators. Financial allocations should prioritize three areas: (a) precision agriculture technologies to enhance productivity while reducing emissions; (b) sustainable land use planning systems that incorporate renewable energy compatibility assessments; and (c) food supply chain low-carbon transition programs that focus on production, processing, and distribution. This institutional realignment should preserve the successful consistency mechanisms observed in energy policy (particularly binding targets and market instruments) while adapting them to sector-specific contexts through pilot programs in key agricultural regions.

(2) Instrument rebalancing through policy innovation. The synergy analysis reveals substantial potential for cross-sectoral policy instrument transfer. Four specific inter-

ventions are proposed: (a) regulatory enhancements should introduce new land use zoning laws that incorporate renewable energy compatibility assessments, drawing lessons from the EU's renewable energy directive; (b) market mechanisms require expansion, including extending carbon pricing to agricultural emissions and establishing water right trading systems that account for energy–water interdependencies; (c) voluntary measures should be strengthened through sector-specific certification schemes for low-carbon food production and solar–agriculture symbiosis systems; (d) implementation should be supported by digital technologies, such as blockchain-based traceability systems to monitor cross-sectoral policy impacts in real-time. These innovations should be phased in through regional pilots before national rollout, with particular attention to addressing equity concerns for smallholder farmers.

(3) Adaptive governance mechanisms for context-sensitive implementation. Effective low-carbon transitions require policy architectures that are not only internally consistent but also institutionally adaptable to diverse local conditions and evolving WELF dynamics. We propose establishing adaptive governance mechanisms that integrate regional policy demonstration zones (piloting context-specific WELF models in ecologically diverse regions), dynamic feedback systems (institutionalizing iterative policy reviews informed by PMC-Index metrics), and capacity-building networks (facilitating cross-regional knowledge sharing, particularly for lagging food/land sectors). This approach would institutionalize flexibility while maintaining strategic coherence, directly addressing the 'one-size-fits-all' limitations identified in our PMC-Index analysis (where land and food policies scored lowest) and operationalizing the participatory governance principles demonstrated in successful WELF planning pilots. By embedding adaptability into nexus governance structures, this recommendation complements the institutional restructuring and instrument rebalancing proposals while responding to the IPCC's urgent call for integrated, context-sensitive climate solutions.

6. Conclusions

This study provides the first systematic assessment of water–energy–land–food (WELF) policy consistency and synergy in China's low-carbon transition through a modified PMC-Index and Content Analysis Methodology.

The PMC-Index reveals a clear hierarchy in policy consistency across WELF sectors, with energy policies demonstrating the highest coherence (PMC-Index = 9.06), followed by water (8.26), land (7.03), and food policies (6.91). This ranking reflects China's strategic prioritization of the energy system's low-carbon transition, where comprehensive policy instruments and binding targets have been effectively implemented. The energy sector's near-perfect score stems from its sophisticated integration of climate objectives through renewable deployment, grid modernization, and carbon pricing mechanisms. In contrast, the land and food sectors' lower score indicates persistent governance fragmentation, particularly in addressing cross-sectoral interdependencies in the WELF nexus.

The synergy analysis shows parallel sectoral variations, with energy policies again leading (PS = 0.89), followed by water (0.81), land (0.68), and food policies (0.64). This consistency in rankings between internal policy coherence and external alignment suggests that well-structured sectoral policies are more likely to achieve effective integration with national strategic objectives. The energy sector's exceptional performance confirms that its policies comprehensively address low-carbon transition objectives through robust implementation frameworks that feature binding targets and market-based instruments; conversely, food policies' underperformance signals untapped potential in linking agricultural systems with low-carbon transition principles.

Our analysis yield these principal findings that advance both theoretical understanding and practical governance approaches. The global relevance of our analytical framework offers a replicable template for other emerging economies facing similar WELF challenges, particularly in Southeast Asia and Latin America, where rapid development often occurs at the expense of resource sustainability. The methodology's adaptability allows for context-specific modifications while maintaining comparative analytical rigor, making it valuable for cross-national policy learning.

Future research should focus on two key areas to build on these findings: first, exploring the political economy dimensions of WELF governance to better understand the power dynamics and vested interests that influence policy consistency, and second, developing dynamic modeling tools to simulate policy cascade effects across different temporal and spatial scales that would significantly enhance our ability to anticipate and mitigate unintended consequences of resource policies. These advances are critical for supporting evidence-based policymaking in an era of increasing resource constraints and climate uncertainty.

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