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Research Progress and Future Trends in Biomass Energy Spatial Planning

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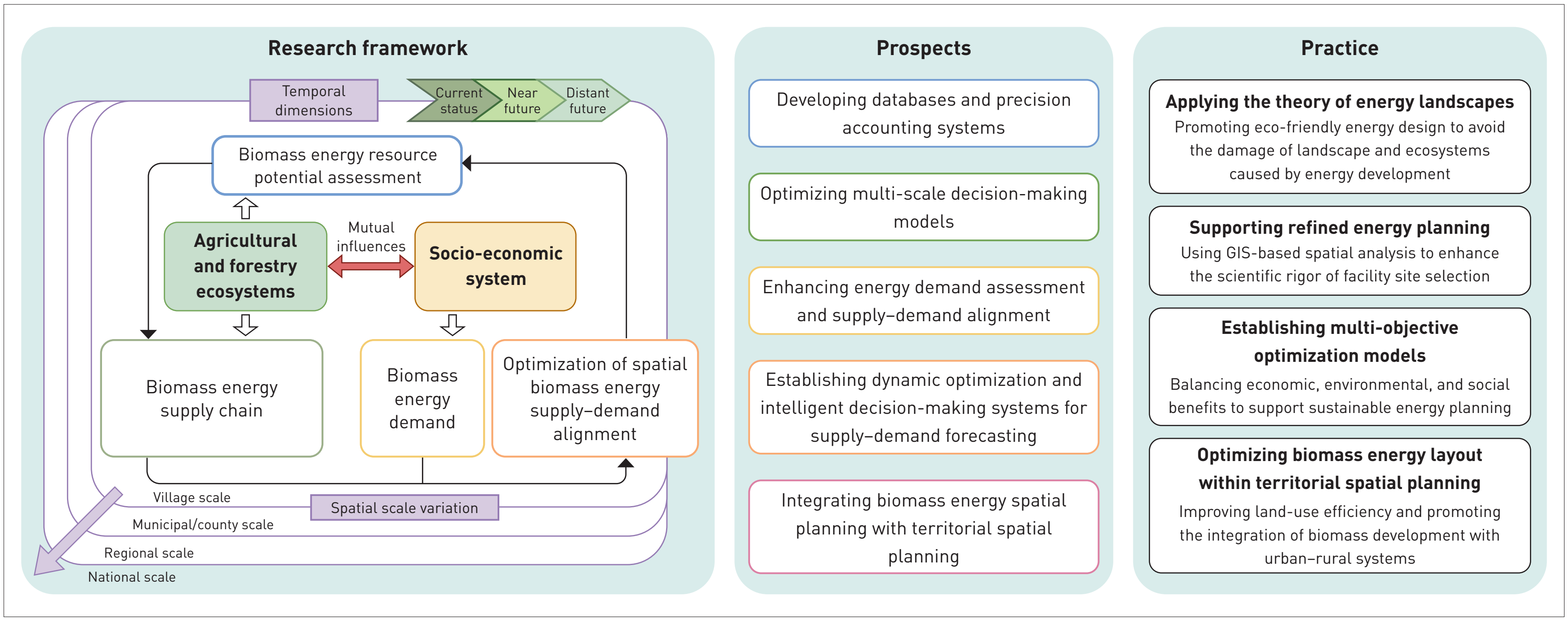
GRAPHICAL ABSTRACT



ABSTRACT

Biomass energy, as a renewable and abundant source of clean energy, offers strong support for mitigating the environmental crises caused by fossil fuel consumption and realizing global carbon neutrality goals. Research on biomass energy spatial planning is inherently complex and interdisciplinary. Although existing studies span a wide range of spatial scales and thematic focuses, there remains a lack of review that constructs the research framework from a holistic perspective, systematically synthesizing existing literature, identifying research hotspots, and analyzing evolving trends. To address this gap, this research employs CiteSpace to visualize the research trends of the field. Thereby, grounded in “energy landscapes” theory, this research constructs the “resource–supply chain–demand–optimization” spatial operational logic and corresponding biomass energy spatial planning research framework. It reviews existing literature on potential assessment, supply chain, energy demand, and spatial optimization of supply–demand alignment, to clarify the interconnections among research themes, methods, and subfields, enhance the practical feasibility of biomass energy assessment and spatial planning, and improve the scientific rigor and applicability of optimization strategies. Finally, the research outlines future research directions, emphasizing the need to integrate energy planning with spatial planning. Through scientifically guided planning and rational allocation of biomass resources, the added spatial value of renewable energy can be fully leveraged to support sustainable development.

KEYWORDS

Renewable Energy; Energy Landscapes; Potential Assessment; Supply Chain; Supply–Demand Alignment; Biomass Combined Heat and Power Plant

HIGHLIGHTS

- Develops a research framework of biomass energy spatial planning
- Proposes the "resource–supply chain–demand–optimization" biomass energy spatial operational logic
- Reviews the recent developments and future directions of biomass energy spatial planning research

RESEARCH FUNDS

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1 Introduction

The rapid growth of the global economy has long relied on fossil fuels, leading to a series of environmental crises. Currently, greenhouse gas emissions from power plants account for approximately 35% of the total global emissions[1]. As a clean energy source, biomass energy offers the advantage of zero or even negative carbon emissions[2], making it a key contributor to the transition toward low-carbon energy systems and the realization of global carbon neutrality goals. According to the International Energy Agency (IEA), biomass energy accounts for 55% of the world's renewable energy supply and over 6% of the total global energy consumption[3], positioning it as a critical component of the national energy strategy of China. Biomass energy refers to the energy stored in biomass carriers through photosynthesis, by which solar energy is converted into biological matter[4]. These carriers include agricultural, forestry, and industrial residues, giving biomass a distinctive advantage in storage and making it one of the most widely promotable renewable energy sources[5].

Carbon neutrality has become not only a major driving force for territorial spatial planning but also a key criterion for evaluating its core outcomes. The transition to renewable energies significantly influences land-use functions and environmental conditions[6]. In response, planners and designers have increasingly engaged in related research, leveraging their interdisciplinary strengths to provide scientific support for spatial analysis and policy-making in renewable energy deployment. With the spatial restructuring guided by urban planning, the medium- and long-term goals of renewable energy development have gradually shifted from centralized power generation to distributed systems. This transition fosters a closer spatial integration between newly constructed infrastructure and densely populated areas, thereby reshaping urban landscapes[7]. Consequently, energy solutions can no longer be separated from spatial considerations[8]. Future energy transitions should integrate spatial and energy planning—particularly by coupling biomass energy supply and demand within specific regions and landscapes.

Thomas Blaschke et al. introduced the concept of landscape into the energy domain, giving rise to the theory of energy landscapes[9]. An energy landscape refers to a complex spatiotemporal configuration that connects energy supply, demand, and infrastructure within a given landscape context[10]. This framework emphasizes the integration of actual and potential energy sources, transportation pathways, and localized energy demand, while also considering synergies with other ecosystem products and services[11]. Within this theoretical context, spatial planning for biomass energy is a form of strategic planning that leverages energy modeling and spatial analysis to examine the current status, spatial heterogeneity, and temporal dynamics of biomass energy resources, and to coordinate resource distribution, transportation conditions, and demand-side layout for optimized spatial allocation of biomass conversion facilities. Such planning contributes to reducing transportation and processing costs while balancing ecological protection and resource efficiency. It also supports decision-making in territorial spatial planning, offering a critical pathway for maximizing the benefits and minimizing the ecological impacts of biomass energy development[12]. For instance, Seolhee Cho et al. proposed a strategic planning model for optimizing biomass-based hydrogen energy networks, identifying both optimal investment timing and regional allocation[13]. At present, Geographic Information System (GIS) technology—owing to its strengths in spatial mapping and analysis—has become a key tool for biomass resource potential assessment and energy infrastructure site selection[14][15]. Junnian Song et al. projected the trade-offs and contributions of three types of agricultural residues to sustainable development in 31 provincial regions of China by 2030, based on the environmental, economic, and social impacts of biomass energy and a multi-resource–technology–output life cycle framework[16].

Although recent years have seen considerable progress in biomass energy policies and technologies development[17][18], there is still an absence of comprehensive reviews through the lens of spatial planning. Existing studies lack systematic synthesis, research hotspot identification, and analysis of research trends, highlighting the need for an integrative framework that connects biomass energy studies with territorial spatial planning. To address this gap, this research utilizes CiteSpace to visualize and analyze research dynamics in the field, and constructs a research framework of biomass energy spatial planning framework on the basis of the theory of energy landscapes. This study incorporates multi-scale and multi-spatial analysis approaches, with particular emphasis on small and micro-scale spatial contexts, to clarify the interconnections among research themes, methods, and subfields, enhance the practical feasibility of biomass energy spatial assessment and planning, improve the scientific rigor and applicability of optimization strategies, and ultimately support the geographic planning of future energy development while increasing the social acceptance of energy landscapes.

2 Research Overview

2.1 Bibliometric Analysis of Current Research

This study utilized the Web of Science (WoS) Core Collection database to retrieve literature by searching the topic terms of “biomass energy spatial planning,” “bioenergy spatial planning,” and “energyscape.” The search was limited to articles and review papers published in English from January 1, 2015 to December 31, 2024, yielding a total of 236 records. To ensure the quality and relevance of the dataset, unrelated publications were excluded, resulting in 194 retained articles. To further enhance the representativeness of the dataset and cover the research development over a decade, an additional 22 highly relevant publications—though not fully matched by the topic terms—were manually included, leading to 216 valid records for analysis. Subsequently, descriptive statistics were conducted using built-in analysis tools of WoS, covering publication year, research area, citation count, etc. CiteSpace was then employed to perform international collaboration network analysis, keyword co-occurrence analysis, cluster detection, and timeline visualization.

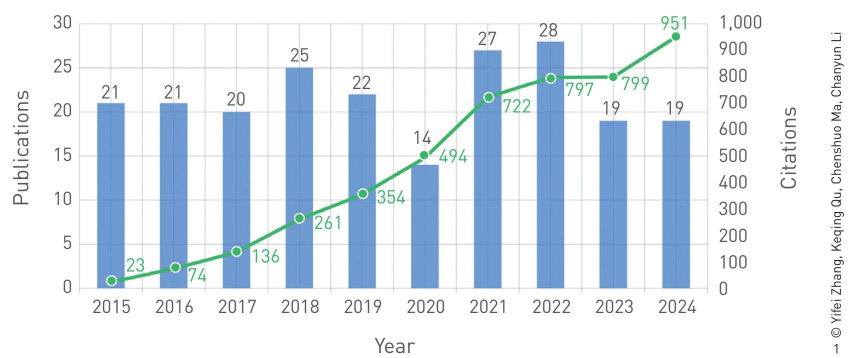
2.1.1 General Characteristics and Evolution of the Research Field

The total number of publications in the field of biomass energy spatial planning remains relatively low, with annual outputs showing noticeable fluctuations. Publication peaks occurred in 2018 and 2022, while the overall citation count has steadily increased over the past decade (Fig. 1). This field demonstrates broad disciplinary coverage, spanning 46 WoS categories. Among them, “Energy & Fuels” accounts for the largest proportion, representing 45.83% of the total publications.

2.1.2 International Collaboration Analysis

Betweenness centrality (BC) is a network metric to assess a node’s bridging ability for information flow within a network structure[19]. The international collaboration network on biomass energy spatial planning and related data indicates that the United States of America (USA), Germany, and the Netherlands have both high publication output and the highest BC values, 0.24, 0.20, and 0.19, respectively, suggesting their key roles as international collaboration hubs. In contrast, China, despite its high publication volume, exhibits a relatively low BC value (0.02), implying that its influence within the global collaboration network remains limited. Early contributors to this field include Finland, Germany, Denmark, Ireland, and Croatia. China, the USA, Germany, and Italy have emerged as major contributors in terms of cumulative research output and consistent publishing, providing a theoretical

1. Publication and citation count in the field of biomass energy spatial planning.

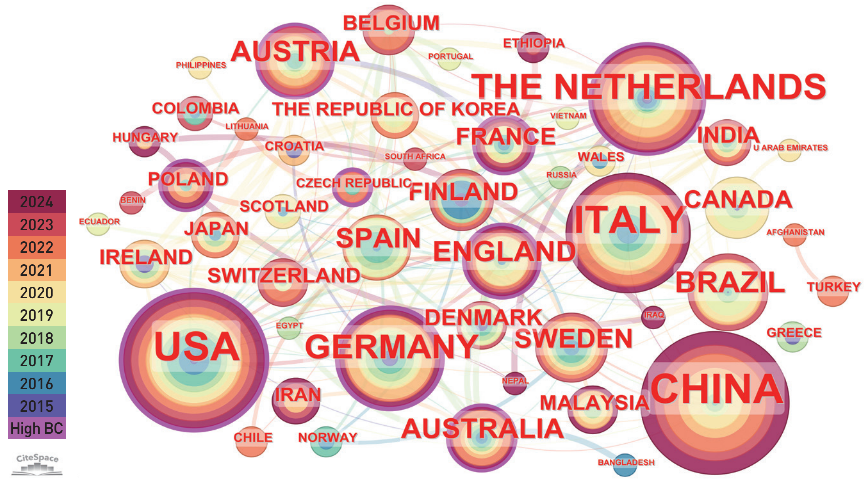


foundation for the development of this field. However, in terms of collaboration pathways, China and the USA, although both are central nodes, show limited direct cooperation and remain largely disconnected. China's collaborations are more closely linked with Finland and Sweden. The overall network reveals that European and North American countries tend to form more multinational research collaborations, with Germany, the USA, and the Netherlands maintaining the most linkages. In contrast, East Asian countries show limited interconnectivity and have yet to establish a cohesive cooperation mechanism. Additionally, several Asian and Middle Eastern countries (e.g., Malaysia, Iran) have also appeared in the collaboration network, indicating a trend toward diversification and regional diffusion in this field's development (Fig. 2).

2.1.3 Keyword Clustering Analysis

Keyword clustering focuses on intrinsic similarities of the keywords, such as semantic meaning, co-occurrence frequency, and word vector similarity. By selecting "Keyword" as the node type and using default parameter settings, a keyword co-occurrence network was generated (Fig. 3). Excluding "biomass," "bioenergy," and "energy" in the topic terms, the ten keywords with the highest BC values are: optimization, renewable energy, availability, systems/system, life cycle assessment, spatial analysis, crop residues, land use, model, and management. The findings indicate that the research hotspots of biomass energy spatial planning are primarily focused on the optimization of land-use patterns, the assessment of biomass resource availability and optimized allocation planning, modeling rely on spatial analysis and life cycle assessment, and efficient management and comprehensive layout to support renewable energy systems.

Keyword co-occurrence analysis helps identify the core areas of research attention, while clustering analysis further uncovers the structural relationships among keywords, enabling the construction of the internal logic and evolutionary pathways of research themes, offering insights into emerging directions. This research applied clustering and timeline visualization functions of CiteSpace (Fig. 4), using the log-likelihood ratio (LLR) algorithm for clustering. To ensure the interpretability of cluster labels, three labeling strategies—title terms, keywords, and subject categories—were compared, and title terms were finally selected as the basis for naming clusters. The software automatically selected the top seven cluster labels as the output, with a modularity (Q) value of 0.42 and a silhouette (S) value of 0.76, indicating a relatively high degree of structural homogeneity and internal consistency and suggesting that the clustering results are reliable. The seven identified cluster labels are: spatiotemporal assessment, suitable site, marginal area, sustainable energy potential, using algal cultivation, bioenergy market, and landscape framework. These clusters align the connotation of energy landscapes, suggesting that research in this field emphasizes spatial layout, spatiotemporal analysis, potential assessment, management processes, and marketing and management. In terms of temporal distribution, Cluster #0 spatiotemporal assessment emerged the earliest and has remained active the longest, reflecting its role as a core and persistent research direction. In the early development stage of this field (2015 ~ 2017), studies mainly focused on fundamental methodological development and model construction. Since 2018, the research emphasis has shifted from theoretical exploration toward practical applications. After 2020, increasing attention has



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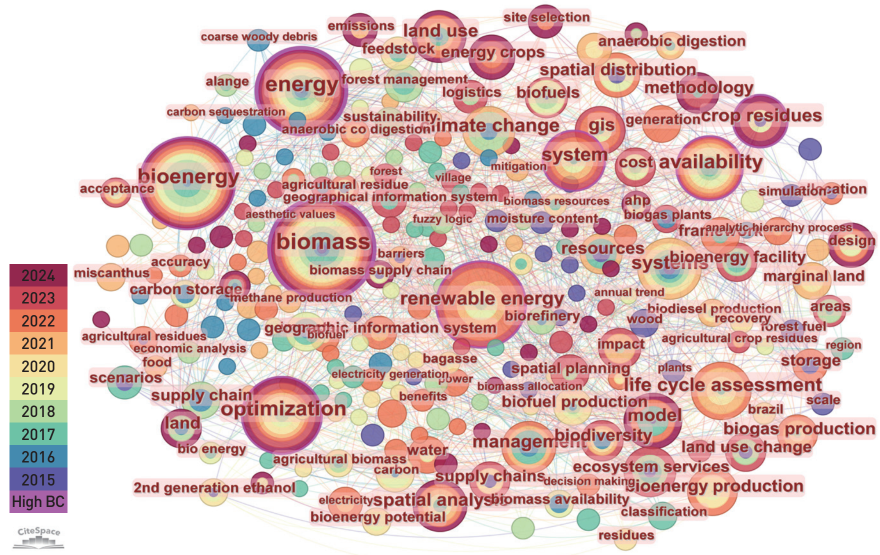

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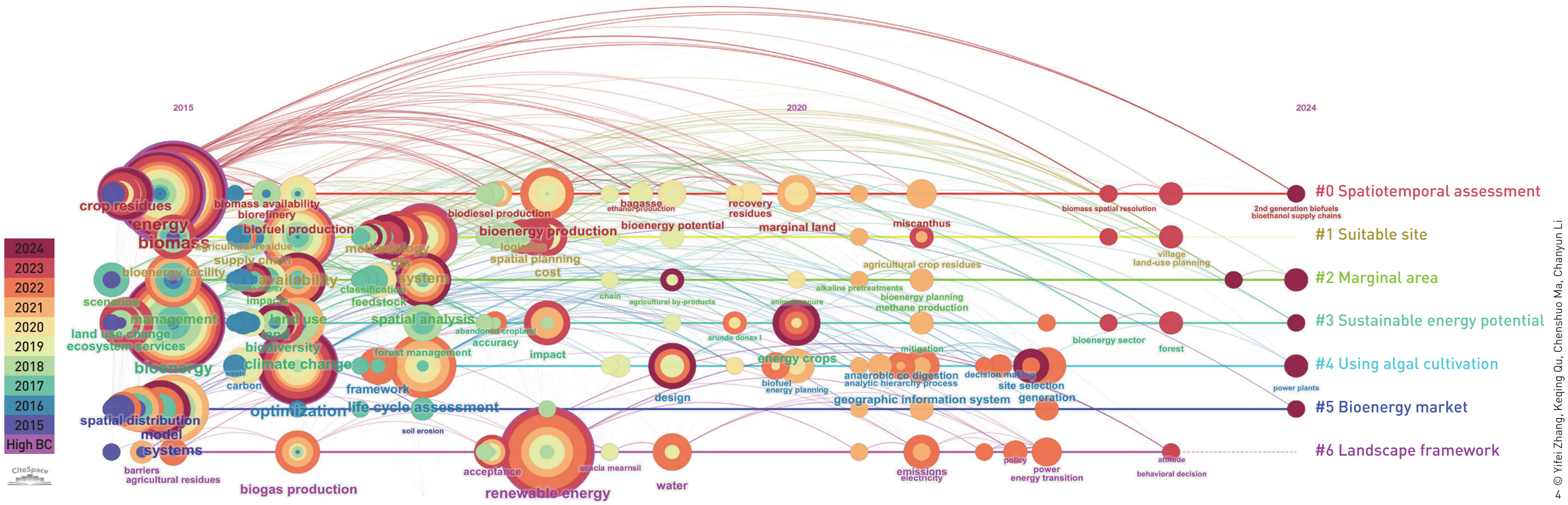
2. International collaboration network in the field of biomass energy spatial planning.
3. Keyword co-occurrence network in the field of biomass energy spatial planning.



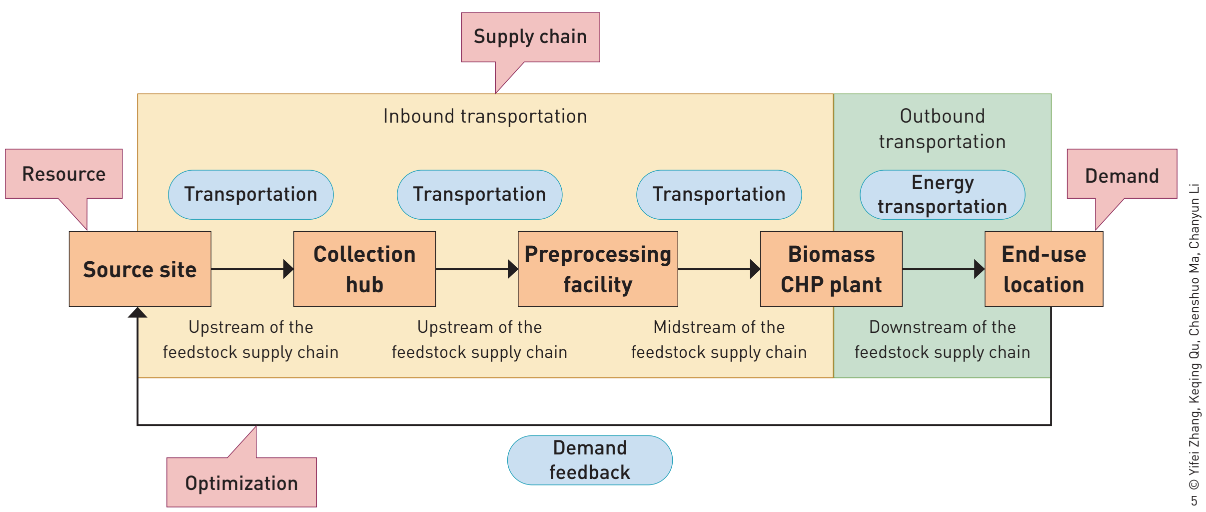
4. Temporal evolution of keyword co-occurrence clusters in the field of biomass energy spatial planning.

been paid to facility layout optimization and multi-dimensional spatial matching, presenting a trend of transitioning from isolated factor analysis to systemic integration and region-wide spatial coordination in this field.

2.2 Spatial Operational Logic of Biomass Energy From the Energy Landscape Perspective

The industrial processes encompassed by energy landscapes cover the dimensions of energy demand, supply, and flow, the description of which enables the identification of coupled pathways among energy production, conversion, distribution, and consumption; highlight constraints related to spatial planning, policy-making, and social acceptance; and reveal critical linkages between energy systems and other socioeconomic systems[20].

Among the high BC value keywords identified in the co-occurrence network, "life cycle assessment" (LCA) refers to the evaluation of a product or service throughout its entire life cycle—from raw material extraction, production, and use to disposal[21]. Following this logic and building upon existing studies on biomass energy supply chains[22][23], this research divides the operation cycle into distinct stages: initial feedstock collection at the source site, establishment of biomass collection hubs, preprocessing, processing at biomass combined heat and power (CHP) plants①, end-use of biofuels, forming multi-type transmission networks (logistics and electricity distribution), and establishing dynamic supply–demand relationship based on deployment feedback. Thereby, this research extracted the spatial operational logic of "resource–supply chain–demand–optimization" (Fig. 5).



① This research focuses on biomass CHP plants as representative conversion nodes, as they serve both energy conversion and end-use supply functions within the biomass energy supply chain. Given the representativeness and widespread application of CHP plants, the research did not separately analyze other types of biomass conversion facilities (e.g., biogas plants, ethanol factories), but instead incorporated them within the CHP plant.

5. Schematic diagram of typical biomass energy supply pathways and end-use applications.

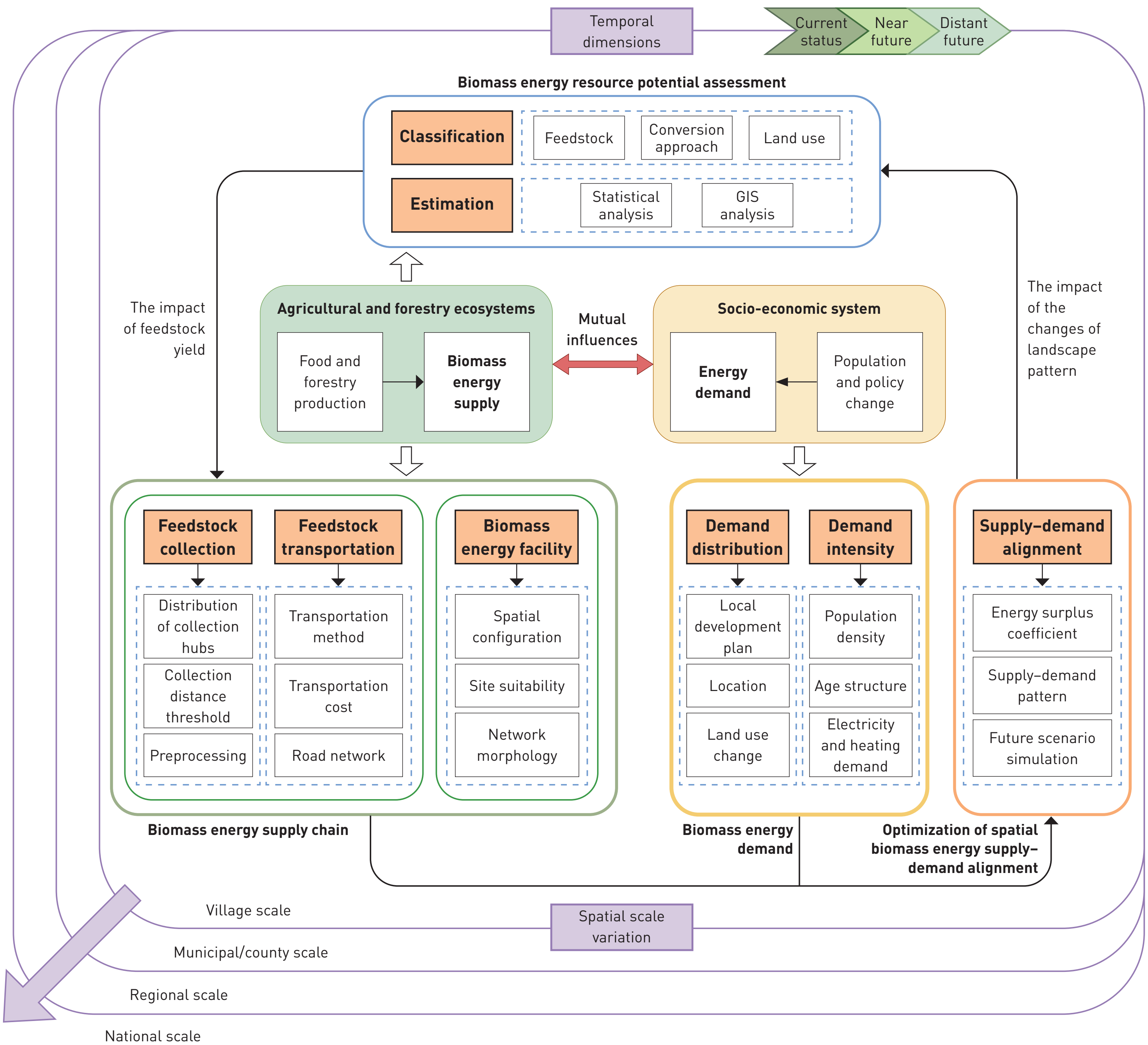
2.3 Biomass Energy Spatial Planning Research Framework

To systematically understand biomass energy spatial planning and to capture the production–consumption processes of biomass energy across multiple spatial scales, this research integrates the spatial operational logic of biomass systems with current and future scenario analysis (near- and long-term). A research framework is established on the "resource–supply chain–demand–optimization" logic, consisting of four core components: resource potential assessment, biomass energy supply chain analysis, energy demand characterization, and spatial supply–demand alignment (Fig. 6).

3 Research Progress

3.1 Biomass Energy Potential Assessment

Assessing the development potential of biomass energy and accurately characterizing its spatial distribution are fundamental prerequisites for defining energy utilization pathways and formulating development plans[24]. Due to limitations in data availability, most existing studies focused on national and regional scales[25]. The diversity of biomass feedstock and conversion technologies increases the complexity of potential assessments—



6. Biomass energy spatial planning research framework.

biomass feedstock includes agricultural residues, forestry residues, municipal solid waste, and animal manure[26], which can be converted through various technologies into electricity, heat, and a range of bio-based products (e.g., bioethanol, biomethane, biogas)[27].

Existing biomass energy potential assessment can be categorized into three types: first, theoretical and technical potential assessment; second, demand-driven assessment, including economic potential and implementation potential; third, integrated modeling assessment that links theoretical potential to sustainable implementation potential[28][29]. At the national level, existing research has estimated the potential of available biomass in China[30] and assessed the potential contribution of biomass resources to emission reduction targets[31]. Integrated modeling assessment is more prevalent at regional to village scales. These studies typically incorporate potential assessments with refined planning and management, emphasizing the optimization of policy-making according to the spatial heterogeneity of resource distribution within specific regions[32][33].

To meet the goal of promoting the efficient and coordinated development of land resources within territorial spatial planning, biomass energy potential assessments should be integrated with land-use configurations. For instance, due to the land use conflict of food crops and energy crops, the production potential of marginal land②[34] has received growing attention[35]. Such land is often suitable for cultivating non-food energy plants such as starchy crops, sugar-rich plants, and woody oil plants[36]. The conversion technologies associated with these biomass sources are relatively mature and have demonstrated preliminary economic and environmental competitiveness compared with fossil fuels. As a result, research on suitability analysis[37], estimation of energy crop cultivation areas, and corresponding potential assessments of marginal land has become prominent[38].

Biomass energy potential assessment can provide essential data to delineate resource utilization limits for territorial spatial functional zoning, and serve as a basis for energy infrastructure spatial planning. However, current studies still face several challenges, including quantitative estimation difficulties, conversion technology bottlenecks, and insufficient policy support[29]. Due to varying interpretations of biomass among researchers, differences in resource classification and assessment approaches and the absence of localized or standardized key parameters have led to low comparability across studies[28]. Moreover, many assessments assume uniform yield and spatial distribution within a given area, neglecting the variety of biomass types[38]. For example, crop straws exhibit strong seasonality, while most studies rely on annual-scale data that overlook the cyclical fluctuations in resource availability[39].

3.2 Biomass Energy Supply Chain

The biomass energy supply chain refers to the process by which feedstock is collected, processed, and converted into usable fuel products[40][41]. Relevant research primarily focuses on improving economic efficiency or achieving multi-objective optimization within complex systems to support optimal decision-making[42]. As the supply chain is closely linked to user demands and stakeholder interests[43], its design and outcomes directly influence the social acceptance of biomass energy. From a geospatial planning perspective, biomass energy supply chain studies mainly address the site selection and the number of energy facilities, their processing, conversion, and production capacities, as well as the allocation and transportation of biomass between different processing facilities[44].

3.2.1 Biomass Energy Feedstock Collection and Preprocessing

Research on biomass feedstock collection largely addresses the processes occurring before the biomass reaches the preprocessing facilities[45], with most conducted at regional to village scales. The collected biomass is typically stored at the source site, the biomass conversion plant, or designated collection hubs[46]. As intermediate points between the source sites and the CHP plants, the location of collection hubs should prioritize the areas with high biomass yield and short transportation distances[47]. Most studies are conducted at the village scale and concentrate on optimizing collection hub locations to streamline logistics, reduce transportation costs, and enhance overall efficiency[48], thereby supporting the development of biomass resource collection models and energy facility site selection strategies[49].

During the collection stage, biomass feedstock is preprocessed to be converted into higher-density energy carriers, improving energy conversion efficiency. Additionally, adding preprocessing facilities can enhance storage and transportation efficiency[50]. Previous studies have identified optimal site selection strategies for preprocessing facilities by combining resource availability assessments with suitability analyses of potential locations[51].

3.2.2 Biomass Energy Transportation

Logistics research in the context of biomass energy must consider

② Marginal land refers to the land with limited potential for agricultural use due to constraints such as poor soil quality, insufficient water and thermal resources, and unfavorable topography, typically exhibiting low economic returns and fragile ecosystems (source: Ref. [34]). It was automatically captured as "marginal area" by CiteSpace in previous keyword clustering analysis.

transportation methods, costs, and road network accessibility to enhance the feasibility and effectiveness of decision-making. Among the various transportation methods, road transport currently dominates, while multimodal transport systems—combining road, rail, waterway, and pipeline transport—are emerging as a growing trend[52][53]. Within the biomass energy supply chain, inbound transportation refers to the movement of feedstock to CHP plants, whereas outbound transportation involves the delivery of final products from these plants to end users. Existing studies have predominantly focused on the inbound segment of the supply chain[54].

Research on transportation costs within the biomass supply chain involves the transportation route development based on multi-models and feasibility analyses, vehicle type and capacity selection, schedule delivery, overall logistics costs and operation time reduction, and environmental impacts mitigation[55]. Scholars have identified a range of potential factors influencing transportation costs, including feedstock volume and type, moisture content, round-trip distance, and regional conditions. However, conclusions across studies often vary[54]. For example, Marc Schröder et al. found that vehicle fuel consumption and emissions are key contributors to transportation costs by incorporating road slope and three-dimensional routing models[56]. In contrast, Rajdeep Golecha et al. emphasized the curvature factor (the ratio of actual transport distance to the Euclidean distance) and biomass yield density as the primary determinants of transportation cost[57].

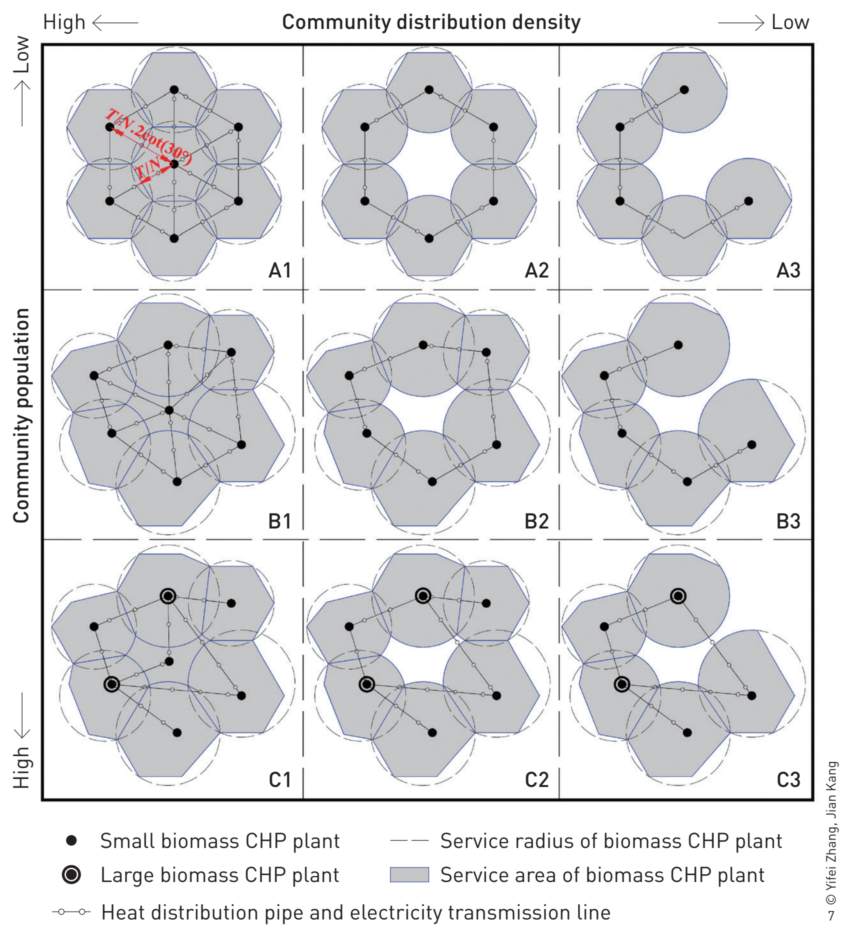
3.2.3 Site Selection and Network Layout of Biomass Combined Heat and Power Plants

The construction and operation of biomass CHP plants are widely recognized as one of the most efficient approaches to developing biomass energy[58]. The site selection of biomass CHP plants should take into account local climatic and environmental conditions, address challenges related to resource supply and environmental risks, and avoid adverse impacts on natural environment. Furthermore, it should also align with local urban development plans and ecological protection requirements. A range of approaches can be employed for comprehensive site assessment, including multi-criteria decision analysis[59], risk assessment[60], environmental impact assessment[61], and fuzzy logic evaluation[62].

The biomass raw material collection distance threshold (BCDT) refers to the maximum road distance between a source site and a CHP plant, which is commonly used in feedstock accessibility study. An increase in BCDT expands the choice of potential destinations that a given source site can supply, allowing greater flexibility of biomass distribution strategies[63].

Most studies on the biomass CHP plant site selection are conducted at regional or village spatial scales. Regional-scale research typically focuses on evaluating overall conditions of the selected sites; whereas village-scale studies aim to provide practical and detailed planning or logistics solutions through suitability or optimality analyses, the quantitative indicators of which commonly include resource availability, supply chain cost, and greenhouse gas emission from transportation processes[44]. In village-scale spatial planning, the configuration of CHP plant network forms the basis of site selection. The total power output of the plants is determined by the regional distribution of energy demand, while the heat transmission threshold (T) defines the spatial relationship between the service coverage of a CHP plant and the surrounding communities. Given the irregularity of road networks between towns, a road nonlinearity coefficient (N) is introduced to calculate the average service radius of a CHP plant (T/N)[64]. The community distribution density and community population also influence the overall CHP network configuration (Fig. 7).

7. Ideal network configuration of biomass CHP plants (A1) and actual configuration (others in the figure) (source: Ref. [64]).



Overall, biomass energy supply chain research can provide scientific support for territorial spatial planning in terms of resource distribution, processing procedure, transportation routing, facility site selection, and logistics cost analysis. However, current studies still face several limitations. First, numerical inaccuracies and spatial deviations in potential assessments can directly affect the construction of an integrated and effective supply chain system. Second, planning and design commonly rely on a fixed number of facilities to cover end-use locations, which often fails to reflect the actual optimal cost configuration, thereby limiting applicability[65]. Finally, the multi-tiered structure of the supply chain may result in mismatches between resource endowment and infrastructure capacity, making policy implementation difficult. In addition, inconsistencies across different governance levels—such as differences in indicator systems, policy priorities, and administrative capacity—can lead to poor coordination between decision-making processes.

3.3 Biomass Energy Demand

Biomass energy demand is closely related to factors such as price, gross domestic product (GDP), and population[66]. Spatial-related energy demand research involves two dimensions: the spatial distribution of demand and demand intensity. Estimating and forecasting the related factors are highly challenging due to the influence of dynamic market conditions and policy changes. Relevant studies cover multiple spatial scales, including national, regional, municipal/county, and village levels. However, in practical modeling, differences in data resolution, boundary definitions, and planning objectives across these administrative levels make them difficult to match with the biomass supply chain analysis[16].

3.3.1 Spatial Distribution of Biomass Energy Demand

The spatial imbalance of biomass energy demand presents significant challenges for the site selection of CHP plants and the spatial configuration of urban energy systems. At the macro scale, seasonal fluctuations in demand caused by latitudinal variation are particularly pronounced—heating and cooling needs represent major components of energy demand[67]. Chenshuo Ma et al. compared 50 cities and counties across different latitudes where winter heating is required. They found that during non-heating periods, latitude and per capita feedstock consumption by biomass CHP plants had a linear negative correlation, whereas during heating periods, the relationship followed an inverse S-shaped curve.[68] Moreover, the spatial distribution of biomass energy demand becomes increasingly complex as the scale of analysis expands. For example, Sandra Venghaus et al. demonstrated that the contribution of biomass energy to improving rural residents' quality of life was significantly more pronounced at the regional level than that at the individual level[69].

3.3.2 Biomass Energy Demand Intensity

Energy demand intensity is normally measured by the amount of energy consumed per unit of GDP[70]. Population is a fundamental determinant of energy demand[71], and its spatial distribution and migration patterns offer crucial insights into the characteristics and intensity of energy use, encompassing population growth[72], urban migration[73], and changes in population density[74]. In addition, demographic characteristics (e.g., education level[74], age structure[75]) also play significant roles in energy demand analysis. For example, in designing biomass CHP plant networks, variables such as the size and density of population, and other demographic trends can be applied to determine the capacity and operational efficiency of biomass CHP plants[76].

The scale, structure, and spatial distribution of energy demand directly affect the strategy and spatial layout in territorial spatial planning. At the national level, it is essential to coordinate the spatial relationship between energy production and consumption areas; at the regional level, the planning should promote supply–demand balance; and at the municipal/county and village levels, adjustments to the layout of energy infrastructure (e.g., heating, electricity, transportation systems) are required. Currently, the demand-side research faces several limitations. First, the assessments at small scales often involve a high degree of subjectivity. Second, many energy demand models tend to hypothesize that there is a simple linear relationship between energy consumption and economic activity, overlooking nonlinear dynamics and the influence of multidimensional factors, thereby failing to capture the complexity of the energy system[77]. Third, existing studies offer limited analysis on the combined effects of policy, economic, and technological drivers. For instance, estimating demand based solely on population metrics results in an oversimplified, homogeneous, and uniform result.

3.4 Optimization of Spatial Biomass Energy Supply–Demand Alignment

Spatial supply–demand alignment analysis of biomass energy can identify areas of potential resource shortages or surpluses under dynamic spatiotemporal conditions. This enhances the resilience of territorial spatial planning towards uncertainties in future energy markets and serves as a key approach to exploring sustainable pathways in the bioeconomy[78]. Based on the analysis of supply–demand relationships and scenario simulation results, the spatial optimization of energy facility layout and supply chain pathways can be conducted to improve overall system efficiency and adaptability.

The demand feedback represents the response mechanism to future demand changes in the model, enabling a dynamic feedback loop from forecasting to planning. This research area involves statistical data and distribution characteristics from both the supply and demand sides, including spatial matching patterns and the energy surplus coefficient[39]. Existing studies primarily focus on the regional scale, with some extending to the national or global scale to explore, from a macro perspective, the potential of biomass energy as a substitute for fossil fuels[79] and to provide a reference for development suitability. The energy surplus coefficient is defined as the ratio between the energy-convertible potential of biomass and the actual energy demand, serving as an intuitive indicator of regional energy self-sufficiency. This coefficient enables the assessment of various biomass conversion technologies, covering the forms of solid, liquid, and gaseous biomass[80]. It also highlights the comparative advantages and disadvantages of biomass energy versus other renewable energy sources in production and conversion, thus contributing to the development of integrated and complementary sustainable energy systems[81]. However, current supply–demand alignment analyses face limitations in spatial and temporal alignment due to constraints in data availability and methodological applicability. Future research should take into account resources, technologies, policies, and public participation to achieve the efficient and sustainable development and utilization of biomass energy.

Scenario simulation research aims to forecast planning and decision-making outcomes under varying sets of driving factors. The temporal settings of future scenarios are typically aligned with national energy strategies[82], carbon peaking targets[83], and climate change projection models[84]. In addition, to avoid the risk of ecological deficits, spatial planning should coordinate the supply and demand of key ecosystem services such as carbon storage, biodiversity, water cycling, and soil health[85]. Scenario simulation provides a useful tool for anticipating trade-offs among multiple ecosystem services under different development trajectories, thereby informing the design of ecological protection or restoration initiatives to compensate for potential environmental losses.

4 Research Trends and Future Perspectives

4.1 Global Research Trends

This research further refines the global landscape of biomass energy research by examining the top ten countries and regions in terms of publication volume. For each, the five keywords with the highest BC values were identified as key research hotspots, while persistent clustering themes were extracted to indicate emerging trends (Table 1). China and the USA, as the leading contributors, both place strong emphasis on feedstock assessment and greenhouse gas emission mitigation strategies. However, the USA focuses more on modeling frameworks and process analysis, whereas China emphasizes engineering application and adaptive development. In European collaboration networks, research is more about ecological sustainability and spatial optimization. In terms of research hotspots, combining the operational logic of resource–supply chain–demand–optimization, it is clear that research on feedstock potential is the most well-developed. Countries such as China, the USA, and Italy frequently feature keywords related to resource identification and potential assessment (e.g., "crop residues," "energy crops"). Supply chain studies are also relatively advanced, with keywords such as "life cycle assessment," "transportation," "logistics," and "bioenergy facility" appearing in the literature from China, the USA, the Netherlands, Australia, and Spain. In contrast, research on demand-side response and system optimization remains underdeveloped. Related keywords tend to be broad and conceptual, lacking specificity. This gap highlights the necessity and relevance to construct the four-tier framework in this research, which extends the existing research logic and enhance the value of future planning. Globally, biomass energy research is shifting toward a more integrated paradigm, spanning multiple dimensions and spatial scales. Countries such as the Netherlands, Germany, and Australia highlight the increasing importance of spatial analysis and data platforms in decision-making processes. China, Italy, Australia, and England are advancing research at the intersection of renewable resource acquisition and ecosystem functionality. Meanwhile, China, the USA, the Netherlands, Brazil, and Australia are expected to maintain a strong focus on goal-oriented spatial planning, emphasizing refined dynamic supply–demand alignment and regulatory adaptability. Together, these developments reflect a broader transition from static layouts to responsive, systematic biomass energy planning.

4.2 Future Perspectives

Building upon the aforementioned research hotspots, current

Table 1: Research hotspots and emerging trends in the top publishing countries/regions

Publication ranking	Country/region	Research hotspots	Emerging trends
1	China	Crop residue, climate change, transportation, GIS, impact	Sensitivity analysis, location-allocation, zoning, agricultural biomass
2	The USA	LCA, emission, energy crop, biofuel production, corn stover	Co-generation, planning and analysis
3	Italy	Renewable energy, biogas production, food, climate change, energy crop	Energy crop, agriculture by-product, enterprise input-output analysis
4	The Netherlands	Decision making, LCA, marginal land, biofuels, impact	Bio-refinery supply chain, spatial distribution, Integrated Land and Water Information System, spatial analysis
5	Germany	Challenge, ecosystem service, information, electricity, impact	Spatial analysis, power plant
6	Brazil	GIS, 2nd generation ethanol, LCA, aviation biofuel, generation	Capacitated location-allocation, optimization
7	Austria	Land use, spatial analysis, renewable energy, greenhouse gas emission, bioenergy policy	Tree plantation
8	England	Land use, land, jet fuel, design, aviation biofuel	Sustainable fuel
9	Australia	Emission, chain, logistics, forest biomass, storage	Spatial analysis, tree and stand reconstruction
10	Spain	Renewable energy, area, fuzzy logic, system, bioenergy facility	Accessibility

findings, and emerging trends, this study proposes five key directions for future research in biomass energy spatial planning.

1) Developing databases and precision accounting systems. Advancements in data technologies and modeling methods will provide a robust foundation for energy planning and policy-making across multiple spatial scales. Future studies should prioritize the dynamic monitoring and spatial variation analysis of biomass resources. This includes establishing databases capable of real-time data tracking and updates, capturing the socioeconomic impacts of biomass energy, and providing interpretable indicators. In addition, it is crucial to develop standardized assessment frameworks to ensure the consistency, comparability, and accuracy of biomass resource accounting.

2) Optimizing multi-scale decision-making models. Future research should focus on the development of multi-scale decision-making models that incorporate regional heterogeneity to optimize biomass energy supply chains. Promoting cross-scale coordination is essential to ensure policy coherence and consistency across various governance levels. This includes integrating long-term policy shifts and climate change scenarios into decision-making processes to enhance continuity, and expanding multi-objective planning approaches that operate across scales.

3) Enhancing energy demand assessment and supply–demand alignment. To enable more accurate biomass energy planning, a comprehensive and systematic demand assessment framework should be developed to support effective supply–demand alignment. This includes in-depth analysis of the variations in energy use types and regional demand levels associated with different biomass conversion approaches, comparative studies of demand disparity across multiple renewable energy resources. The relationship between biomass energy and ecosystem services should also be considered. Multi-level scheduling and coordination mechanisms can be applied to flexibly adjust production plans and supply chain configurations, thereby

improving supply–demand alignment.

4) Establishing dynamic optimization and intelligent decision-making systems for supply–demand forecasting. Future research can incorporate machine learning and artificial intelligence technologies to enhance the forecasting capacity of energy planning under conditions of uncertainties and dynamic changes, using historical and real-time data. Dynamic dispatch systems should also be established to enable real-time adjustment of strategies in biomass production, transmission, storage, and consumption. Furthermore, mechanisms for renewable energy load shifting and peak regulation should be developed to improve resource utilization efficiency.

5) Integrating biomass energy spatial planning with territorial spatial planning. Territorial spatial planning can provide regulatory constraints and strategic guidance for biomass energy planning, while biomass energy planning can inform territorial planning through its policy coordination frameworks. Database interoperability between the two domains should be promoted. Future research should emphasize on their integration to avoid the occupation of protected functional zones, balance resource exploitation with land use, and enhance the resilience and adaptability of territorial spatial planning systems.

5 Conclusions

This research systematically reviews the core of biomass energy spatial planning and develops an integrated research framework encompassing biomass potential assessment, supply chain analysis, energy demand evaluation, supply–demand alignment, and future scenario simulation grounded in the theory of energy landscapes. This paper explores the fundamental operation mechanisms of biomass energy—from production and transportation to end use—and summarizes the current research dynamics and characteristics of the field on the basis of the bibliometric analysis. Compared with earlier studies that tended to focus on isolated aspects, this research establishes a comprehensive analytical framework with the resources–supply chain–demand–optimization operational logic, integrating multiple spatial scales and temporal dimensions (past, present, and future) to explore the spatial optimization of biomass energy deployment in a more refined manner.

In terms of practice, this study offers several insights for the discipline of planning and design. Optimizing biomass energy layout within territorial spatial planning to improve land-use efficiency and promote the integration of biomass development with urban–rural systems; supporting refined energy planning through GIS-based spatial analysis to enhance the scientific rigor of facility site selection; advancing eco-friendly energy design by applying the theory of energy landscapes; and establishing multi-objective optimization models that balance economic, environmental, and social benefits to support sustainable energy planning. Furthermore, this study provides a scientific approaches for biomass energy spatial configuration, offering valuable references for government agencies and energy enterprises, particularly in policy formulation, agricultural waste utilization, and rural clean energy development.

Competing interests | The authors declare that they have no competing interests.

REFERENCES

[1] Maamoun, N., Kennedy, R., Jin, X., & Urpelainen, J. (2020). Identifying coal-fired power plants for early retirement. *Renewable and Sustainable Energy Reviews*, (126), 109833.

[2] Zhuang, X., Zhang, X., Zhang, Q., Chen, L., & Ma, L. (2024). Development status and challenges of biomass energy utilization technology under background of emission peak and carbon neutrality strategy in China. *Solar Energy*, 7(363), 40–49.

[3] International Energy Agency. (n.d.). *Bioenergy*.

[4] Lu, Y. (2014). Review and prospect of clean, renewable energy utilization. *Science & Technology Review*, 32(Z2), 15–26.

[5] Hepbasli, A. (2008). A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. *Renewable and Sustainable Energy Reviews*, 12(3), 593–661.

[6] de Waal, R., & Stremke, S. (2014). Energy transition: Missed opportunities and emerging challenges for landscape planning and designing. *Sustainability*, 6(7), 4386–4415.

[7] Ramirez Camargo, L., & Stoeglehner, G. (2018). Spatiotemporal modelling for integrated spatial and energy planning. *Energy, Sustainability and Society*, 8(1), 32.

[8] Wolsink, M. (2012). The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources. *Renewable and Sustainable Energy Reviews*, 16(1), 822–835.

[9] Blaschke, T., Biberacher, M., Gadocha, S., & Schardinger, I. (2013). 'Energy landscapes': Meeting energy demands and human aspirations. *Biomass and Bioenergy*, (55), 3–16.

[10] Howard, D. C., Burgess, P. J., Butler, S. J., Carver, S. J., Cockerill, T., Coleby, A. M., Gan, G., Goodier, C. J., Van der Horst, D., Hubacek, K., Lord, R., Mead, A., Rivas-Casado, M., Wadsworth, R., & Scholefield, P. (2013). Energyscapes: Linking the energy system and ecosystem services in real landscapes. *Biomass and Bioenergy*, (55), 17–26.

[11] Ginelli, E., & Daglio, L. (2014). Energyscapes: Developing a Multiscalar Systemic Approach to Assess the Environmental, Social and Economic Impact of Renewable Energy Systems on Landscape. *Proceedings of the 2nd International Conference on Architecture and Urban Design (ICAUD 2014)*. Epoka University Press.

[12] Geng, A., Pan, W., & Yang, H. (2020). Quantifying the mitigating effects and benefits from substituting wood biomass for coal in energy production in China. *Resources Science*, 42(3), 536–547.

[13] Cho, S., & Kim, J. (2019). Multi-site and multi-period optimization model for strategic planning of a renewable hydrogen energy network from biomass waste and energy crops. *Energy*, (185), 527–540.

[14] Nebey, A. H., Taye, B. Z., & Workineh, T. G. (2020). Site suitability analysis of solar PV power generation in South Gondar, Amhara Region. *Journal of Energy*, (2020), 3519257.

[15] Sun, Y., Wang, R., Liu, J., Xiao, L., Lin, Y., & Kao, W. (2013). Spatial planning framework for biomass resources for power production at regional level: A case study for Fujian Province, China. *Applied Energy*, (106), 391–406.

[16] Song, J., Liu, C., Xing, J., Yang, W., & Ren, J. (2023). Linking bioenergy production by agricultural residues to sustainable development goals: Prospects by 2030 in China. *Energy Conversion and Management*, (276), 116568.

[17] Xin, B., Lyu, L., Wang, S., Dong, J., Zhang, N., & Yang, C. (2024). Research progress of biomass energy field based on bibliometric investigation. *China Environmental Science*, 44(4), 1875–1884.

[18] Zhang, Y., Yang, H., & Liu, L. (2024). Comparative analysis of biomass energy research in China and America. *World Sci-Tech R&D*.

[19] Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, 57(3), 359–377.

[20] de Jong, J., & Stremke, S. (2020). Evolution of energy landscapes: A regional case study in the Western Netherlands. *Sustainability*, 12(11), 4554.

[21] Wang, C., Chang, Y., Zhang, L., Pang, M., & Hao, Y. (2017). A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. *Energy*, (120), 374–384.

[22] Martinez-Valencia, L., Camenzind, D., Wigmosta, M., Garcia-Perez, M., & Wolcott, M. (2021). Biomass supply chain equipment for renewable fuels production: A review. *Biomass and Bioenergy*, (148), 106054.

[23] Rimppi, H., Uusitalo, V., Väisänen, S., & Soukka, R. (2016). Sustainability criteria and indicators of bioenergy systems from steering, research and Finnish bioenergy business operators' perspectives. *Ecological Indicators*, (66), 357–368.

[24] Liu, Z., Wang, Y., & Ding, Y. (2023). Evaluation of biomass energy resource potential and emission reduction of energy-based pollutants in Shaanxi Province. *Environmental Science and Management*, 48(11), 22–27.

[25] Bilandzija, N., Voca, N., Jelcic, B., Jurisic, V., Matin, A., Grubor, M., & Kricka, T. (2018). Evaluation of Croatian agricultural solid biomass energy potential. *Renewable and Sustainable Energy Reviews*, (93), 225–230.

[26] Anitescu, G., & Bruno, T. J. (2012). Liquid biofuels: Fluid properties to optimize feedstock selection, processing, refining/blending, storage/ transportation, and combustion. *Energy & Fuels*, 26(1), 324–348.

[27] Fu, J., Yan, X., & Jiang, D. (2021). Assessing the sweet sorghum-based ethanol potential on saline–alkali land with DSSAT model and LCA approach. *Biotechnology for Biofuels*, 14(1), 44.

[28] Zhang, R., & Shen, W. (2021). Research and prospects on the evaluation of the potential of agriculture and forestry biomass resources. *China Forestry Economics*, (6), 46–49.

[29] Zhou, Y., Wang, J., Wang, S., Xi, F., Bing, L., Yin, Y., Hu, Q., & Zhang, L. (2024). Assessment of biomass resources for energy use potential in China. *Chinese Journal of Ecology*, 43(9), 2702–2713.

[30] Nie, Y., Chang, S., Cai, W., Wang, C., Fu, J., Hui, J., Yu, L., Zhu, W., Huang, G., Kumar, A., Guo, W., & Ding, Q. (2020). Spatial distribution of usable biomass feedstock and technical bioenergy potential in China. *GCB Bioenergy*, 12(1), 54–70.

[31] Yan, P., Xiao, C., Xu, L., Yu, G., Li, A., Piao, S., & He, N. (2020). Biomass energy in China's terrestrial ecosystems: Insights into the nation's sustainable energy supply. *Renewable and Sustainable Energy Reviews*,

(127), 109857.
[32] Dabas, J., Mondal, S., & Thapar, S. (2023). Application of geospatial technology for assessment of agricultural residue based renewable energy potential in Punjab, India. *Energy for Sustainable Development*, (72), 340–350.
[33] Younis, A., Trujillo, Y., Benders, R., & Faaij, A. (2021). Regionalized cost supply potential of bioenergy crops and residues in Colombia: A hybrid statistical balance and land suitability allocation scenario analysis. *Biomass and Bioenergy*, (150), 106096.
[34] Cao, X., Sun, B., Chen, H., Zhou, J., Song, X., Liu, X., Deng, X., Li, X., Zhao, Y., Zhang, J., & Li, J. (2021). Approaches and research progresses of marginal land productivity expansion and ecological benefit improvement in China. *Bulletin of the Chinese Academy of Sciences*, 36(3), 336–348.
[35] Fu, J., Du, J., Jiang, D., & Wang, D. (2020). Analysis of the marginal land resources suitable for developing liquid biofuel in China. *Science & Technology Review*, (11), 31–40.
[36] Viccaro, M., Caniani, D., Masi, S., Romano, S., & Cozzi, M. (2022). Biofuels or not biofuels? The "Nexus Thinking" in land suitability analysis for energy crops. *Renewable Energy*, (187), 1050–1064.
[37] Cervelli, E., Recchi, P. F., Fagnano, M., di Perta, E. S., & Pindozzi, S. (2024). Marginal lands between recovery and valorization. An inclusive definition to support bio-energy supply chains. The Southern Italy contexts case study. *Agricultural Systems*, (217), 103951.
[38] Chen, X. (2016). Economic potential of biomass supply from crop residues in China. *Applied Energy*, (166), 141–149.
[39] Chukwuma, E. C., Okey-Onyesolu, F. C., Ani, K. A., & Nwanna, E. C. (2021). GIS bio-waste assessment and suitability analysis for biogas power plant: A case study of Anambra state of Nigeria. *Renewable Energy*, (163), 1182–1194.
[40] Wolfsmayr, U. J., & Rauch, P. (2014). The primary forest fuel supply chain: A literature review. *Biomass & Bioenergy*, (60), 203–221.
[41] Mamo, T., Montastruc, L., Negny, S., & Dendena, L. (2024). Considering economic-environmental dimension in the integrated strategic and tactical optimization of Ethiopia's bioethanol supply chain coupled with operational planning. *Computers and Chemical Engineering*, (189), 108781.
[42] Lin, T., Rodríguez, L. F., Shastri, Y. N., Hansen, A. C., & Ting, K. C. (2013). GIS-enabled biomass- ethanol supply chain optimization: Model development and Miscanthus application. *Biofuels, Bioproducts and Biorefining*, 7(3), 314–333.
[43] Mamo, T., Montastruc, L., Negny, S., & Dendena, L. (2023). Integreted strategic and tactical optimization planning of biomass to bioethanol supply chains coupled with operational plan using vehicle routing: A case study in Ethiopia. *Computers and Chemical Engineering*, (172), 108186.
[44] Sánchez-García, S., Athanassiadis, D., Martínez-Alonso, C., Tolosana, E., Majada, J., & Canga, E. (2017). A GIS methodology for optimal location of a wood-fired power plant: Quantification of available woodfuel, supply chain costs and GHG emissions. *Journal of Cleaner Production*, (157), 201–212.
[45] Wu, J., Zhang, J., Yi, W., Cai, H., Li, Y., & Su, Z. (2022). Agri-biomass supply chain optimization in north China: Model development and application. *Energy*, (239), 122374.
[46] Balaman, E. Y., Wright, D. G., Scott, J., & Matopoulos, A. (2018). Network design and technology management for waste to energy production: An integrated optimization framework under the principles of circular economy. *Energy*, (143), 911–933.
[47] Morato, T., Vaezi, M., & Kumar, A. (2019). Developing a framework to optimally locate biomass collection points to improve the biomass-based energy facilities locating procedure—A case study for Bolivia. *Renewable and Sustainable Energy Reviews*, (107), 183–199.
[48] Cao, J., Pang, B., Mo, X., & Xu, F. (2016). A new model that using transfer stations for straw collection and transportation in the rural areas of China: A case of Jinghai, Tianjin. *Renewable Energy*, (99), 911–918.
[49] Tang, Z.-H., Liang, C., & Zhang, R.-C. (2023). Optimizing crop residues collection patterns in rural areas to reduce transportation costs and carbon emissions. *Environmental Technology & Innovation*, (32), 103367.
[50] Mafakheri, F., & Nasiri, F. (2014). Modeling of biomass-to-energy supply chain operations: Applications, challenges and research directions. *Energy Policy*, (67), 116–126.
[51] Mohd Idris, M. N., Hashim, H., & Razak, N. H. (2018). Spatial optimisation of oil palm biomass co-firing for emissions reduction in coal-fired power plant. *Journal of Cleaner Production*, (172), 3428–3447.
[52] Flodén, J. (2016). Opportunities and challenges for rail transport of solid wood biofuel. *European Journal of Transport and Infrastructure Research*, 16(4), 512–553.
[53] Stephen, J. D., Mabee, W. E., & Saddler, J. N. (2010). Biomass logistics as a determinant of second-generation biofuel facility scale, location and technology selection. Biofuels, *Bioproducts & Biorefining*, 4(5), 503–518.
[54] Ko, S., Lautala, P., & Handler, R. M. (2018). Securing the feedstock procurement for bioenergy products: A literature review on the biomass transportation and logistics. *Journal of Cleaner Production*, (200), 205–218.
[55] Mirkouei, A., Haapala, K. R., Sessions, J., & Murthy, G. S. (2017). A mixed biomass-based energy supply chain for enhancing economic and environmental sustainability benefits: A multi-criteria decision making framework. *Applied Energy*, (206), 1088–1101.
[56] Schröder, M., & Cabral, P. (2019b). Eco-friendly 3D-Routing: A GIS based 3D-Routing-Model to estimate and reduce CO_2-emissions of distribution transports. *Computers, Environment and Urban Systems*, (73), 40–55.
[57] Golecha, R., & Gan, J. (2016). Biomass transport cost from field to conversion facility when biomass yield density and road network vary with transport radius. *Applied Energy*, (164), 321–331.
[58] Levihn, F., & Nuur, C. (2014). Biomass and waste incineration CHP: The co-benefits of primary energy savings, reduced emissions and costs. *WIT Transactions on Ecology and the Environment*, (190), 127–138.
[59] Zhao, B., Wang, H., Huang, Z., & Sun, Q. (2022). Location mapping for constructing biomass power plant using multi-criteria decision-making method. *Sustainable Energy Technologies and Assessments*, (49), 101707.
[60] Mokarram, M., Shafie-Khah, M., & Aghaei, J. (2021). Risk-based multi-criteria decision analysis of gas power plants placement in semi-arid

regions. *Energy Reports*, (7), 3362–3372.
[61] Pergola, M., Rita, A., Tortora, A., Castellaneta, M., Borghetti, M., De Franchi, A. S., Lapolla, A., Moretti, N., Pecora, G., Pierangeli, D., Todaro, L., & Ripullone, F. (2020). Identification of suitable areas for biomass power plant construction through environmental impact assessment of forest harvesting residues transportation. *Energies*, 13(11), 2699.
[62] Franco, C., Bojesen, M., Hougaard, J. L., & Nielsen, K. (2015). A fuzzy approach to a multiple criteria and Geographical Information System for decision support on suitable locations for biogas plants. *Applied Energy*, (140), 304–315.
[63] Ma, C., Zhang, Y., & Ma, K. (2022). The effect of biomass raw material collection distance on energy surplus factor. *Journal of Environmental Management*, (317), 115461.
[64] Zhang, Y., & Kang, J. (2018). Effect of the distribution density of biomass combined heat and power plant networks on total energy utilization efficiency. *Journal of Renewable and Sustainable Energy*, 10(6), 065902.
[65] Wolf, G. W. (2022). Solving location-allocation problems with professional optimization software. *Transactions in GIS*, 26(7), 2741–2775.
[66] Suganthi, L., & Samuel, A. A. (2012). Energy models for demand forecasting—A review. *Renewable and Sustainable Energy Reviews*, 16(2), 1223–1240.
[67] Peng, C., Li, Z., Xu, Q., Li, X., Li, X., & Chen, H. (2024). Spatial distribution of energy consumption: Integrating climate and macro-statistics for insights from clustering and sensitivity analysis. *Energy & Buildings*, (318), 114446.
[68] Ma, C., Zhang, Y., & Zhao, W. (2021). Influence of latitude on raw material consumption by biomass combined heat and power plants: Energy conservation study of 50 cities and counties in the cold region of China. *Journal of Cleaner Production*, (278), 123796.
[69] Venghaus, S., & Hoffmann, J. (2016). The impacts of energy from biomass on the perceived quality of life of the rural population in Brandenburg, Germany. *Innovation: The European Journal of Social Science Research*, (29), 337–372.
[70] Li, L., Zhang, J., Tang, L., & Yu, L. (2017). Analysis on factors of China's energy intensity changes for 1997–2012: Based on structural decomposition analysis. *Chinese Journal of Management Science*, 25(9), 125–132.
[71] Yasmeen, R., Cui, Z., Shah, W. U. H., Kamal, M. A., & Khan, A. (2022). Exploring the role of biomass energy consumption, ecological footprint through FDI and technological innovation in B&R economies: A simultaneous equation approach. *Energy*, (244), 122703.
[72] Mutschler, R., Rüdisüli, M., Heer, P., & Eggimann, S. (2021). Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake. *Applied Energy*, (288), 116636.
[73] Hao, Y., Wang, L., Fan, W., Wei, Y., Wen, T., & Zhang, K. (2018). What determines China's electricity consumption? New evidence using the logarithmic mean Divisia index method. *Journal of Renewable and Sustainable Energy*, (10), 015909.
[74] Wang, S., Xie, Z., & Wu, R. (2020). Examining the effects of education level inequality on energy consumption: Evidence from Guangdong Province. *Journal of Environmental Management*, (269), 110761.
[75] Otsuka, A. (2018). Population agglomeration and residential energy consumption: Evidence from Japan. *Sustainability*, 10(2), 469.
[76] Zhang, Y., Qin, C., & Liu, Y. (2018). Effects of population density of a village and town system on the transportation cost for a biomass combined heat and power plant. *Journal of Environmental Managemen*t, (223), 444–451.
[77] Li, J., Guo, J., & Yuan, Q. (2018). Forecast of energy demand and policy impact under the background of the coordinated development in Beijing–Tianjin–Hebei region. *Journal of Arid Zone Resources and Environment*, 32(5), 5–11.
[78] Popp, J., Kovács, S., Oláh, J., Divéki, Z., & Balázs, E. (2021). Bioeconomy: Biomass and biomass-based energy supply and demand. *New Biotechnology*, (60), 76–84.
[79] Cintas, O., Berndes, G., Englund, O., & Johnsson, F. (2021). Geospatial supply-demand modeling of lignocellulosic biomass for electricity and biofuels in the European Union. *Biomass and Bioenergy*, (144), 105870.
[80] He, Y., Zhang, Y., & Ma, K. (2024). A comprehensive planning study on the thermal potential of various biomass conversion technologies: Case study of 47 cities in China. *Journal of Cleaner Production*, (437), 140305.
[81] Hassan, Q., Algburi, S., Al-Musawi, T. J., Viktor, P., Jaszczur, M., Barakat, M., Sameen, A. Z., & Hussein, A. H. (2024). GIS-based multi-criteria analysis for solar, wind, and biomass energy potential: A case study of Iraq with implications for climate goals. *Results in Engineering*, (22), 102212.
[82] Lemm, R., Haymoz, R., Gurung, A. B., Burg, V., Strebel, T., & Thees, O. (2020). Replacing fossil fuels and nuclear power with renewable energy: Utopia or valid option? A Swiss case study of bioenergy. *Energies*, 13(8), 2051.
[83] Shi, Z., Ferrari, G., Ai, P., Marinello, F., & Pezzuolo, A. (2024). Bioenergy potential from agricultural by-product in 2030: An AI-based spatial analysis and climate change scenarios in a Chinese region. *Journal of Cleaner Production*, (436), 140621.
[84] Nie, Y., Cai, W., Wang, C., Huang, G., Ding, Q., Yu, L., Li, H., & Ji, D. (2019). Assessment of the potential and distribution of an energy crop at 1-km resolution from 2010 to 2100 in China—The case of sweet sorghum. *Applied Energy*, (239), 395–407.
[85] Cervelli, E., di Perta, E. S., & Pindozzi, S. (2020). Energy crops in marginal areas: Scenario-based assessment through ecosystem services, as support to sustainable development. *Ecological Indicators*, (113), 106180.

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生物质能空间规划研究进展与趋势展望

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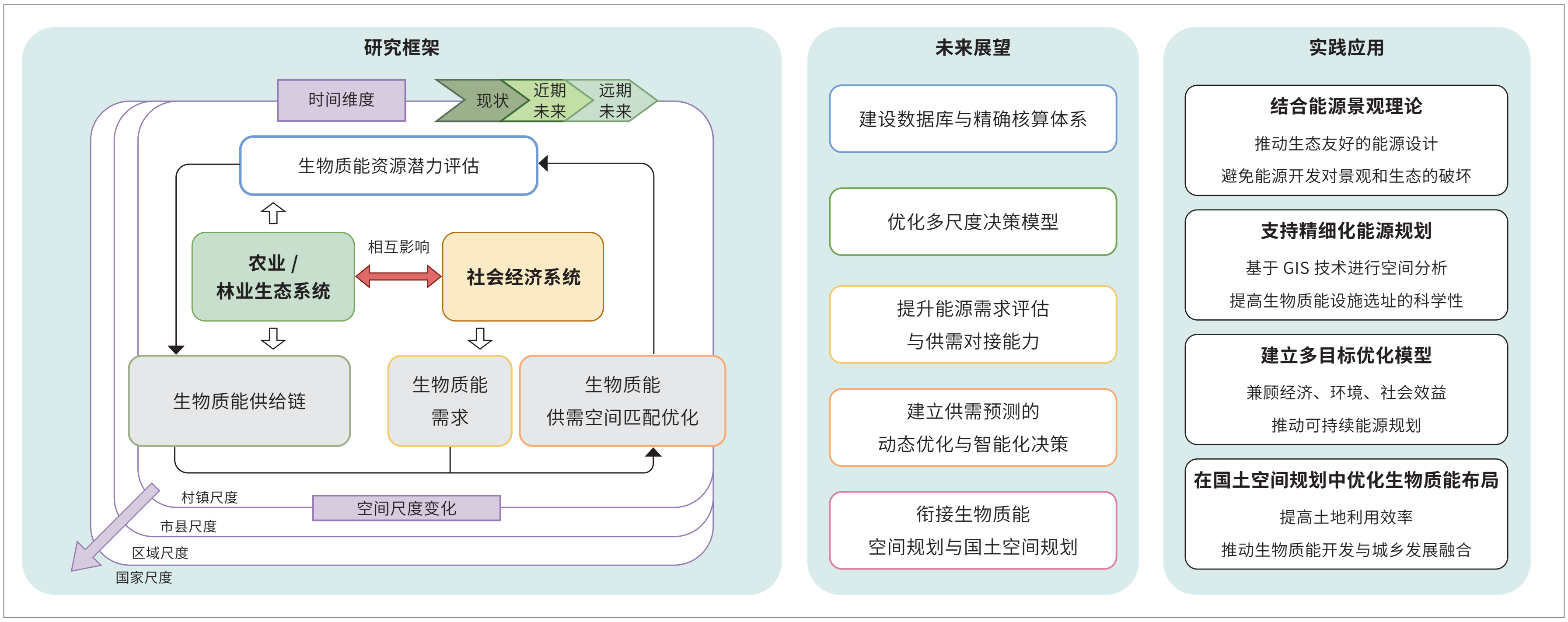
图文摘要



摘要

生物质能作为储量丰富且可再生的清洁能源，可为缓解化石能源使用所引发的环境危机和全球碳中和目标的实现提供有力支持。生物质能空间规划研究具有高度复杂性和学科交叉特征，现有文献在研究尺度和内容方面呈现出多样化态势，但欠缺从全局角度形成研究内容框架的综述类研究，对既有文献进行总体概括、热点梳理、演化趋势分析。因此，本研究首先借助CiteSpace可视化图谱呈现该领域的研究动态。进而，以“能源景观”理论为基础，构建“资源–供应链–需求–优化”的空间运营逻辑及相应的生物质能空间规划研究框架。通过从潜力评估、供应链、能源需求、供需空间匹配优化四方面梳理现有研究，建立研究内容、方法和各研究方向之间的联系，增强生物质能相关评估和空间规划方案的实操性，提升生物质能空间优化方案的科学性和适用性。最后，研究展望了未来研究方向，强调后续研究应进一步加强能源规划与空间规划的融合，通过科学规划与合理布局充分发挥可再生能源的空间附加价值，实现可持续发展。

关键词

可再生能源；能源景观；潜力估算；供应链；供需匹配；生物质热电厂

文章亮点

- 构建生物质能空间规划研究框架
- 提出“资源－供应链－需求－优化”生物质能空间运营逻辑
- 梳理生物质能空间规划研究的现状与未来趋势

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1 引言

全球经济快速发展长期依赖化石能源，由此引发了多种环境危机。当前，发电厂的温室气体排放量约占全球总排放量的35%[1]。生物质能作为一种清洁能源，具备零／负碳排放的优势[2]，可为能源结构转型和全球碳中和目标的实现提供有力支持。根据国际能源署的数据，当前生物质能占全球可再生能源总量的55%，占全球能源供应的6%以上[3]，也是中国国家能源战略的重要组成部分。生物质能指通过光合作用由太阳能转化为生物质载体中贮存的能量[4]，其载体涵盖农业、林业、工业废弃物等形式，具有可储存性强的独特优势[5]，是最具推广性的可再生能源之一。

碳中和目标既是国土空间规划的重要驱动力，也是衡量其核心成果的关键标准。可再生能源转型将影响土地利用功能和环境状况[6]，为此，规划师和设计师已参与到相关研究中，凭借其跨学科优势在空间分析、政策制定等方面为可再生能源布局提供科学支撑。随着城市规划空间布局的引导，可再生能源中远期目标逐渐从集中式发电转型到分布式发电，使得新建基础设施与人口聚集区的空间结合将更加紧密，进而改变城市景观[7]。因此，能源解决方案不能脱离空间问题单独存在[8]，未来能源转型应耦合空间规划和能源规划，特别是局部区域或景观中的生物质资源供需状况。

托马斯·布拉施克等人将“景观”概念引入能源领域，形成“能源景观”理论[9]。能源景观是连接景观中能源供应、需求和基础设施的复杂时空组合[10]。能源景观需要整合实际和潜在的能源来源、能源运输途径和当地能源需求，并与其他生态产品和生态系统服务相协同[11]。在此理论下，生物质能空间规划是基于能源建模与空间分析方法，通过分析生物质能现状、空间分异特征与其随时间变化规律，统筹资源分布、交通条件和需求端布局，进而实现生物质能转换设施的空间布局优化的战略规划。这类规划有助于降低运输和加工成本，同时协调生态保护和资源优化，辅助国土空间规划决策，是实现生物质能开发效益最大化和生态影响最小化的重要路径[12]。例如，赵雪熙等人提出了优化生物质氢能网络的战略规划，并以此识别了最佳投资时机和最佳区域分配[13]。目前，GIS技术凭借其在空间制图和空间分析方面的优势，已成为生物质资源潜力评估与能源设施规划的关键工具[14][15]。宋俊年等人基于生物质能的环境、经济和社会影响状况，以及多资源－技术－产出生命周期框架，预测了中国31个省级行政区2030年三种农业残留物生物质能的对地区可持续发展的贡献和权衡效应[16]。

近年来，针对生物质能开发政策和技术的研究成果较多[17][18]，但依旧欠缺空间规划视角下的综述类研究，缺乏总体概括、热点梳理、演化趋势分析，有待从全局角度形成研究内容框架，增强与国土空间规划的结合。因此，本研究借助CiteSpace可视化图谱呈现该领域的研究动态，并结合能源景观理论构建生物质能空间规划研究框架。本研究引入多尺度、多空间分析方法（尤其强调小微空间尺度），旨在阐明相关研究内容、方法和不同研究方向之间的联系，增强生物质能空间定量评价和规划方案的实操性，提升生物质能空间优化方案的科学性和适用性，为优化未来能源发展的地理空间布局提供基础，提升能源景观的社会接受度。

2 研究内容概述

2.1 基于文献计量法的现状分析

研究利用Web of Science（WoS）核心合集数据库，以“biomass energy spatial planning”“bioenergy spatial planning”“energyscape”为主题词进行检索，设定文献类型为“论文”和“综述论文”，语言仅限英语，时间范围为2015年1月1日至2024年12月31日，共检索得到236

篇文献。为保障所筛选文献的质量与相关性，剔除无关文献后保留文献194篇。为进一步提升数据集的代表性，研究另外纳入了22篇主题词未完全匹配但内容高度相关的核心文献，后共得到有效文献216篇作为分析样本，来相对全面地覆盖生物质能空间规划领域十年间的研究进展。随后，使用WoS内置分析功能对文献的发表时间、研究领域、引文量等进行描述性分析，并使用CiteSpace进行国际合作网络分析、关键词共现网络分析、聚类与时间线视图分析。

2.1.1 研究领域总体特征与演变

生物质能空间规划领域文献总量相对较低，年发文量波动较为明显，在2018年和2022年出现波峰；被引量则在十年间逐步上升（图1）。该领域文献学科覆盖面广，涉及46个WoS学科类别，其中“能源与燃料”（Energy & Fuels）占比最高（45.83%）。

2.1.2 国际合作关系分析

中介中心性用于衡量节点在网络结构中作为信息桥梁的能力[19]。生物质能空间规划领域文献的国际合作关系网络及相关数据表明，美国、德国、荷兰发文量大，同时中介中心性最高，分别为0.24、0.2和0.19，起到国际合作枢纽的作用；相比之下，中国发文量大而中介中心性较低（0.02），在该领域的影响力仍有待提升。最早进行生物质能空间规划研究的国家有芬兰、德国、丹麦、爱尔兰、克罗地亚。而中国、美国、德国、意大利作为该领域研究成果主要贡献者，连年发表研究成果，持续为领域发展提供理论基础。在研究合作关系方面，中国和美国作为大节点却互相路径独立，合作有限；中国与芬兰、瑞典合作相对密切。从网络结构来看，欧美国家跨国合作较多，如德国、美国、荷兰；东亚地区则未能形成有效合作机制。另外，部分亚洲与中东国家（如马来西亚、伊朗）也出现在合作网络中，显现出该领域的多元化与区域扩散趋势（图2）。

2.1.3 关键词聚类分析

关键词聚类侧重的是其本身的相似性，如语义、共现频率、词向量相似度等。节点类型选择“关键词”（Keyword），参数使用默认设置，得到关键词共现网络（图3）。除去在主题词中出现的“生物质”（biomass）、“生物能源”（bioenergy）和“能源”（energy），中介中心性最高的10个关键词为“优化”（optimization）、“可再生能源”（renewable energy）、“可利用性”（availability）、“体系”（systems / system）、“生命周期评价”（life cycle assessment）、“空间分析”（spatial analysis）、“农作物秸秆”（crop residues）、“土地利用”（land use）、“模型”（model）和“管理”（management）。由此可知，生物质能空间规划领域研究热点主要涉及土地空间格局优化、生物质能资源可利用性分析和最优配置规划，普遍依托空间分析与生命周期的建模方法，服务于可再生能源的高效管理与综合布局。

关键词共现分析可揭示研究内容的核心关注点，而聚类分析则进一步挖掘关键词之间的结构性联系，从而构建出研究主题的内在逻辑与演化路径，揭示潜在研究方向。研究进一步利用CiteSpace的聚类与时间线视图功能，选取对数似然率聚类方法。为了获得更具可读性的聚类标签，本文对比了标题词、关键词和学科分类三种标签方式，最终选用标题词作为聚类命名依据。软件自动选取排名靠前的7个聚类标签，结果显示，Q值为0.42，S值为0.76，说明结构同质性高，内部一致性较高且聚类效果较为理想（图4）。所提取的7个研究聚类标签为“时空评估”（spatiotemporal assessment）、“适宜选址”（suitable site）、“边际土地”（marginal area）、“可持续能源潜力”（sustainable energy potential）、“藻类培养应用”（using algal cultivation）、“生物能源市场”（bioenergy market）、“景观框架”（landscape framework）。本领域研究的聚类主题与能源景观的基本内涵相契合，反映出此类研究注重能源空间布局与时空分析、潜力评估、管理流程与市场运营等研究方向。从时间分布来看，聚类#0“时空评估”起始时间最早，时间跨度也最长，是本领域最早活跃且至今保持热度的核心方向。早期（2015～2017年）相关研究以基础方法探索和模型构建为主，2018年后研究重心从理论方法转移到实际应用场景，2020年后开始关注于设施布局优化和多维空间匹配，显示出研究正从单一要素分析走向系统协同与区域综合布局的新阶段。

2.2 能源景观视角下的生物质能空间运营逻辑

能源景观涵盖的产业过程可以通过能源需求、供应和流动来描述，从而帮助识别能源生产、转换、分配与消费之间的路径耦合，空间规划、政策制定或社会接受度等方面的限制，以及能源系统与其他社会经济系统之间的重要关联[20]。关键词共现网络中的高中介中间性关键词“生命周期评价”，指从原材料获取、生产、使用直至废弃的整个过程对某一产品（或服务）进行评估[21]。本研究依此思路，结合现有生物质能供应链相关研究[22][23]，将其运营周期划分为：从原料产地进行初步收集、建立原料收集点、预处理、生物质热电厂①进行加工精炼、生物燃料的使用、建立多类传输网络（包含运输物流及电力传输）、基于使用后的需求反馈形成动态供需关系；进而提炼出“资源－供应链－需求－优化”的空间运营逻辑（图5）。

① 本文以生物质热电厂为代表性转化节点展开研究，其在生物质能供应链中兼具能量转化与终端供能功能。考虑到热电厂的代表性与工程应用普遍性，本文未对其他类型生物质转化设施（如沼气站、乙醇厂等）单独展开分析，而统一纳入热电厂中予以体现。

2.3 生物质能空间规划研究框架

为了系统性地认识生物质能空间规划，理解多种空间尺度下的生物质能生产－使用过程，研究基于现状探索短期或长期未来情景，结合生物质能空间运营逻辑，建立“资源－供应链－需求－优化”的逻辑关系和研究框架，涵盖资源潜力评估、供应链、能源需求和供需空间匹配优化四部分（图6）。

3 研究进展

3.1 生物质能潜力评估

评估生物质能开发潜力并确切描述其空间分布特征，是明确能源用途并形成发展规划的基本条件[24]。受数据的可获取性影响，现有研究多集中于国家和区域尺度[25]。生物质能原料和转化工艺的多样性增加了生物质能潜力评估的复杂性，例如，生物质能原料包括农业残留物、林业残留物、市政固体废物、动物粪便等[26]，经过多种转化工艺和技术可产出电能、热能，以及生物乙醇、生物甲烷、沼气等多种产品[27]。

现有生物质能潜力评估分为三类：第一，理论和技术潜力的估算；第二，以需求为导向的潜力估算，包括经济潜力和实施潜力；第三，链接理论潜力和可持续实施潜力的综合建模评估[28][29]。当前，已有学者基于国家尺度估算了中国可用生物质资源潜力[30]和生物质资源对减排目标的潜在贡献[31]。综合建模评估更多见于区域至村镇尺度，这类研究将潜力评估与精细化的规划管理因素结合，强调结合区域内资源分布的不均衡性优化政策制定[32][33]。

为响应国土空间规划中促进土地资源高效协调发展的目标，需要结合土地利用功能配置评估生物质能潜力。例如，针对粮食作物和能源作物的土地利用冲突，边际土地②[34]的生产潜力备受关注[35]。通常可在边际土地上尝试种植非粮淀粉、糖料、木本油料等能源植物[36]，与这些生物质能原料相关的转化技术已经较为成熟，在经济和环境效益方面初步具备与化石燃料竞争的能力。因此，边际土地的适宜性分析[37]、能源作物种植面积核算，以及其潜力评估已成为研究热点[38]。

生物质能潜力评估能为国土空间规划功能分区的资源上限的界定提供数据支撑，并为能源设施的空间布局提供依据。然而，当前潜力评估研究仍面临定量估算困难、转化技术存在瓶颈、政策支持不足等困境[29]。因学者对生物质的理解不同，所采用的资源分类、测算方法不同，以及关键参数未本地化、标准化，导致相关评价结果缺乏可比性[28]。在评估时，大部分研究假定区域内产量恒定、空间分布均匀，忽略了不同生物质原料的类型差异[38]。例如，农作物秸秆具有明显的季节性特点，而研究常用数据通常是以“年”为时间单位，忽视了资源的周期性波动[39]。

3.2 生物质能供应链

生物质能供应链是原料从收集、加工到投入使用，最终形成燃料产品的过程[40][41]。相关研究主要聚焦于提升经济效益，或实现复杂体系中的多目标优化并形成最优决策[42]。供应链与用户的需求和利益密切相关[43]，其决策成果将直接影响生物质能的社会接受度。地理空间规划视角下的生物质能供应链研究主要关注能源设施的位置与数量及其处理、转化与生产能力，以及不同处理设施之间的生物质分配和运输方式[44]。

3.2.1 生物质能原料收集与预处理

生物质原料收集相关研究侧重于在生物质到达预处理设施之前的过程[45]，现有研究以区域至村镇尺度为主。收集所得的生物质原料通常可在出产地、生物质转换工厂或原料收集点存储[46]。作为原料产地与热电厂之间的中转站，原料收集点的选址需要优先考虑生物量高且运输距离短的区域[47]。相关研究一般以村镇尺度为基本单位，主要关注如何通过选址优化物流路径、降低运输成本，并提升整体效率[48]，进而构建生物质资源收集模式和能源设施选址方式[49]。

通常会在原料收集阶段对生物质原料进行预处理，将其转化为能量密度更高的能源载体，提升能量转化率。同时，也可通过增设预处理点提升储存和运输效率[50]。已有研究通过资源可用性评估和潜在预处理点的适宜性分析确定最优选址方案[51]。

3.2.2 生物质能运输

对物流的研究需要将生物质的运输方式、运输成本、路网可达性均纳入考量，以有效提高决策的可行性。目前公路运输占主导地位，并有伴随铁路运输、水路运输、管道运输形成多式联运的趋势[52][53]。在生物质能供应链中，入境运输为将原料运往热电厂的过程，出境运输则指最终产品从热电厂运往消费地点的过程，相关研究聚焦于入境部分[54]。

生物质供应链运输成本研究涉及借助多种模型和可行性分析的路线开发、运输工具类型和容量的选择与时间表制定，以及如何减少供应链运输成本、缩短运营时间、减弱对环境的影响[55]。学者已探究和识别到各种运输成本潜在影响因素，包含原料的模式容量、类型和含水量、往返距离和区域条件等，其结论显示出明显差异[54]。例如，马尔克・施罗德等人利用道路坡度等因素和3D路线模型分析出车辆的油耗和排放为运输成本的主要影响因素[56]；而拉吉迪普・戈雷查等人则提出弯曲因子（实际运输距离与欧氏距离的比值）和生物质产量密度是影响运输成本的关键因素[57]。

② “边际土地”指受土壤、水热资源、地形因素制约而导致农业利用潜力有限、经济效益低下、生态系统脆弱的土地（来源：参考文献[34]）。该词在前文关键词聚类分析中被 CiteSpace 自动抓取为“marginal area”。

3.2.3 生物质热电厂选址与网络布局

建设和运营生物质热电厂是被普遍认可的高效发展生物质能的方式之一[58]。生物质热电厂选址需要考虑当地气候条件和环境特征，应对资源供应问题与环境风险，避免对自然环境产生负面影响，还应符合当地城市发展规划和生态保护要求。通常，可通过多准则决策分析[59]、风险评估[60]、环境影响评估[61]、模糊逻辑评估[62]等方法对厂址进行综合考评。

生物质原料收集距离阈值指生物质原料资源点与热电厂之间的最大道路长度，通常被用于原料到热电厂的可达性研究。当热电厂的原料收集阈值变大时，可供资源点选择的运输目的地相应增加，生物质原料的分配方案更加灵活[63]。

生物质热电厂选址相关的研究多为区域和村镇尺度。区域尺度的研究通常聚焦选址地点的整体评价，村镇尺度的研究则旨在通过适宜性分析或最优性分析为规划和物流决策提供实用、详细的方案，量化指标包括资源可得性、供应链成本、运输环节温室气体排放量等[44]。在村镇尺度的空间规划方案中，热电厂网络的形态是选址设计的基础。热电厂总功率由区域能源需求分布状态决定，而热能传输阈值（T）可以确定热电厂的服务范围及其与社区之间的区位关系。由于城镇之间道路体系呈现不规则网络状，需引入道路非直线系数（N）获取热电厂的平均服务半径（T/N）[64]。社区分布密度和社区人口均会影响热电厂网络形态（图7）。

总体而言，供应链研究可从资源分布、加工流程、运输路径、设施选址和物流成本等方面为国土空间规划提供科学支撑。当前研究仍存在以下局限性：首先，潜力评估研究中依旧存在数值偏差、空间偏移的问题，会直接影响供应链整体运营体系的构建；其次，规划设计中常以固定数量的设施覆盖需求点，难以获取实际最优成本方案，实践性偏低[65]；最后，由于供应链层级较多，可能存在资源禀赋和基础设施错配，政策难以落地的情况；或由于不同层级之间存在指标体系、治理优先级和执行能力等方面的差异，导致决策难以衔接。

3.3 生物质能需求

生物质能需求与其价格、国内生产总值（GDP）、人口等方面密切相关[66]。具有空间属性的能源需求研究包含需求分布与需求强度两个维度，相关指标的估算和预测因受市场和政策的影响而极具挑战性。相关研究涉及国家、区域、市县及村镇的尺度，在实际建模过程中，不同层级之间的数据分辨率、边界标准和目标导向存在差异，与供应链分析匹配难度较大[16]。

3.3.1 生物质能需求分布

需求分布的不均衡性给热电厂的选址及城市能源空间布局带来了挑战。宏观尺度上，纬度变化造成的季节性需求波动尤为突出——供暖和制冷需求都是能源需求的重要构成[67]。马晨硕等人对比了50个纬度不同且需冬季供暖的市县，发现在非采暖期纬度与生物质热电厂人均原料消耗量呈线性负相关，而在采暖期呈“反S”型关系[68]。同时，生物质能需求的空间分布会随研究尺度的扩大而复杂化。例如，桑德拉·文豪斯等人研究表明，生物质能对区域尺度乡村居民生活质量的提升显著高于个人尺度[69]。

3.3.2 生物质能需求强度

能源需求强度通常以单位GDP所消耗的能源来衡量[70]。人口是决定能源需求的核心要素[71]，其分布和迁移特征有助于理解能源需求的特征与强度，如人口增长[72]、人口的城市化迁移[73]和人口密度变化[74]等。此外，教育水平[74]、年龄结构[75]等人口特征也是能源需求研究的重要因素。例如，在构建生物质热电厂网络时，可通过人口数量、密度或其他特征变化确定生物质热电厂的产能量级和运营效率[76]。

能源需求的规模、结构和空间分布直接影响国土空间规划策略与布局，即需要在国家尺度战略统筹能源生产与消费区域的空间联系，在区域尺度推动供需平衡，在市县、村镇尺度调整供热、供电和交通等能源设施布局。当前，需求侧的研究存在如下局限性：其一，小尺度的生物质能的需求量化研究主观性强；其二，能源需求模型常将能源需求与经济活动假设为简单线性关系，忽略了非线性关系和多维复杂因素的影响，而难以反映能源系统全貌[77]；其三，现有研究对政策、经济、技术等多方面影响因素的解析有限，如仅从“人口”角度进行需求估算的做法是单一化、简单化、均匀化的。

3.4 生物质能供需空间匹配优化

生物质能供需匹配分析可识别动态时空下潜在的资源短缺或过剩区域，增强国土空间规划应对未来能源市场需求不确定性的韧性，是探索生物经济可持续发展路径的关键方法[78]。在资源供需关系分析基础上，结合情景模拟结果，可对能源设施布局与供应链路径进行空间优化，从而提升整体系统效率与适应性。

“需求反馈”部分体现了模型对未来需求变化的响应机制，实现从预测到规划的动态闭环。其研究涉及供给端和需求端的统计数据和分布特征，主要包括空间匹配格局、能源盈余系数等[39]。相关研究多聚焦区域尺度，部分可扩展至国家乃至全球尺度，从宏观层面探讨生物质能源替代化石能源的潜力[79]并提供开发适宜性参考。能源盈余系数指相关资源可被能源化利用的潜力与能源需求量的比值，可直观体现区域能源自给能力。利用该系数不仅能够评估不同固体、液体、气体生物质转化技术的潜力[80]，还可以揭示生物质能与其他可再生能源在生产和转化中的优劣势，进而构建优势互补的可持续能源系统[81]。当前的供需匹配分析中，受制于数据可得性和方法适用性，供需两侧在空间和时间尺度的匹

配都存在局限性，后续研究还需综合考虑资源、技术、政策及社会参与度等因素，以实现生物质能的高效和可持续开发与利用。

情景模拟研究通过设置不同驱动因素的方式来预估规划和决策成果。通常，未来情景模拟的时间设置需结合国家能源战略[82]、碳达峰目标[83]等战略规划内容和气候变化预测模型[84]。此外，为规避生态赤字风险，空间规划需协调如碳储存、生物多样性、水循环及土壤健康等生态系统服务的供需情况[85]。未来情景模拟有助于权衡不同情景下多种生态系统服务的效益，进而设立生态保护或修复项目以补偿潜在损失。

4 研究趋势与未来展望

4.1 全球研究趋势

研究进一步细化全球生物质能领域的研究特点，选择发文量前十的国家和地区，分别提取中介中心性最高的五个关键词为研究热点，提取持续出现的聚类主题为未来研究趋势（表1）。中国与美国作为全球该领域的研究主力，均展现出对生物质原料资源评估及其减缓温室气体排放路径的高度关注，但美国更偏重模型构建与过程分析，而中国则更强调工程落地与适应性发展。欧洲的合作关系网则更倾向于生态可持续与空间优化。在研究方向偏好方面，结合资源－供应链－需求－优化空间运营逻辑可知，当前聚焦于资源潜力的研究较为完备，中国、美国、意大利均出现了资源识别与潜力评估相关的关键词（如“作物残留物”“能源作物”）；供应链研究也相对成熟，中国、美国、荷兰、澳大利亚、西班牙等国出现供应链过程相关的关键词（如“生命周期评价”“运输”“物流”“生物质能设施”）。相对而言，需求和优化两个层面的研究整体不足，相关关键词表现出宏观、泛化倾向。这一判断也从侧面印证了本研究构建四层级分析框架的必要性，其拓展了现有研究的逻辑与规划价值。全球生物质能研究已逐步迈向多维度、跨尺度的综合研究范式。从未来研究趋势来看，荷兰、德国、澳大利亚反映出空间分析与数据信息平台在支撑规划决策中的关键地位。中国、意大利、澳大利亚、英格兰表现出可再生原料获取与生态系统功能协同发展的关注点。中国、美国、荷兰、巴西、澳大利亚将持续关注目标导向的空间规划，强调供需精准匹配与未来调控能力，体现出规划从静态布局走向动态调控、从资源识别转向系统布局的趋势。

4.2 未来展望

结合前述研究热点、现有研究内容和研究趋势，本文提出未来生物质能空间规划研究可从以下五个方向展开。

1）建设数据库与精确核算体系：数据技术和建模手段的进步将为不

表 1：高发文量国家／地区研究热点与未来研究趋势

发文量排序	国家／地区	研究热点	未来研究趋势
1	中国	作物残留物、气候变化、运输、地理信息系统、影响	敏感性分析、选址－分配模型、功能分区、农业生物质
2	美国	生命周期评价、排放物、能源作物、生物燃料生产、玉米秸秆	热电联产、规划和分析
3	意大利	可再生能源、生物气体生产、食物、气候变化、能源作物	能源作物、农业副产品、企业输入输出分析
4	荷兰	决策、生命周期评价、边际土地、生物燃料、影响	生物炼制供应链、空间分布、集成土地与水信息系统、空间分析
5	德国	挑战、生态系统服务、信息、电力、影响	空间分析、发电厂
6	巴西	地理信息系统、第二代乙醇、生命周期评价、航空生物燃料、生产	带容量约束的选址－分配模型、优化
7	奥地利	土地利用、空间分析、可再生能源、温室气体排放、生物能源政策	林木种植
8	英格兰	土地利用、土地、喷气燃料、设计、航空生物燃料	可持续燃料
9	澳大利亚	排放物、链、物流、森林生物质、储存	空间分析、树木与林分重建
10	西班牙	可再生能源、区域、模糊逻辑、体系、生物质能设施	可达性

同尺度的政策制定和能源规划提供坚实的数据支持。相关研究应重点关注生物质资源的动态监测和空间变动分析，包括搭建可实时跟踪和更新数据、评估生物质能开发的社会经济影响、有解释力的需求数据库；建立标准化评估体系，确保资源核算和数据的统一性、可对比性。

2）优化多尺度决策模型：未来研究应开发多尺度决策模型，结合区域差异化特点，优化生物质能供应链。促进跨尺度协同发展，确保不同层级的政策与实践保持连贯和一致，包括在决策情景中纳入长期政策变动及气候变化等因素以提高决策的可持续性，以及拓展跨尺度的多目标规划方法。

3）提升能源需求评估与供需对接能力：针对生物质能的精准需求构建更全面、更系统的需求评估框架，实现供需有效对接，包括深入分析不同的生物质能转化方式所面向的用能类型与区域需求量的差异，比较各种新能源的需求差异，关注生物质能与生态系统服务之间的协同关系；通过多层级的调度与协调机制，灵活调整生物质能的生产计划和供应链布局，实现供需匹配。

4）建立供需预测的动态优化与智能化决策体系：相关研究可引入机器学习与人工智能等技术，基于历史和实时数据增强规划决策在不确定性和动态变化环境中的预测能力。此外，应建立动态调度系统，在生物质能的生产、传输、储存和消费过程中自动调节生产和配送策略，并建立可再生能源错峰调配机制，提升资源利用率。

5）衔接生物质能空间规划与国土空间规划：国土空间规划可为生物质能空间规划提供约束和指导，生物质能空间规划则可为国土空间规划提供政策协调思路，二者数据库可共享。后续研究应注重二者的衔接，确保开发活动不占用保护性功能区，平衡生物质能开发与土地资源利用，提升国土空间规划的韧性与适应性。

5 结语

本研究梳理了生物质能空间规划的核心内容，并基于能源景观理论构建了涵盖生物质能潜力评估、供应链、能源需求分析、供需匹配优化的研究框架。本文结合文献计量分析，探讨了生物质能从生产、运输到使用的基本运营机制，并总结了该领域的研究动态与特征。相较于以往仅关注单一环节的研究，本研究从资源–供应链–需求–优化的运营逻辑出发形成了完整的分析框架，在不同空间尺度和时间维度（过去、现状和未来），以更精细化的视角探讨生物质能的优化布局。

在实践应用层面，本研究可对规划设计学科提供以下参考：在国土空间规划中优化生物质能布局，提高土地利用效率，推动生物质能开发与城乡发展融合；实现精细化能源规划，利用GIS技术进行空间分析，提高生物质能设施选址的科学性；结合能源景观理论，推动生态友好的能源设计；建立多目标优化模型，兼顾经济、环境和社会效益，推动可持续能源规划。本研究还可为政府部门和能源企业提供科学的生物质能空间布局方法，为相关产业政策制定、农业废弃物资源化、农村清洁能源利用等方向提供参考。

图 1. 生物质能空间规划领域发文量及被引量
图 2. 生物质能空间规划领域国际合作网络（图中节点大小代表发文量，连线粗细及颜色代表合作关系）。
图 3. 生物质能空间规划领域研究关键词共现网络
图 4. 生物质能空间规划领域关键词共现聚类时间演化图
图 5. 生物质能典型供应路径与终端用能示意图
图 6. 生物质能空间规划研究框架
图 7. 生物质热电厂网络理想形态（A1）与实际形态（图上其余 8 种）（来源：参考文献 [64]）