Index System of Evaluation of Rural Eco-Environmental Quality: A Review

Ge Yu[1,*], Kim Dirks[1], and Priyanka Dhopade[2]

[1]Civil and Environmental Engineering, Faculty of Engineering and Design, University of Auckland, Auckland, New Zealand
[2]Mechanical and Mechatronics Engineering, Faculty of Engineering and Design, University of Auckland, Auckland, New Zealand
Email: gyu431@aucklanduni.ac.nz (G.Y.); k.dirks@auckland.ac.nz (K.D.); priyanka.dhopade@auckland.ac.nz (P.D.)
*Corresponding author

Manuscript received September 22, 2025; revised November 3, 2025; accepted December 22, 2025; published April 7, 2026

***Abstract*—Compared to urban ecosystems, rural eco-environmental conditions have received relatively little attention from experts and scholars. However, evaluating rural eco-environmental quality serves as a crucial component and scientific basis for promoting sustainable ecological development. It facilitates a deeper understanding of the actual state of rural eco-environments, thereby providing scientific support for precise management by administrative departments, holding practical significance for advancing urbanization. This paper summarizes recent research progress in rural eco-environmental quality evaluation, covering aspects such as indicator systems, evaluation methods, and development prospects. It also provides recommendations for constructing an indicator system for rural eco-environmental quality evaluation. From 2001 to August 2025, 556 key articles indexed in SCI and SSCI were systematically reviewed to examine the development of rural eco-environmental quality evaluation methods. The results show that, influenced by domestic policy orientations, most case studies have been concentrated in China and focus primarily on understanding ecological functions, with limited integration of spatiotemporal and multi-dimensional analysis. To address these limitations, this study proposes a rural-oriented eco-environmental quality evaluation framework that adopts a comprehensive weighting strategy combining both objective and subjective methods, and leverages dynamic, spatially explicit indices such as the Remote Sensing Ecological Index (RSEI) to meet the demands of precise rural management. The application of this framework enhances the comprehensiveness of eco-environmental quality evaluation, yielding more actionable insights to inform rural planning and policy decisions.**

***Keywords*—rural ecological environment, eco-environmental quality evaluation, eco-environmental index**

I. Introduction

A sound ecological environment is a fundamental condition for human survival and development. Ecological environmental evaluation serves as a prerequisite for environmental protection and the promotion of sustainable human societal development. Since the 20th century, with population growth and increasing levels of social industrialization, the scope and intensity of human activities have expanded unprecedentedly. The natural world is increasingly bearing the imprint of human actions, and the contradictions between population growth, resource use, and environmental degradation have become increasingly acute. Ecological and environmental issues, such as desertification and soil erosion, have become increasingly prominent, posing a severe threat to human survival and development.

To address these challenges, humanity requires a deeper understanding of the structure, functions, and processes of the ecological environment. Rural eco-environmental systems, as socio-economic-natural compound ecosystems comprising townships and villages, necessitate indicator systems that integrate both static and dynamic metrics to reflect developmental trends [1]. The rural ecological environment is characterized by greater heterogeneity and fragmentation, as reflected in significant differences in natural conditions, land-use patterns, and socio-economic activities. However, urban-oriented eco-environmental evaluation models often fail to capture these unique interactions in rural contexts [2].

Currently, a series of theoretical and methodological studies on rural eco-environmental quality evaluations has been carried out across the globe [3–6]. However, the data sources, evaluation index systems, and evaluation methods vary due to the differences in research regions, research scales, and thematic focuses. Based on existing studies, this paper analyzes and summarizes the connotations, evaluation indicator systems, and assessment methods for rural eco-environmental quality, providing perspectives on current limitations, including incomplete evaluation frameworks, single-dimensional indicators, and the insufficient adaptability of existing approaches. To address these issues, this study proposes a rural-oriented eco-environmental quality evaluation framework that integrates ecological, economic, and human-disturbance indicators, combines subjective and objective weighting, and employs spatial tools such as the Remote Sensing Ecological Index (RSEI) and Geographic Information System (GIS) for dynamic, fine-scale evaluation. These features provide a more comprehensive and rural-specific framework than current models, offering scientific support for local governments in implementing precise rural management.

II. Characteristics of Rural Eco-Environmental Evaluation

From a methodological perspective, ecological environment evaluation can generally be divided into two categories: qualitative methods and quantitative methods, each with distinct characteristics. Among them, qualitative methods are currently more widely applied in ecological environment assessments, as they are relatively simple to implement and easy to master. However, because the outcomes of qualitative assessments are influenced by the subjective judgments of decision-makers, their accuracy may not be guaranteed. In contrast, quantitative methods can provide more objective and reliable results in eco-environmental quality evaluation, although they may be constrained by data availability and the limitations of mathematical models. Nonetheless, quantitative approaches represent an important trend for the future development of ecological environment evaluation [7].

Currently, most academic studies have focused on ecology and the environment [8–11], and mostly on specific areas such as wetlands [12], river basins [13], islands [14], forests [15], and cities [16], with little attention paid to changes in the eco-environmental quality of rural areas. However, various forms of environmental pollution and ecological destruction are on the rise, with pollution emissions from township enterprises becoming increasingly prominent and the scope of ecological deterioration continuously expanding [17]. Most townships are unable to accurately assess the quality of their ecological environment due to poor environmental monitoring equipment and a lack of professional expertise. Moreover, environmental regulatory authorities often face difficulties in effectively overseeing environmental conditions at the township level, which hinders the implementation of environmental protection work in the region and poses a serious threat to public health and sustainable economic development [7].

Compared to eco-environmental quality evaluations in larger regions such as cities, provinces, and river basins, specialized research on rural eco-environmental quality monitoring and evaluation remains relatively scarce. Many relevant technologies and studies still rely on evaluation models designed for urban areas, rendering them unsuitable for assessing rural eco-environmental quality [2]. Moreover, environmental pollution has become one of the primary factors affecting human health. Due to differences in industrial structures and patterns of production and daily life, pollution sources and the severity of pollution vary across regions, calling for a comprehensive, rational, and targeted evaluation indicator system. Therefore, when evaluating the eco-environmental quality of rural areas, it is essential not only to account for the variability introduced by scale but also to consider the specific characteristics of regional industrial structures and pollution sources [7], enabling targeted assessments of the rural ecological environment.

III. Bibliometric Analysis

A. Publication and Research Landscape

A systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Relevant literature was first identified through a topic-based search in the Web of Science Core Collection (WoSCC) using the following retrieval mode: TS = (Rural OR Village$ OR Town$) AND TS = (Eco* Environment$ Quality) AND TS = (Evaluation OR Assessment). Subsequently, the records were refined by restricting the Web of Science index categories to SCI-Expanded and SSCI, and then further filtered to include only English-language articles published between January 1, 2001, and August 28, 2025. Duplicate and irrelevant records were excluded, resulting in a final dataset of 556 articles (Fig. 1). The bibliometric analysis was then conducted using VOSviewer (version 1.6.20).

In VOSviewer, a minimum occurrence threshold of five was set for countries to ensure statistical reliability. The clustering was performed using the LinLog/modularity algorithm. The annual publication trend shows an apparent increase over time, with a notable acceleration after 2017 (Fig. 2). This shift coincides with the implementation of China's Rural Revitalization Strategy, indicating a transition of the field from an exploratory phase to a stage of rapid development, peaking around 2022. In summary, the field of rural eco-environmental quality evaluation is a flourishing field of research and remains of high research value.

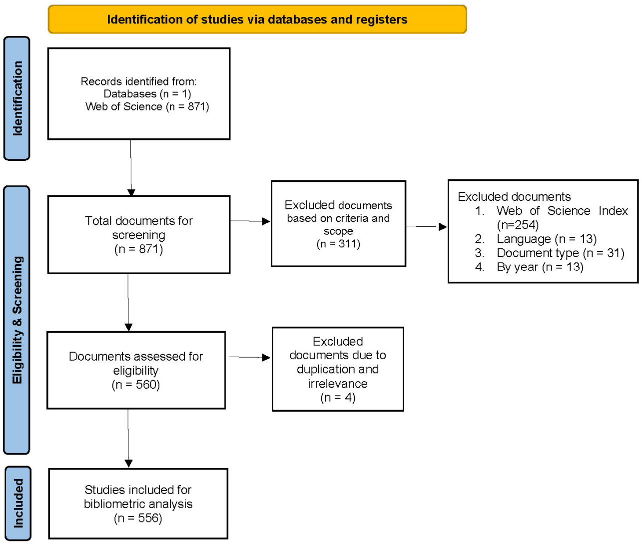

Fig. 1. PRISMA flow diagram of literature screening for bibliometric analysis.

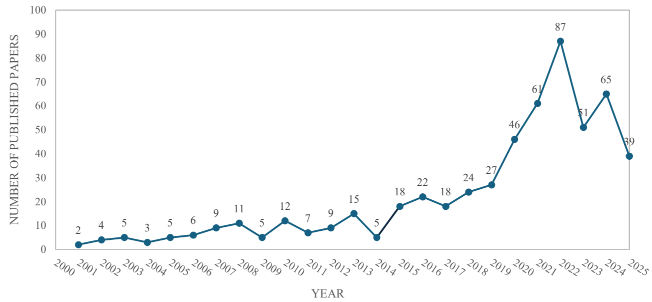

Fig. 2. Annual number of publications on rural eco-environment quality evaluation in WoSCC (SCI-Expanded and SSCI).

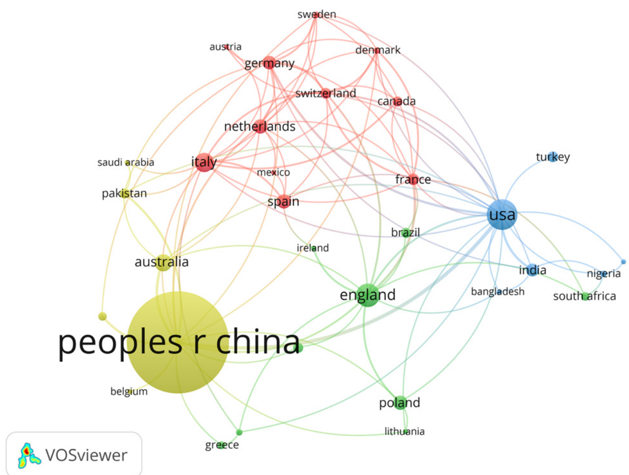

Fig. 3. Country collaboration network based on publication data.

As illustrated in Fig. 3, the analysis generated a merged network comprising 35 nodes and multiple connections. The node size represents publication volume, with larger nodes indicating a higher number of publications, while the links signify collaborative relationships between countries. Country-level analysis reveals a highly uneven global distribution of research output. Publications originated from

35 countries, with the top five contributors accounting for over 50% of the total. China ranked first (190 papers, 34.17%), followed by the United States (6.12%), England (4.32%), Italy (3.24%), and Australia (2.70%) (Fig. 3). China also occupied a central position in international collaboration networks (TLS = 29), reflecting its dominant influence in this research field.

Keyword co-occurrence analysis identified 39 high-frequency keywords (minimum occurrence ⩾ 9). The most frequent terms included "ecosystem services" (36), "urbanization" (32), "China" (31), "management" (30), and "environment" and "quality" (29 each) (Fig. 4a). These high-frequency keywords collectively suggest that current research on rural eco-environmental quality is strongly oriented toward understanding ecological functions, assessing the impacts of accelerated urban expansion, examining region-specific case studies (particularly in China), and exploring management-oriented approaches to improve environmental conditions. Meanwhile, to provide a more intuitive representation of research hotspots, a density visualization map of keywords (Fig. 4b) was generated, where warmer colors (red areas) indicate higher research focus, such as "China", "environment", "ecosystem services", "management", "pattern", "model", "quality" and "index". These keywords play a crucial role in the research field, serving as a bridge between research hotspots. These also represent the strongest emerging trends in the field of rural eco-environmental quality evaluation research.

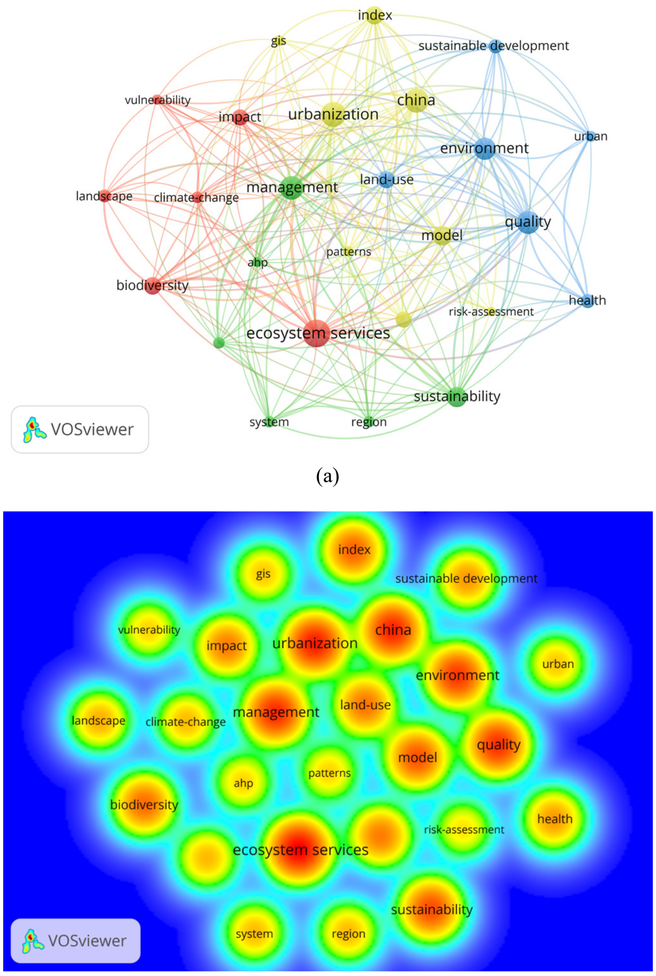

Fig. 4. Bibliometric visualization of keyword relationships: (a) Co-occurrence network of keywords. (b) Keyword density visualization.

The findings above reveal that most of the reviewed studies were conducted within China's policy framework, particularly under the Rural Revitalization Strategy. This domestic focus has resulted in research that largely emphasizes policy-oriented indicators and single-dimensional analyses, with limited integration of multi-dimensional and spatiotemporal perspectives. Such limitations may reduce the applicability of existing index systems to other regions with distinct policies and socio-economic contexts, such as Europe or Africa. Therefore, future research should incorporate multi-dimensional and spatiotemporal analyses and conduct comparative validations of these indicators across different geographical and policy contexts to enhance their global applicability.

B. Advances in Research

Many countries around the world attach great importance to eco-environmental quality evaluation. The United States was the earliest to initiate such work [18], and subsequent countries established relevant environmental protection systems, such as New Zealand's environmental protection and improvement regulations in 1973, and Australia's Environmental Protection Act [19]. Although dozens of methodologies for assessing eco-environmental quality and evaluating environmental impacts emerged since the 1960s and matured by the late 1980s [20], these approaches mainly targeted urban environments in highly urbanized regions, leaving township-level assessments underexplored [7]. For example, Musse *et al.* [21] synthesized ecological status in Colombia using remote sensing and social data, Ashok et al. [22] evaluated inter-annual variability of wetlands in India, and Bektas [23] studied the impact of greenness, dryness, and hotness on the ecological quality of Istanbul. These studies demonstrate methodological sophistication but reveal a consistent bias toward urban and large-scale evaluations, with limited attention to rural contexts.

International research on rural eco-environmental quality evaluation has primarily focused on policy, programs, and methodologies. Chibilev *et al.* [24] applied cluster analysis to systematically examine rural settlements in Russia, highlighting development patterns, whereas Rashid and Pandit [25] emphasized the role of local perceptions in guiding rural development strategies in India. These works illustrate diverse approaches but often lack integration of multi-dimensional indicators and spatial analysis across scales. Overall, international studies show promising methods but limited applicability to rural regions with heterogeneous socio-ecological conditions.

As a developing nation, China has placed significant emphasis on environmental issues, particularly urban environmental challenges, since the early 1970s. Eco-environmental quality evaluations in China have historically focused on urban living and ecological environments, reflecting policy priorities and a high urbanization bias. However, China remains an agricultural powerhouse with an urbanization rate below the global average, lagging significantly behind developed countries. With rural eco-environmental quality gaining attention, research on evaluating rural eco-environmental quality in China has focused on policy-driven assessments, particularly under the

Rural Revitalization initiative, with a concentration on ecological and environmental indicators at local or provincial scales. For example, Bin *et al.* [26] analyzed spatial differences and influencing factors in rural human settlements within the counties of Guangdong Province by constructing an evaluation index system using a spatial econometric model. Zhang and Wei [2] evaluated three administrative villages in Anshun City using the Analytic Hierarchy Process (AHP) framework and the hierarchical fuzzy evaluation method. In summary, although existing studies have provided valuable insights into rural eco-environmental quality evaluation, critical gaps remain: they often overlook multi-dimensional integration, spatial heterogeneity, and validation of indicators across diverse socio-economic contexts. Addressing these limitations should be a priority for future research.

IV. Construction of Rural Eco-Environmental Indicator Systems

A. *Indicator Selection*

In rural eco-environmental quality evaluation, the determination of indicators directly impacts data collection and the construction of the evaluation system. Selecting appropriate evaluation indicators based on village and town characteristics represents both the focus and challenge of the evaluation work. Commonly used methods for determining evaluation indicators include theoretical analysis, expert consultation, and public participation [27]. Theoretical analysis involves examining the regional characteristics of the study area, assessment standards, and relevant sources such as local statistical yearbooks and environmental bulletins, in order to identify the most prominent environmental issues as evaluation indicators. This approach maximizes consideration of local conditions but often yields numerous and complex indicators, some of which are difficult to obtain, creating challenges for the evaluation process. Expert consultation involves soliciting opinions from specialists and selecting indicators based on their professional experience. While this is a more appropriate number of indicators, it is heavily influenced by subjective judgment and may not accurately reflect local environmental characteristics. Public participation involves collecting public opinions through questionnaires or online surveys to determine evaluation indicators based on the feedback received. While this approach better aligns with reality and can identify key concerns by highlighting the differences between survey results and actual conditions, it is time-consuming and labor-intensive, and the quality of the indicators may not meet the required standards. Therefore, in practical work, appropriate indicator selection methods should be chosen based on the specific circumstances of the evaluated villages and towns, and multiple methods should be combined to facilitate subsequent data collection and model construction.

B. *Indicator Acquisition*

The acquisition of indicators for evaluating rural eco-environmental quality can generally be divided into four categories, each with its own methodological characteristics and application scope (Table 1). Statistical data provides long-term comparability, field monitoring ensures high accuracy, remote sensing monitoring enables large-scale and dynamic spatial observations, and questionnaire surveys capture human perceptions and behavioral factors. These complementary data sources collectively support a more comprehensive and multi-dimensional evaluation of rural eco-environmental conditions.

Table 1. Comparison of existing indicator acquisition methods

Method		Main Approach	Advantage	Limitation
Official Statistical Data Collection		Review of official reports, statistical yearbooks, and environmental bulletins.	Authoritative; wide coverage; cost-effective; traceable.	Limited timeliness; low spatial resolution; limited indicators [28]
Field	Manual Monitoring	On-site sampling and laboratory analysis.	Provides comprehensive, accurate, and high-resolution data.	Labor-intensive; equipment maintenance required [6].
	Automatic Monitoring	Deployment of sensors.		
Remote Sensing Monitoring		Acquisition and interpretation of satellite or aerial imagery.	Fast; objective; enables dynamic monitoring; integration with cloud computing platforms (e.g., Google Earth Engine) and machine learning greatly improves accuracy and automation.	Data processing complexity; specialized technical requirements [17].
Questionnaire Survey		Distribution and collection of questionnaires; household interviews.	Captures local perceptions and qualitative data; reflects actual conditions.	Labor-intensive; low response rates; data quality may vary [1].

C. *Determination of Indicator Weights*

The determination of indicator weights primarily involves subjective and objective weighting methods (Table 2) [27]. Subjective weighting methods include expert consultation approaches, which establish indicator weights by consulting field experts. This method often relies excessively on experts' subjective judgments and lacks analysis of the actual conditions within the study area, such as Delphi and AHP. The objective weighting method determines the weights of evaluation indicators based on the characteristics of the study area and the relationships among the indicators through statistical analysis. This approach overcomes the subjectivity inherent in experience-based weighting, is less influenced by human factors, and can objectively reflect the relationships among indicators. Commonly used objective weighting approaches include Principal Component Analysis (PCA), the Entropy Method, and the Coefficient of Variation Method (CV).

The comparison in Table 2 indicates that no single weighting method can fully satisfy the requirements of rural eco-environmental quality evaluation. To enhance the robustness of indicator weighting, recent studies increasingly adopt combination-weighting approaches that integrate subjective and objective methods [29, 30]. Subjective techniques, such as expert scoring and AHP, incorporate expert knowledge and contextual understanding, whereas objective methods, such as the entropy method, quantify the variability and information content of indicators. By integrating both types of methods, the resulting weights better balance expert judgment with data-driven evidence, thus improving the reliability and adaptability of rural eco-environmental quality evaluation. For example, Zhang *et al.* [31] developed an evaluation index system for the living environment in impoverished rural areas of Western Hunan, China, calculated indicator weights using an integrated approach of AHP and entropy weight, and analyzed the evolution patterns of the living environment in these impoverished regions. This hybrid approach enabled the authors to capture both expert knowledge and objective indicator variability, thereby providing a more comprehensive understanding of the spatiotemporal evolution of rural living environmental quality. This suggests that combination-weighting strategies are particularly suitable for evaluating rural eco-environmental quality, where data availability is heterogeneous, and management goals vary across regions. Integrating subjective and objective methods can improve both the reliability and interpretability of indicator weights, thereby enhancing decision support for rural environmental management.

Table 2. Comparison of common weighting methods

Method	Main Steps	Advantage	Limitation
Delphi Method	Experts iteratively revise opinions until reaching a consensus	Converts subjective expert judgments into reliable quantitative results	Influenced by expert subjectivity, time-consuming
AHP	Build hierarchy → Pairwise comparisons → Compute weights	Handles complex problems hierarchically; quantifies expert judgment	Depends on the consistency of expert judgment
PCA	Standardize data → Extract principal components	Simplifies complex datasets; identifies key contributing factors	May lose information
Entropy Method	Calculate entropy-based weights from indicator data	Objective weighting reduces subjectivity	Sensitive to outliers; requires complete data
CV	Use the coefficient of variation to assign weights	Simple to compute; emphasizes variable indicators	Ignores correlations among indicators

Table 3. Comparison of existing integrated evaluation methods

Method	Main Steps	Advantage	Limitation
Comprehensive Index Evaluation Method	Standardize data → Assign weights → Calculate composite index	Simple and intuitive; reflects overall quality	Subjective weighting; ignores indicator interactions
Fuzzy Evaluation Method	Build membership functions → Apply fuzzy reasoning	Handles qualitative and uncertain data	Depends on expert-defined functions; subject to bias
Artificial Neural Network Method (ANN)	Train with sample data → Validate model → Predict environmental quality	Captures complex nonlinear relationships	Requires large datasets; limited interpretability
Grey Relational Analysis (GRA)	Normalize data →Compute grey relational grades	Works with small or incomplete datasets; emphasizes trend similarity	Weak in modeling nonlinear complexity

D. Methods for Indicator Integration

Currently, numerous methods exist for eco-environmental quality evaluation, among which the Comprehensive Index Evaluation Method, the Fuzzy Evaluation Method, and the Artificial Neural Network (ANN) Method have been widely applied. When assessing rural eco-environmental quality, various methods exhibit distinct advantages and limitations in their practical applications. When selecting an appropriate method, comprehensive consideration should be given to the purpose of the assessment, data availability, and the characteristics of the research subject.

As shown in Table 3, methods for indicator integration differ substantially in terms of complexity, data requirements, and interpretability. The Comprehensive Index Evaluation Method is widely applied due to its transparency and ease of implementation, making it suitable for policy-oriented rural eco-environmental quality evaluations. In contrast, advanced methods such as ANN offer higher nonlinear fitting capability but require larger datasets and suffer from limited interpretability. This comparison implies that method selection should be aligned with the evaluation objective: policy formulation and communication favor interpretable approaches, whereas scenario simulation and pattern recognition may benefit from data-driven models.

E. Comparison of Major Evaluation Methods

The applicability of different eco-environmental quality evaluation methods varies depending on specific research objectives (Table 4). For instance, RSEI is highly suitable for monitoring physical environmental quality, providing objective, spatially explicit, and temporally consistent information on land cover, vegetation, and ecological changes. This makes it highly effective for identifying environmental degradation and recovery patterns in rural areas. In contrast, the Ecological Footprint approach is more suitable for macro-level sustainability assessments, enabling comprehensive measurement of resource consumption and ecological pressures at regional or national scales. While useful for cross-regional comparison, its aggregated nature limits its ability to reflect local environmental heterogeneity and specific ecological processes. Meanwhile, frameworks such as Driver-Pressure-State-Impact-Response (DPSIR) emphasize causal linkages between human activities and environmental change, making it well-suited for integrated socio-ecological evaluation and policy analysis. However, its conceptual structure relies heavily on indicator selection and often lacks explicit spatial representation [32, 33]. Therefore, for rural eco-environmental quality evaluation that requires both dynamic spatial monitoring and policy interpretability, RSEI or DPSIR-based approaches are more suitable than purely aggregate methods such as the Ecological Footprint.

However, while RSEI excels at capturing spatial patterns and DPSIR provides a conceptual causal framework, both approaches have limited capacity to quantitatively explain the driving mechanisms behind observed spatial heterogeneity. To address this gap, GeoDetector or Explainable Artificial Intelligence (XAI) techniques can be integrated to identify key driving factors and reveal their relative contributions and interactions, thereby enhancing the interpretability and explanatory power of rural eco-environmental quality evaluation.

Table 4. Comparison of major eco-environmental quality evaluation methods

Method	Main Steps	Advantage	Limitation
RSEI	Acquire satellite images → Calculate indices → Integrate into composite ecological score	Captures spatial heterogeneity; enables dynamic monitoring	Requires remote sensing expertise; sensitive to image quality
Ecological Footprint	Quantify resource consumption & ecological demand → Compare with biocapacity	Simple, intuitive; easy for policy communication	Oversimplifies complex ecological processes; lacks spatial resolution
DPSIR Framework	Define Drivers → Pressures → State → Impact → Response	Integrates socio-economic and environmental factors; policy-relevant	Qualitative; implementation can be subjective

F. Proposed Integrated Framework for Future Research

To enhance the comprehensiveness and applicability of future regional sustainability assessments, a detailed integrated framework is proposed. This framework aims to synthesize the strengths of existing methodologies from multiple perspectives, ensuring both methodological rigor and practical interpretability.

First, subjective and objective weighting methods, such as AHP, entropy, or PCA, can be combined to balance expert knowledge with data-driven evidence, thereby improving the reliability of indicator weighting.

Second, a comprehensive index evaluation method or an ANN method can be employed to integrate diverse indicators from ecological, economic, and social dimensions into a unified assessment system.

Third, RSEI and GIS tools can be utilized for spatial visualization and spatiotemporal analysis, enabling the dynamic tracking of regional sustainability changes and providing an intuitive representation of spatial patterns.

Finally, to explore the underlying driving mechanisms of the observed sustainability patterns, GeoDetector or XAI techniques can be applied. While GeoDetector identifies spatial heterogeneity and factor interactions, XAI (e.g., SHAP or LIME) provides model-based interpretability, revealing how each variable contributes to the integrated results.

This integrated protocol not only strengthens the analytical robustness but also supports the development of globally comparable, interpretable, and spatially explicit evaluation frameworks.

G. Hypothetical Application Scenario

To enhance the practical interpretability of the proposed framework, a hypothetical application scenario is provided. For a typical rural region, multi-source data (statistical, remote sensing, and survey data) are first integrated to construct a multi-dimensional indicator system. Subjective and objective weighting methods are then combined to determine indicator weights, followed by indicator integration using a comprehensive index evaluation method or ANN. RSEI and GIS tools are subsequently employed to support spatial visualization and spatiotemporal analysis of patterns in eco-environmental quality. Finally, GeoDetector or XAI techniques are applied to interpret the underlying driving mechanisms of the observed spatial patterns. The overall workflow of this application scenario is illustrated in Fig. 5.

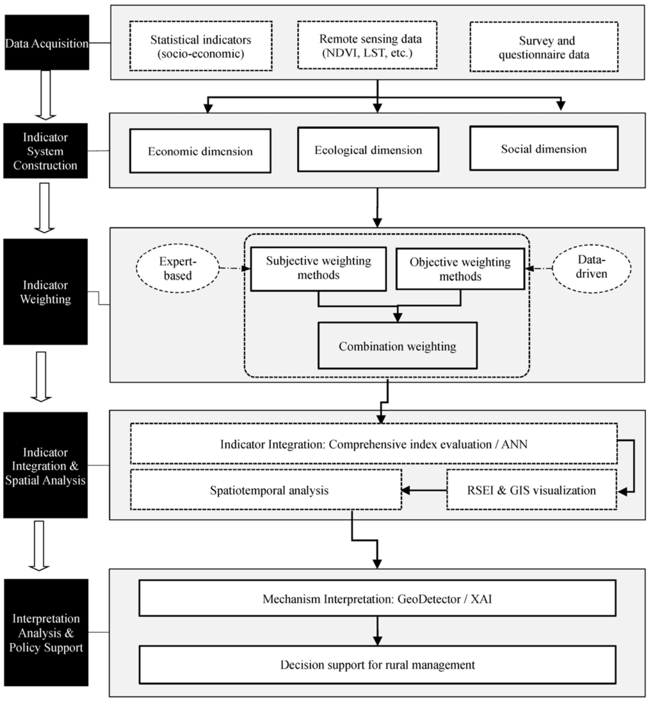

Fig. 5. Workflow of the proposed integrated framework for rural eco-environmental quality evaluation.

V. Conclusion

Through a comprehensive review and synthesis of relevant literature, it is evident that research into ecological environment-related topics and theoretical frameworks has reached a relatively mature stage, indicating a high level of scholarly attention to this field. In rural eco-environmental quality research, most studies primarily focus on evaluation, with the construction of an indicator system serving as the foundation for this evaluation. Given the complexity of the evaluation subjects, indicator selection and weighting inevitably involve a degree of subjectivity. Moreover, the lack of a unified indicator integration system—despite consideration of the advantages and limitations of different methods—constrains the objectivity of evaluation outcomes. In addition, most existing studies remain confined to a single temporal scale, typically focusing on the spatial distribution of rural eco-environmental quality in a given year, which limits understanding of interactions between natural and socio-economic factors.

Considering the advantages and limitations of single weighting methods, future eco-environmental quality evaluations can adopt comprehensive weighting approaches that combine both objective and subjective methods. This strategy helps reduce the influence of individual subjectivity while improving the robustness of indicator weighting. Meanwhile, integrating emerging theories and technologies with remote sensing and GIS offers new opportunities for advancing rural eco-environmental quality evaluation. For instance, RSEI, characterized by simple data acquisition and visually interpretable results, enables efficient analysis of spatiotemporal changes in rural ecosystems.

Based on these insights, this study proposes a four-step integrated framework that combines subjective-objective weighting and RSEI-GIS analysis, offering practical policy implications for rural government management and ecological revitalization. Specifically, establishing a standardized multi-dimensional indicator system can help local governments identify environmental bottlenecks and allocate restoration resources more efficiently. Integrating subjective and objective weighting methods enables policymakers to balance expert knowledge with data-driven insights, thereby enhancing the scientific rigor of evaluations. Furthermore, the application of dynamic and spatial tools such as RSEI and GIS supports real-time monitoring, early warning, and precise management of rural ecological risks. The evaluation results can also serve as an empirical foundation for formulating targeted ecological revitalization strategies, including land consolidation, habitat improvement, pollution control, and the planning of green infrastructure.

Despite the contributions of this study, several limitations should be acknowledged. The proposed framework is primarily developed based on a literature synthesis and has not yet been empirically validated across different regions and scales. Therefore, future research should place greater emphasis on cross-scale analysis in rural eco-environmental studies. By integrating data and methodologies across multiple spatial and temporal scales, it will not only minimize biases arising from single-scale analyses but also provide more accurate insights into ecosystem dynamics and rural eco-environmental quality. To strengthen multi-source integration, qualitative local perceptions may be combined with quantitative spatial data. In this context, Citizen Science platforms, such as participatory data collection and community-based mapping, can be integrated with remote sensing and GIS to form a hybrid monitoring framework. This approach can further support the development of Digital Twin systems for rural areas, enabling real-time visualization, simulation, and dynamic tracking of sustainability changes, and ultimately supporting more scientifically grounded policy decisions.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ge Yu conducted the research; wrote the paper; Kim Dirks & Priyanka Dhopade edited and revised the paper; all authors approved the final version.

Acknowledgment

The author gratefully acknowledges financial support from the China Scholarship Council (CSC).

References

[1] C. Li, Q. Liu, Z. Zong, and Y. Fang, "Rural environmental quality evaluation indicator system: Application in Shangluo city, Shaanxi province," *Sustainability*, vol. 16, no. 8, p. 3198, Jan. 2024.

[2] L. Zhang and Y. Wei, "Evaluation and management strategy for rural eco-environment quality under the rural revitalization background," *Anhui Agric. Sci. Bull.*, vol. 26, no. 20, pp. 153–157, 2020.

[3] Md. M. Morshed, Md. A. Fattah, S. R. Morshed, and S. Sydunnaher, "Assessment and prediction of mega-infrastructure projects on rural ecosystems using machine learning algorithms," *Environ. Dev. Sustain.*, June 2024.

[4] C. Ying *et al.*, "Evolution and prediction of rural ecological environment quality in eastern coastal area of China," *Front. Environ. Sci.*, vol. 12, July 2024.

[5] A. E. M. Gherdan, R. V. Bacter, C. M. Maerescu, T. Iancu, R. Ciolac, and A. Ungureanu, "Sustainable tourism development in mountain regions: A case study of Peştera village, Brasov county, applying the analytic hierarchy process," *Sustainability*, vol. 17, no. 4, p. 1452, Jan. 2025.

[6] L. Mohammad *et al.*, "Evaluation of the spatiotemporal changes in ecological quality and public health status: A case study of Jharkhand state in India," *Environ. Dev. Sustain.*, vol. 27, no. 6, pp. 14841–14877, June 2025.

[7] Cui Y., Cha H., Wang L., Yang S., and Duan X., "Evaluation of ecological environment quality in townships and its influencing factors, exemplified in Jiangsu province," *Resour. Environ. Yangtze Basin*, vol. 32, no. 9, pp. 1922–1931, 2023.

[8] W. Zhou *et al.*, "Urban tree canopy has greater cooling effects in socially vulnerable communities in the US," *One Earth*, vol. 4, no. 12, pp. 1764–1775, Dec. 2021.

[9] Ş. M. Yakut and B. Baran, "A hybrid machine learning and stochastic modeling framework for probabilistic reliability analysis of Kızılırmak river water quality," *Water Environ. Res.*, vol. 97, no. 9, e70169, 2025.

[10] L. Liu and Y. Zhang, "Urban heat island analysis using the Landsat TM data and ASTER data: A case study in Hong Kong," *Remote Sens.*, vol. 3, no. 7, pp. 1535–1552, July 2011.

[11] L. Lin, Z. Hao, C. J. Post, and E. A. Mikhailova, "Monitoring ecological changes on a rapidly urbanizing island using a remote sensing-based ecological index produced time series," *Remote Sens.*, vol. 14, no. 22, Art. no. 22, Jan. 2022.

[12] A. E. Braswell and J. B. Heffernan, "Coastal wetland distributions: Delineating domains of macroscale drivers and local feedbacks," *Ecosystems*, vol. 22, no. 6, pp. 1256–1270, Sept. 2019.

[13] P. K. Singh and S. Saxena, "Towards developing a river health index," *Ecol. Indic.*, vol. 85, pp. 999–1011, Feb. 2018.

[14] R. Sun *et al.*, "Effects of land-use change on eco-environmental quality in Hainan Island, China," *Ecol. Indic.*, vol. 109, 105777, Feb. 2020.

[15] L. E. O'Brien, R. E. Urbanek, and J. D. Gregory, "Ecological functions and human benefits of urban forests," *Urban For. Urban Green.*, vol. 75, p. 127707, Sept. 2022.

[16] P. Singh, N. Kikon, and P. Verma, "Impact of land use change and urbanization on urban heat island in Lucknow city, central India. A remote sensing based estimate," *Sustain. Cities Soc.*, vol. 32, pp. 100–114, July 2017.

[17] W. Li, M. An, H. Wu, H. An, J. Huang, and R. Khanal, "The local coupling and telecoupling of urbanization and ecological environment quality based on multisource remote sensing data," *J. Environ. Manage.*, vol. 327, 116921, Feb. 2023.

[18] B. T. Bower, "Environmental quality management in the United States in the 1980s and beyond: An appraisal," *Environmentalist*, vol. 4, no. 4, pp. 253–264, Dec. 1984.

[19] W. N. Vant and B. J. McGlinchy, "New Zealand environmental standards and energy policies," *Environ. Manage.*, vol. 7, no. 6, pp. 525–530, Nov. 1983.

[20] M. A. Luck, G. D. Jenerette, J. Wu, and N. B. Grimm, "The urban funnel model and the spatially heterogeneous ecological footprint," *Ecosystems*, vol. 4, no. 8, pp. 782–796, Dec. 2001.

[21] M. A. Musse, D. A. Barona, and L. M. Santana Rodriguez, "Urban environmental quality assessment using remote sensing and census data," *Int. J. Appl. Earth Obs. Geoinformation*, vol. 71, pp. 95–108, Sept. 2018.

[22] A. Ashok, H. P. Rani, and K. V. Jayakumar, "Monitoring of dynamic wetland changes using NDVI and NDWI based Landsat imagery," *Remote Sens. Appl. Soc. Environ.*, vol. 23, 100547, Aug. 2021.

[23] F. Bektaş Balçik, "Determining the impact of urban components on land surface temperature of Istanbul by using remote sensing indices," *Environ. Monit. Assess.*, vol. 186, no. 2, pp. 859–872, Feb. 2014.

[24] A. A. Chibilev, R. Sh. Akhmetov, V. P. Petrishchev, and Yu. V. Cherkasova, "Cluster differentiation of municipal districts of Orenburg

Oblast by features of rural settlement pattern," *Reg. Res. Russ.*, vol. 5, no. 3, pp. 263–269, July 2015.
[25] M. Rashid and D. Pandit, "Determination of appropriate service quality attributes for household toilets in rural settlements of India based on user perception," *Environ. Dev. Sustain.*, vol. 19, no. 4, pp. 1381–1406, Aug. 2017.
[26] J. Bin, X. Tang, and S. Chen, "Spatial distribution and influencing factors of rural human settlement quality in Guangdong province," *Ecol. Econ.*, vol. 37, no. 12, pp. 203–209, 223, 2021.
[27] L. Ge, "Construction of evaluation index system of rural ecological environment from the perspective of ecological civilization," *Int. J. Ecol.*, vol. 9, p. 245, Aug. 2020.
[28] X. Chen, F. Rong, and S. Li, "Driving force-pressure-state-impact-response-based evaluation of rural human settlements' resilience and their influencing factors: Evidence from Guangdong, China," *Sustainability*, vol. 16, no. 2, p. 813, Jan. 2024.
[29] F. Cai, Z. Hu, B. Jiang, W. Ruan, S. Cai, and H. Zou, "Ecological health assessment with the combination weight method for the river reach after the retirement and renovation of small hydropower stations," *Water*, vol. 15, no. 2, p. 355, Jan. 2023.
[30] J. Huang, Y. Zhang, J. Zhang, J. Qi, P. Liu, and C. Liang, "Eco-geological environment quality assessment based on FAHP-CV combination weighting," *Sustainability*, vol. 15, no. 14, 10830, Jan. 2023.
[31] J. Zhang, W. Duan, and X. Zhu, "Comprehensive evaluation of the living environment in rural impoverished areas of western Hunan," *Enterp. Econ.*, vol. 37, no. 9, pp. 176–181, 2018.
[32] A. B. Dar, N. Bhanja, M. Paul, and U. Farooq, "Shaping a greener tomorrow: Analysing the impact of environment-friendly technology on ecological footprints in emerging Asian economies," *J. Clean. Prod.*, vol. 452, 142130, May 2024.
[33] Y. Xu, H. Wang, K. Zhang, and Y. Han, "Ecological security assessment of urban park landscape using the DPSIR model and EW-PCA method," *Environ. Dev. Sustain.*, vol. 26, no. 12, pp. 31301–31321, Dec. 2024.