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Analysis of Decentralized Energy Systems in Rural Communities: A Focus on Accessibility and Sustainability

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Abstract: Limited access to energy in rural areas undermines the quality of life and hinders the short-term economic growth in a community. It is therefore essential to identify the evolution of technological tools, the social factors, and the current development in the forms of energy commercialization. Using a bibliometric approach and systematic review, this study aimed to conduct case studies in rural communities that implemented decentralized and sustainable energy systems. The methodology involved: i) A bibliometric analysis under the mapping of co-occurrence by keywords and trend topics using scientific databases like Scopus and Web of Science (WoS); ii) The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method; and iii) A systematic review using the Mixed Methods Appraisal Tool (MMAT). A total of 259 articles from rural communities were analyzed from year 1979 to 2024 to prove that biomass, prevailing throughout history, is the most feasible source of energy generated during implementation; the analysis also provided a better understanding of its utilization mechanisms. Bioenergy accounted for 36% of the scientific contribution, primarily out of its widespread availability and the diversity of methods for harnessing energy from this resource. The energy transition of the last two decades was reflected in renewable energy sources (29%), energy mix (18%), and solar energy (9%), relegating conventional energy to only 2%. This study discovered that the research areas of hydropower and wind energy were influenced by the feasibility and social acceptability of their respective projects. Meanwhile, the use of blockchain, exerting an impact on the traceability of decentralized energy trading, advocated a proposal for change in current markets to strengthen the sustainability of projects, streamline processes, and back up information. To sum up, this study examined the utilization and implementation of renewable energy in decentralized energy projects, thereby contributing to energy autonomy and optimized resource utilization.

Keywords: Energy systems; Energy security; Energy accessibility; Clean energy; Sustainable development; Scientometrics

1. Introduction

Energy, an indicator of the quality of living standards, plays a key role in the socio-economic growth of a country. Therefore, the interaction of activities within a society over time is crucial. There are multiple sources of energy, including renewable and non-renewable options, as well as associated energy systems for their use (Nguyen et al., 2021). For example, renewable energy communities in Italy demonstrated that the use of top-down and bottom-up tools allows the optimization of energy resources and a greater involvement of all stakeholders (Mutani et al., 2025).

Global primary energy consumption is primarily represented by non-renewable energy sources, including oil (29.67%), coal (24.6%), and natural gas (22.15%). The contribution of renewable energy sources is minor. For example, solar (2.76%), wind (3.29%), hydropower (5.83%), biomass (6.69%), nuclear (3.68%) and other renewables (1.33%) (Ritchie & Rosado, 2020). Renewable energy sources are gaining greater relevance as they are considered low-emission sources, contributing to the sustainability of territories.

Renewable energy sources comprising solar, wind, hydropower, biofuels and others could serve as the center of transition to less carbon-intensive and more sustainable energy systems (International Energy Agency (IEA) (2025)). Renewable energy sources contribute to diversifying a country's energy matrix, withstanding vulnerability to price fluctuations compared to fossil fuels, and reducing the risks associated with energy imports (Pereira et al., 2023). In this context, the application of building-integrated photovoltaic (BIPV) systems in electric vehicles (EVs) has emerged in urban environments, due to the accelerating demand for sustainable energy solutions (Mauludin et al., 2025).

Biomass, consisting of natural polymers, is a renewable resource derived from plants or animals that can be utilized for generating bioenergy, producing bioplastics and making other compounds (International Atomic Energy Agency (IAEA) (2023)). Globally, there is a consensus on the advantages of biomass such as their renewable character, cleanliness, and cost-effectiveness for development into biofuels. This is reflected in the fact that, in year 2000 there was an equivalent of 112 TWh, whereas by year 2024, it is estimated to be a production of 1,024 TWh (Our World in Data, 2025). These characteristics enable biomass to address problems of energy supply, optimize its structure, ensure efficient distribution, reduce greenhouse gas emissions, and foster economic growth at the regional level. Another example is biogas used for cooking and heating homes through biodigesters (Malik et al., 2024); it is generated from organic waste such as animal manure and agricultural waste.

Exploiting the potential and kinetic energy of water to generate electricity is known as hydropower, and it is one of the most used energy inputs in the catalogue of renewable energy. Hydropower is developed in hydroelectric power plants, which use pipes, turbines, and generators to produce electricity. In coastal communities, the seas have great potential for electricity generation (Andreev et al., 2023).

Another alternative to improving the use of renewable energies is solar energy, which is based on harnessing solar radiation through photovoltaic panels and concentrated systems. These systems are applied in residences, commercial buildings and even industrial facilities to generate electricity and steam and to provide heat (García-Guillén et al., 2025). Additionally, wind energy is considered an opportunity to take advantage of the kinetic energy of the wind to turn it into electricity (Arumugam et al., 2021). The benefits of implementing wind projects involve job creation, expansion of services and increase in circulation of goods, especially in regions with low levels of human development (Olofsson & Castro, 2024).

Geothermal energy is obtained by harnessing the Earth's internal heat. It is estimated that geothermal resources have energy storage of approximately 3.6×10^{14} gigawatt-hours (GWh) in the upper 10 km of the Earth's crust (Mobaraki et al., 2024). Theoretically, geothermal reserves can supply global energy consumption for approximately 2.17 million years, based on an international energy consumption rate of roughly 1.7×10^{8} GWh in year 2022 (Ciriaco et al., 2020). The geothermal resources that are exploited are basically hydrothermal though the others like steam, geo-pressure, hot, dry rock, radiogenic, magma, and lava indicate significant potential for energy storage and generation (Younger, 2015).

Energy is mainly supplied in centralized areas such as urban areas, where energy demand is high and efficient systems are necessary to ensure constant supply in street lighting, buildings, transport, commerce and industrial development (Hiremath et al., 2007). Energy in centralized areas is managed through a combination of energy sources or energy mix, combining renewables and non-renewables to guarantee a continuous and reliable supply. In urban areas, thermoelectric power plants use fossil fuels such as coal, natural gas, and oil to generate electricity (Mendoza et al., 2023). These plants are often located on the outskirts of cities to minimize environmental impacts and comply with emission regulations. Centralized areas also harness renewable energy sources, such as solar and wind power, by installing solar panels and wind turbines (Josimović et al., 2024).

Sustainability is a balancing act between social, environmental, and economic dimensions. The concept of sustainability in the energy sector has become a central principle for quantifying the growing global challenges of environmental degradation and resource depletion (Muniz et al., 2023). Energy-focused sustainability indicators are the primary tool for assessing and monitoring progress towards a more sustainable energy system. For this reason, sustainability indicators such as ecological footprints and energy consumption, provide key information on the sustainability dimensions of energy practices and their long-term effects (Sultanova & Naser, 2025).

In decentralized areas where access to energy sources is limited, harnessing resources available in communities improves their quality of life and promotes sustainability. These areas are often disconnected from electricity grids and they rely heavily on local energy sources to meet energy requirements (Canizares et al., 2019). The importance of energy in these communities lies in its potential to promote agricultural activities, improve basic infrastructure, and provide essential services such as internet, lighting, heating, and cooling. One example of using decentralized solar energy systems in rural areas to generate electricity sustainably and affordably is installing solar panels on the roofs of houses and community centers. Thus, the energy from the sun can be harnessed to power lamps and household appliances (Darwish & Darwish, 2023). This study aimed to analyze case studies in rural communities that implemented decentralized and sustainable energy systems. The following two research questions would be addressed: (i) What are the primary renewable resources that have been implemented in rural communities; and (ii) How are these successful cases related to the improvement in local energy efficiency and the development of scientific content? Scientific databases like Scopus and Web of Science (WoS) were utilized for bibliometric networks, and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was employed for systematic review. Ultimately, this approach would facilitate a synthesis of experiences related to these energy systems, thereby contributing to the sustainable development of the territories.

2. Methodology

The methodological process involved a combination of qualitative analysis for the systematic review and quantitative analysis with the bibliometric approach. This study focused on scientific publications associated with sustainability in the Scopus and WoS databases on decentralized energy in rural areas. A bibliometric analysis of scientific publications, research trends, and countries was performed. Subsequently, the PRISMA method was applied to select case studies that utilized decentralized energy systems in rural communities (Patriarca et al., 2025). A total of 1098 articles were initially retrieved and analyzed through a bibliometric approach to identify publication patterns and research trends. From this larger set, 259 studies meeting the predefined eligibility criteria were selected for systematic review and qualitative synthesis. Finally, these selected documents were reviewed for a quantitative and qualitative synthesis of sustainability and energy access using the Mixed Methods Appraisal Tool (MMAT) (Rodríguez-Abad et al., 2021). The methods applied are shown in Figure 1.

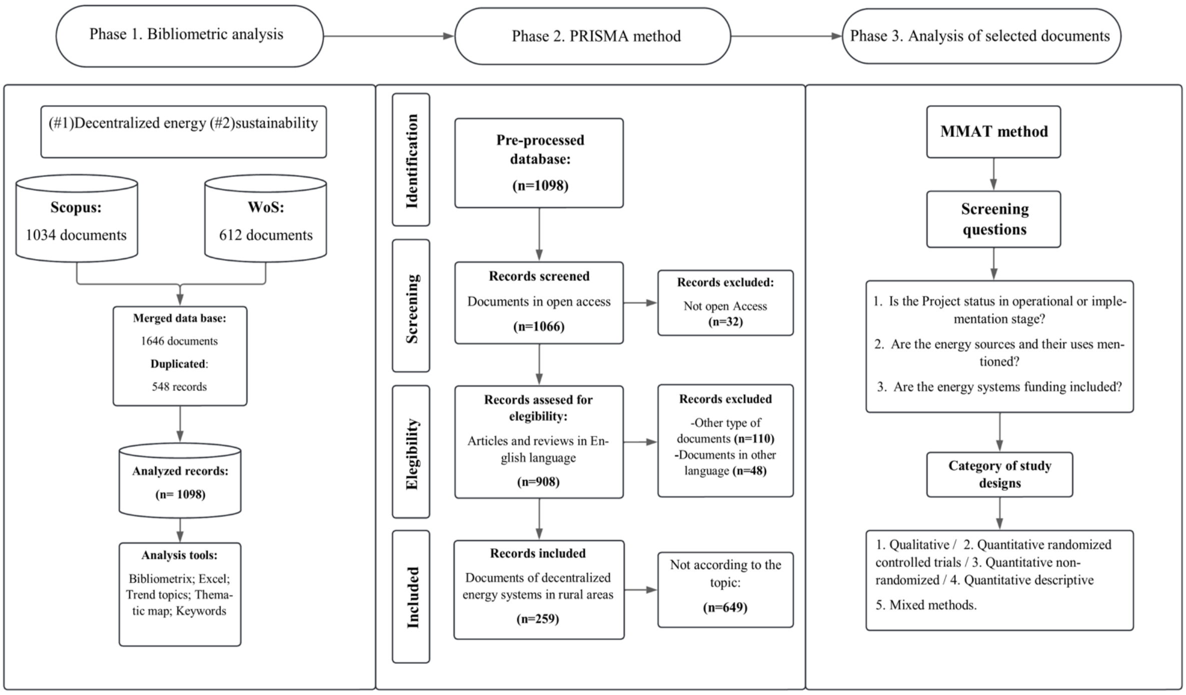

Figure 1. Methodological approach

2.1 Scientific Information and Data Analysis

This section established a search strategy taking into consideration the Scopus and WoS databases as they annexed high-quality scientific information (Echchakoui, 2020). In the search strategy, related key terms such as "decentralized energy systems" (#1) and "energy sustainability" (#2) were considered in Table 1.

Table 1. Search strategy

Topics	Keywords	Scopus	WoS
Decentralised energy (#1)	"decentralized energ*" OR "decentralized energ*" OR "decentralized power*" OR "decentralized power*" OR "localised power*" OR "rural power*" OR "rural energ*"	6122	3795
Sustainability	"sustainablilit*" OR "sustainabl*" OR "SDG*"	1,050,034	711,936
Search strategy	#1 AND #2	1034	612

The database was downloaded at the end of January 2025 to obtain 1646 records, of which 548 duplicate records were removed. Subsequently, an analysis of the remaining 1098 documents was performed using bibliometrix (Biblioshiny, 2023). This approach allowed the identification of research trends, countries, relevant papers, and institutions with higher productivity. Research trend analysis is a data mining technique that uses keywords to identify and extract the main themes from a large corpus of texts (Nabgan et al., 2023).

2.2 Inclusion and Exclusion Criteria Using the PRISMA Method

Using the PRISMA method, this phase involved disagreeing with the information to determine the evolution of energy use in decentralised systems for rural areas. A schematic understanding ensured a level of homogeneous evidence and avoided the mixing of different levels of methodological quality, thereby providing correct objectivity and reproducibility of the study (Setiyo et al., 2024). Based on this premise, the exclusion criteria were defined as: i) Types of documents (only scientific articles and reviews were considered); ii) Thematic relevance and availability of the documents, e.g., from Open Access, which guarantees equity to access all evidence for future research; and iii) Documents in English, to reduce bias in interpretations to align with the predominant language in global scientific communication.

2.3 Analysis of Selected Documents Using the MMAT Method

After identifying scientific papers for systematic review, the methodological quality and risks of bias in the selected documents were assessed using the MMAT method (Rodríguez-Abad et al., 2021). This method was selected based on its generality for studies that employ both qualitative and quantitative methods, as is the case in the present study (Emary et al., 2023). The titles and abstracts were analyzed to select papers on decentralized energy in rural areas. Subsequently, a qualitative and quantitative synthesis of the chosen case studies was performed to classify them by energy sources: solar, hydropower, wind, bioenergy, renewable energy sources, energy mix, and fossil fuels. The validation distinguished five classifications for the used methodology, i.e., qualitative, descriptive quantitative, non-randomized quantitative, randomized quantitative, and mixed, with a general analysis of the selected documents in response to the following queries: i) Does the study have a clearly stated research question? ii) Do the inclusion criteria used by the study not generate a bias that limits its scope? iii) Are the methods and design applied justified? To quantify the quality of the documents, the MMAT tool considered the reference percentages of ≥ 75% as high quality; 50–74% as moderate quality, and < 50% as low quality, based on the ratings generated by the designations of [yes, no, nd (cannot be determined)] as shown Table A1.

3. Results

3.1. Scientific Production and Their Evolution

One thousand and ninety-eight publications addressed scientific production in decentralized energy and sustainability as shown in Figure 2. The period of analysis was between years 1979 and 2024, divided into four sub-periods: Period I (Year 1979–1999), Period II (Year 2000–2010), Period III (Year 2011–2020), and Period IV (Year 2021–2024).

Period I (Year 1979–1999): A methodological gap in the utilization of rural resources compromises the energy demand in rural areas. Higher energy prices and increased environmental awareness are driving the generation of scientific content by improving the process in which organic waste is utilized in rural areas (Ravindranath, 1993). Using technologies such as biomass gasifiers for electricity generation provides self-sufficiency and creates green jobs. Low utilization efficiency of less than 10% predominates due to the means of consumption (Bala, 1997).

Period II (Year 2000–2010): Solar energy has an abundant supply but lacks efficient energy storage, so the investment cost is high (Cook et al., 2010). The markets for rural household lighting with photovoltaics, biogas and hydropower are booming, hence generating new business models (Martinot et al., 2002). Decentralized energy systems base their energy planning on renewable energy sources. Bioenergy in the developing countries plays a role in the security of supply and regional development; it represents the most significant energy consumption in rural areas (Demirbas & Demirbas, 2007). Rural electrification, public policies in the sector, and using renewable energy technologies effectively guarantee access to energy.

Period III (Year 2011–2020): Clean energy communities (CECs) are transforming current socio-technical regimes towards a more decentralized future, thus serving the long-term transition and co-evolution between energy systems and communities to achieve a low-carbon economy (Gui & MacGill, 2018). Sustainability pathways lead societies to a ‘safe operating space’, a priority due to climatic crises affecting food, biodiversity, and energy systems (Pereira et al., 2015). In rural areas, biomass is used in household and economic activities, but its collection and management are complex (Kaygusuz, 2011). Though technologies and virtual financial services are disruptive, they increase access to basic electricity services while providing energy traceability.

Period IV (Year 2021–2024): The COVID-19 pandemic and the war between Russia and Ukraine demonstrate the vulnerability of the energy sector. These events caused abrupt changes in energy demand, fluctuations in oil prices, disruptions in the supply chain, and problems of energy security (Zakeri et al., 2022). Therefore, a timely energy transition reduces dependence on fossil fuels and aims to achieve resilient and sustainable energy systems. As exemplified by electric vehicles, decarbonization, digitalization, and decentralization are three key pillars for an increase in the carbon-neutral economy (Otoum et al., 2023). Blockchain and edge computing digitize processes and build informed, networked and stable value chains. Today, new decentralized power generation technologies have become more economically competitive and have created opportunities to manage infrastructure less hierarchically and more flexibly (Kojonsaari & Palm, 2021).

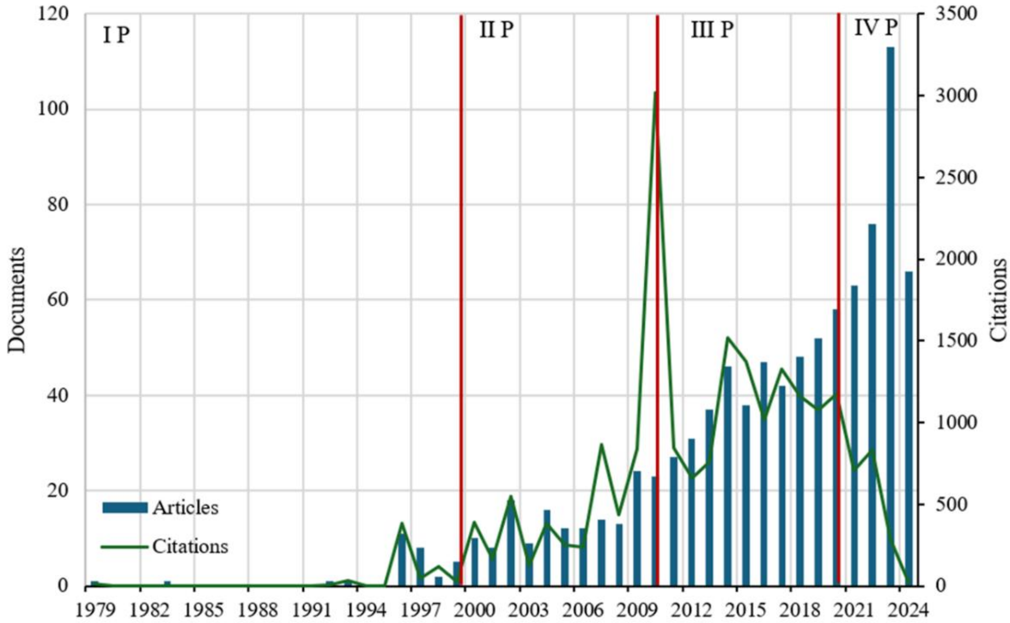

Figure 2. Publications and citations per year

3.2. Trends of Research

Research trends were analyzed from the top 14 research topics, i.e., frequency greater than eight from year 1979 to 2024 in Figure 3. Fuelwood used in years 2002 and 2018 is enduring for its versatility, importance, and availability as a fuel source in rural communities, hence exemplifying the beginning of decentralized energy use. Next, the emergence of sustainability in year 2017 was relevant and central to the global agenda. Renewable energy in year 2020 marked a turning point towards energy transition, hence justifying it to be the most frequently researched term for understanding the changes in political and social visions brought forth by the pandemic. Current trends showed new ways of trading energy driven by blockchain, to enable reliable systems with fair payments, traceability, and a reputation scheme that benefitted prosumers with security and profitability. In addition, microgrids are an example of decentralized system generation, storage and distribution (Abou El Houda & Brik, 2023).

Nodes were grouped by themes and organized into quadrants including driving, niche, emerging/declining, and basic as shown in Figure 4 (Herrera-Franco et al., 2024). Driving illustrated the relationship between biomass, rural energy, and biogas, thus highlighting location as a constraint. The niche themes contained gas production, electric vehicles, and concentrated solar power, which exemplified the three pillars for energy transition. In addition, the core themes highlighted the relationship among decentralized energy, sustainability, and energy market as a transactional resource, through smart grids that leverage blockchain. Microgrids, sustainable energy, and optimization are common factors, illustrating that any projects involved renewable energy for rural areas should decentralize its transmission networks.

The keyword co-occurrence analysis in Figure 5 resulted in three clusters, which associate terms that link to one another and their frequency levels. The clusters deal with renewable energy in blue, sustainability in green, and energy markets in red.

Cluster I (blue), renewable energy: Investment in renewable energy generates green jobs, fosters innovation, and decreases dependence on foreign energy procurement and imported fuels. The energy transition requires robust institutional arrangements and socio-technological structures (Domínguez et al., 2024).

Cluster II (green), sustainability: Public opposition and location need to be considered as determinants in energy planning. A comprehensive rural energy planning plan aims to establish specific strategies at the local level to optimize the use of the available energy potential in rural areas (Fuchs et al., 2024).

Cluster III (red), energy market: The development of decentralized energy systems for households enables the growth of supply and demand by generating peer-to-peer energy markets for sustainable energy supply. This model implies imposing an active role on citizens in the energy market. The patterns of generation and consumption are the basis for these markets (Edussuriya et al., 2023).

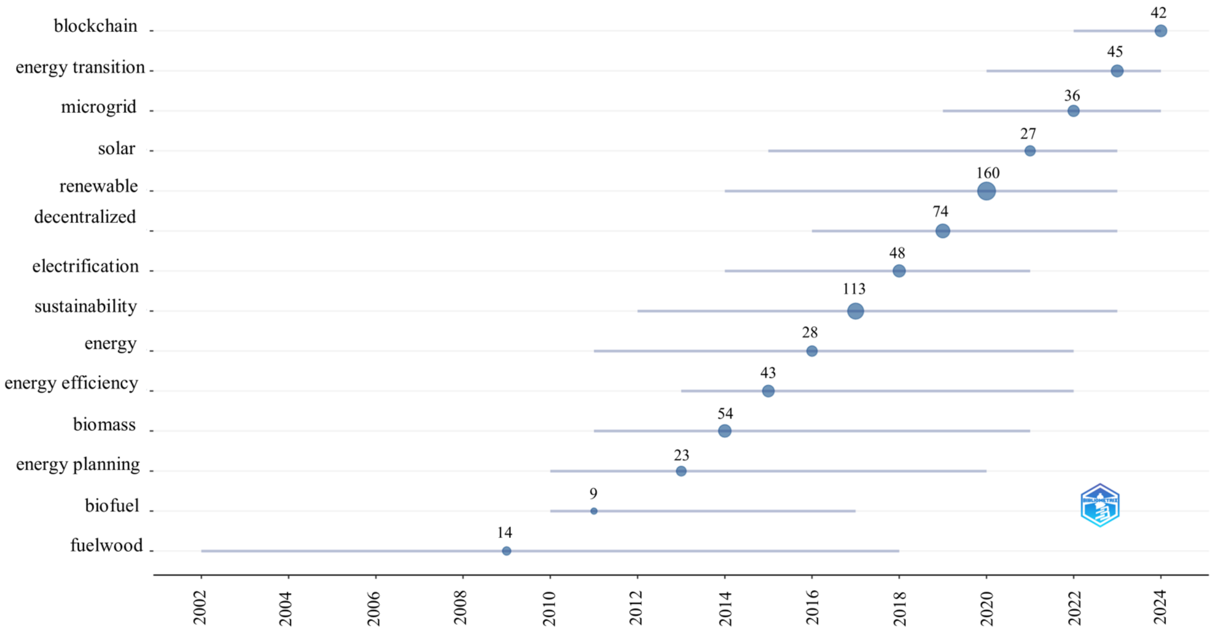

Figure 3. Analysis of research trends

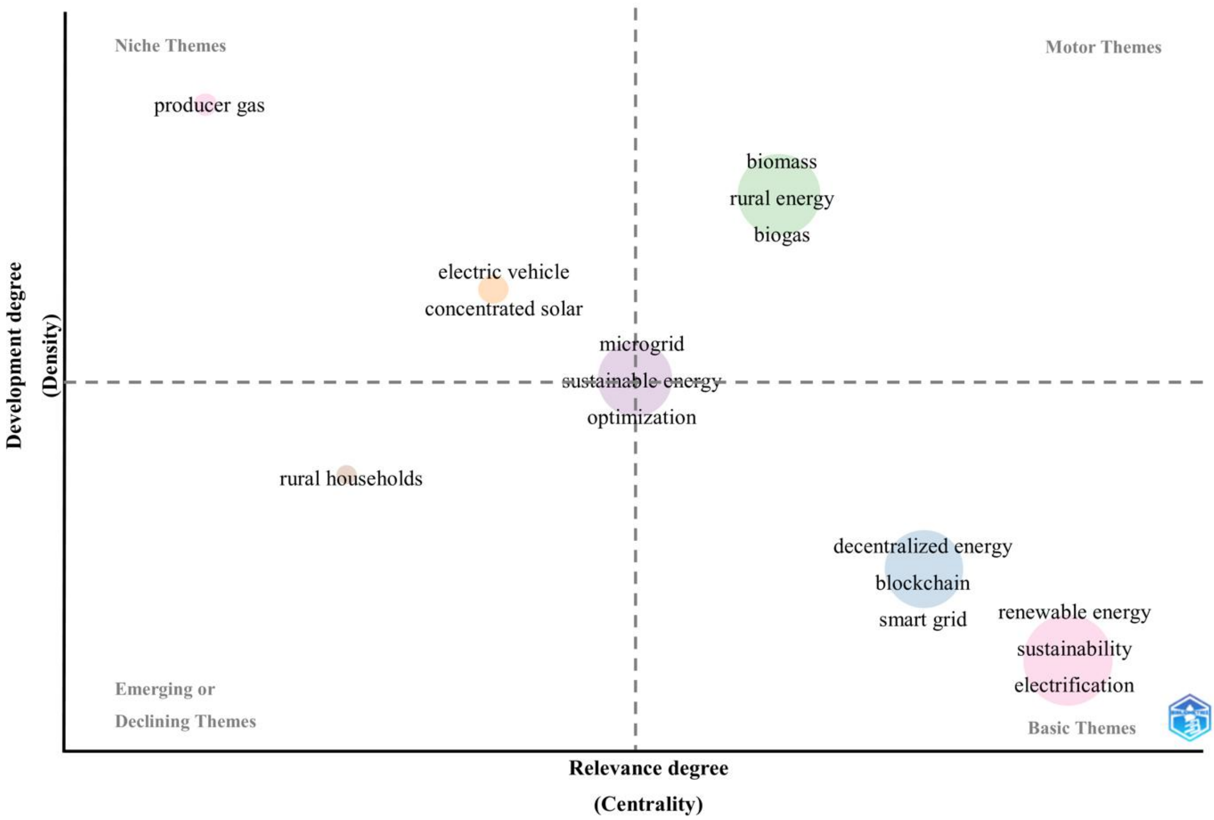

Figure 4. Thematic map

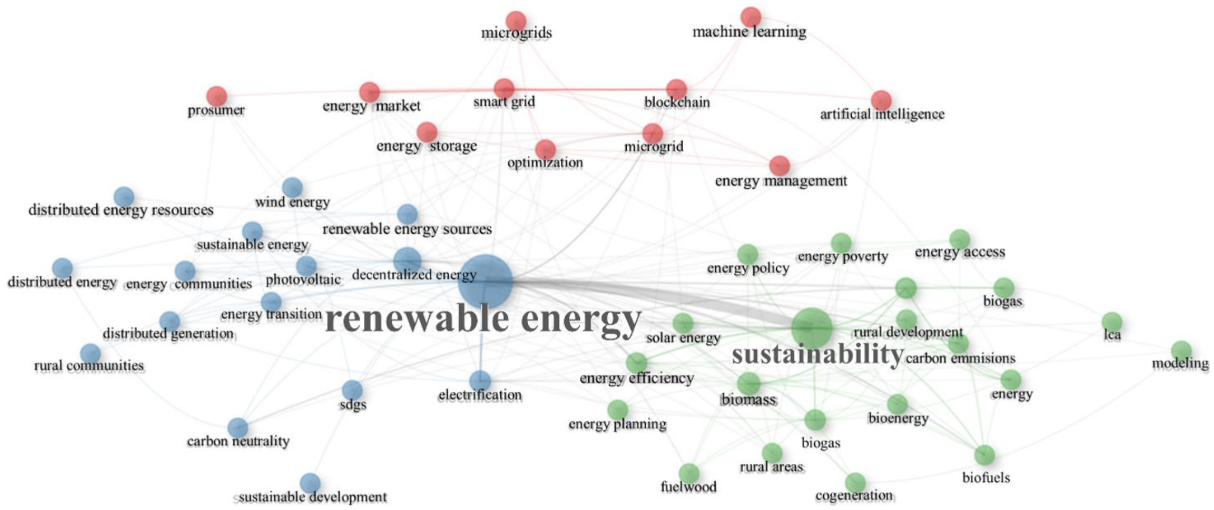

Figure 5. Co-occurrence by author's keywords

3.3. Findings in the Systematic Review Using the MMAT Method

Of the 1098 documents, 259 articles were analyzed; they met the selection criteria including Decentralised Energy Planning (DEP) as an option to meet rural energy needs in a reliable, affordable, and environmentally sustainable manner (Schnidrig et al., 2024). The central aspect of the DEP should consider the characteristics of the area to meet the energy needs of the economy and environment at the lowest cost. Decentralised bioenergy systems that produce biogas and electricity using local biomass resources have been shown to promote development compared to other renewable energy sources (Robin & Ehimen, 2024). The review featured the distribution by energy types of the cases, focusing on bioenergy (36%), renewable energy sources (29%), energy mix like renewables and fossil fuels (18%), solar energy (9%), and others (8%) as in Figure 6. This analysis revealed that 233 documents (89.6% of all) have a score greater than or equal to 75%, indicating high methodological quality. In comparison, 26 documents (10.4% of all) have scores in the range of 50-74%, classified as moderate quality. Qualitatively analysis was conducted on the most significant limitations identified in the moderate studies, involving "dependence on secondary literature in reviews", "low integration of qualitative and quantitative data in mixed studies", and "influence of external variables not measured or adjusted in non-randomised studies".

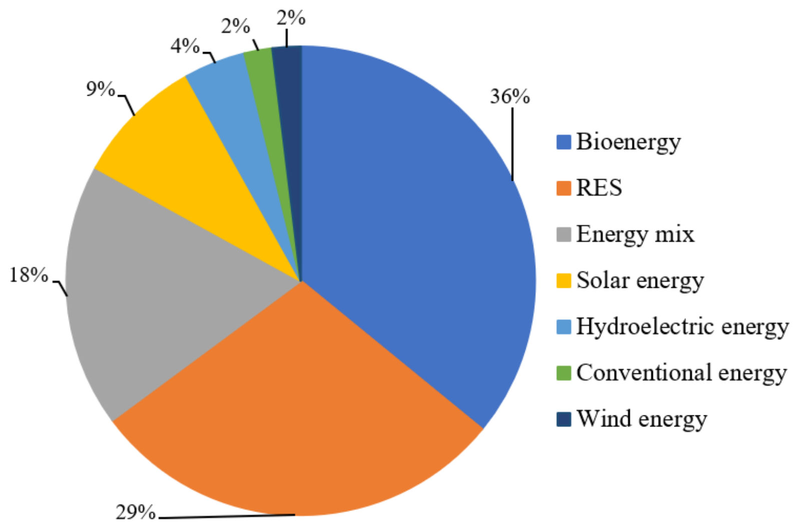

Figure 6. Cases of decentralized energy in rural areas

3.3.1 Bioenergy

Bioenergy utilization occurs in thermochemical conversion technologies such as pyrolysis, gasification and liquefaction (Wang et al., 2020). Biomass is incinerated to generate heat and electricity, transformed into gas-like fuels such as biomethane and biohydrogen, or transformed into liquid fuels, e.g., methanol and ethanol.

Technological advances in modern biomass combined heat and power (CHP) plants are cleaner, more efficient and, under certain conditions, cost-effective compared to utility grids, fossil fuel boilers or generators (Pandey & Erbaugh, 2024). China (24.73%), India (21.50%), and Ethiopia (6.45%) showed higher scientific content in this topic.

(1) Biomass and Vegetable Coal

Insufficient energy supply and low levels of development are directly related. Larger projects may have greater financial benefits but generate long-term impacts on the natural resources of adjacent communities. Low adoption rates of modern bioenergy systems in rural areas indicate institutional weaknesses in creating an enabling environment for their development (Tolessa, 2023). The analysis combining Strengths, Weaknesses, Opportunities, Threats (SWOT) and Analytical Hierarchical Process (AHP) showed that the negative aspects associated with the rural environment dominated their positive counterparts (Kaoma & Gheewala, 2021). There are policy considerations vital to improving the environment in this context: i) strengthening the analytical capacity of key policy actors in biomass supply chains; ii) supporting the developed countries for effective transfer of bioelectricity technologies; and iii) developing a framework for sustainability planning of rural-based bioenergy systems. These strategies should align with the national development objectives of a country (Bazmi et al., 2011).

(2) Liquid Biofuels

Diesel engines have proven helpful in the transport, agriculture, and energy sectors and are potential sources of decentralized power generation for rural electrification. The long-term availability of petroleum diesel and stringent environmental regulations have forced the search for a renewable alternative to diesel (Baumert et al., 2018). Vegetable oils have been considered reasonable alternatives to diesel in recent years, but many problems are associated with using vegetable oils in diesel engines (Rodrigues et al., 2021). The steady expansion of biofuel production and consumption raises concerns about the social and environmental sustainability of the production, processing, and trade of biofuel feedstocks. The literature considered larger and heavier vehicles as well as advanced biofuels potential logistical solutions to improve the energy efficiency of the forest industry. In addition, advanced biofuels could be blended with natural biofuels, which are advantageous for road freight fuel service, when delivery logistics and large infrastructure are available (Palander et al., 2018).

(3) Biogas

Biogas is produced through anaerobic digestion, biomethanization or fermentation of organic matters, for instance, animal manure and bedding, aquatic algae, and non-woody agricultural residues such as rice and wheat straw, cotton and millet stalks as well as bagasse in a biodigester (Yalew, 2021). The use of biogas in households takes advantage of waste generated by agricultural activities. Fuel consumption tests showed that households with biodigesters used 2.1 to 3.3 tons less fuelwood per year than similar households without biodigesters (Robinson et al., 2023). One of the primary challenges of utilizing this type of energy is the high initial cost, limited access to credit, and need for regular maintenance.

3.3.2 Solar energy

Using local and renewable energy sources, such as solar energy, ensures that rural communities have greater independence and energy supply security (Nedjalkov et al., 2019). The countries with the highest contribution in this area were India, China, Bangladesh, and Zimbabwe, respectively. Transport in mountainous regions is often tricky, and it is preferable to use local and decentralized energy sources. Photovoltaic (PV) cells are silent; they convert light into electricity without relying on mechanical or chemical processes. They neither require fuels nor start to degrade for at least 20 years (García et al., 2024). The most advanced systems have a charge controller and/or inverter that can convert direct current (DC) to alternating current (AC) for household appliances. Increasing the efficiency of solar systems and their utilization in remote areas is crucial to achieving sustainable development. Considerations should be taken in some aspects of technical systems, such as the production of technical components and the organization of maintenance, dissemination, design, local adaptation of components, and the socio-technical interface where technology and users converge (Hellqvist & Heubaum, 2023).

3.3.3 Hydropower

Decentralized energy supply systems, such as small-scale hydropower, are recommended energy projects for the developing countries as a clean development model to be in line with global climate change mitigation policies (Kaunda, 2013). It was found that the countries with the highest scientific content in this area are China, India, and Nepal, with an average of 22.22%. The population in these countries perceived negative impacts on the environmental and socio-economic sector due to projects using hydrological resources. For example, there is a decrease in flora/fauna, agriculture, tourism, water pollution, and erosion (Hussain et al., 2021). Positive impacts are related to increased living standards, road connectivity, transport, public services, and environmental awareness.

3.3.4 Wind energy

The ability to supply energy to rural areas and agricultural plants with renewable wind energy technologies is advantageous in terms of sustainability. Still, it is challenging due to the high cost of energy. Considering the cost of energy production per unit, these systems are not economically competitive compared to other energies (Arumugam et al., 2021). Therefore, these systems should be produced on a large scale to become financially viable, and their size should be scaled up to reduce costs. The economic and political partnership of Europe and the United States has the highest scientific content. In this regard, community energy initiatives for wind energy projects have the potential to boost rural economies, improve acceptance, and develop local knowledge networks (Murshed et al., 2023). However, there are many obstacles to commercialising turbines on a large scale, including lower turbine efficiency associated with high vibrational losses, cost criteria, insufficient technical knowledge among manufacturers, and a lack of awareness among end-users (Jones & Olsson, 2017).

3.3.5 Sources of renewable energy

Local and renewable energy resources ensure greater independence in energy consumption and security of energy supply in rural communities (Nedjalkov et al., 2019). Rural communities preferably use biomass as their primary energy source for heating and household cooking. In countries with a high average household energy cost generally caused by a lack of government subsidy, alternatives such as solar cookstoves become cost-effective. If the strategy has time, it is feasible to offset the household cost of biogas digesters. Rural households are transforming the traditional dominance of low-efficiency biomass to integrated consumption of conventional and renewable energies. However, most of the rural population in many developing countries still has little or no access to modern energy technologies (Matheri et al., 2023). The countries with the highest scientific content in this area were China (18.92%), India (17.57%), South Africa, and Nigeria (5.41%), respectively.

3.3.6 Energy mix

Energy mix involving the combination of conventional energy and renewable energy, is a pillar in energy transition arising from the complexity of changing the energy matrix (Schöne et al., 2024). The countries with the highest scientific content in this area were China (20.41%) and India (18.37%). The interrelationship between the use of local energy resources and land degradation leads to a paradoxical situation in current energy consumption. The scarcier the local energy resource base is, the higher the total energy consumption at the household level appears to be (Halabi et al., 2017). The pattern of energy use is the government's tool for regulating energy prices and driving market development.

4. Discussion

The systematic review focused on the types and use of renewable energy sources; it identified the solutions offered by different transformation mechanisms, hence contributing in adopting decentralized low-emission energy to tackle the energy problems faced by a nation. The proposed analysis in rural areas helped recognize the types of energy for improving the quality of life of those marginalized by having little or no access to electricity transmitted by centralized energy networks (González et al., 2016). This review demonstrated the non-utilization of energy from the life cycles of natural resources available in rural communities. It validated with examples that the residual biomass generated and the non-use of available renewable resources diminished the economic growth of a region by threatening energy security (Matheri et al., 2023). In addition, there were limitations to the scope of grid projects focused on direct transmission, whereas the importance of generating independent energy communities was highlighted. Decentralized energy systems for rural areas were proposed as highly feasible projects (Ugwoke et al., 2020).

Beyond empirical findings, the results were framed within broader perspectives to enhance their relevancy to policies. Therefore, anaerobic biogas digesters represent a technological approach to support modern, sustainable, and fair access to energy, while improving efficiency and contributing to transition pathways aim at meeting the United Nations (UN) Sustainable Development Goals (SDGs), specifically SDG7 for ensuring affordable, reliable, sustainable, and modern energy for all (Robinson et al., 2023). The findings also reflected the principles of energy justice, hence emphasizing equity in distribution, participation, and recognition of marginalised groups. Diversifying and shifting to cleaner energy sources have recently become key strategies in the energy sector. The sustainable use of natural resources was exemplified by Jatropha Curcas, which was being promoted in India as a sustainable alternative to diesel fuels, thus resulting in a reduction in nitrogen oxides and improving the principles above (Chauhan et al., 2010). Finally, to align with the Multi-Level Perspective (MLP), innovations such as microgrids or biogas plants gradually reshaped existing energy regimes. This framing showed decentralized systems as both technical solutions and drivers of sustainability (Geels, 2002).

Bibliometric approaches showed that, in a timeline of year 1979–2024, knowledge was aligned with technological development. Household energy constituted an object of study and served as the basis throughout the transition in Figure 3. Energy transition is a key point in generating necessary energy independence, which ensures the adequate transmission of energy to those who make up the community, thereby facilitating sustainable development. Renewable resources was proposed as they are an inexhaustible source of energy (Grabher et al., 2024). Renewable energy as an axis for decentralized energy systems enables territories to move towards a more efficient energy network, an energy transaction channel that lends itself to traceability in contracting processes; the use of resources could become more transparent and innovation could be driven with low carbon emissions, hence contributing to an efficient distribution in the matrix for the growth of a community as shown in Figure 5.

The availability of energy and its quality are key determinants of economic productivity. The actual contributions of energy resources in a sustainable development framework involve more complex issues, particularly the nature and degree of technological participation (Chodkowska-Miszczuk et al., 2022) A devoted commitment between governmental and non-governmental parties and a targeted campaign to promote their use is required to ensure long-term viability and to increase the likelihood of achieving environmental and health objectives.

Findings suggested that access to modern and decentralised energy solutions did not lead to complete energy transitions. The case studies suggested potential improvements in food security, increased income, better health tools, and opportunities for resource conservation (Herrera-Franco et al., 2024). One proposed solution suggested that wind-concentrating systems could generate more energy than conventional wind turbines because they utilized the energy potential of wind in the area more effectively as well as the energy available in each unit. When adopting low-carbon electricity generation technologies and promoting a decentralised energy strategy through public and private companies, using locally available renewable energy resources is therefore necessary (Kong et al., 2016).

With the growth of the digital economy, the sustainability of rural energy is crucial. However, traditional rural energy models have the drawback of not considering digital technology and renewable energy (Wang et al., 2021). There is an urgent need for rational rural energy planning and development integrated into spatial planning. Accordingly, a multi-energy coupling model for rural energy systems is needed, considering equipment capacity planning and operation scheduling optimization based on a multi-energy coupling structure.

The advanced digital technology introduced by the model rendered it more flexible to cope with the diversified energy sources and complex operational scheduling situations involved in rural energy systems. The model could improve the speed of response and adaptability of the system, which could then be more resilient and efficient (Peng et al., 2024). Energy performance contracting is an up-and-coming area for attracting private investment in the renewable energy sector. The concept of energy performance contracting is a well-established mechanism aimed at increasing the energy efficiency of a facility and reducing annual maintenance costs (Chodkowska-Miszczuk et al., 2022).

This study focused on specific energy systems and technologies, such as photovoltaic (PV) systems, bioenergy, wind energy, and hydropower. While helpful in highlighting the practical use of these solutions, this focus might have overlooked other critical factors such as political, economic, and social barriers that influenced the implementation of decentralized energy. The results were valuable in technical terms, and it remained essential to delve into the interdisciplinary aspects that played a key role in long-term sustainability and success (Bose et al., 2021). The findings raised important policy and equity implications. While China and India dominated scientific contributions, their models required adaptation to local socio-economic realities elsewhere. In many rural regions, adoption is limited by high upfront costs, scarce credit, and weak maintenance capacity, emphasizing affordability as a key challenge (Bhattacharyya, 2012). Inclusivity is also essential to ensure women, indigenous populations, and other marginalized groups benefit equally. Long-term sustainability depends on integrating decentralized systems into broader energy planning, strengthening local capacities, and building resilience to external shocks. This shifts the debate from technical feasibility to equitable and durable energy transitions (Johnson, 2020).

The developing countries are bound to link their economic growth to the availability and supply of energy (Oladigbolu et al., 2020). A major change in energy policy to accommodate the conversion of biofuels to versatile energy carriers in a decentralized system have to meet the energy needs of the population and provide a basis for rural development and employment in rural areas (Matheri et al., 2023).

This systematic review conducted a formal assessment of the quality and risks of bias of the 259 studies using the MMAT tool, in order to highlight the strengths and limitations of the analysed documents. It is worth noting that the values of 89.6% for the high-quality documents supported the reliability of the synthesis performed. It is recommended that future research should adopt comparative designs to provide more detailed information regarding the integration of mixed methods.

5. Conclusions

This study focused on the interaction of decentralized energy systems in rural communities by analyzing 1098 scientific publications using bibliometric networks. This analysis showed that China and India were the countries with the most scientific content, hence demonstrating that it is crucial to develop policies for supporting expansion and sustainability in rural sectors. Bioenergy is the most used source in rural communities (36%), followed by renewable sources (29%), energy mix (18%), and solar energy (9%), among others (8%). This predominance considered the local availability of resources and the adaptability of technologies to rural conditions. A systematic review of 259 documents found that diversifying the energy matrix and digitizing processes was crucial for improving the efficiency and reliability of energy systems. Implementing blockchain and microgrids suggested a shift towards more decentralized and autonomous systems as these not only reduced costs but also promoted local energy autonomy and sustainability.

Rural communities are undergoing a profound transformation due to the introduction of decentralized renewable energy. The systems offer significant social benefits and present a viable and sustainable alternative to conventional national electricity grids, especially in remote regions. Despite advances, the reliability and integration of these technologies in rural settings remain significant challenges. Energy systems and innovations, such as biodigesters, have the potential to overcome these barriers, hence directing further research and development of locally adapted solutions.

For future studies, it is recommended that the definition of costs associated with energy production over the lifetime of energy projects should consider indicators such as net present value and return on investment. Analyzing these parameters would allow the selection of technologies and strategies to be optimized to ensure that rural electrification is not only practical, but also economically viable and environmentally sustainable.

This article identified a limitation from the inclusion and exclusion criteria for bibliometric analyses as the criteria have biased a large percentage of scientific content, thereby limiting the complete analysis of the visions that some authors could present. This is because the exclusion criteria in this study have reduced the uncertainty of freely available knowledge and removed conference papers owing to their category, yet these criteria could be considered in the future research as they are not adopted in the current approach.

Author Contributions

Conceptualization, G.H.-F.; E.A.-R.; L.B.-M.; J.C.-P. and E.B.; methodology, E.A.-R.; L.B.-M.; J.C.-P.; software, E.A.-R.; J.C.-P; validation, E.A.-R.; J.C.-P; formal analysis, G.H.-F.; L.B.-M. and E.B.; investigation, G.H.-F.;E.A.-R.; L.B.-M. and E.B.; resources, G.H.-F.; data curation, E.A.-R.; L.B.-M.; J.C.-P.; writing—original draft preparation, G.H.-F.;E.A.-R.; L.B.-M.; J.C.-P. and E.B.; writing—review and editing, G.H.-F.;E.A.-R.; L.B.-M.; and E.B.; visualization, E.A.-R.; L.B.-M.; J.C.-P.; supervision, G.H.-F. and L.B.-M.; project administration, G.H.-F.; funding acquisition, G.H.-F. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data supporting our research results were included in the article or supplementary materials (Table A1).

Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix

Table A1. Application of Mixed Methods Appraisal Tool (MMAT) for the analysed database

Study Category	Number of Documents	Methodological Criteria	Yes	No	Don't Know
Screening questions	Applied to 259 documents	Is the Project status in operational or implementation stage?	233	22	4
		Are the energy sources and their uses mentioned?	230	24	5
		Are the energy systems funding included?	238	9	12
1.Qualitative	Applied to 60 documents	Is the qualitative approach appropriate for the research question?	50	10	
		Are the data collection methods adequate?	45	10	5
		Are the findings adequately derived from the data?	50	7	3
		Do the data support the interpretation?	55	3	2
		Is there consistency between sources, collection, analysis, and interpretation?	57	1	2
2.Quantitative randomized controlled trials	Applied to 5 documents	Was randomization appropriate?	5		
		Are the groups comparable at baseline?	4	1	
		Are the outcome data complete?	3		2
		Were the outcome assessors blinded?	3	2	
		Did participants adhere to the assigned intervention?	3	1	1
3.Quantitative non-randomized	Applied to 70 documents	Are participants representative of the target population?	65	5	
		Are the measurements appropriate for the outcome and intervention?	64	2	4
		Are the outcome data complete?	68	1	1
		Were confounding factors controlled for in the design and analysis?	63	4	3
		Did the intervention or exposure occur as planned?	61	5	4
4.Quantitative descriptive	Applied to 110 documents	Is the sampling strategy relevant?	90	5	15
		Is the sample representative of the target population?	98	9	3
		Are the measurements appropriate?	95	2	18
		Is the risk of bias due to non-response low?	97	10	3
		Is the statistical analysis adequate?	92	16	2

5.Mixed methods	Applied to 15 documents	Is there adequate justification for the mixed design?	10	5	
		Are the components effectively integrated?	11	2	2
		Is the qualitative-quantitative integration well interpreted?	14		1
		Were discrepancies between qualitative and quantitative results addressed?	9		7
		Does each component meet the quality criteria of its methodological tradition?	9	5	1

Source: Rodríguez-Abad et al. (2021)