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Research progress on eco-product value realization and rural revitalization and its inspiration for karst desertification control: a systematic literature review between 1997 and 2023

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Ecological product value realization (EPVR) and rural revitalization (RR) are essential guarantees for ensuring human well-being and a better life. They are also crucial components of a promising vision for the future of the world and play a significant role in promoting the sustainable management of ecological restoration. The chain-driven mechanism of EPVR—ecological industry (EI)—RR in the karst desertification control (KDC) area has already become a key scientific issue that urgently needs to be solved during the process of promoting industrial green transformation and consolidating the results of poverty alleviation in the region, however, there is currently no clear synthesis of this issue. To address this shortfall, we have adopted a systematic literature review (SLR) framework. Based on the Web of Science (WOS) and the China National Knowledge Infrastructure (CNKI) databases, we conducted a comprehensive literature search and rigorous evaluation, obtaining 321 documents published between 1997 and 2023. These documents were systematically integrated and analyzed in depth through a systematic literature review process, aiming to provide a holistic perspective. The results indicate that (1) there is an overall fluctuating upward trend in the number of literatures issued in the time series, and the study trend is categorized into accumulation, development, and expansion periods; (2) the research area is mainly concentrated in China's EPVR and RR pilot areas. There is a significant overlap between the hotspot of research institutions, their areas of specialization, research foundations, and geographical locations. The research content mainly includes EPVR, EI, relationship between EI and RR, models of RR and EPVR pathways; (3) the main progress and landmark results are summarized based on the research content. A series of related scientific issues and technical needs, such as eco-product (EP) value accounting, value realization mechanisms, EI formation, RR, and the chain-driven mechanism between them, are explored for future research. While summarizing the general laws, it also provides targeted insights and revelations for the subsequent sustainable management of the KDC ecosystem.

KEYWORDS

ecological products value realization, rural revitalization, ecosystem services, karst desertification control, research progress, sustainability

1 Introduction

Ecosystem services (ES) are crucial for connecting ecological health with social and economic development, thereby enhancing human well-being (Mekuria et al., 2023). They play a key role in providing environmental benefits to meet human needs (O'Sullivan et al., 2017). As socioeconomic and ecological elements become more intertwined (Schlüter et al., 2019), their interactions can generate eco-product (EP), a concept introduced by the Chinese government in the 2010 National Main Function Areas Program (Liu et al., 2019; Zhou et al., 2022). Although there is no standardized definition of EP, it is generally understood as ecosystems providing sustainable goods or services through biological and human production processes (Zhang L. et al., 2019). In a broader sense, EP highlights the social aspects of ecosystems and focuses on positive human impacts on their productivity, essentially expanding the commodification of ecosystem services (Zhang L. et al., 2021; Wang et al., 2023). On this basis, ecologists and economists have introduced the concept of ecological product value realization (EPVR) to achieve sustainable economic and ecological growth (Wang, 2016; Xie and Chen, 2022). Their goal is to rationally recognize ecological value, promote economic restructuring and green transformation, enhance rural spatial management, and ultimately support rural revitalization (RR) (Ge, 2022).

Rural revitalization is not only viewed as a "ballast" for the stable development of the country but also plays a critical role in addressing global challenges. Maximizing the potential of EP is essential for promoting sustainable recovery and development in rural areas (Wang, 2022). Globalization, industrialization, and rapid urbanization have exposed the fragility of rural development, hindered by technology gaps, poverty, policy biases, and poor land management. Rural areas worldwide have been experiencing a rapid decline, which has become a global trend (Liu and Li, 2017). A significant amount of ecological and cultural resources have been wasted, economic decline, agricultural inefficiency, and the growing urban–rural divide, underscores the urgent need to revitalize global rural areas (Maxwell et al., 2016; Li et al., 2018). The 2019 Global Food Policy Report by the International Food Policy Research Institute (IFPRI) highlights that rural areas have emerged as a crucial factor in ensuring food security and providing valuable environmental services (Li et al., 2020b). These regions are key EP hubs, and play a pivotal role in showcasing the value and benefits of EP for human well-being. EP in rural areas fosters ecological industry (EI) by leveraging green production and efficient outputs, offering rural populations with limited urban job prospects a viable economic alternative and basic survival means (He, 2020). This approach is crucial for achieving the UN Sustainable Development Goals (SDGs) (Weiland et al., 2021).

In ecologically fragile areas, hidden ecological values, wasted resources, and rural decline are prominent (Zhou et al., 2020), greatly reducing the benefits of ecological restoration and protection (Wang X. et al., 2019; Zhang et al., 2020). The karst region is one of the world's major ecologically fragile areas, covering 15% of the global landmass and home to approximately a quarter of the world's population (Ford and Williams, 2007). Karst desertification (KD) is a phenomenon where desert-like landscapes form on the surface due to the fragile ecological environment of karst areas combined with excessive negative human interference. It represents an extreme form of land degradation, primarily found in rural areas (Xiong et al., 2016; Zhang Y. et al., 2024). Given the excessive population pressure and reliance on traditional mountain agriculture, many farmers persist in high-intensity, exploitative resource use (Yan and Cai, 2015). This situation makes the region vulnerable to a harmful cycle of "ecological function degradation—loss of ecological assets—decline in ES provision capacity—decrease in farmers' food and income—deepening poverty" (Zuo et al., 2022; Zhang S. et al., 2024). To address the serious human-land conflicts, the Chinese government has incorporated karst desertification control (KDC) into the strategic priorities of national ecological security and ecological civilization, and has invested a great deal of policy, technical and financial support in South China Karst. The successful implementation of the KDC project has made the region a major global center for ecological and greening initiatives (D'Ettorre et al., 2024). Ecosystem functions and services in this area have significantly improved, creating a unique KDC ecosystem (Wang K. et al., 2019). On this foundation, the region's ecological assets are gradually becoming high-quality EP.

Nevertheless, the characteristics of the fragile nature of the karst ecosystem remain unchanged (Canedoli et al., 2022), and there are difficulties in meeting the ecosystem's needs of the ecosystem for diversity, stability, and continuity, a single path for EPVR, insufficient endogenous impetus to drive the development of the regional economy, and other related problems (Zhang Y. et al., 2019). The United Nations Decade of Ecosystem Restoration (2021–2030) has emphasized the need to promote sustainable management practices for ecosystems (Cooke et al., 2019). Therefore, achieving sustainable management in the later stages of KDC has garnered significant attention in the global arena of ecological fragility (Bai et al., 2023). Currently, there exists a substantial body of literature on EPVR and RR as distinct subjects. Various perspectives, such as enhancing the value and supply capacity of ES, have been employed to analyze specific cases of RR (Liu, 2020; Ma et al., 2020; Yu H. et al., 2020; Wang et al., 2021). Given this foundation, we believe that examining the cascading relationship between EPVR, EI, and RR is crucial for understanding KDC's future sustainability.

The process of KDC ecosystems—EP-EI-RR cascade involves a series of factor transformations and stage transitions (Figure 1). Initially, natural resources and services within KDC ecosystems, as ecological assets, are combined with nature and human labor to generate primary EP (Xie and Chen, 2022; Brander et al., 2024). Secondly, leveraging the ecological environment's positive externality, the primary EP can enhance rights conversion and EPVR premiums through technology, resource integration, scaling, and industry growth with clear property rights (Chen et al., 2024). For EP that has not yet formed into an industry, the path of EI industrialization will enable scale integration, socialized production, and market-oriented operations, enhancing value across the industrial, supply, and consumption chains. For industries that have begun to take shape, they should adopt green, recycling, and low-carbon practices, integrate socially and industrially, enhance eco-value, expand market reach, and strengthen brand value. Eventually, sustainable management of EI will extend the terminal EP conversion chain and boost the rural industry revitalization,

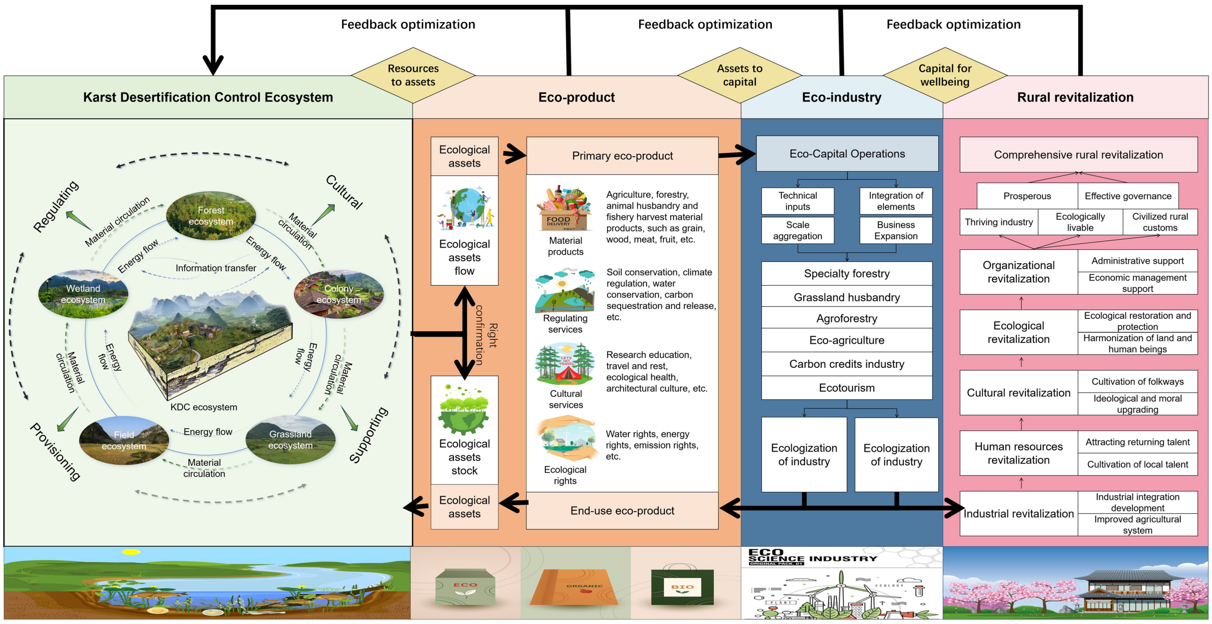

FIGURE 1
The chain-driven framework of ES-EP-EI-RR of KDC area.

revitalizing talent, ecology, culture, and organization overall (Li X. et al., 2024), thereby improving KDC management and fostering a positive development cycle.

This study addresses the pressing necessity for establishing sustainable reciprocity between the realization of ecological values and socio-economic development in KDC. It underscores the frontiers and scientific challenges associated with ecological conservation, as well as the consequent benefits to human well-being in rural areas. We integrated the scientific and technological requirements to establish a synergistic mutual feedback loop between ecological economy and human well-being in global karst areas, examined global research advancements in EPVR and RR. We highlighted key milestones and scientific challenges, explored research priorities and future directions, and offered insights on KDC. This consolidation underscores the importance of the field and serves as a resource for scholars, aiding their understanding of emerging scientific issues and advancing their research using both domestic and international findings.

2 Materials and methods

Our research employs the systematic literature review (SLR) framework, which encompassing a series of processes, including protocol development, search strategy execution, evaluation of selected studies, synthesis of findings, and report composition (Figure 2). The methodology's logical system is standardized and convenient, offering the advantages of transparency, independence, robustness, comprehensiveness, and reproducibility (Pullin and Stewart, 2006; Mengist et al., 2020). It enables identify, evaluate, and synthesize the processes of completed and documented work by researchers and practitioners. This method is suitable for conducting literature reviews across various disciplines.

2.1 Protocol

To ensure the transparency, systematicity, transferability, and replicability of our systematic literature reviews, we established a working protocol prior to commencing database searches. A pivotal aspect of defining this protocol was identifying the review's purpose, which was essential for formulating research questions that could be effectively addressed and for establishing precise research boundaries. The primary research questions addressed in this study include: (1) analyzing trends in the number of literature publications over the years and identifying distinct research phases; (2) categorizing research themes based on their content and frequency; (3) highlighting significant advancements and milestones in current research; (4) outlining critical scientific inquiries for future exploration; and (5) reflecting on insights gained from organizing key scientific issues and research progress to inform the subsequent management of KDC.

2.2 Search

Given the extensive diversity and inherent complexity of global languages, along with the unique geographical characteristics of our research content, we have selected two authoritative databases, for a comprehensive and accurate literature search: the Web of Science (WOS)[1] and the China National Knowledge Infrastructure (CNKI).[2] English is a widely used and understood language across the globe, and the WOS database is highly regarded for its

1 https://webofscience.clarivate.cn/wos/woscc/basic-search
2 https://www.cnki.net

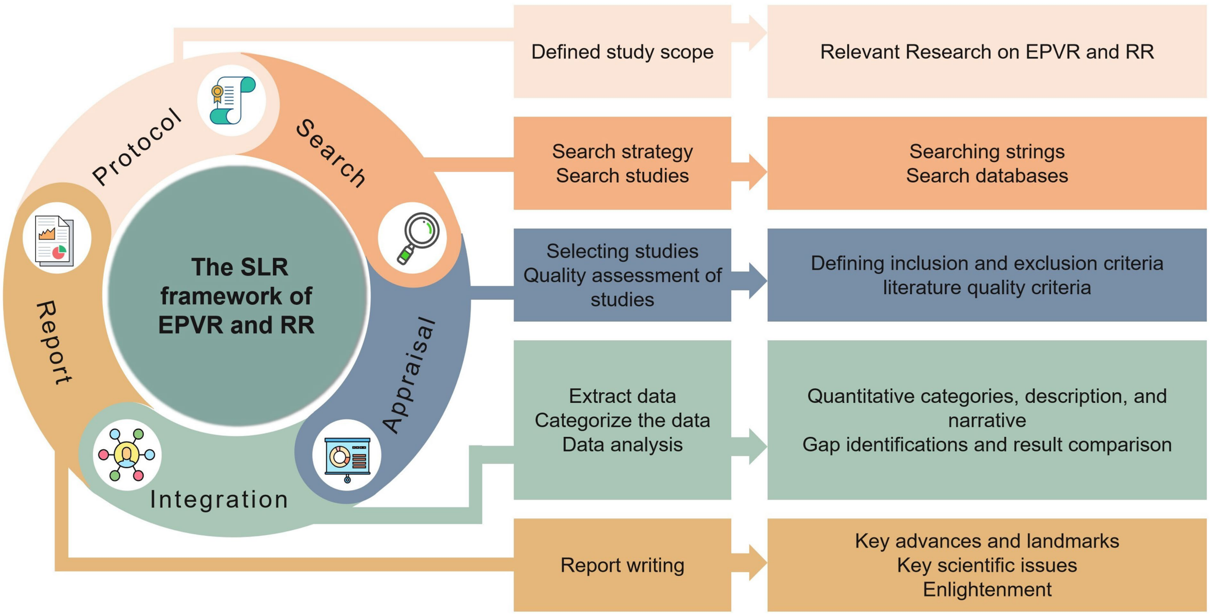

FIGURE 2
Systematic analysis framework diagram.

collection of high-quality academic works spanning various disciplines, featuring frequent updates and a substantial readership. Consequently, the WOS database was selected for the English literature search. Concepts of EP and RR are particularly pertinent to China, while KDC is predominantly practiced in the southern regions of the country, positioning it at the forefront of global research in this field. Therefore, Chinese literature offers valuable insights and was deemed essential for inclusion in the search scope. CNKI is recognized as the largest, most comprehensive, and most significant literature database in China, making it the preferred choice for accessing Chinese literature.

In 1997, Costanza's initial quantitative assessment of the global value of ecosystem services heightened awareness of ecological value and sparked global discussions and applications (Costanza et al., 1997). Consequently, to ensure the timeliness and completeness of the literature, we employed the advanced search pattern. By integrating the designated keywords with logical operators, we leveraged the database's secondary search function to gather relevant literature, spanning from January 1, 1997, to December 31, 2023. Based on these principles, we initially identified the search terms "EP" and "RR," along with various related expressions and synonyms. In the subsequent stage, we conducted two searches in the WOS and CNKI databases. The first search utilized the term "subject" in conjunction with the logical operator "or" to concentrate on EP and its related terms. The second search employed "RR" and its synonyms as subject terms to refine the results obtained from the first search, thereby completing the search phase (Figure 3).

2.3 Appraisal

The appraisal stage involves evaluating the selected literature based on the objectives of the review, with the aim of narrowing the results to the most pertinent papers. We have strictly adhered to the established procedures for reviewing the study's content, defining inclusion and exclusion criteria for the selected literature, and utilizing the 616 retrieved papers for identification and screening (Figure 3). The inclusion criteria included: (1) the presence of specific keywords in the titles, keywords, or abstracts of the CNKI and WOS databases, particularly those related to "EPVR" and "RR"; (2) academic papers published in peer-reviewed scientific journals; (3) papers written in either English or Chinese; and (4) empirical content pertaining to ecological industrialization, industrial ecology, or rural space governance. The exclusion criteria comprised: (1) duplicate papers identified in the literature; (2) papers that were inaccessible; (3) papers whose primary research focus was not related to "EP" or "RR"; and (4) papers published prior to 1997. This systematic process yielded a total of 274 relevant documents. The papers that met the inclusion criteria were subsequently analyzed for validity. Subsequently, we conducted a validity analysis of the papers that met the criteria by meticulously reviewing the literature. Employing a "snowball" method, we examined the references of key documents as well as the documents that cited them to identify articles pertinent to the research topic that had not been previously retrieved. This approach facilitated a comprehensive review of the initially selected sources, allowing us to uncover additional high-quality documents. Consequently, we identified an extra 47 papers, increasing the total number of included sources to 321.

2.4 Integration

At this juncture, following a comprehensive review of the selected literature, the pertinent variables of interest have been identified and systematically categorized to conclude. Current research on the EPVR and RR remains limited to exploring the importance, classification,

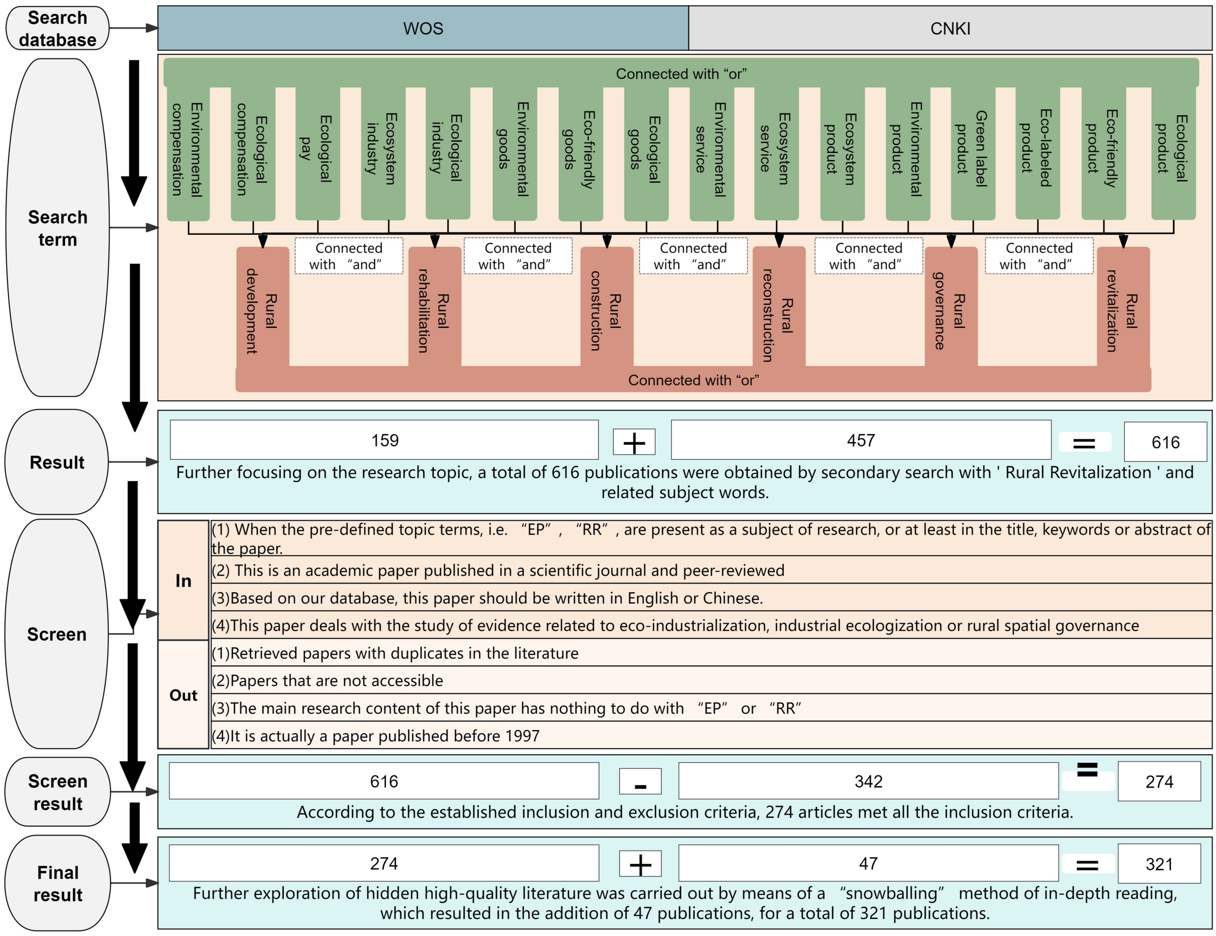

FIGURE 3
The flow diagram of the literature search and appraisal process of databases used for systematic evaluation.

accounting, and feasibility analysis of the theoretical path. However, it largely overlooks the processes involved in transforming and enhancing ecological value, as well as the driving mechanisms behind rural industrial development and comprehensive environmental improvement. Consequently, we posit that it is imperative to concentrate on these overlooked elements, integrate EP, EI, and RR, and engage in comprehensive discussions.

2.5 Report

This phase will finalize the fifth step of the SLR working framework, which entails reporting the analyzed results. Based on the distribution of the studies, we have delineated four primary topics. First, an overview of the quantitative categories and results derived from the literature, as structured by the systematic framework, is presented in sections 3.1–3.2 of the results and analysis chapter. Following this, the four sub-themes are elaborated in section 3.3 to effectively convey the principal milestone findings. Building on this foundation, the key scientific questions that need to be addressed are summarized in section 3.4. During the analysis process, we will conduct a comprehensive examination of each topic summary, reflecting on the key insights from the KDC and integrating them into the relevant content to provide more targeted support.

3 Results

3.1 Annual distribution

Research on EPVR and RR has experienced significant growth since the early 21st century, with notable research milestones in 2008 and 2016. Notably, the number of publications has surged rapidly since 2017 (Figure 4). Overall, the study can be divided into three distinct phases: (1) The first phase (1997–2008) was characterized by a limited and sporadic publication output. Research during this period primarily concentrated on the management frameworks for ecological resources and the accounting of natural capital, largely consisting of descriptive theoretical studies and the synthesis of historical experiences. Consequently, the research lacked systematic coherence, indicating a nascent stage; (2) The second phase (2009–2016) unfolded against the backdrop of global sustainable development, during which interest in ES began to rise steadily. This phase demonstrated temporal continuity in research efforts, leading to a clearer conceptual and theoretical foundation for ES. Moreover, these efforts started to align with national strategies for precision poverty alleviation and resource recovery, bolstered by supportive policies, thus representing an exploratory stage; (3) The third phase (2017–present) is characterized by rapid development, with a

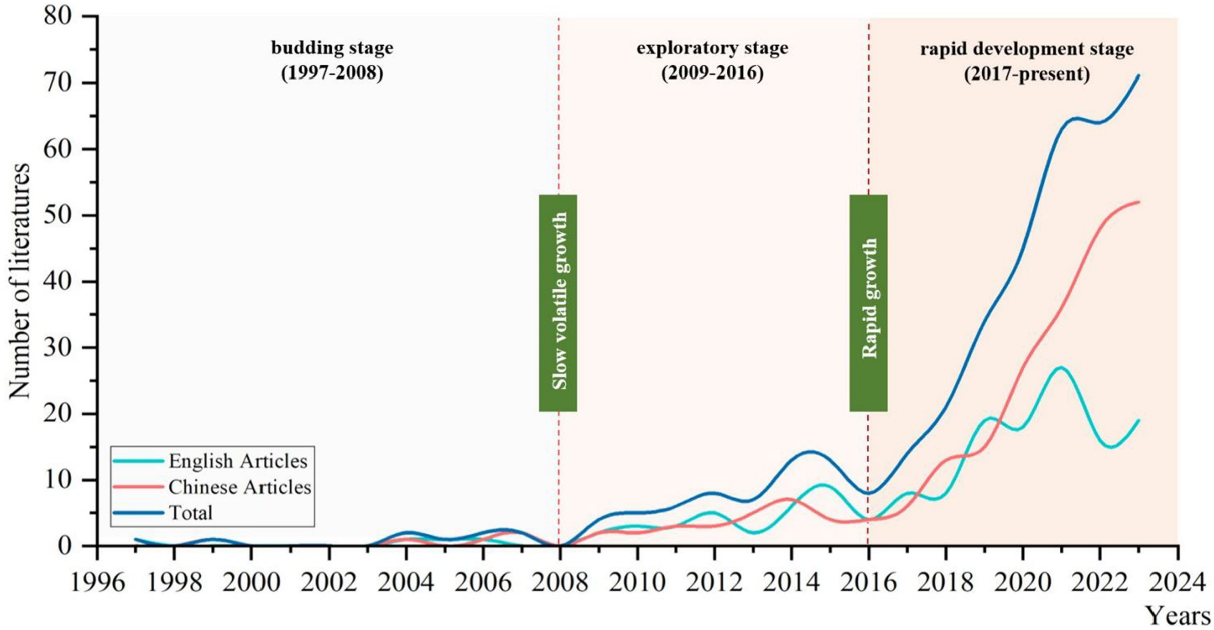

FIGURE 4
Annual distribution of literatures.

dramatic increase in the volume of literature, exhibiting exponential growth annually. Research focusing on the value accounting, and value realization mechanism of EP and RR research has garnered considerable attention, resulting in the EPVR and RR models being put forward and implemented as pilots, highlighting a trend toward multidisciplinary collaboration.

3.2 Distribution of research fields

3.2.1 Distribution of research area and research organization

The regional distribution of research indicates that EP and RR, as distinct concepts within the Chinese context, have the highest number of publications in China, exceeding 140 articles. To facilitate analysis, we categorized the top 20 issuing institutions based on the volume of relevant articles published by the first author's institution (Figure 5). These institutions primarily engage in regional ecological construction, agricultural and rural development, and sustainable development within higher education and advanced research institutes. Many of these institutions are situated in areas where national EPVR mechanisms are being piloted or are actively investigating themes related to EPVR and RR. For instance, Zhejiang Agricultural and Forestry University, Fujian Agricultural and Forestry University, Nanjing Forestry University, Shandong University, Jiangxi Agricultural University, and Guizhou Normal University. There is a clear overlap among the institutions studied about EPVR and RR, particularly regarding research focus, funding sources, professional networks, and geographic proximity.

3.2.2 Distribution of content

The literature reviewed in this study is categorized into four primary research directions: EPVR, EI, the relationship between EI and RR, Models of RR, and pathways for EPVR. Additionally, a small portion of the literature offers insights related to the study topic, but due to unclear categorization, it is classified as "other research" (Figure 6). Notably, the EPVR is currently the predominant research focus in this field, comprising 43.93% of the total literature. This body of work primarily addresses the conceptual framework, classification types, value accounting, and mechanisms for realization. EI constitutes 21.50% of the literature, mainly exploring the theoretical frameworks and the integration of industrial and ecological transformations. The relationship between EI and RR accounting for 12.77%, focusing on effective coupling and optimization strategy for eco-industrialization and industrial ecologization. Meanwhile, models of RR and pathways for EPVR represent 15.89% of the literature, emphasizing model effectiveness and exemplary cases, as well as distilling and summarizing pathways for EPVR within current RR models. In summary, research on EPVR and RR at a single level is maturing. However, the overall research on their synergistic effects and mutual feedback is still in the developmental stage, with a predominant focus on theoretical studies and the synthesis of practical experiences.

3.3 Research progress and landmark results

3.3.1 Ecological product value realization

1 By categorizing and exploring the subject of ecological carrying capacity and ES supply and demand, the relationship between the subject and object of EP supply and types clarified.

The evaluation of EP supply capacity primarily involves two key components: ES themselves and the ability to provide public goods.

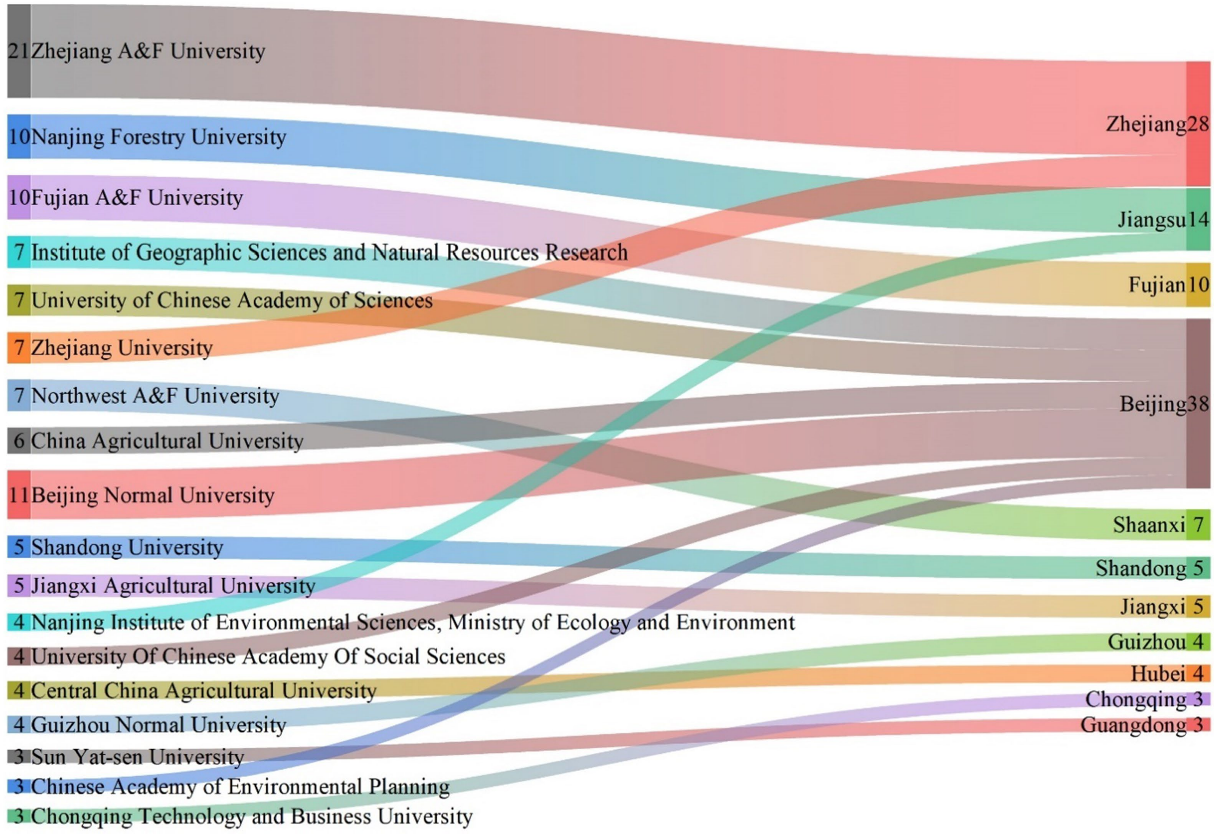

FIGURE 5
The distribution map of research area and research organization.

The notion of "ecological carrying capacity" was first introduced by Wackernagel and Rees (1998), suggesting that ecological carrying capacity reflects the potential provision of ES. Burkhard emphasized the significance of environmental capacity in the supply of ES by considering both supply and demand aspects, highlighting that the development of this supply should be grounded in availability and utilization (Burkhard et al., 2012). Schröter identified a distinction between potential provisioning and actual provisioning, noting that while potential provisioning does not always translate into actual provisioning (Schröter et al., 2014), overcoming spatial dependencies can facilitate this transition. In terms of resource distribution, regions abundant in ecological resources are the primary sources of EP supply, with ecologically resource-scarce regions serving as recipients, and a regional equilibrium is maintained through market exchanges (Sun et al., 2015). Regarding the stakeholders involved, EP supply encompasses various levels of government, communities, individuals, and other social entities as suppliers, while all individuals and businesses that consume EP act as recipients (Lin, 2016; Li et al., 2023; Bernardino et al., 2024).

The scientific promotion of comprehensive control measures for KD, alongside the preservation of the ecosystem's authenticity, integrity, and stability, is essential for ensuring ecosystem productivity, species richness, and ecological service capacity. Given the inherent vulnerability of the KDC, it remains crucial to adhere to the core governance principle of ecological restoration. This involves assessing the ecosystem's self-demand capacity to evaluate the supply capacity of EP. Furthermore, fostering direct free trade, horizontal compensation, and the flow of resources among KD areas at varying levels is an effective strategy for achieving regional balance and enhancing the supply capacity of ecosystem services.

2 By conducting out EP value accounting in pilot areas, clarified the advantages and limitations of various methods, as well as the spatial and temporal dynamic patterns of EP value across different scales.

Research on ES has established a significant foundation for evaluating the value of EP. various methodologies have been developed, including biophysical modeling, the equivalent factor approach, the "ecological element" approach, the functional value approach, and the statistical reporting approach. The findings of Costanza and Daily on ES have garnered considerable attention from the international community (Costanza et al., 1997; Daily, 1997). Subsequently, initiatives such as the Millennium Ecosystem Assessment (MA) and the System of Environmental-Economic Accounting Ecosystem Accounting (SEEA-EA), represented by organizations like the United Nations, have been implemented. Building on this research foundation, numerous Chinese scholars have conducted studies that explore different spatial scales and ecological elements to assess the value of terrestrial ES in China. They have systematically analyzed the spatial patterns and evolutionary characteristics of different ecological types and services across the

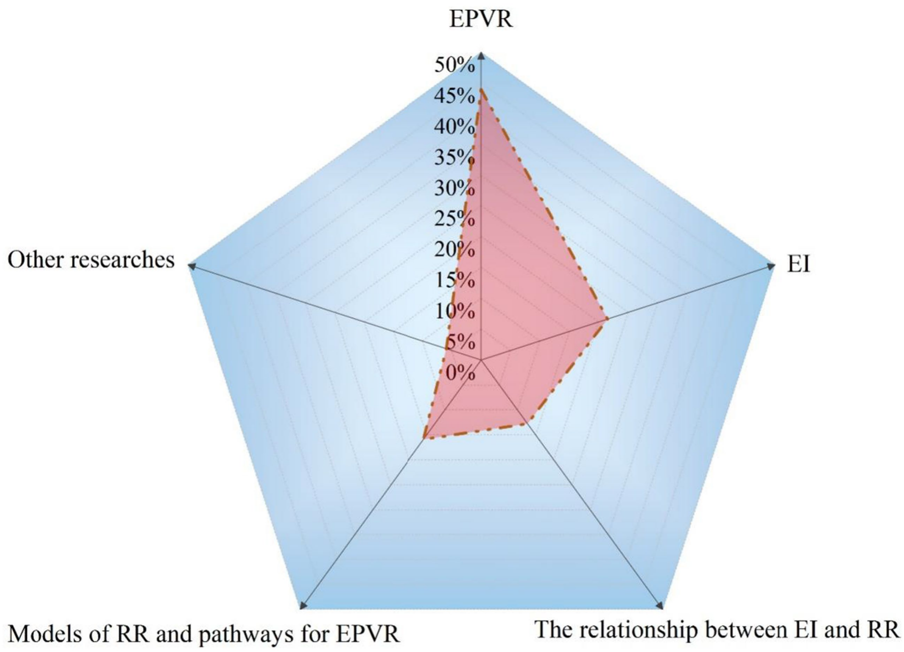

FIGURE 6
Research content distribution.

country (Xie et al., 2008; Fu et al., 2009). In 2003, Zhiyun Ouyang introduced the concept of Gross Ecological Product (GEP), defined as the total value of end-use ES used to measure ecosystem functioning (Ouyang et al., 2013). This concept was integrated into the SEEA-EA framework as a composite indicator in 2021. The same year, China issued the "Opinions on Establishing Mechanisms for Realizing Value from Sound Ecological Products" through the General Office of Central Committee and General Office of State Council, marking the beginning of a comprehensive pilot project for EP accounting in China. Pilot projects at all levels are now fully launched (Cai et al., 2021), with local authorities independently exploring and implementing the GEP accounting system.

The assessment of the value of desertification ES has made significant progress. Numerous scholars have assessed the value of ES functions of different grades of KDC ecosystems (Hu et al., 2020; Xu et al., 2022), and analyzed the relationship with land use changes (Chen W. et al., 2021; Zhang S. et al., 2021). The fragmented and decentralized landscape pattern of the KDC area indicates that the value of EP has obvious spatial differences. Exploring the value of EP within small scales, small watersheds, and small patches, and reflecting the value in an intuitive monetary form are conducive to enhancing the precision of the accounting results.

3 Based on the categorization and valuation attributes of EP, four mechanisms have been proposed: ecological property rights trading, value-added ecological governance, ecological industrialization management, and ecological protection compensation.

The process of EPVR involves various stakeholders such as the government, market, and society. At its core this process entails the transformation of use value into transaction value (Gao et al., 2022; Chen et al., 2024). Four paths have been proposed to elucidate the essential characteristics of EP value transformation, including ecological resource indicators and property rights transactions, ecological governance and value enhancement, ecological industrialization management, and ecological protection compensation, based on the mechanisms of EP operation and development, protection compensation, and value realization.

Ecological resources indicators and property rights trading, combined with the role of the government and the market, have been used as a core approach for natural resources property rights trading and government-controlled indicator limit trading (Xuan et al., 2020). For example, Chongqing municipality has expanded the ecological function of land tickets by allowing urban and rural land elements to circulate in a market-oriented manner, thus realizing the value of EP (Su et al., 2022). The U.S. conservation easement system protects farmland from development through fees and tax exemptions, safeguarding the ecological environment without altering land ownership and exemplifying the transfer of resource property rights (Claassen et al., 2008).

Ecological governance aims at enhancing value through activities such as ecological restoration, environmental management, and comprehensive development. This includes restoring or utilizing ecosystem structure and function while developing eco-agriculture, eco-industrial, and eco-tourism based on local conditions to increase the supply of EP and achieve premium benefits from ecological carriers (Zhang L. et al., 2021).

Ecological industrialization operation is a market-led approach that focuses on developing sustainable operational EP for trade (Liu et al., 2024). Lishui city serves as an example where they transform their advantages in ecological resources into commodity advantages and brand value gains by releasing ecological dividends through resource utilization (Wu et al., 2021). Shibadong village in Hunan province leverages local agricultural and forestry resources to develop its cultural services industry, serving as a model for rural mountain areas to achieve economic growth (Nie et al., 2022).

Ecological protection compensation primarily involves government-led purchase of public EP (Li G. et al., 2021). The Dongjiang source area in Jiangxi province establishes compensation standards based on environmental protection costs and watershed construction expenses effectively addressing socioeconomic imbalances between regions (Wu et al., 2019). Brazil's fiscal transfer payment system, linked to the success of ecological protection efforts, has greatly increased local governments' motivation to pursue environmental initiatives (Verde Selva et al., 2020).

The ES of KDC and the products derived from them exhibit significant territoriality and scarcity. A comprehensive list of EP should be established to foster synergy among products and industries across various ecologically fragile grades, thereby facilitating the selection of realistic pathways in a targeted manner. The social attributes of the KDC ecosystem imply that enhancing the transformation efficiency of EP value must be grounded in the characteristics of the integrated natural-social system. Furthermore, different types, attributes, and functions of EP should be categorized according to the varying grades of KD and the corresponding control measures. This categorization will aid in selecting appropriate pathways, such as property rights trading, enhancing control measures to promote premiums, industrialized operation, or ecological compensation.

3.3.2 Ecological industry

1 Through the study of the quaternary industry of EP, we have clarified the evolutionary logic of theoretical thinking, tracing its development from the realization of EP to the formation of ecological industrialization, and revealed that EI can enhance the efficiency of ecological governance and strengthen the endogenous power of the regional economy.

Among the various types of EI, ecological agriculture prioritizes ensuring national food security and safeguarding the rights and interests of farmers. It follows the "ecological +" approach, providing an effective strategy for advancing agricultural industrialization (Wang Y., 2019; Zhang K. et al., 2023). Wang Jinnan initially introduced the concept, characteristics, formation mechanisms, and constituent elements of the quaternary industry of EP (Wang et al., 2021a), and proposed a policy guarantee mechanism to support its development. Facilitating the market-oriented supply of EP contributes to building and extending the industrial chain, while enhancing the market-oriented mechanism promotes further diversification of EP supply (Li L. et al., 2021). For instance, in the karst region, the development of EI serves as a crucial initiative for KDC, which is essential for improving resource allocation, extending the industrial chain, enhancing product quality, addressing rural development issues, improving production and life quality, and reducing rural non-point source pollution (Kong and Lu, 2019). By advocating for the restoration of vegetation landscape and promoting sustainable ecological derivative industries, we can integrate ecological governance with rural development, bolster the regional economy, and promote "production, living, and ecological" development in the region (Wang et al., 2020). Both theories validate the interconnectedness between the value of EP and EI, emphasizing their mutual dependence.

2 Research on EI integration has enhanced farmers' economic income, improved the efficiency and quality of ecological agriculture, expanded the industrial security system, and facilitated the agglomeration of ecological agriculture elements as well as the extension of the industrial chain.

Industrial cross-integration is the right way to improve the level of agricultural development, agricultural production efficiency, and farmers' income. It helps to encourage agricultural producers to expand their production scale and extend the industrial chain (Li et al., 2018; Xiang et al., 2022). Switzerland has established a sustainable mountain ecotourism route by effectively leveraging ecological resources and integrating local cultural and landscape characteristics (Reynard et al., 2021). Denmark has utilized its industrial strengths to prioritize environmental protection. By adopting the ecological three-dimensional breeding method, it has tackled pollution in breeding and become a global leader in the pig industry (Jensen et al., 2018). In Asia, Japan and South Korea began to carry out research on rural industrial integration in the 1990s (Otsuka and Banerjee, 1998). The upgrading of the consumption structure among urban and rural residents in China has stimulated supply-side structural reform in agriculture, which, in turn, has facilitated the extension of the agricultural industry chain and enhanced integration within the industry (Xing and Ye, 2023). By promoting the expansion of agricultural production scale, fostering technological innovation, and enhancing personnel training, a conducive policy environment for industrial integration can be established (Liu et al., 2022; Chen et al., 2024). Concurrently, the policy system for EPVR is continually evolving. However, factors such as the development environment, developmental stage, and regulatory framework impose limitations on the market-oriented mechanisms in effectively addressing pollution control and emission reduction (Andreoni and Tregenna, 2020; Wang et al., 2023). In summary, the realization mechanism of market-oriented ecological value is in an auxiliary position in the environmental governance policy system at this stage. In the long run, environmental regulation will still play a central role in the environmental governance system.

The EI of KDC is characterized by both inheritance and scarcity (Bajec and Kranjc, 2022). As market demand expands, the development mode can be transformed through the support of agricultural technology innovations. Additionally, the utilization of Internet information platforms can catalyze the gradual establishment of a cooperative mechanism among multiple stakeholders, synchronizing economic benefits, providing ecological compensation, sharing production risks, and fostering continuous innovation. Concurrently, as the environmental governance system improves and government supervision becomes more effective, the impact of ecological restoration on the productization, scaling, and industrialization of ecological resources is expected to increase gradually.

3.3.3 The relationship between ecological industry and rural revitalization

1 Studying the interaction mechanism between ecological agriculture and other industries, reveals EI has a significant positive promoting effect on RR.

The ultimate goal of the EI is to optimize the efficiency of industrial activities while promoting sustainable and coordinated ecological development. Furthermore, the advancement of EI offers both theoretical support and a coherent framework for RR (Wang and Liu, 2023). Integrating smallholder production into the modern agricultural development system and promoting the multi-dimensional expansion of the agricultural industrial chain can significantly enhance the development of the EI (Goswami et al., 2023). By leveraging community support and improved organizational and ecological resource management can drive supply-side agricultural reform, optimizing resource allocation and fostering a healthy production system with fair resource distribution (Phoochinda, 2014; Wang S., 2019). In the tourism industry, enhancing residents' understanding of the impact of rural tourism development, while integrating this knowledge with the realities of a degraded ecosystem, serves as an effective strategy for rural areas to engage in the ongoing management of ecological governance (Chai et al., 2021; Shen and Chou, 2022). Resource endowment and cultural tradition, governance structure and autonomy tradition, elites, and social capital are the four important conditions to promote the endogenous power of rural EI revitalization (Guo et al., 2022; Peng et al., 2023).

The revitalization of the EI requires the involvement of both the government and the market (Liang et al., 2024). Optimizing the allocation of resources in industrial activities through technological innovation enhances the circulation and turnover of social-ecological services (Gan et al., 2022; Yu et al., 2022). Furthermore, EI serves as an effective means of facilitating the transition of farmers toward sustainable livelihoods (Paul and Vogl, 2013; Jhariya et al., 2021). While EI may not serve as the primary source of income for farmers during the transition from poverty alleviation to RR (Zheng and Zhou, 2020), it represents a viable pathway for long-term economic and ecological sustainability. Therefore, in the process of transforming traditional industries ecologically, it is essential to consider the positive impact of integrated industrial development on the establishment of EI.

The ecological vulnerability of the KDC region is notable, with the potential to create a detrimental cycle of "ecological deterioration leading to increased poverty." To address this issue, A typical KDC area has already formed an EI model, establishing a positive "ecology-economy" system by integrating "forestry, agriculture, and animal husbandry" in a mutually beneficial manner (Figure 7). This model not only aids in combating ecological decline and supports the RR strategy but also ensures the sustainable management of rural ecological resources (Tang et al., 2023). Furthermore, it promotes the efficient conversion of EP value, thereby laying a solid foundation for the growth of rural industries and improving farmers' livelihoods.

2 The research on the ecological industrialization of rural resources has elucidated the intrinsic relationship between industry, culture, talent, and coordinated ecological development. Furthermore, it has proposed ideas and directions for developing ecological industrialization.

The development of EI is a new driving force to meet consumption upgrading, provide EP supply, build livable environments, and maintain the regional sense of locality (Wang and Liu, 2020; Huang et al., 2022). The recognition and utilization of local resources in rural areas constitute a vital means of livelihood for these communities, serving as a catalyst for the revitalization of cultural industries (Huang et al., 2020a). Currently, RR is facing the dilemma of lacking the main body, carrier, and endogenous driving force. To address these issues, adjustments need to be made from four key areas: refining local culture, fostering an endogenous driving force, adhering to comprehensive governance principles, and optimizing the target service objects (Zhou and Zheng, 2022). The prominent characteristics of high-quality development include a distinguished industrial culture, noticeable format advantages, high-quality product supply, significant industrial effects, and green development quality (Yeh et al., 2021; Shen and Chou, 2022). Talents play a crucial role in RR, creating a sustainable ecology for rural innovation and entrepreneurship (Cui et al., 2023). In addition, with the rise of more and more people returning to their hometowns to start businesses, the concentration of resources and environmental adaptability of key industries have been improved, promoting the expansion of the market and the circulation of EP (Zhang and Wu, 2021; Zhang G. et al., 2021). Meanwhile, cultivating local college students, returned college students and returned farmers has become an important potential group for implementing the RR strategy, injecting new vitality into economic development (Jia et al., 2020; Bao et al., 2022; Yin X. et al., 2022). Therefore, following the law of evolution and development of the education ecosystem, innovating the discipline of ecological agriculture engineering (Fu et al., 2021), and building a perfect innovation and entrepreneurship ecosystem are important ways to help talents and industrial development(Miles and Morrison, 2020).

Retaining local talent is a crucial strategy for promoting ecological industrialization and RR. In karst regions, villages often exist within environments characterized by varying karst landforms and differing levels of KD, leading to significant regional disparities. However, these areas are plagued by the "three left behind" (children, elderly, and women) phenomenon, as well as social hollowing out and atomization. Based on national support for rural areas, it is essential to effectively utilize local resources such as restricted land to provide policy and technical assistance to "backbone farmers" who have not yet entered the city to obtain and expand production resources. It also provides space for the survival and development of the first generation of migrant workers returning to their hometowns for elderly care, fully leveraging the role of rural areas as stabilizers and as a way out for farmers.

3.3.4 Models of rural revitalization and pathways for ecological product value realization

1 Through the research on the "ecological +" model dominated by the government, market, and society, a RR model based on the EPVR and the support of EI has been established.

Eco-product has the dual attributes of public products and private products, which determines that the EPVR is not limited to a single

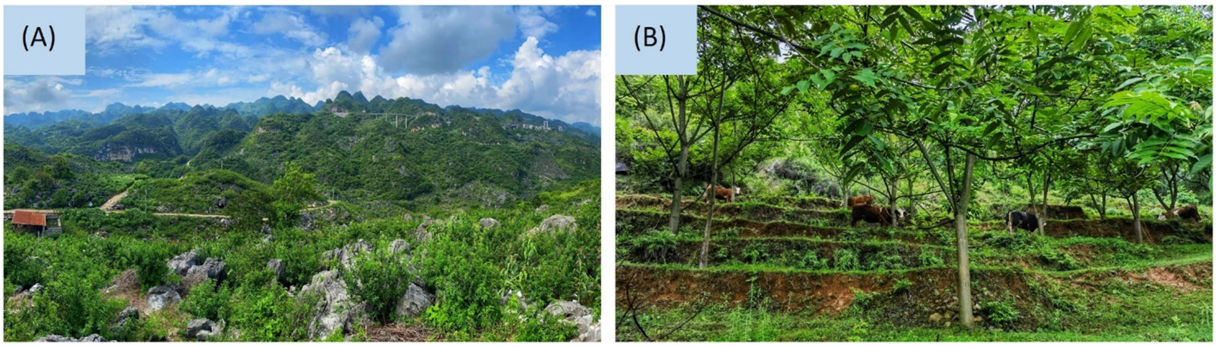

FIGURE 7
EI allocation of "forest-agriculture-animal husbandry" in KDC. **(A)** Mugong village, Huajiang town, Guanling county, Guizhou province, China; **(B)** Yongfeng village, Salaxi town, Qixingguan district, Bijie city, Guizhou province, China.

model (Chen et al., 2022). From the perspective of the leading initiator, EPVR models can be categorized as government-led, market-led, or social-led (Qiu and Jin, 2021). The establishment of national parks in provinces such as Hainan, Gansu, and Sichuan exemplifies a typical model of EPVR within the context of national parks. In local practice, Xianju County in Zhejiang Province has developed a national park product brand value-added model characterized by green conventions, green asset lists, and green currencies (Zang et al., 2021), representing a preliminary realization of value transformation. Nanping City in Fujian Province has implemented a "decentralized input and centralized output' approach, based on the operating model of banks, and constructed a forest ecological bank model. It integrates and optimizes fragmented and decentralized forestry resources, and opens up the channel for ecological resources to be capitalized (Huang et al., 2020b). The Three Rivers Source region has formed a "water bank" trading model by clarifying the trading subject, object, and trading system of aquatic (Jiang et al., 2021). Models of EPVR with different types and attributes have effectively contributed to the formation of EI.

The arid landscapes found in karst regions exhibit inherent limitations, necessitating a comprehensive analysis of the interactions between regional constraints at various levels of the KDC environment and EI decisions. Additionally, it is crucial to consider the ecosystems' capacity to withstand disturbances and self-repair under harsh climatic conditions (Coulibaly et al., 2017). The EI framework can be optimized according to the vegetation attributes unique to the karst environment. To enhance the overall ecological landscape, the selection and distribution of suitable plant species in karst regions should be refined to minimize ecological niche overlap and enhance the efficient utilization of natural resources (Liu et al., 2021; Yang X. et al., 2021). This approach will ensure a sustainable and consistent provision of ES. The evolution of ES, including distinct forests, mixed agricultural forests, grasslands, farmlands, and settlements that arise following the implementation of KDC engineering interventions, will be guided by the enhancement of EI through optimization efforts.

2 Based on the EI, there is a notable trend advocating for a development model that integrates governmental support, farmer leadership, and market mechanisms. This approach promotes the efficient allocation of resources, including human capital, land, and financial assets.

Rural revitalization must respect the inherent value of the local, should be based on the local value system, focus on industrial prosperity, and improve the level of people's livelihood security (Xie and Chen, 2022). Drawing upon the ecological tourism industry to innovate the EI and RR development model. The proposed model emphasizes "ecological leadership with co-creation between upper and lower levels," "villager-oriented approaches that promote win-win outcomes both internally and externally," and "culture-rooted strategies that foster symbiosis between hosts and guests" (Li Y., 2019). The non-agricultural industry-driven type, agricultural product processing industry-driven type, agricultural tourism integration-driven type, industrial integration-driven type, and planting structure optimization-driven type are significant driving forces behind the development of rural EI in China (Kong and Lu, 2019). In response to the challenges posed by rural decline and structural differentiation—exemplified by the migration of elites to urban areas, the aging population remaining in rural locales, and the subsequent hollowing out of villages—promoting the EI as a strategic measure has emerged. This initiative provides targeted support for the "people-land-money" framework systematically (Li T., 2019), it has basically formed an EI model and an EPVR path combining government support, farmer-led, and market operation.

In the KDC region, where the conflict between human populations and land resources is pronounced, local residents have developed a "family livelihood model based on intergenerational division of labor and a combination of work and farming" to alleviate economic pressure. However, the persistent urban–rural divide, urban-centric development strategies, citizen-focused distribution systems, and heavy-industry-oriented industrial structures have exacerbated the urban–rural gap. This situation has intensified conflicts related to urban–rural disparities, decentralized land management, and the disconnect between population and land resources. To address these challenges, there is an urgent need for targeted scientific research to explore effective RR models in the KDC district. Additionally, establishing an EPVR-based EI support system is crucial. These studies require not only in-depth analysis of natural sciences such as geography and ecology but also a comprehensive consideration of interdisciplinary perspectives, including sociology and economics. This approach aims to provide a scientific foundation and guidance for resolving the conflict between human populations and land resources and achieving sustainable development.

3 By fostering EI in ecologically fragile areas to restore ecology, the EI pattern of mountains, rivers, forests, fields, lakes and grasslands has been constructed. This initiative has laid the groundwork for a sustainable development model centered on ecological derivative industries.

The high coupling between ecologically fragile areas and poverty in terms of geographical distribution, suggests that unreasonable human activities can easily lead to ecological degradation. Embedding production behavior into ecology and cultivating villagers' awareness of common economic interests are crucial for the formation and sustainable development of eco-agriculture (Yan, 2019). In the Loess Plateau, a sustainable RR model has been implemented in the hilly and gully regions by developing fruit industries and medicinal ecological parks at the mountaintop, establishing grass-shrub composite ecosystems on the mountainside, promoting ecological agriculture in the foothills, and implementing scientific reservoir construction at the sources of small watersheds to provide drip irrigation water for the mountain medicinal orchards and facility agriculture (Li Y. et al., 2021; Qu et al., 2023). Additionally, projects aimed at combating KD have been initiated in southern China, with efforts directed towards the industrialization and development of ecological and derivative industries (Cao et al., 2016; Jiang et al., 2016; Wang et al., 2016; Xiong et al., 2016), These initiatives have begun to take shape and serve as a typical example of EI.

3.4 Key scientific issues to be addressed

1 To address the scientific issue of the mutual feedback between the monetization results of the EP value and the actual economic value, a standardized assessment and accounting system can be developed to establish a clear theoretical framework, thereby clarifying the direct relationship between ES, GEP, and EP values.

The current EP value accounting generally directly applies the ES function value accounting system, which has problems such as unclear accounting objects, overlapping with other product values (Hao et al., 2022). In addition, the varying pricing methods for EP lead to considerable uncertainty in the accounting results, suggesting that the existing accounting outcomes do not reflect traditional economic value. In contrast to GDP, the value calculated by GEP is not fully realized in the market, and the majority of its absolute value composition comes from estimates of alternative markets and virtual markets (Zheng H. et al., 2023). When evaluating the value of EP, most only consider the natural and artificial value of resources. However, the intergenerational compensation value and external compensation value are often overlooked (Ouyang et al., 2020). Therefore, further clarifying the relationship between EP and EI, value and price, distinguishing potential and final value, forming a unified EP value accounting principle, determining the indicator system based on the screening principle, providing a benchmark for defining the accounting scope. Additionally, the focus will be on measuring the degree of EPVR across various regions, using indicators such as conversion rate and economic contribution rate (Yu F. et al., 2020), can laying a theoretical foundation for the evaluation of the effectiveness of EPVR.

Karst desertification predominantly takes place in tropical and subtropical climate zones characterized by warm and humid conditions, where precipitation and high temperatures coincide within the same season. This phenomenon is further exacerbated by the presence of extensive outcrops of pure carbonate rocks, pronounced karst processes, steep and fragmented topography, and well-developed karst landforms at both surface and subsurface levels, resulting in the formation of complex and diverse horizontal and vertical ecological niches (Zhang et al., 2016). The land within these areas is fragmented, demonstrating a patchy distribution (Figure 8). A critical question arises regarding how to measure the value of ecosystem regulation services and the market value after artificial investment and brand enhancement on a micro-scale. Additionally, the definition of these values represent an important direction that urgently requires exploration. Furthermore, the ecological derivative industries of KDC mainly rely on material products, but research on regulation services and cultural services is still relatively lacking. However, these two factors are important indicators reflecting the karst ecosystem and are also the main components of EP. Using GEP as the calculation result makes it difficult to reflect the external value of regulation and cultural services, and it is also difficult to reflect their actual economic value.

2 Regarding the issue of EP transformation and enhancing value-added and premium effects, the value assessment and trading mechanism of tradable ecological elements can be elucidated through the coordinated establishment of the natural resources property rights system.

Eco-product have the combined characteristics of exclusivity, competitiveness, non-exclusivity and non-competitiveness. Traditional ecological material products can be traded in the market, but there are problems such as multiple links, high costs, information mismatches, and weak branding, limit the potential for an "ecological premium" associated with EP (Liu et al., 2019). For instance, ecotourism faces challenges related to an insufficient supply of both human and artificial capital, which hinders product development, marketing, and brand building (Samal and Dash, 2023). Regulatory services and derivatives possess strong external and public attributes but lack a distinct identity in ownership management. The scope of ownership is narrow, the boundaries are fuzzy, and the supply–demand relationship is unclear, complicating market transactions (Tao et al., 2018). To address these challenges, it is essential to register the ownership of natural resources, clarify the negative list of natural resource assets, innovate the implementation forms of national and collective ownership of natural resources, explore the separation of ownership and use rights, and moderately expand the usage of use rights such as transfer, lease, guarantee, and equity investment, establish an accounting mechanism for natural resource assets, including water, land, forests, socio-economic assets, and liabilities.

The principle of ecological restoration in KDC underscores that the realization of EPVR in the region hinges on maintaining ecosystem health. Initially, pilot projects should focus on compiling natural resource balance sheets and establishing an inventory of natural resource assets, alongside socio-economic assets and liabilities. By comprehensively understanding the ecosystem's health requirements, it is essential to clarify the classification standards and statistical

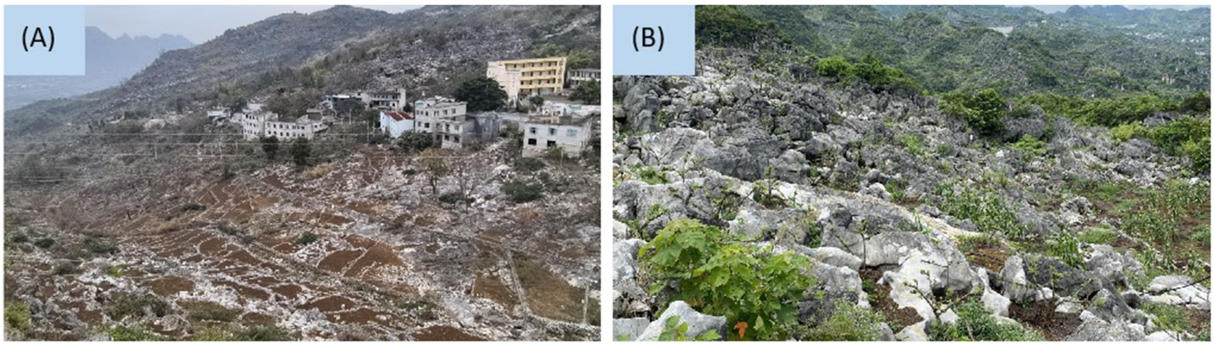

FIGURE 8
Broken and scattered landscape pattern of KD areas. **(A)** Chaeryan village, Beipanjiang town, Zhenfeng county, Guizhou province, China; **(B)** Bashan village, Huajiang town, Guanling county, Guizhou province, China.

norms for ecological products, which will inform the utilization plan for EP. Moreover, technologies such as remote sensing and GIS can be used in KDC areas with different sizes and landscape types. For example, future landscape changes can be simulated based on historical data to assess EP values and thus support land use management decisions (Chen and Ning, 2024; Xiong and Li, 2024). These predictive models include system dynamics model, CLUE-S, CA-Markov, FLUS, etc. These forward-looking technologies, combined with big data analysis techniques and field-proven data, can effectively study the accuracy of the results. Based on this, these methods will not only improve the production and supply capacity of ecosystem products but also offer clearer proposals for sharing and recommending mechanisms for the value of ecosystem products across diverse types and ownerships, thereby establishing a robust foundation for further quantifying the level of EI.

3 To address the issue of establishing a robust ecological protection compensation mechanism, it is essential to clarify the supply–demand relationship among the various participating entities and broaden the scope of participation to include multiple stakeholders.

Ecological compensation is a crucial pathway for EPVR. Currently, vertical transfer payments from the central government to local governments, as well as from provinces to cities and counties remain the primary approach. This is largely achieved through ecological function zone transfer payments and special transfer payments, which include those for forests, grasslands, and wetlands. However, several issues persist, including limited compensation efforts, compensation funds that do not adequately reflect regional differences in EP supply capacity, and low utilization rates of these funds (Li, 2020). Nonetheless, the horizontal ecological protection compensation established between regions is still in the pilot phase and may encounter sustainability challenges. Additionally, a variety of compensation methods have yet to be developed (Gao et al., 2023). Consequently, there is a pressing need to enhance the ecological protection compensation system. In optimizing the government's purchasing strategies, it is essential to refine the standards for both horizontal and vertical diversified protection compensation, conduct regular benefit evaluations, and establish incentive and constraint mechanisms that link the effectiveness of ecological protection with fund allocation.

The ecological patterns and human activities in KDC areas are unique. Based on stakeholder input and continuous efforts, a watershed horizontal ecological compensation mechanism has been explored and is fundamentally constructed, characterized by wide coverage, strong comprehensiveness, strong incentives, and karst governance features (Hao et al., 2019; Tian et al., 2019). However, due to the distinct ecological patterns and human activities, stakeholders in various environments exhibit diverse behavioral choices. To address this issue, it is essential to clarify the supply and demand system involving government entities, individuals, enterprises, and NGOs. While enhancing the production and supply capacity of EP, it is also necessary to propose a value realization mechanism tailored to different types and attributes. This includes improving standardized institutional systems, clarifying the interrelationship between beneficiary areas and protected areas, increasing horizontal ecological compensation standards, and providing a significant pathway to enhance the sustainability and 'hematopoietic' compensation capacity of protection compensation. This can be achieved by expanding diversified ecological protection compensation methods, objects, and scope.

4 Aiming at the scientific issue of how to realize diversified integration of eco-industries and expanding the industrial chain, we will establish a comprehensive industrial supporting system through research on concerted action-service-sharing-regulation, and promote the diversified and coordinated integration of EI and local characteristic industries.

The key issues constraining the development of the current EI include its small scale, single-product structure, short industrial chain, low integration among primary, secondary, and tertiary industries, insufficient brand influence, and weak market risk resistance. During the EI development process, excessive reliance on government investment and a lack of industrial support have resulted in a deficiency in innovative driving forces within ecological culture, thereby weakening the impetus for economic development (Li et al., 2020a). Establishing an ecological industrialization operation system and a capital trading market system is essential for addressing the challenges in trading (Shi et al., 2023). The scale, transformation, and structure of the EI are critical for realizing the value of EP (Wang et al., 2021b). Focusing on the main body, value, transaction, industry, capital, technology, and other elements of industrial development,

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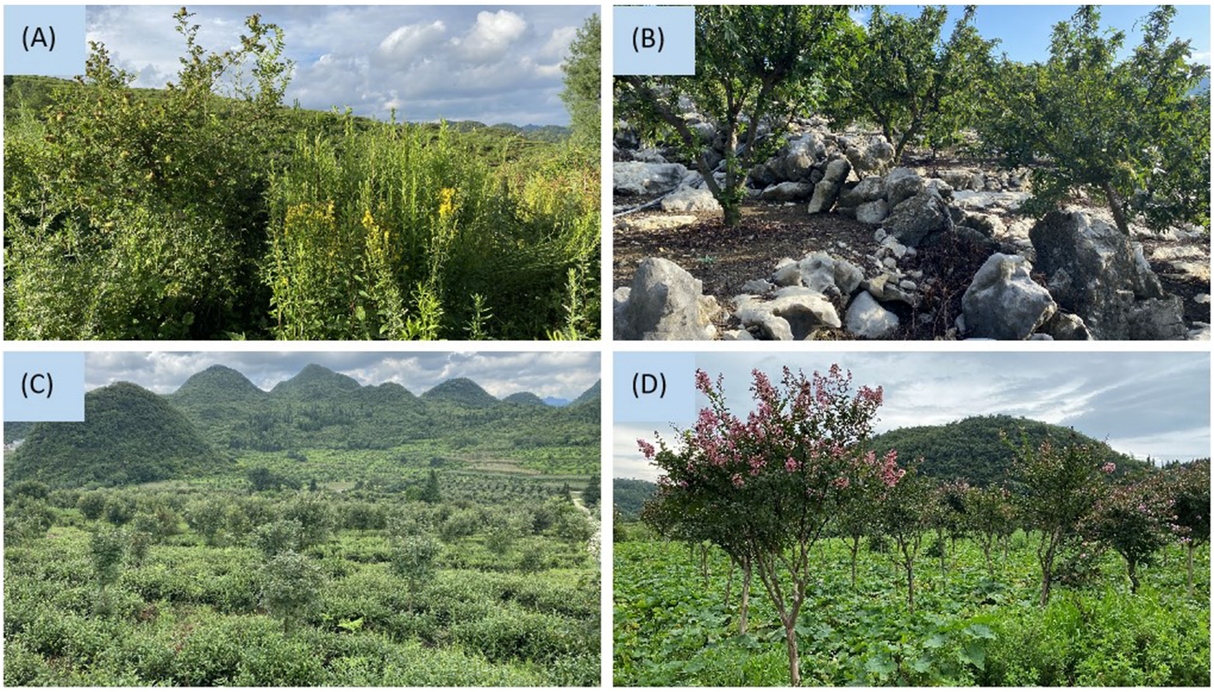

FIGURE 9
A significant number of plant characteristic resources are cultivated by KDC. **(A)** *Rosa roxburghii*-Chinese herbal medicine agriculture and forestry planting, Longfeng village, Salaxi town, Qixingguan district, Guizhou province, China; **(B)** Zanthoxylum bungeanum planting, Mugong village, Huajiang town, Guanling county, Guizhou province, China; **(C,D)**, Acer truncatum planting and vegetable-Bauhinia planting, Minle village, Hongfenghu town, Qingzhen city, Guizhou province.

jointly promote the integration of EI (Li, 2023; Liu et al., 2023), and cultivate and develop ecological derivative industries that are compatible with the direction of ecological protection and restoration.

In the process of KDC, a significant number of EP focused on ecological restoration have been cultivated. However, challenges persist, including low industrial integration and a lack of a comprehensive industrial chain in product development and industry formation. Regarding engineering layout, the primary emphasis remains on closed mountain afforestation, artificial afforestation, degraded forest restoration, grassland improvement, and small-scale water conservancy projects. There is a predominant focus on employing a single-scale management model at the same location, with minimal consideration for intensive management and industrial integration from a regional or watershed perspective. The reliance on ecological restoration models characterized by a singular structure and primary industries hinders the effective enhancement of ecosystem stability and ecological services. Therefore, it is essential to enhance the observation and monitoring of multi-factor and inter-industry interactions and integration within the EI, shift the focus from a single to a multi-industry integration perspective, and promote the formation of an EI system in KDC areas.

5 In response to the scientific issue of how to improve the quality and efficiency of products at the primary end of the ecological chain to stabilize marketability, the theoretical support for enhancing the quality and efficiency of ecological primary products can be strengthened by advancing research on the mechanism of aggregating a single element of ES to a multifaceted EP.

The research on EI and RR primarily concentrates on rural tourism, ecological agriculture, and the ethnic characteristics of rural cultural industries. However, challenges such as resource capitalization, the transformation of capitalization, ecological compensation, and the establishment of market-oriented operational mechanisms for EP hinder the maintenance and enhancement of value over time (He and Wang, 2023; Peng et al., 2023). In comparison to urban areas, the development of rural financial markets is relatively underdeveloped, facing obstacles including an incomplete financial service system, insufficient product innovation, and a notable lack of skilled personnel (Khan, 2023; Zheng Y. et al., 2023). The excessive focus on short-term economic gains, coupled with the neglect of long-term ecological benefits and inadequate supervision significantly restricts both ecological industrialization and industrial ecology. Furthermore, the pronounced homogenization and variability in the quality of EP impede their industrialization and ecological integration. Therefore, the integration of ES with ecological governance practices is essential for EPVR and advancing RR.

Currently, the Karst regions have developed a configuration model for the KDC project aimed at restoring forest and grass vegetation, with a particular emphasis on the specialty forest industry. This model encompasses a core framework that includes "typical protection forest—high-quality fruit and economic forest—local medicinal herbs—specialty flowers and seedlings—suitable pasture—EP" (Figure 9). Consequently, the primary plant resources utilized for karst ecological management are predominantly bulk economic plant resources. Building upon this foundation, efforts are directed towards the rational allocation of land resources, industrial optimization, and research into the quality, in-depth development, and utilization of plant resources for KDC that aim to ensure the sustainable development of both ecological and economic benefits.

6 Aiming at the issue of how to build a professional operation system for the "ecological bank" model, through the construction of a platform for ecological resource management, integration, conversion, and enhancement, thus revealing the intrinsic driving mechanism of the EP transformation efficiency improvement on the improvement of ecological industrialization operation level.

In recent years, Fujian province, Zhejiang province, and other regions of China have implemented an "ecological bank" model that emphasizes the integration of ecological resources, development of EP, and the realization of value through decentralized input of commercial bank funds and centralized outputs of capital. As a market-oriented innovation mechanism, the "ecological bank" has yielded significant ecological, economic, and social benefits (Cui et al., 2019). However, challenges have emerged during the development process including unclear accountability among departments, low levels of professional operation, insufficient market connections, and the urgent need to establish an integrated operational platform (Sharma and Choubey, 2022). The critical ecological function areas, particularly those represented by karst landscapes, possess substantial potential for ecological regulation services and are vital components of the "ecological bank" model. Therefore, the professional operation system of the distinctive "ecological bank" model, developed during the formation of the EI of KDC, should establish standards, define a unified nomenclature, clarify conceptual meanings, outline operational procedures, and implement risk prevention and control mechanisms. Additionally, it is essential to enhance the supervisory framework and risk management protocols for financial institutions' products and services, as well as to create a platform for the management, integration, transformation, and promotion of ecological resources to improve their utilization efficiency.

7 Regarding the stability and sustainability of rural EI revitalization in ecological restoration and governance, an exploration of local cultural characteristics can illuminate the mechanism for effectively embedding the value of EP into RR efforts.

Currently, several ecological management models have been established in ecological function areas, particularly in KD zones and ecologically fragile regions. These models have demonstrated significant achievements and have begun to show potential for scaling and industrialization. However, challenges remain, including inadequate stability and sustainability of EI, as well as weak follow-up development momentum (Xu and Zuo, 2019; Zhang J. et al., 2019). The characteristics of the karst landscape, influenced by both water erosion and dissolution, result in rugged terrain (Sweeting, 2012). The erodibility of shallow soil in the superimposed surface karst zone, combined with the solubility of rock fractures, complicates the development of traditional agriculture on slopes (Peng et al., 2020). The output of rural agriculture is mainly for household use, with less reliance on market circulation. Projects such as artificial afforestation and grass planting have led to a reduction in regional arable land, but farmers have a strong sense of dependence on traditional agriculture and have fewer alternative livelihood options (Agustono et al., 2021; Ren et al., 2022). While addressing these issues, cultural factors play a crucial role in ecological restoration and economic growth in fragile areas. They enhance community involvement and ecological awareness, thereby strengthening regional socio-economic resilience.

Karst culture, shaped by the long-term interaction between people and nature, exhibits distinct regional characteristics and unique values (Bajec and Kranjc, 2022; Zhang et al., 2022). The special treatment of KD further enriches the cultural cluster defined by the characteristic of "rock," which serves as a core element of rural cultural revitalization in KDC areas. Therefore, it is essential to emphasize the status of residents as the primary agents, aligning with regional realities, exploring local characteristics and folk wisdom, and responding to stakeholder demands. Additionally, it is crucial to implement matching practical long-term industrial projects that can take root in the local area (Wen, 2021). By leveraging the rich social capital and strong personal abilities of regional elites, we can effectively guide villagers in developing industries through division of labor and cooperation. This approach seeks to correct the perception of residents as mere objects of action, instead relying on their subjectivity and developmental motivation, thereby enhancing the endogenous driving force for EPVR.

3.5 Comparison to existing reviews and limitations of this study

3.5.1 Comparison to existing reviews

Prior to this study, many scholars had begun to discuss EPVR and RR separately to address the gaps and connections in perception. For instance, a series of results have been achieved regarding the conceptual connotation, value accounting, green finance, and practical experience summary of EP (Qiu and Jin, 2021; Kong et al., 2022; Yang and Yin, 2022; Qiu et al., 2023; Zhang L. et al., 2023). RR primarily focuses on an overview of urban–rural integration, land consolidation, and the impact of industrial development (Liu et al., 2020; Chen M. et al., 2021; Yang J. et al., 2021; Yang X. et al., 2023; Yin Q. et al., 2022). In the KDC area, a systematic review was conducted primarily from the perspective of ES, emphasizing the revitalization of ecological assets, the manifestation of ecological value, and the development of ecological derivatives within forest, agroforestry, and grassland ecosystems (Xiao and Xiong, 2022; Xu et al., 2022; Yang B. et al., 2023; Yang Y. et al., 2023 Li Y. et al., 2024). These studies, primarily utilizing qualitative analysis and case summaries, have established a solid theoretical foundation for the chain-driven framework we aim to develop, while also providing methodological support for technology utilization and model management in future practice. However, unlike most reviews, our study emphasizes a more systematic and holistic research framework. Therefore, we summarize the relevant milestones and discuss key issues based on the EP, EI, and RR driven chain, offering targeted insights for the sustainable management of KDC achievements in the future. These insights will enhance the cascading framework for ecological restoration of human-land systems in ecologically fragile areas and provide new perspectives on the application of ecological economics in specific geographical environments.

3.5.2 Study limitations

Notwithstanding its contributions to the field, this paper acknowledges several limitations. First, despite employing multiple search engines and screening mechanisms during the literature search process, we encountered challenges related to the complexity inherent in using literature database search engines, the limitations of our search methods, and the influence of unavoidable human subjective judgments. Consequently, the results of our literature search may be somewhat uncertain, potentially leading to the omission of relevant research literature. Second, in the context of the rapidly growing global awareness of ecological issues and the construction of ecological civilization, research on EPVR and RR has emerged as a significant focus. A substantial number of pertinent research papers are published in languages other than English and Chinese, including Japanese, Korean, and French. Future research could address this gap by incorporating multi-language papers and grey literature sources. Additionally, there may be relevant literature that discusses EPVR and RR using terms associated with specific administrative or geographical regions, which we may have overlooked. These factors may have contributed to a reduced number of documents included in our final analysis. However, it is important to note that these uncertainties did not significantly impact the overall direction of the research. In future research endeavors, we intend to improve the application of more objective and scientifically rigorous measurement methodologies and screening mechanisms. This effort aims to yield valuable insights into bridging the gap between karst ecological restoration and protection and the enhancement of human well-being.

4 Conclusion

In this study, a literature search was conducted using the CKNI and WOS databases to analyze and review research on EPVR and RR, resulting in the systematic examination of 321 documents. The main conclusions are as follows: (1) The overall number of annual literatures is increasing, with ongoing theoretical exploration of the concept, value accounting, and value realization pathways of EP and RR constantly deepening. However, practice and theory have not developed in synergy; (2) To address practical challenges such as the difficulty in trading ecological resource rights and interests, the low premium effect of ecological transformation, the pronounced homogenization of EI, and weak linkage and feedback mechanisms with RR, it is essential to explore the mechanisms for realizing the value of EP in KDC areas from the perspective of various stakeholders. This approach can enhance the formation and optimization design of EI and guide rural governance practices; (3) Future research should emphasize interdisciplinary collaboration, considering the unique geographical contexts, habitat characteristics, and socio-economic diversity. It is vital to clarify how the value of EP can be realized at different levels of KDC, which will drive the formation of EI and support RR, thereby addressing critical national and local scientific and technological needs; (4) The management and practice of karst ecological achievements must confront the spatial and temporal dynamics of ecosystems. Comprehensive biological and engineering measures should account for potential future emergencies, such as climate change challenges, as well as the unique characteristics of KD habitats. Scientific planning based on these considerations is an effective strategy for maintaining the sustainability of ES and RR in KDC.

Author contributions

JY: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Methodology, Resources, Validation, Visualization. KX: Writing – review & editing, Conceptualization, Funding acquisition, Project administration, Resources. YF: Writing – review & editing, Data curation, Formal analysis. NY: Writing – review & editing, Validation. ZZ: Writing – review & editing, Visualization. PZ: Visualization, Writing – review & editing.

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Conflict of interest

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

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