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Research Article

A systematic literature review on renewable energy technologies for energy sustainability in Nepal: Key challenges and opportunities

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Abstract. Energy security is getting louder globally as there are growing concerns about the risk of climate change from using traditional non-renewable energy sources. This systematic literature review is conducted to identify the current state of renewable energy technologies in Nepal supporting the energy sustainability issue, opportunities, and challenges. The peer-reviewed journal articles published in Scopus, Web of Science, and Google Scholar databases were searched with specified search strings. Preferred Reporting Items for Systematic Reviews and Meta-Analysis(PRISMA) framework was utilized to search and screen the relevant literature published from 2012 to 2023 related to renewable energy development in Nepal. The Biblioshiny () function of the R-tool was utilized to conduct the meta-analysis of the identified literature. The result shows that the majority of articles were produced after 2019 and among them 50% of the research were conducted on mixed renewables, 19.4% on hydro, 14.5% solar, 8.1% wind, and 8.1% bio-energy. Renewable energy, climate change, sustainability, and policy interventions were identified as major themes in the research. Biomass (66.4%) still dominates the total energy mix and hydropower dominates in electricity generation. This review has explored how the studies were conducted on energy sustainability and renewable energy technologies in the context of Nepal. The review also provides challenges faced by Nepal's renewable energy sectoral development and the underlined opportunities towards energy sustainability.

Keywords: Climate change; Energy mix; Energy sustainability; PRISMA framework; Renewable energy; Sustainable development goal; Systematic literature review

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1. Introduction

Energy is the basic essential product for human survival and its usage also produces unwanted by-product gases which are harmful to mankind and the planet. Nearly 60% of the total world's greenhouse gas emissions are related to energy supply management, and renewable energy sources account for about 17% of total energy consumption (UN SDG, 2022). The Intergovernmental Panel on Climate Change warns that by 2050, the renewable energy consumption share must reach 85% to prevent the worst effects of climate change on the earth (UN, 2022).

Renewable energy resources are used to derive energy from natural resources which are replenished continuously and never depleted. Major renewable energy resources are solar, wind, hydropower, geothermal heat, and biomass. Renewable energy sources are naturally occurring phenomena and can be harnessed energy without being depleted over time(US_EIA, 2022).

The UN's Sustainable Development Goal 7 was formulated to achieve some key targets by 2030. The targets are to increase the renewable energy share significantly and to ensure the accessibility of affordable and reliable clean energy services to everyone. Another target is to double the energy-efficient growth rate across the world (UN SDG, 2022). Therefore, the world has now started to focus its attention on renewable energy promotion and development. At the same time, it reduces the dependency on traditional fossil fuels and minimizes greenhouse gas emissions.

Renewable energy is considered the major driver for achieving sustainable development goals. It ensures energy sustainability and helps to mitigate climate change by lowering greenhouse emissions compared to fossil fuels and traditional biomass. The long-term available renewable energy resources are wind/solar/water, etc. which can be converted into the required energy form for usage. Cîrstea *et al.* (2018) indicated the positive contribution of renewable energy towards achieving the sustainable development goals, as defined by the UN, in the energy sector and helping to combat the climate change impact. With the growing concern of climate change impact and the attention towards renewable energy production in the world, countries are focusing their action plans and key tasks to protect the climate by increasing renewable energy shares and reducing fossil fuel-based energy sources.

The graphs of Figure 1 show the renewable energy generation in gigawatts and the share of renewable energy(in %) to the total energy generation trend in the world and it confirms

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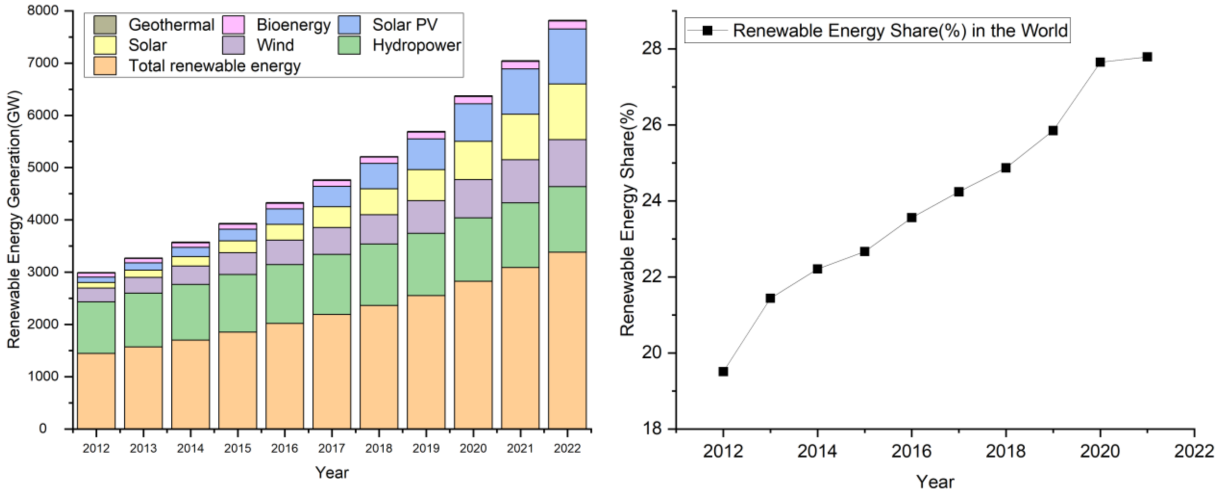

Fig 1. Renewable energy generation trend and its share in the world (IRENA, 2023)

that there is an increasing trend in renewable energy generation and the share of renewable energy to the total energy generation in the world(IRENA, 2023). The trend analysis also shows that hydropower has the dominant role in clean energy generation over other renewable resources such as solar, wind, geothermal, and bioenergy.

Renewable energy sources not only enhance energy security in the country but also boost economic growth, job creation, and adoption of innovation in the energy sector(Khare *et al.*, 2022). The latest technological advancements and innovations have been playing a crucial role in increasing energy efficiency, cost reduction in energy services, and more accessibility to the general people.

Being a member country of the UN and having an obligation to follow the SDG's policy, guidelines, and action plans, Nepal has been working to achieve sustainable development goals by formulating appropriate policy and action plans. Nepal has also formed institutional frameworks to implement, facilitate, and monitor sustainable development goal-related policy and action plans(MoWERI/GoN, 2023). Nepal government formed the Alternative Energy Promotion Centre(AEPC) to promote, develop, and facilitate alternative energy technologies in Nepal (AEPC, 2022b), Nepal Electricity Authority(NEA) to generate, transmit, and distribute electrical energy with sufficient quantity, high reliability, and at affordable cost (NEA, 2022).

The energy demand in Nepal has been increasing with the Gross Domestic Product(GDP) and economic development of the country. However, firewood (70% share) followed by fossil fuels (13% share) are still dominant energy sources in Nepal, though there is great potential for hydro and renewable energy sources(WECS/GON, 2017). The per capita electricity demand is estimated to reach 1536 KWh by 2040 from 136 KWh in 2015 and the substantial growth of electricity demand has to be fulfilled by different energy sources(WECS/GON, 2017). Despite a sharp increase in annual per capita energy consumption (63 kilowatt-hours (kWh) in 2000 to 177 kWh in 2018), Nepal's per capita power usage is still quite low. The annual per capita energy consumption ranking of Nepal is one-twentieth of the global average.(Herath Gunatilake, Priyantha Wijayatunga, 2020).

AEPC claims that nearly 90% of the total population has access to electricity generated by different sources, but the quality of the supplied energy is poor(AEPC, 2022a). An estimated 89% of population has the energy access from NEA generation (mostly hydro) and 4.2% of the population has been consuming the electricity generated from alternative energy sources (Micro/mini hydro, solar, and solar/wind mini grid). 15.3% of the population has access to electricity supplied by both the NEA and AEPC (AEPC, 2022a).

Household energy consumption produces nearly 70% of total global greenhouse gas emissions(Streimikiene *et al.*, 2024). Therefore, the need for the development and integration of renewable energy in households is essential and that will help to reduce greenhouse gas emissions substantially. Apart from solar, wind, hydropower, and biomass, in recent research and development, a major focus has been given to electrical energy storage (EES) and hydrogen energy as a supplement to renewable energy sources. The hybridization of the renewable energy system using hydrogen energy and energy storage system has been gaining concern for higher energy sustainability and reducing greenhouse gas emissions (Kyriakopoulos and Arabatzis 2016; Kyriakopoulos and Aravossis 2023). Furthermore, for environmental and energy sustainability, consumer awareness and knowledge of energy systems should also be provided and it should be started at the school level(Drosos *et al.*, 2021).

Regarding the renewable energy and energy sustainability issues in Nepal, few researches have been carried out. Some of them are a systematic literature review on investment in hydropower to develop energy sustainability (Adhikari *et al.*, 2023), a study on solar and wind energy potential at the provincial level of Nepal by Neupane *et al.*(2022), a review on hydropower-renewable energy solutions for sustainable(Shrestha *et al.*, 2022), an analysis of barriers to renewable energy development in the context of Nepal (Ghimire & Kim, 2018). Neupane *et al.* (2022) estimated that Nepal has an enormous resource of solar energy, Kunwar (2014) recommended complementing the hydropower energy shortfall by using solar and wind energy in Nepal. Laudari *et al.* (2015) researched to assess the economic viability of wind energy in Nepal by selecting ten different sites in the Terai and hilly regions. Gurung *et al.* (2013) also studied the potential of wind energy in Nepal and found that there is a possibility of wind energy in Nepal. Dhakal *et al.* (2020) researched to study the feasibility of distributed wind energy generation in Jumla, Nepal. There were also several studies on the possibility and economic viability on waste to energy conversion and energy sustainability in Nepal (Baral & Kim, 2014; Sodari & Nakarmi, 2018; Dhakal *et al.*, 2016; Shrestha *et al.*, 2014; Lohani *et al.*, 2022). A systematic review explores and assesses all the studies conducted in any sector, and finds the themes, related data, and trends for better understanding to the scholars and policymakers. The systematic literature reviews in renewable energy sectors provide the accumulated knowledge about the studies, findings, gaps, and future prospective or pathways for the development, promotion, and consumption of energy in a specific country or the world. However, the systematic literature review on renewable energy development and its role in energy sustainability in the context of Nepal was not found in recent years. It could assess not only the current state of research, opportunities, and challenges in renewable energy technology in Nepal but also present how a systematic literature review helps to find less explored areas and paves the way for future studies, especially the role of renewable energy technology in energy sustainability and powering the communication and digitalization infrastructures. Therefore, it is essential to conduct a systematic literature review on renewable energy and energy sustainability issues in Nepal using systematic and scientific methods for thoroughly study of high-quality literature in the context of Nepal's renewable energy sector. The objective of this paper is to collect the available literature published in indexed journals (Scopus, Web of Science (WOS), and Google Scholar) and review systematically to address research questions as given below.

- What is the current state of research on the contribution of renewable energy to achieving energy sustainability in Nepal?
- What are the opportunities and challenges for renewable energy development and the path towards energy sustainability in Nepal?

This paper considers the above research questions and aims to find out the answers from the systematic literature review process. The findings of the systematic review are expected to provide an important document for scholars and policymakers to study and analyse the renewable energy and energy sustainability issues in Nepal.

2. Methods

A systematic literature review is a comprehensive and rigorous method to search, identify, abstract, evaluate, and synthesize existing literature relevant to the particular research questions of the topic(Janjua *et al.*, 2021). It is an evidence-based research method and is commonly used in academic fields. The systematic literature review follows the defined procedures such as formulating the research questions, strategy to search the journal articles from the databases, and screening the papers to select the relevant and concise research articles suitable to address the research questions. It also involves data extraction, data analysis, data synthesis, and interpretation of the results with the conclusion (Azril *et al.*, 2018).

2.1. Defining the research strategies

The PICOT method was chosen to formulate the research strategy to answer the research question in this literature review. PICOT is a structured approach to developing clear, focused research questions and research strategies in evidence-based practices. PICOT stands for Population(P), Intervention(I), Comparison(C), Outcome(O), and Time(T) frame (Riva *et al.*, 2012). In the context of this systematic literature review, the research questions were formulated in the PICOT method where the "population" refers to the country under research 'Nepal' focusing on its renewable energy systems and associated policy frameworks related to renewable energy development and promotion. "Intervention" is the initiatives taken for developing renewable energy sources such as solar, hydropower, wind, and bioenergy. "Comparison" relates to contrasting the current state of renewable energy generation with conventional energy sources and comparing the country's effort to best practices and standards in renewable energy adoption. The "outcome" or result is associated with the achievement of energy sustainability and the assessment of the economic, environmental, and social outcomes linked with the sustainable development and adoption of renewable energy in Nepal. The time duration for the study was limited to 2012 to 2023. Similarly, the systematic literature review strategy also resembles the PICOT strategy. The "population" refers to the research papers published in peer-reviewed journals in the context of Nepal on renewable energy technology and energy sustainability, "intervention" indicates the search strategy(inclusion and exclusion criteria) adopted to identify the relevant literature, "Comparison" contrasts the identified journal articles published in Web of Science, Scopus, and Google Scholar whereas "Outcome" is the final eligible journal articles for the review to answer the research questions for this systematic literature review, and (T) denotes the duration(from 2012 to 2023) considered for the research articles published in the journal databases.

2.2. The review procedures

The systematic literature review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework(Adeyinka-Ojo, 2016). There are, also other various frameworks for conducting a systematic literature review on the defined topic. PRISMA framework is mostly used in the environmental, social science, and engineering fields. It offers unique benefits to defining research questions that permit systematic research, examining the large databases of scientific literature in a defined time, and identifying the inclusion and exclusion criteria to concise the research areas and select the required literature for the analysis (Pielken *et al.*, 1987).

2.2.1. Selection of the journal database and search criteria

The potential literature was searched from indexed journals (Scopus, WOS, and Google Scholar) only and any other literature published is not considered for the review purpose. These databases are large enough to cover most of the research articles from the area considered research population viz. Nepal. WoS is the largest and a robust database that covers more than 256 disciplines including environmental, engineering, social affairs, and development-related areas. it covers a large number of articles from more than 100 years with proper citations, analysis, and ranks. Similarly, Scopus is the second-largest database used in this review. It has an estimated number of 22,800 journals from 5000 publishers worldwide(Adriaanse & Rensleigh, 2011; Azril *et al.*, 2018). It also covers diverse disciplines such as environmental, engineering, social science, and biological sciences. Similarly, Google Scholar is also a large database with diverse areas of research and mostly covers open-access journals(Adriaanse & Rensleigh, 2011). Therefore, to minimize or eliminate the Type-I and Type-II errors in the research, major journal databases such as Scopus, Web of Science, and Google Scholars have been selected for literature search so that most of the high-quality research papers and areas of the related research will be covered in this review work

2.2.2. Journal articles screening methods

To identify the relevant journal articles, search keywords are formulated based on the research questions and objectives. The literature is retrieved from Web of Science, Scopus, and Google Scholar databases with the defined search strings formulated by

Table 1
Journal search from Web of Science, Scopus, and Google Scholar databases.

Databases	Generalized Search Strings
Web of Science	All fields: ("Renewable Energy" OR "Sustainable Energy" OR "Solar Energy" OR "Solar PV" OR "Energy Sustainability" OR "Wind Energy") AND Nepal AND Keywords: "Renewable Energy" OR "Sustainable Energy" OR " Solar PV" OR "Wind Energy" OR Biomass
Scopus	All fields: ("Renewable Energy" OR "Sustainable Energy") AND ("Energy Sustainability") AND Nepal AND (Publication Year 2011-2023) AND (Document Type: article) AND (Source Type: Journal) Limit Keywords "Renewable Energy", "Sustainability"
Google Scholar	Adopted advanced search option to concise the literature to meet the specific objectives of the paper. With all of the words: "Renewable Energy in Nepal" Where my words occur: In the title of the article

Boolean expressions. The Boolean expression is constructed using keywords and Boolean operators such as; AND, OR, NOT, etc. The keywords selected are; sustainable, sustainability, renewable energy, and renewable energies. The search strings are given in Table 1.

2.2.3. Eligibility and exclusion criteria

The database is screened using eligibility criteria and exclusion criteria. At this point, the subject area is more focused based on objectives and the research questions. The journal papers are selected from the defined databases excluding all the books, conference papers, and proceedings, reports. The research area of the articles is confined to Nepal and the time period is considered the last 12 years since 2012. This time period was chosen so that the latest research within 12 years would be included in the study and the required significant information would be included. The journal scopes were chosen only the renewable energy and energy sustainability. The screening criteria are presented in Table 2.

Using the eligibility and exclusion criteria as shown in Table 2, a total 183 articles were identified among them 31 from Web of Science, 79 from Scopus, and 73 from Google Scholar databases. After the identification of the 183 articles, the article screening was performed by the title review of the articles to match the objectives and excluded irrelevant articles as seen on title screening. The duplicate articles, books, book chapters, conference proceedings, and non-English language articles published before 2012 are also excluded. To focus on the subjects and the more concise information on the research area, the most suitable eligible articles are identified by assessing the abstract and the full texts. The included articles have undergone through study for qualitative analysis and synthesis. The flow diagram of the PRISMA framework for screening and identification of the eligible journal articles is given in Figure 2.

2.2.4. Further screening for eligibility

The database records are further screened as per the following PRISMA flow diagram as depicted in the Figure 2 (Moher *et al.*, 2009). The journal papers are identified, at the initial, from the databases using the search keywords. The identified articles are screened by excluding the books, book chapters, conference proceedings, and non-English content. The records are further screened by abstract assessment, full-text assessment, and removing duplication and finally, the inclusion list for the systematic review is determined.

2.2.5. Data abstraction and analysis

Data abstraction is the method to identify and record the relevant information from the selected journal articles. The remaining articles from the inclusion criteria were assessed and analysed. Special focus was given to research questions while abstraction and analysis of data so that the research objective was met. The data extraction was done by reading full articles to identify the themes and sub-themes in renewable energy and energy sustainability in Nepal. The themes and sub-themes are

Table 2
Eligibility and exclusion criteria

Criteria	Eligibility	Exclusion
Databases	• Web of Science, Scopus, Google Scholar	• Other database
Period consideration	• 2012-2023	• Before 2012
Subject area/Field of Study	• Energy • Renewable Energy • Sustainability • Energy Sustainability • Renewable Energy types (Solar, Wind Hydro, Biomass, Geothermal) • Environment, Sustainable Development	• Nuclear energy • Fossil fuel energy • Traditional energy
Study region	• Nepal	• Outside Nepal
Document Type	• Full-length articles, Review Articles • Published and final publication stages • English language	• Books, book chapters, • Conference/Seminar proceedings, reports, • Articles under processing • Non-English

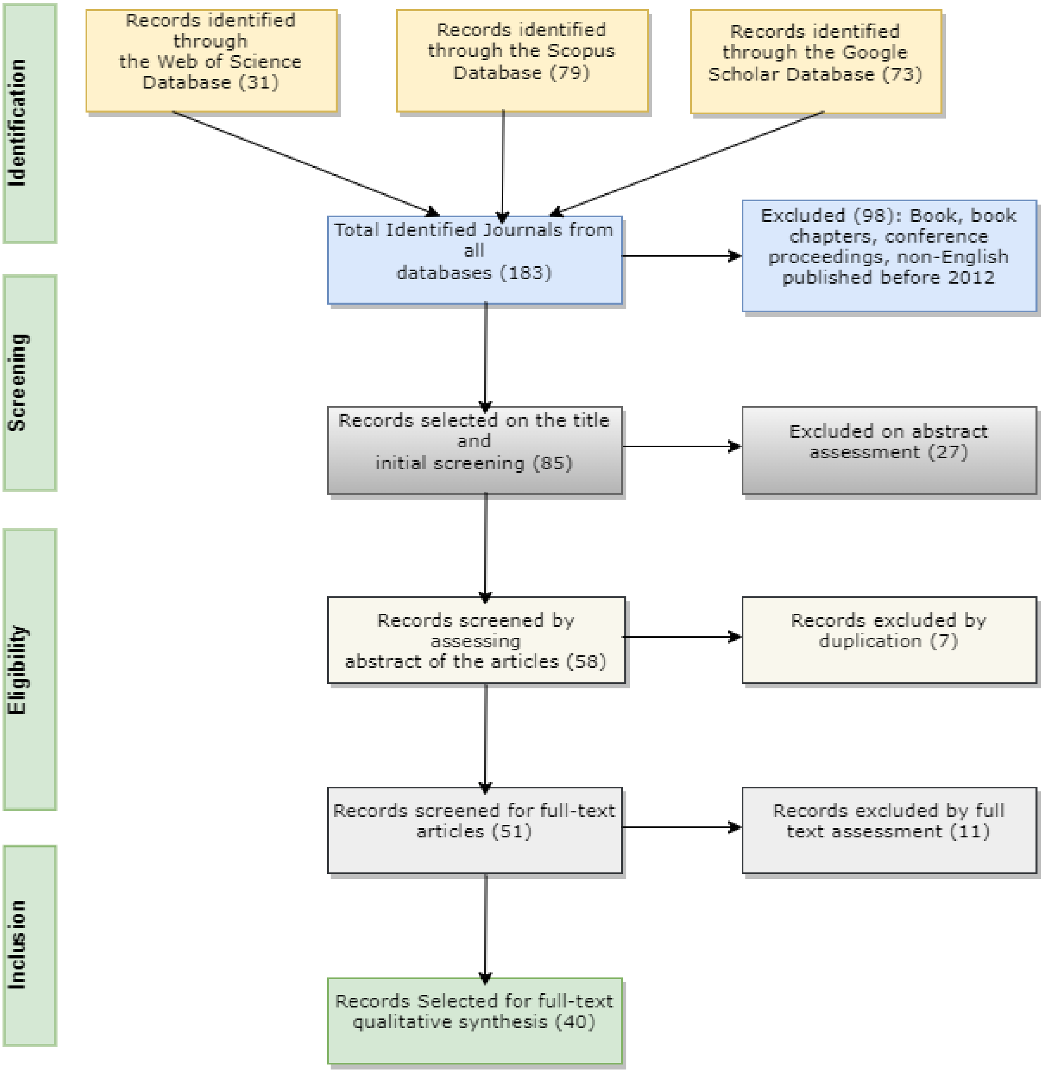

Fig 2. The PRISMA flow diagram adapted from (Moher *et al.*, 2009)

Table 3
The themes and sub-themes and the authors included in the studies

The themes of the Articles	Sub-Themes	Authors
Renewable Energy Development	• Energy Sustainability • Sustainable Development	Bhandari *et al.* (2017); Bhandari *et al.* (2014); Clements *et al.* (2021); Dhonju *et al.* (2022); Sanjel & Baral(2021); Poudyal *et al.* (2019); Nepal(2012); Lohani *et al.* (2022); Ghimire & Kim(2018); Bhardwaj *et al.* (2022); Baral & Kim(2014); Gurung *et al.* (2013); Nakarmi *et al.* (2014)
Environmental Impacts	• Climate Change	Suman (2021); Dhital *et al.* (2014)
Renewable Energy Policy	• Policy intervention	Underwood *et al.* (2020); Butchers *et al.* (2020);
Renewable Energy Conversion Technology	• Solar energy	Poudyal and Shakya(2016); Bhattarai *et al.* (2022); Poudel *et al.* (2021); Neupane *et al.* (2021); Dhakal *et al.* (2021); Baral (2019); Lohani *et al.* (2021)
	• Wind energy	Pandeya *et al.* (2021); Laudari *et al.* (2020); Dhakal *et al.*(2014); Neupane *et al.* (2021)
	• Hydropower	Budhathoki *et al.* (2021);Crootof *et al.* (2021); Shrestha *et al.* (2022); Subedi *et al.* (2021); Sarangi *et al.* (2014); Sanjel and Baral(2021)
	• Biomass/Bio-energy	Bista *et al.* (2022); Cheng *et al.* (2013);Lohani *et al.* (2021); Bhattarai *et al.* (2022);
Energy Consumption	• Consumption trend • Energy Applications	Pariyar *et al.* (2022); Bhardwaj *et al.* (2023); Malla (2013); Clement *et al.* (2020)

grouped under the Table 3. The authors used the *Biblioshiny ()* function of the R- R-Studio tool for the meta-analysis of the literature.

The Scopus and Web of Science bibliographic data are exported into *.bib and *.txt files. These files are combined using the R-programming function. The merged bibliometric file

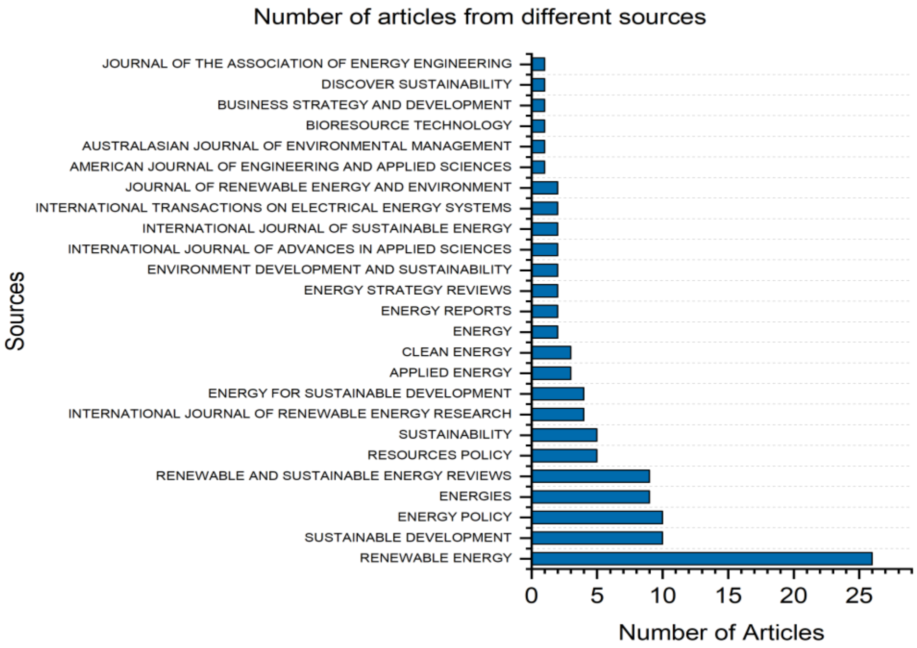

Fig 3. Number of publications from 2012 to 2023

(*.bib) was loaded in R-tools using the *Biblioshiny ()* function. Different bibliometric meta-analysis graphs/charts and tables are generated as per the requirement. Due to the inconsistency of the database in Google Scholar, the bibliometric files of Google Scholar couldn't be merged with Scopus and Web of Science database files and hence were excluded from generating some Tables and Graphs (Figure 7&8).

3. Results

The results section describes the evolution of the literature and the contents analysis of the literature related to renewable energy and energy sustainability. The *Biblioshiny ()* function of the R-studio was utilized to perform the meta-analysis of the identified literature from Scopus and Web of Science databases.

3.1. Bibliometric data analysis

The major bibliometric data of the literature identified using the search strings from the selected databases are presented using the R-Tool and *Biblioshiny ()* function. The major data extracted in this paper during the time span of 2012 to 2023 are: articles number and source journals, year-wise publication of research papers, shares of papers based on database sources and types of study, most cited journals and articles, most cited countries in the identified literature, and trend of research based on the keywords/terms/subjects. The name of the journals and the number of articles selected from the specific journal for this systematic literature purpose is depicted in Figure 3 which is created from the paper identified from the inclusion criteria, shows that major articles are extracted from the journals such as "Renewable Energy", "Energy Policy", "Renewable Energy and Sustainable Development", and "Sustainability". Almost all the articles identified are extracted from journals with renewable energy, environment, and sustainability-related themes.

The journal articles and the publication years from 2012 to 2023 are discussed in the evolution of the literature as shown in Figure 4. This graph shows that most of the articles, identified from the search criteria, were produced after 2018 and

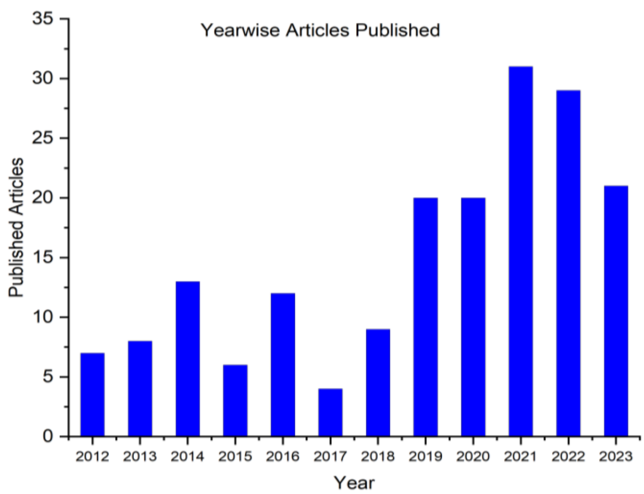

Fig 4. Number of publications on year wise from 2012 to 2023

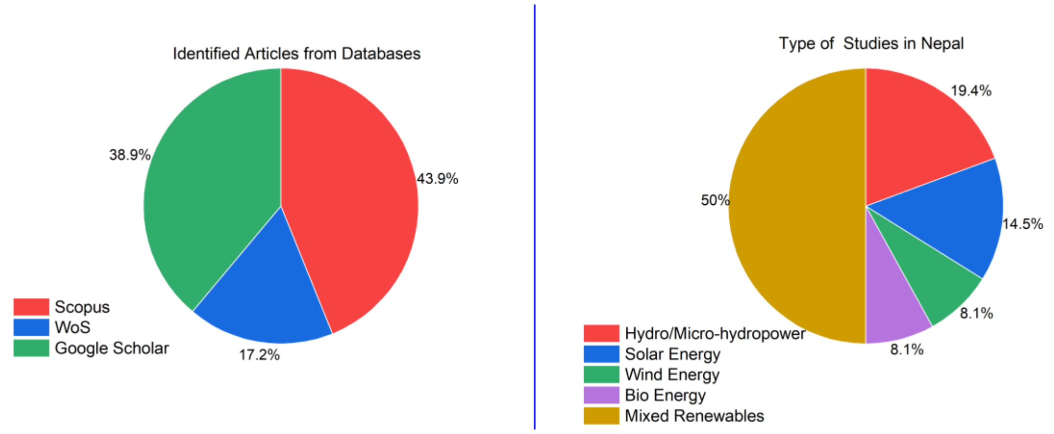

Fig 5. (a): Identified articles based on database, (b): Articles based on types of studies

significant numbers were produced from 2019 to 2023. This shows that the knowledge and data presented in this review contain the latest information to make this review article a high-quality with new knowledge.

The content analysis based on the database and study types is given in Figure 5(a & b) which is prepared from the identified articles from the inclusion criteria. As depicted in Figure 5(a) 43.9% of the identified articles are extracted from the Scopus database, 17.2% from Web of Science, and remaining 38.9% from the Google Scholar. Since Scopus and Web of Science databases are treated as the most reliable and quality databases, most of the articles extracted from these two databases. This shows that the information extracted from the selected articles is highly reliable and high-quality types.

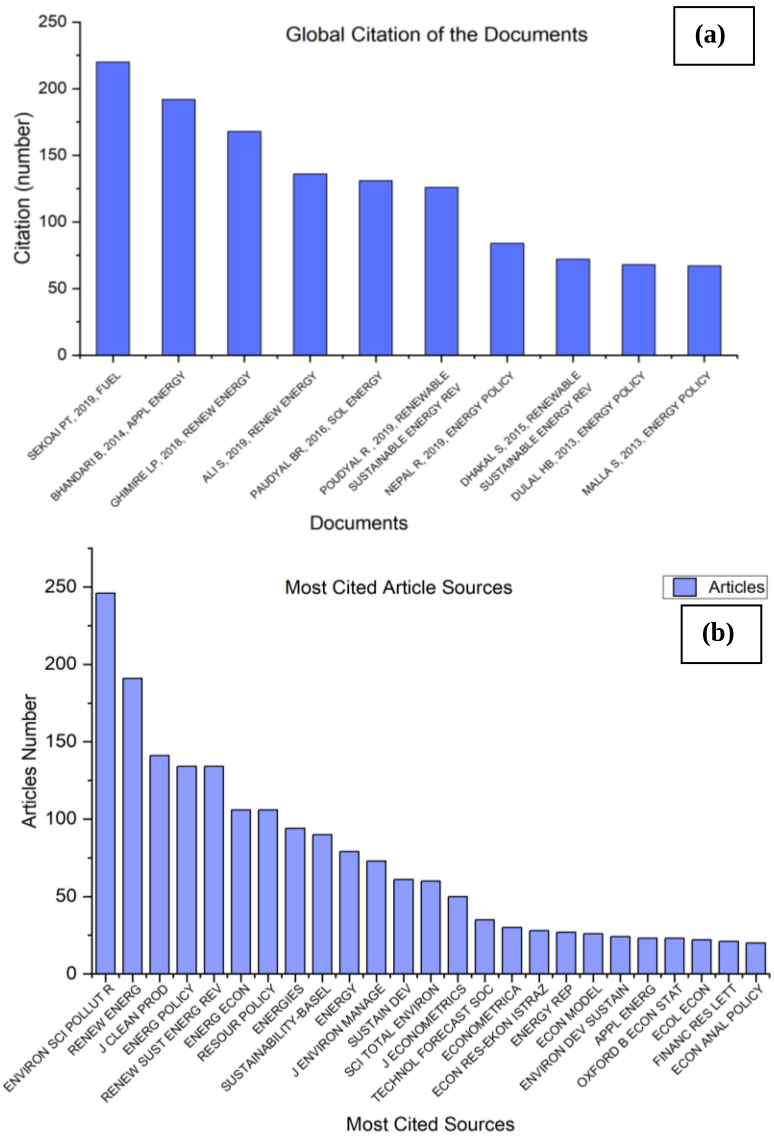

Fig 6. (a) Most cited global documents identified from the inclusion criteria, (b) Most cited articles sources in the identified literature

The study areas or subjects of renewable energy technologies and energy conversion technologies are confined mainly to mixed renewables, i.e. hydropower, wind energy, solar energy, and biomass. 50% of the studies are combined studies or research on renewable energy technologies, their development, usage, and future prospects. Among the selected articles, 19.4% of studies were conducted on hydro/micro-hydro power, 14.5% on solar energy, 8.1% on wind energy, and 8.1% on bio-energy technologies as shown in Figure 5(b).

The meta-analysis of the literature was identified using inclusion criteria with the *Biblioshiny ()* functions, used to identify the most cited global documents given in Figure 6(a)and the most cited article sources given in Figure 6(b). The most cited articles and article sources are mainly related to keywords such as environment, pollution, renewable energy, energy policy, sustainability, environment management, and sustainable development-related journals.

In the same way, the most cited countries in the identified journal articles are also analysed using the same *Biblioshiny ()* function of the R-Studio tool, and the result is depicted in Figure 7. The Y-axis represents the number of citations. Figure 7, prepared from the identified papers from the inclusion criteria of database search, shows that Nepal is the highly cited country in the searched database and identified journals for this systematic literature review. Korea, South Africa, the UK, Thailand, and China are the other top countries with higher citation numbers in the identified journal articles.

The top trend of the study topics, keywords, and subjects were also analysed using the same *Biblioshiny()* function of R-studio tool. Figure 8 shows that study trends in recent years were following topics/keywords and subjects. Topics/Keywords/Subjects with higher trends in the identified journal articles are Energy consumption, economic growth, alternative energy, renewable energy, wind power, solar power,

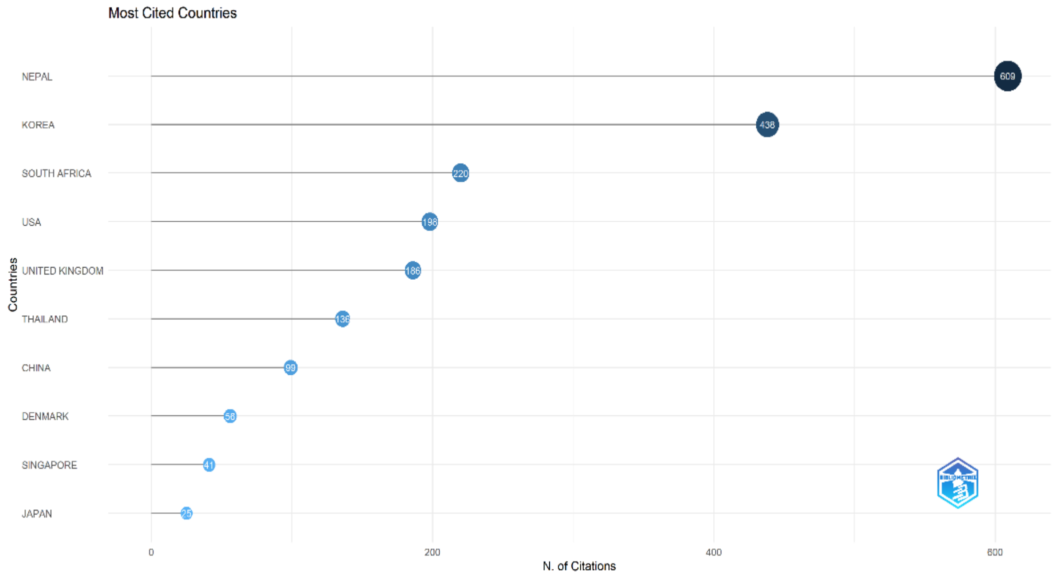

Fig 7. Most cited countries in the identified articles

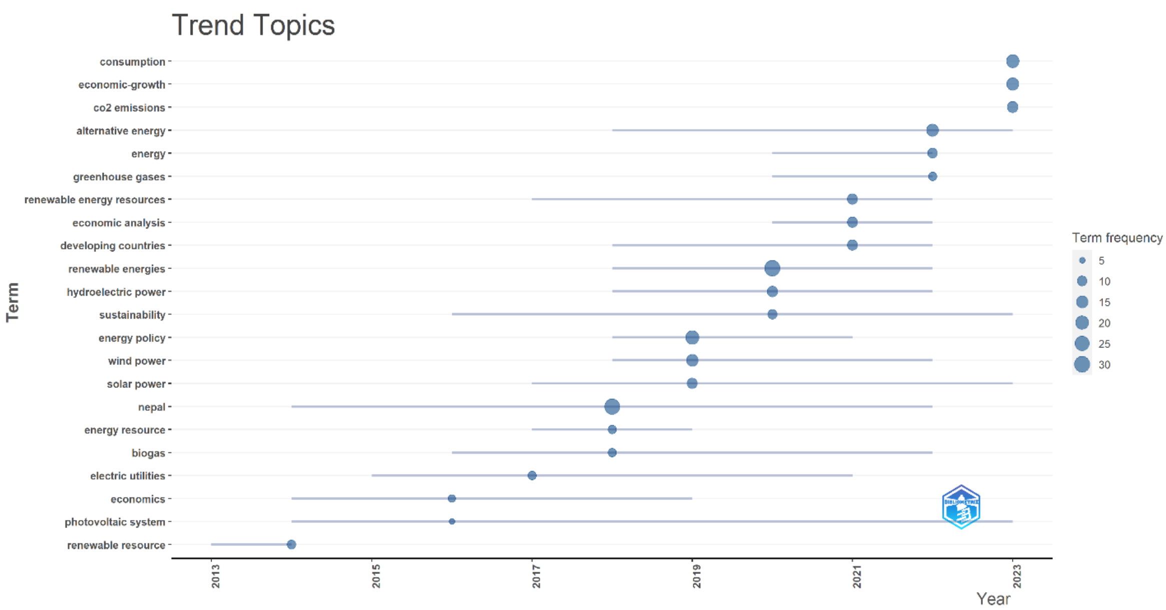

Fig 8. Study trend based on the topics/keywords from 2012 to 2023

hydropower, CO_2 emission, greenhouse gas, etc. as shown in Figure 8.

3.2. Themes of the research articles

Major themes of the studies were also analysed from the selected articles. Most of the authors confined their research under Renewable energy development with sub-themes of energy sustainability and sustainable development by renewable energy development. Similarly, the other themes, sub-themes, and authors list are given in Table 3.

The major themes identified in the literature were renewable energy development, environmental impacts, renewable energy policy, renewable energy conversion technologies, and energy consumption. The majority of the research was conducted on sub-themes of energy sustainability and sustainable development, solar energy, hydropower energy, and bioenergy. Climate change and policy intervention in renewable energy development and promotion were also studied substantially.

3.3. Energy Mix Scenario in Nepal

The Energy mix is the composition of the different energy sources measured by the share of fossil fuels and renewables in total energy contribution (El Anshasy & Katsaiti, 2014). Nepal is rich in renewable energy sources such as hydropower, solar, wind, and biomass. Despite the abundant renewable energy sources, the energy supplied is still dominated by traditional biomass and fossil fuel-based energy sources. Traditional biomass energy refers to the direct combustion of wood, charcoal, leaves, agricultural residue, and animal dung for cooking, and drying purpose(Coelho, 2012). The majority of energy consumption is utilized from traditional biomass (66.4%) followed by fossil fuel (27.2%), hydropower (3.5 %), and remaining renewables (Solar, Wind, and Micro-hydro) as depicted in Figure 9. (Lohani *et al.*, 2022; Suman 2021). As shown in Figure 9, the energy mix contribution from hydropower and renewable is much less compared to traditional biomass and fossil fuel, however, electricity generation is dominated by hydropower in Nepal.

The energy consumption is mainly confined to domestic usage, industrials, commercials, and others (Lohani *et al.*, 2022). Domestic usage is related to the heating, cooking, and lighting for households; industrial usage is related to running the machinery systems and logistic support in the industrial sectors; and commercial usage is mainly confined to business and marketing such as transport and service sectors. The total energy consumption (in GWhr) is on an increasing trend as

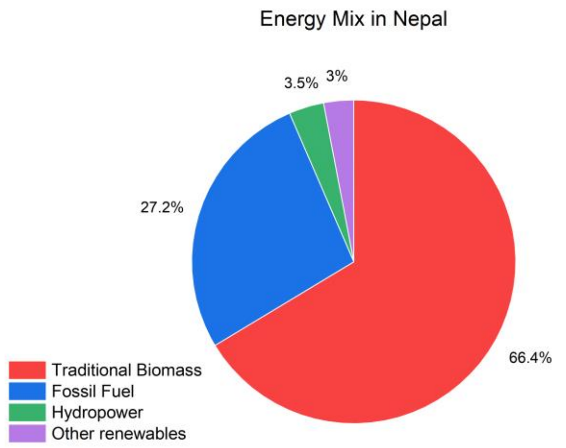

Fig 9 Energy mix scenario of Nepal (Lohani et al. 2022)

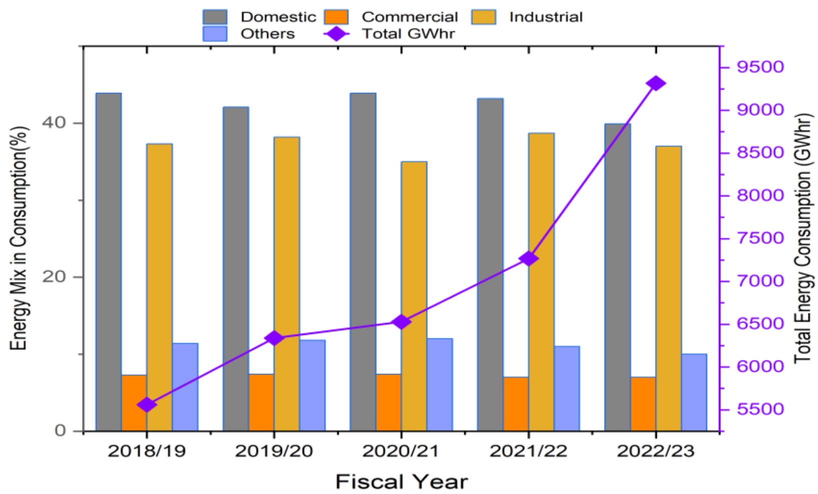

Fig 10. Energy consumption trend in Nepal (Lohani *et al.* 2022; MOF/GON 2023)

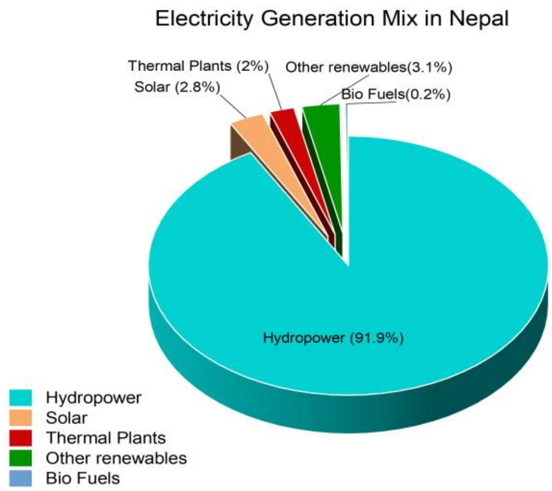

Fig 11. Electricity generation mix of Nepal (Lohani *et al.*2022; MOF/GON 2023)

depicted in Figure 10. The energy consumption proportion among domestic, industrial, commercial, and others has been changing over the years as given in Figure 10. The consumption of industrial and commercial energy heavily depends on the economic activity of the country. The COVID-19 impact in 2020/21 in the industrial sector was noticeable in the energy consumption value.

The electricity generation mix (shares of electricity sources) as shown in Figure 11 indicates that the mega hydropower project generated electricity contributed 91.9% of total electricity generation in Nepal followed by bigger solar plants 2.8%, other renewables sources (micro-hydro, solar, and Wind) 3.1 %, and 2% from thermal plants (Lohani *et al.*, 2022; MOF/GON, 2023). 87% of the population now has electricity access.(Clements *et al.* 2020). Figures 9 and 11 show that the energy consumption in Nepal is primarily dominated by traditional biomass and fossil fuels. However, renewables, specifically hydropower have the dominant role in electricity generation. Figure 10 shows that the total energy consumption is growing continuously. The growing energy gap must be filled by renewables to maintain energy sustainability and pave the path toward carbon neutrality in the country.

The dominant share of hydropower in electricity generation (Figure 11) may impact the energy balance. The electricity generation from the hydropower might be adversely impacted during the earthquake, flood, and adverse environmental situation. Therefore, to balance the electricity, the share of electricity generation from the solar and wind should also be considered for energy sustainability in Nepal.

4. Discussions

The results of the systematic review on renewable energy development and energy-related literature in Nepal show that a substantial number of studies and research were conducted in Nepal in the field of renewable energy sectors in recent years to support energy sustainability, sustainable development, and environmental adaptation along with the reducing the dependency of the imported fossil fuel and minimizing the greenhouse gas emission. Nepal has a huge potential in renewable energy resources and a high opportunity to capture renewable energy from these sources to lead energy sustainability and protect the planet by minimizing greenhouse gas emissions.

4.1. Current Perspectives of Renewable Energy in Nepal

Nepal has big potential for renewable resources for utilizing the daily usage of energy and electricity generation purposes. Mega hydropower projects, micro-hydro projects, solar plants, small solar houses, solar-wind hybrid mini-grids, and bio-energy (biogas and waste-to-energy conversion technology) are the most identified renewable energy resources(Clements *et al.*, 2020). Approximately 6000 rivers flowing from high hilly areas to plain areas created a unique advantage in hydropower generation (Poudyal *et al.*, 2019). The average solar radiation in Nepal ranges from 3.6 to 6.2 kWh/m^2/day ensuring favourable solar energy condition for energy sustainability(Bhattarai *et al.*, 2023). Likewise, the mean wind power density of the 10% windiest area in Nepal is 531 W/m^2 as reported by the Global Wind Atlas. This shows that Nepal also has good wind energy potential. The national economy in Nepal is agricultural-based and it contributes a livelihood for over 67% of its population. The agricultural sector contributes approximately 33% of its Gross Domestic Product (GDP)(MOF/GON, 2023) and the livestock manure and organic waste materials provide big bioenergy potential.(Poudyal *et al.*, 2019; Thapa *et al.*, 2020). Innovative technical and subsidy policy intervention is essential to reduce inequality between low and high-energy household share variation, elevate gender participation in renewable energy sector development, and reduce traditional fuel sources (Shrestha *et al.,* 2020).

4.2. Renewable energy development and energy sustainability in Nepal

Renewable energy conversion technologies are used to convert the potential energy stored or available in renewable energy sources into a suitable form of energy such as heat, electricity, mechanical energy, etc. Therefore, the energy conversion technologies designed for hydropower, solar, wind, and biomass are installed in Nepal for conversion of energy into suitable consumable form to ensure energy sustainability in Nepal. To increase the renewable energy share and usage, the smart grid technology becomes an instrumental tool for energy sustainability in the rural areas (Bhattarai *et al.*, 2023).

4.2.1. Hydropower

The hydroelectric potential of Nepal is remarkable, as evidenced by the statistics and research data in this field. Globally, hydro resources contribute to nearly 17% of total power generation, with a substantial 70% share in renewable power generation (Khatri & Paija, 2022). Approximately 6,000 rivers and an annual water discharge of 174 billion m^3, possess a unique advantage in hydropower generation in Nepal (Poudyal *et al*., 2019). These big and small rivers cover an impressive elevation difference of 70 to 8,848 meters within a narrow width of 193 kilometers (Khatri & Paija, 2022). The theoretical potential of Nepal's hydropower sector is estimated to be a staggering 83,000 MW, with economic feasibility of approximately 42,000 MW of capacity, although the current growth rate stands at just 8 MW per year (Khatri & Paija, 2022). Suman (2021) also supports this estimate, reporting theoretical, technical, and economically feasible hydro energy potential of around 83,000 MW, 45,000 MW, and 42,000 MW, respectively. Baral & Kim (2014) further highlight the country's potential with an estimation of 43,000 MW of power generation capacity from its many rivers. Lohani *et al*. (2023) go even further, projecting a theoretical energy generation potential of 475 TWh from the hydropower sector.

With 45.6 GW of hydropower being technically feasible (Clements *et al*., 2020), it's evident that the research conducted showed that Nepal has a significant untapped renewable hydropower resource. By September 2021, Nepal had an installed electricity of 2000 MW, but the country has ambitious plans to develop the electricity. Approximately 50,000 MW of hydropower projects in Nepal have in different stages, from construction licenses to survey licenses (Budhathoki *et al*., 2021). Despite this huge potential, the per capita energy consumption value in Nepal still remains relatively low, 350 kWh as of 2018, 10 times less than the world's average value (Budhathoki *et al*., 2021)

The growth in electricity consumption in Nepal is promising accounting for 10% over the last decade. Water and Energy Commission Service(WECS) under the government of Nepal, conducted a study in 2019 revealed that Nepal has a total hydropower potential of 72,544 MW (Budhathoki *et al*., 2021). If the environmental, social, and financial risks are managed properly, hydropower will be the leading renewable energy source for Nepal and South Asia's energy future. Most of this energy will be consumed in the industrial sector and the help to decarbonize the industrial sector (Vaidya *et al*., 2021). These statistics show Nepal's significant role in the future of renewable energy production, lead energy security, and regional energy trade in south Asia.

4.2.2. Micro-hydropower

Nepal has made significant decisive steps in harnessing the micro-hydropower for generation of electricity and other forms of energy applications. Thapa *et al*. (2020) studied to prioritize the different renewable energy sources for electrification in rural areas. They found that the micro-hydropower is the most suitable renewable energy resource followed by solar home systems, solar-mini-grid, and wind-solar hybrid for decentralized electrification in Nepal. Gurung *et al*. (2013) estimated that over 50 MW of electricity can be generated from the micro-hydro plans, while Poudyal *et al*. (2019) projected the potential of 100 MW or more energy from mini/micro-hydroelectricity and 25,000 to 30,000 MW from improved watermills. With the local level incentives and promotional schemes, more than 400 small-scale micro-hydropower plants were installed between 2007 and 2014, generating approximately 1,095 kW of electricity to supply over 150,000 families in rural areas (Suman, 2021). It was an impressive step that Nepal had successfully electrified more than 200,000 remote and off-grid households through more than 2,000 micro-hydropower projects by 2020(Subedi *et al*., 2023). However, the electricity charge is a crucial factor for social acceptance and affordability of the service to all. The grid electricity is 33% cheaper than the electricity from the micro-hydropower sources in the country(Butchers *et al*., 2020). There needs some sort of incentives for micro-hydropower-generated electricity. Despite the cost challenges, these statistics reveal the pivotal role of micro-hydro and watermill technologies for rural electrification and sustainable energy management efforts in Nepal. These systems must make substantial progress in bringing electricity to remote areas of Nepal. These technologies have a vital role in utilizing renewable energy resources and creating sustainable energy in Nepal.

4.2.3. Solar Energy

Nepal possesses abundant potential in solar energy resources which shows a promising path towards sustainable and renewable energy development. As per the research findings, it is estimated that Nepal has solar energy potential to be around 2100 MW (Baral & Kim 2014; Gurung, *et al*., 2013; Clements *et al*., 2020). Lohani *et al*. (2023) also projected a promising figure of 500,000 TWh energy potential from solar PV alone which has been taped negligibly to date.

Lohani & Blakers (2021) indicated that the solar potential in Nepal is about 100 times larger than what the energy requires to support the whole energy supply from solar energy systems alone to match the per capita energy consumption value similar to the developed country without support from the fossil fuels or high dammed hydroelectricity in Nepal. This also suggests that Nepal has sufficient capacity to transition to predominantly solar energy-based systems. Furthermore, the cost of solar PV panels has been declining fast. The current price is half of the price that we had to pay 7 years ago and at the same time, solar panel efficiency is also increasing substantially adding more energy value in the given conditions i.e. more energy yield per meter square of solar irradiation. Current research projection indicates that more than 60% of price reduction is expected for the next decade, making solar energy even economically feasible and more affordable (Suman, 2021). Neupane *et al*. (2022) provided additional insights into the potential of 47,628 MW and the co-location potential of about 890 MW of solar energy with wind energy. They estimated that the electricity generation levelized cost for solar is 91 USD/MWh. The global solar atlas indicates that the average solar radiation in Nepal ranges from 3.6 to 6.2 kWh/m^2/day which is a significant value to tap the sufficient solar energy for energy sustainability. However, the discontinuation of the subsidy funds from donors/government and local government, the sustainability issues are the major challenges to the successful commissioning of solar projects (Bhattarai *et al*., 2023). Such challenges should be addressed to provide sustainable energy in the remote and rural part of Nepal and the concerned authorities shall take the appropriate initiatives. The reduction of the efficiency of the solar panel due the dust deposition in PV modules is the major operational challenge. Such reduction in efficiency was estimated to be 29.76% (Paudyal & Shakya, 2016). So appropriate remedial measures should be taken to keep intact of the solar energy yields from the solar PV modules. The annual average daily global radiation for Kathmandu is measured at 3.83 kW/m^2/day, underlining the city's solar energy potential (Poudyal *et al*., 2012; Poudyal & Shakya, 2016). These findings collectively underscore the substantial renewable energy resources available in Nepal, presenting opportunities for a sustainable energy future while addressing local challenges and optimizing resource utilization.

4.2.4. Wind Energy

Nepal's wind energy potential is a valuable resource for its sustainable energy landscape. Research findings indicate that the country possesses an estimated wind energy potential of 3,000 MW (Baral & Kim, 2014; Clements *et al*., 2020). Wind power density assessment reveals that regions like Jumla and Okhaldhunga belong to wind power Class III, offering moderate potential for wind energy harvesting, with an average wind power density of 336.07 W/m^2 and 326.73 W/m^2, respectively (Pandeya *et al*., 2022).

However, despite its potential, the utilization of wind energy in Nepal has been relatively modest. As of 2018, installed wind turbines in the country had a total generation capacity of 113.6 kW, with contributions from various sectors, including 65 kW from the AEPC, 3.5 kW from Practical Action, and 45.1 kW finances by private sectors (Poudyal *et al*., 2019). Historical efforts, like the Kagbeni wind energy project installed in 1987 with Danish government aid, faced challenges related to maintenance, resulting in project interruptions (Suman, 2021)

Recent research in Jumla has shown promising wind conditions with average hourly wind speeds ranging from 1.5 m/s to 4.6 m/s at a hub height of 30 m. The wind power density and energy density, based on Weinbull distribution, indicate the potential for generating 170.268 MWhr/yr from a 100 kW distributed wind energy system. However, government subsidies and local training for maintenance are required to ensure continuous operations (Dhakal *et al*., 2020)

It was estimated from the research that the financial surplus generated from reducing the petroleum fuel import and the investment grant could support the development of 1082 MW of wind energy in the areas where the wind energy viability is high (Laudari *et al*., 2020). Neupane *et al.* (2022) further affirm the potential with an estimate of 1,686 MW from wind energy in Nepal and co-location potential of about 267 MW of wind energy with solar, with a competitive levelized cost of electricity generation at 46 USD/MWh for wind. Nepal is actively working on creating an 80-100-meter wind resolution map in 10 different regions to create the Wind Atlas of Nepal with the assistance of the Technical University of Denmark. This work will leverage to tap wind energy more effectively in various regions of Nepal (Suman, 2021). However, the cumulative energy generation from the wind-solar hybrid mini-grid system is still low and stands at 563 kW. Still, there is ongoing progress in harnessing wind energy resources in Nepal (Suman, 2021). Continuous efforts and investment towards wind energy in Nepal pose the opportunity to tap into the substantial wind energy potential to contribute to the sustainable energy future of the country.

4.2.5. Bio-energy

The potential of bioenergy resource utilization in Nepal is substantial and can contribute significant value to address the energy requirement and reduce the environmental impact in Nepal. The various researches highlighted several statistics of bioenergy potential in Nepal. It is estimated that Nepal can develop approximately 1.1 million domestic biogas plants which can contribute the sustainable energy equivalent to 110 million LPG cylinders and 100,000 tons of biofuels (Gurung *et al*., 2013; Lohani *et al.,* 2023; Suman, 2021). 283 municipalities and 460 rural municipalities in Nepal have installed biogas plants and this figure shows the widespread adoption of this technology. This is quite an important statistic that approximately 68% of the Nepalese population still relies on traditional biomass for their energy requirements (Suman, 2021). Lohani *et al.* (2021) estimated the total potential of biogas production of 3043.58 million m^3/year from livestock manure. If this capacity is fully utilized, it could avoid the emissions equivalent to 4.35 million tons of CO_2/eq/year.

Biomass plays a significant role in Nepal's renewable energy landscape, constituting 14% of the total energy generated from renewable sources and supplying 10% of the world's primary energy (Suman, 2021). Similarly, biofuels also have a role to play, with an expected potential of 100,000 tons in Nepal (Poudyal *et al*., 2019). A significant portion of Nepal's population, approximately 63% resides in rural areas with limited access to modern cooking fuels, and among them, 85% of these rural households rely on biomass for cooking (Clements *et al.* 2020). Techno-economic analysis and life cycle assessment reveal that bioenergy will be one of the most economical and environmentally friendly technologies for commercial energy sources (Shah *et al*., 2016). Ambient temperature conditions are vital for biogas production. The research showed that a controlled temperature environment yields higher methane content in biogas compared to ambient temperature conditions which emphasized to use of improved biogas plants having temperature control for better performance (Bista *et al*., 2023). The above statistical data reveals that Nepal's bioenergy potential represents a significant opportunity to provide sustainable energy solutions, reduce dependency on traditional biomass, and mitigate environmental impact through reduced emissions.

4.2.6. Geothermal Energy

Geothermal energy utilization for electricity generation has not yet gained significant traction in Nepal. A study conducted in 2012 highlighted that Nepal possesses 32 hot water springs with temperatures exceeding 50 degrees Celsius, identified primarily after 2004. These findings have shed light on the country's geothermal potential. Currently, ongoing efforts are directed toward the development and exploration of these geothermal resources, with approximately 2.1 MW of energy capacity in various stages of investigation and development (Nepal, 2012). Geothermal energy extraction in Nepal is considered capital-intensive due to the substantial initial investment requirement for infrastructure development. As Nepal continues to explore and invest in its geothermal energy potential, it has an opportunity to diversify its energy portfolio, reduce reliance on fossil fuels, and contribute to its broader renewable energy generation effort, thereby mitigating environmental impact (Nepal, 2012).

4.3. Renewable energy and environmental impact

The Nepalese economy is dominated by agriculture, which provides livelihood for over 67% of its population and accounts for 33% of its Gross Domestic Product (GDP) (Poudyal *et al*., 2019). Approximately 63% of people living in rural areas have little or no access to modern cooking fuels and electricity. Out of the 85% of rural households use biomass for cooking (Clements *et al*., 2020b). If the full potential of biogas production from livestock manure is utilized, it can produce an estimated volume of 3043.58 million m3/year of biogas, which could avoid approximately 4.35 million tons of CO_2 eq/year (Lohani *et al*., 2021). Since biomass energy for cooking dominates the country's energy mix, households' CO_2 emissions and indoor pollutant emissions will continue to rise in the coming days (Malla, 2013). The CO_2 emissions from the household sector in the business-as-usual (BAU) scenario are expected to grow by 4.5% per year and are projected to rise from 373 ktoe in 2010 to 1392 ktoe by 2040 (Malla, 2013). Malla (2013) further estimated that CO_2 emissions from households in Nepal were projected to reach 85% from 66% in 2010. However, most of the CO2 contribution is from urban areas, as rural households use biomass fuel, which is a carbon-neutral energy source. Paudel *et al.* (2021) presented data on CO_2 emissions using various energy technologies. He stated that rooftop solar power emits 41 g CO_2/kWh, hydropower emits 24 g CO_2/kWh, biomass emits 230g CO_2/kWh, and diesel generators emit 1270 g CO_2/kWh. This indicates that the transition from traditional fossil fuel-based energy sources to renewable energy sources will produce cleaner energy and contribute substantially to environmental protection. A literature reviews above showed that wind energy potential is high. The full capitalization of wind energy could reduce the use of 0.31 million kl of fossil fuels, substitute about 6.8% of the annual import of petroleum fuels, and avoid 4.5 million tons of CO_2 emission annually. This also increases the independence of the country's energy supply (Laudari *et al.*, 2020). The estimated full potential of biogas production in Nepal is approximately 3043.58 million m^3/year which can avoid approximately 4.35 million tons of CO_2 eq/year (Lohani *et al.*, 2021). Therefore, converting the traditional biomass-based cooking habits of households to biofuel and biogas helps substantially reduce emissions to protect the environment.

Since Nepal has huge potential for renewable energy resources, the development of renewable energy sources such as hydropower, solar, and wind energy has helped to substitute fossil fuels and traditional cooking fuels and therefore contribute to reducing emissions significantly to protect the environment. Renewable energy development reduces the impact of climate change by significantly decreasing greenhouse gas emissions, improving air quality, protecting ecosystems, and enhancing a country's energy resilience. Therefore, renewable energy is a critical component for mitigating climate change and transitioning to a more sustainable and environmentally friendly energy system.

4.4. Policy intervention for renewable energy development

The development and consumption of renewable energy sources are important to address the energy needs and environmental challenges. Although there are several policy frameworks and institutional arrangements for the development and promotion of renewable energy, the development, and adoption are considerably slow, and the challenges are not addressed in line with the requirements. To improve this situation, a comprehensive and innovative approach is required which should be supported by government policy, active and collaborative institutional, and stakeholders' involvement. To reduce the heavy dependency on traditional biomass for cooking and reduce indoor air quality, there should be an effective implementation plan to use biogas, a renewable energy source. Despite the huge potential of biogas, the sustainability issues are greatly impacted by poor knowledge and maintenance at the local level. Malla (2013) emphasizes on provision of appropriate incentive schemes and local-level training for installation and maintenance. Improving the large biogas plant and household digesters is essential to overcome limitations and improve the biogas energy in local areas (Lohani *et al.*, 2021a). Similarly, Micro hydropower(MHP) and solar can be effectively used to generate electricity in local areas to improve rural energy access for electrical appliances(Bharadwaj *et al.*, 2023). However, government incentives and necessary supportive measures are essential.

Government intervention in terms of policy and subsidy for promotion of the renewable energy promotion and development is required for clean energy access in rural areas for energy equity and justice (Pariyar *et al.,* 2022; Underwood *et al.*, 2020). Access to clean energy depends not only on the availability of the services but also on the socio-economic status of the rural people. In urban areas and government office premises, large-scale solar projects can be implemented on the roof of the building which not only supplements the energy demand but also creates the revenue streams. However, the private sector's involvement and government subsidy are required to drive the projects innovatively (Paudel *et al.*, 2021).

Larger hydropower projects are the crucial instrument for clean energy generation. However, social and political conflicts arise due to resource inequalities and the absence of local-level participation in such projects. Therefore, addressing energy injustice and resolving the conflicts in the energy development sector is a crucial requirement that can be managed by providing appropriate policy frameworks, ensuring mutual benefits for the affected communities, and incentivizing the developers. The benefits to the local people could be access to water and electricity (Crootof *et al.*, 2021). Another critical concern is that the wind energy generation is quite low, although the wind energy potential is remarkable in Nepal. The reason behind the low harness of wind energy is the policy implication, mapping of wind energy potential throughout the country, and subsidy from the government and donors. To boost wind energy generation and provide a supplement energy share in the energy mix, a proper subsidy plan and policy should be implemented that can support Nepal's dream of a sustainable energy future (Laudari *et al.*, 2021a)

Sound policy instruments and advancement in technology should align with SDG 7 to harness the indigenous renewable energy resource which can reduce fossil fuel consumption and greenhouse gas emission. Sufficient funding and targeted policy are required to explore renewable energy growth (Nakarmi *et al.*, 2016; Neupane *et al.*, 2022). Bhandari *et al.* (2017) and Clements *et al.* (2020b) also highlighted the need for proper training and awareness programs at the local level and strong collaboration among government, investors, and local communities. Hydropower sectors require further conducive policy instruments, investor-friendly subsidies, and investment policy frameworks (Shrestha *et al.* 2022). Special focus also has to be provided to reduce energy poverty in rural and remote areas (Subedi *et al.*, 2023). Lohani *et al.* (2023) and Nepal (2012) also recommend that investment and technology transfer in less developed economies by offering Solar PV and Pumped Hydro Electric Systems for widespread adoption in the long run. Coordinated efforts, conducive policy framework, innovative technologies, government subsidy policy, and collaboration among stakeholders are the main highlighted policy intervention issues for the development of renewable energy to create a sustainable energy future for Nepal.

4.5. Challenges of Renewable Energy Development

The researchers also highlighted challenges for the development and promotion of renewable energy in Nepal. The challenges are mainly associated with policy issues and technical, economic, social, and knowledge gaps with human resource (HR) scarcity.

a. *Policy level challenges.*

Researchers have pointed out the key challenges of policy issues. Some of the challenges are fewer incentives and unstable government policies, lack of tax benefits and subsidy policy to the investors, not implemented feed-in-tariff policy, less focus on national level planning and regulations, weak institutional capacity to build technical expertise and conduct monitoring and evaluation of the projects (Malla, 2013; Paudel *et al*., 2021; Shakya *et al*., 2023; Nakarmi *et al*., 2016; Neupane *et al*., 2022; Shukla *et al*., 2017; Laudari *et al*., 2020; Shrestha *et al*., 2022; Dhakal *et al*., 2021; Poudyal *et al*., 2020).

b. Technical challenges

The technical and innovation-related issues and challenges are also identified by the researcher for the weak progress on renewable energy development. Pointed-out challenges are the absence of reliable and comprehensive digital mapping, lack of standardized technologies in rural areas, poor maintenance of the projects, unavailability of smart and stable grid connectivity, and intermittent and low-reliability nature of solar and wind energy resources. To enhance the reliability of the services and development of renewable energy, these limitations or challenges must be addressed(Nakarmi *et al*., 2016; Shukla *et al*., 2017; Laudari *et al*., 2020; Bhandari *et al*., 2014; Clements *et al*., 2021; Dhakal *et al*., 2021; Dhonju *et al*., 2022; Nepal, 2012; Gurung *et al*., 2013)

c. Economic challenges

The major economic challenges identified in the literature are limited investment from the government side, less foreign investment, low market potential knowledge, higher risk and uncertainty, small economic scale of the country, higher investment on the project, longer payback periods, and energy poverty of the people (Shukla *et al*., 2017; Laudari *et al*., 2020; Lohani *et al*., 2021; Shrestha *et al*., 2022; Poudyal *et al*., 2020; Nepal, 2012; Gurung *et al*., 2013).

d. Knowledge gap and human resources(HR) challenges

Knowledge gap on renewable energy development, utilization, operation, and maintenance, and lack of skilled human resources have been creating hurdles in renewable energy development. The main raised issues and challenges are; lack of quality information and knowledge on renewable energy resources, technologies, and the benefits, less training in the local areas, limited technical human resources, and lack of technical expertise in policy-making bodies (Cheng *et al*., 2014; Bhandari *et al*., 2017; Clements *et al*., 2020b; Shukla *et al*., 2017; Lohani *et al*., 2021; Shrestha *et al*., 2022; Clements *et al*., 2021)

e. Social challenges

Low social acceptance of modern renewable energy and reluctant to switch to modern energy systems from traditional biomass energy, the less affordable capacity of people due to energy poverty in rural areas, conflicts between local communities and hydropower developers, and less community engagement in the renewable energy promotion and development activities are the mainly raised social concern and challenges for the development and promotion of renewable energy. Similarly Land acquisition issues especially for the development of any energy project either hydro or solar or others are very common in Nepal (Crootof *et al*., 2021; Shakya *et al*., 2023; Nakarmi *et al*., 2016; Bhandari *et al*., 2017; Clements *et al*., 2020b; Lohani *et al*., 2021; Bhandari *et al*., 2014; Shrestha *et al*., 2022; Dhakal *et al*., 2021; Poudyal *et al*., 2020; Gurung *et al*., 2013). It is required to address each challenge systematically to harness the full potential of renewable energy in Nepal and ensure energy sustainability.

Ghimire and Kim (2018) prioritized the challenges for the development and promotion of renewable energy in Nepal. They ranked the political and policy as the top challenges followed by economic, social, and technical challenges for the promotion and development of renewable energy in Nepal. Since the technical barrier is ranked lowest, by overcoming the economic and social barriers renewable energy development and promotion can be achieved substantially.

4.6. Opportunities

Nepal presents significant opportunities for renewable energy development, which can address key gaps in building a sustainable energy future and contribute to various national and global goals.

The country can utilize the significant opportunities to bridge the energy access gaps by expanding the renewable energy infrastructure. The utilization of the full potential of hydropower, solar, wind, and biomass can contribute to Nepal not only future energy security but also open the door to expanding this energy to its neighbouring countries with a stable and diversified energy mix(Vaidya *et al*., 2021). The development and expansion of renewable energy resources not only make a sustainable energy future but also plays a key role in mitigating the impact of climate change by reducing greenhouse gas emissions(Malla, 2013; Lohani and Blakers, 2021). As there is technological advancement and reduced production cost, renewable energy technologies will be more efficient and cost-effective in the days to come and translate opportunities into the reality of a sustainable energy future. Renewable energy resources (wind and hydropower) are mainly confined to remote and rural parts(Bhandari *et al*., 2017). The development and promotion of these technologies will boost the economic activities in those areas. This will not only solve the energy problem but also contribute the significant economic growth by creating employment that helps to vitalize the local economies. There is also a golden opportunity to export the energy to neighbouring countries so that Nepal can contribute to South Asia's clean energy production and boost its economy(Khatri & Paija, 2022). The development of renewable energy also has a good opportunity to play an important and pivotal role in mitigating the negative environmental and health impacts associated with traditional energy sources(Lohani *et al*., 2021). Therefore, to tap these opportunities successfully, Nepal has to address the challenges related to renewable energy development. Nepal has to implement a supportive policy, encourage investors, strengthen the local capacity, and support innovation to realize the huge potential of renewable energy for a sustainable and clean energy future. Therefore, the development and utilization of renewable energy will contribute economic value by generating revenue for the government, creating jobs, and reducing fuel imports. Similarly, the government will get carbon credit from the global carbon trading markets through renewable energy utilization to reduce carbon emissions.

5. Conclusion

This systematic literature review aimed to answer the research questions related to the current state of the research that contributed the energy sustainability in Nepal through renewable energy development, to find out the major challenges in the renewable energy development sectors, and to explore the opportunities in the renewable energy development in Nepal. The renewable energy and energy sustainability issues were systematically reviewed by exploring the scientific publications from the well-renowned journal databases; Scopus, Web of Science, and Google Scholars. The search of the articles was limited to the period of 2012 to 2023 and the review was guided by the PRISMA (Adeyinka-Ojo, 2016). The bibliometric data was analysed by the R-studio tool with *Biblioshiny ()* functions. The databases searched by the keywords "energy, sustainability, renewable energy in Nepal" initially identified 183 articles which were further screened on inclusion and exclusion criteria, title and abstract screened, and full-text assessment. Among the identified papers, 61% of the total papers were identified from Scopus and Web of Science databases. 40 high-quality peer-reviewed journals were selected for the review purpose. The majority of papers were found to have researched all types of renewable energy (50%), then others confined their areas to hydropower, solar, wind, and biomass respectively. The bibliometric data showed that the most cited journals are related to renewable energy, sustainability, energy, environment, and energy policies. The data also, revealed that most of the scientific production was produced after 2019 which shows that the review contained the latest information and data. The major themes identified in the review were energy sustainability, sustainable development, climate change, renewable energy policies, renewable energy sources (hydro, solar, wind, biomass), and energy consumption.

This review has pointed out that Nepal's journey toward energy development and energy sustainability requires more coordinated efforts, innovative policies, government support, and a collaborative approach among the stakeholders. By overcoming certain challenges, Nepal could harness its abundant renewable energy resources to reach the energy sustainability targets and at the same time protect the environment with clean energy and meet sustainable development goals. The review has found some of the challenges or barriers to renewable energy development in Nepal. The major challenges identified are policy, technical, economic, social, and knowledge gap and HR scarcity related. Promotion and development of this huge potential of renewable energy resources are required to overcome these challenges.

The literature showed that Nepal has good opportunities to build a sustainable energy future by harnessing its significant renewable energy potential in an affordable way through technological advancement. Renewable energy development not only solves energy scarcity but also addresses the growing concern about climate change, generates local employment, contributes to economic growth, and builds a diversified energy mix for sustainability.

The review of the literature could not find sufficient research on capturing wind energy and bioenergy potential and its realization. The detailed mapping of wind energy potential in Nepal is essential and proper policy and funding on wind energy could produce substantial renewable energy. Furthermore, the study and research on optimal hybrid power solutions for off-grid areas to power the villages, communication infrastructures, and other modern digital appliances are also found lacking. The major focus given to hydropower could lead to unstable power due to seasonal fluctuation of water discharge and regional imbalance in power generation in Nepal. A major attention to the use of appropriate energy storage systems and production of hydrogen based renewable energy should also be given for higher energy sustainability. There is also a significant lagging on the research on these segments as well. This shows that the research on proper power mix from all renewables for energy sustainability is still lagging and need to be accelerated. The detailed mapping of the potential and used value of renewable energy sources in different parts of Nepal is also lacking in the research.

Declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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