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Nuclear energy consumption, energy access and energy poverty: Policy implications for the COP27 and environmental sustainability

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ABSTRACT

The ever-increasing energy resource demand and subsequent environmental challenges mean that policymakers have shifted their focus to nuclear energy to address energy and environmental issues due to its unlimited potential. The current study investigates the role of nuclear energy consumption to unveil contextual information and report novel evidence concerning the significance of energy and environmental policies. This research is a novel attempt to outline methodological and topical contributions, thematic analysis, co-citation analysis, and country-collaboration analysis. As energy and environmental solutions have been prioritized within sustainable development goals, our research approach would allow policymakers and researchers to understand the extent to which nuclear energy can provide solutions towards environmental sustainability and identify research limitations to overcome by future studies. Moreover, our extensive analysis allows us to argue that nuclear energy impacts energy demand and is the most critical factor in fulfilling environmental commitments under regional and international environmental agreements.

1. Introduction and literature review

The overuse of natural resources for industrial and economic growth has had severe negative implications for biodiversity, environmental pollution, soil degradation, and depletion of energy resources [1,2]. In response to such environmental challenges, there has been a push to achieve a low-carbon economy to preserve environmental and ecological quality [3,4]. Additionally, the gradual replacement of fossil fuels with renewable energy resources remains critical to the outcome of the environmental reforms. As a solution to overcome energy poverty, nuclear energy has gained steady support because failure to substitute just a 10 % share of fossil fuels will lead to an increment of 2 °C in global temperature, ultimately severely damaging environmental quality [5,6]. Hence, we argue that better communication and knowledge of how energy projects affect environmental issues would strengthen sustainable energy practices [7–10].

Recently, renewable energy agreements have attempted to push to increase the share of nuclear energy within the overall energy supply [11–13]. To achieve environmental targets under the Paris Climate Agreement, The UN IPCC panel estimates that global GHG emissions must be reduced by 40 % in the current decade to achieve carbon neutrality by 2050. Accordingly, the IEA suggests that the share of renewable energy must increase by two-thirds until 2050, which would double the share of nuclear energy from 2020 to 2050 [14,15]. Due to its low-carbon nature, nuclear energy is projected to help overcome fossil fuel dependence, prevent 1.5 gigatons emissions yearly, and help

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achieve UN SDGs [16,17]. Additionally, IAEA underlines that nuclear energy is the most reliable energy resource to help progress SDG-7, which can facilitate sustainable economic growth, better living conditions (SDG-8), ensure long-term energy security, and lower carbon footprint [18–20]. In summary, nuclear energy can help global economies shift towards more efficient energy systems [21–23].

In light of the arguments mentioned above, there is a consensus among economists that further energy reforms can make nuclear energy pivotal in overcoming energy poverty [16,24]. Due to excessive industrial demand, energy poverty has emerged as a major issue, especially for developing and emerging economies, and solving it will allow policymakers to push for environmental welfare [2,25]. Despite its potential, the progress toward nuclear energy has been slow due to many varying factors, including economic policies and lack of scientific expertise [26,17]. However, energy issues have contributed in particular focus on using it to increase clean energy consumption and economic affordability to replace fossil fuels [27–29]. This has put the spotlight on nuclear energy, which has significant potential as a stable, clean, and environmentally friendly energy source [30,31].

Hence, the contents of current research become more significant as we evaluate the available literature to discuss the interdisciplinary nature of nuclear energy and its role in energy poverty and environmental sustainability [32]. We observe that findings from current research remain fragmented, especially related to climate change and SDGs. Our review suggests that researchers have examined nuclear energy from the following four perspectives. The first category has examined basic concepts from energy potential perspectives [16]; the second category has evaluated and summarized the pros and cons of nuclear energy within environmental sustainability [19]; the third category details the role of nuclear energy from the perspective of renewable alternatives, energy poverty, and energy policies [17,33], while the fourth category has highlighted policy regulations and how nuclear energy can overcome energy poverty to increase economic and social productivity [34,35]. Against this backdrop, we provide a comprehensive and detailed systematic review, including manual and bibliometric analysis, to advance the discussion about nuclear energy, its related issues, and future policy implications. As global economies face energy issues on a frequent basis, integrative evaluation of nuclear energy will help advance human expertise, skills, and knowledge about future research and detailed evidence on how nuclear energy will aid the efforts toward sustainable development agenda.

In line with the above-mentioned discussion, we extend academic discussion through theoretical and contextual contributions. Our first novelty lies in evaluating methodological & topical contributions to critically analyze energy policies. Moreover, to extend the scope of energy discussion, we review nuclear energy publications to suggest topical propositions. Additionally, researchers have used plenty of econometric strategies, we take stock of these methods to suggest methodological propositions to conduct robust econometric investigations. Secondly, we provide contextual contribution by highlighting which countries suffer from energy poverty and energy access. Evaluating the role of nuclear energy within current energy policies would allow policymakers to increase clean energy consumption and higher energy access. As emerging economies attempt to reconfigure economic policies, a lack of access to energy resources can restrict the outcome of these strategies [36]. Nuclear energy has gained prominence in this context to overcome energy shortages, poverty rates, and macroeconomic development.

Energy accessibility and affordability have significant impacts on the consumption of goods and services, technological divide, energy infrastructure, and energy costs. Following Lee et al. [34], we document the role of nuclear energy in overcoming energy poverty, lowering carbon & ecological footprint, sustainable energy supply, and environmental strategies. Moreover, lack of access to energy resources, i.e., energy poverty, also affects physical health [29]. Our integrative approach towards nuclear energy literature provides us with contextual information about developed, emerging, and developing economies that are facing difficulties in meeting the energy demands of the growing middle class and provide policy implications to overcome energy difficulties. Keeping in mind the impact of energy resources as social, economic, and geopolitical phenomena, we provide policy guidelines regarding SDG 13, 10, and 7 to focus on climate actions for the SDG 2030 agenda, sustainable economic growth, and energy accessibility & affordability [37]. Hence, our contextual contribution provides strong policy implications for future researchers to extend the scope of the energy situation from the country and regional discussion. On the basis of the contribution as mentioned earlier, we provide policy implications for future policymakers, researchers, and academia.

The basic outline for the remaining elements is in the following order. Section 2 summarizes research methodology and data selection; Section 3 offers insights into the main empirical findings through the conceptual, intellectual, and social structure of the current article. Section 4 illustrates the discussion and research avenues for future research, while section 5 offers conclusion and policy implications.

2. Scheme of study and empirical methodology

2.1. Bibliometric dataset

Our review of available review publications indicates that researchers have used theory and meta-based approaches to identify theoretical development [38]. We extend the scope of our investigation, we combine bibliometrics and manual strategies to report novel research findings. According to Ma et al. [2,25], the bibliometrics approach evaluates data trends to highlight individual and group research contributions. However, we also use manual review procedures to summarize content and draw novel policy suggestions regarding nuclear energy consumption [32].

Before downloading and compartmentalizing bibliographic data [11,37,39], we conduct a preliminary investigation to help formulate a systematic review analytical framework by identifying key research tactics (i.e., databases, sources, search items, keywords, time durations) to select relevant literature for further investigation [40]. For such and subsequent exercises, we have used the web of science (WOS) database, which is considered the most authentic and comprehensive dataset than other sources [37]. We chose the key terms of “nuclear energy consumption”, “sustainable development”, “energy access”, “environmental degradation” “ecological footprint “and “carbon footprint” to select publications related to nuclear energy, energy access and energy poverty. After the initial inquiry, we removed any ‘false publications’ to remove any unrelated study [2,41]. Our initial query showed a list of 625 research articles published from 2009 to 2023. To perform a comprehensive and relevant analysis, we removed any article published in any language other than English and excluded any review, conference, and editorial materials to finalize 296 studies for further analysis.

2.2. Bibliometric analysis

Using the bibliometrics approach to document academic research trends [32,37] allows researchers to integrate quantitative and qualitative approaches and identify research gaps in scientific literature [39]. Additionally, researchers are able to highlight influential researchers, co-authorship, research themes, academic collaboration, bibliographic coupling, co-citation analysis, and research affiliations [2,37]. Moreover, advanced bibliographic approaches use robust analytical algorithms and meta-data information to examine research domains within research literature and conduct in-depth theoretical investigations [42]. We have used VOS software, R-package, and Biblioshiny as bibliometric tools to analyze nuclear energy publications [25].

We have chosen VOS viewer because of its ability to visualize interrelationships between keywords, research journals, geographical locations, and co-citations information through a two-dimensional map,

where relatedness or similarity between two nodes is illustrated by the distance between them [2,25]. Sci toolkit uses modular collection techniques to analyze and visualize available information on temporal, geospatial, topical, and network information [43]. However, requires coding expertise to analyze datasets for bibliometric investigation. Lastly, R-package and Biblioshiny use various bibliometric tools to serve as visualization functions for information analysis and scientific mapping [41].

2.3. General description

2.3.1. Publication output and citation growth

Fig. 1 details the per annum trend of publication and citation growth since 2009, with each document reporting 40.52 citations on average. Nuclear energy consumption research as interdisciplinary research has gained significant attention in the recent past. In the late 20th century, nuclear energy and its share in the energy mix to increase environmental sustainability was hardly proclaimed as an integrative issue. However, following the passing of various environmental regulations and a higher focus on determinants of sustainable energy supply, there is scholarly interest in evaluating nuclear energy as a key research area, with the year 2022 reporting most publications (68) and citations (3432). We attribute this to the initial introduction of UN MDGs (millennium development goals), which were later succeeded by Sustainable Development Goals, especially with the seventh SDG to provide access to a dependable energy system and lower dependence on fossil fuels. Most citations reported were by Refs. [44,45], who have researched nuclear energy's interaction with other renewable energy sources to create a balance between environmental sustainability and economic growth.

2.3.2. Source impacts

The current section evaluates the performances of academic journals ranked on the basis of growth in total publications and citations (Fig. 2). Moreover, we also include statistical information about the g-index and h-index, which provide additional details about total median citations, unique largest number, and author-level metrics. Energy policy is ranked first with the most citations (1732), followed by Renewable and Sustainable Energy Reviews (902) and Journal of Cleaner Production (852). Lastly, the values of the g-index and h-index also suggest that energy policy is ranked first in the author-level metrics to signify the advanced nature of published research in the journal.

Published research in 'Energy Policy' has focused on the assemblance of nuclear energy consumption by focusing on perceived risks, benefits and public engagement [46], the role of policymaking in GHG reduction targets [47] and the role of nuclear towards energy transition [48]. Likewise, articles published in 'Environmental science and pollution research' have analyzed asymmetries about the nexus between clean energy and sustainable economic growth [49]. Lastly, 'Energy' has extended academic discussion toward energy investments, transition, and energy efficiency from nuclear energy consumption under carbon reduction scenarios. Alternatively, the Journal of Cleaner Production is ranked 7th with a total citation score of 537 until now. Overall, JCP provides an analytical review of how nuclear energy can serve as an alternate energy source within the context of emerging economies' efforts to introduce environmental regulations and combat climate change [50,51]. The secondary range of academic literature published in the journal has focused on policy fundamentals to further the practical implications of alternate fuel sources, i.e., nuclear and renewable energy consumption.

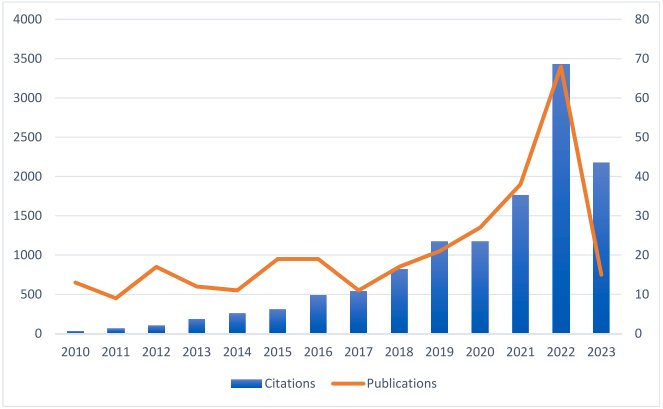

Fig. 1. Publication output and citation's growth trend.

3. Results

3.1. Authors collaboration networks

Next, we use Figs. 3 and 4 to illustrate research collaboration between countries worldwide from the collaboration network and the number of publications by each geographical region. China has the highest collaboration, followed by the USA and Turkey. Alternatively, Fig. 4 reports research output by geographical regions with darker colors indicating the highest frequency. China has reported the most publications (73) [52,53], followed by the USA (49) [45,52,54] and Turkey (31) [55–57]. It has been observed that most of the contribution comes from advanced industrial economies, which is justified by the fact that nuclear energy requires advanced technologies and higher initial costs. Our review of extant literature also indicates that the challenge of integrating nuclear energy to overcome the issues of energy poverty and a source of clean energy would require research in environmental technologies [33,58]. However, as stated previously, due to most recent research focused on industrial economies, there is a need to focus on how nuclear energy can become a feasible energy source for developing economies as energy statistics indicate that demand for energy resources in developing economies will continue to rise in the coming decades.

Next, we discuss co-authorship analysis to examine research collaboration at macro and micro levels. This will document evidence regarding inter-country, inter-state, inter-institutional, and intra-institutional research collaboration [32,37]. Fig. 5 provides a graphical illustration of the co-authorship of top researchers with patterns of research collaborations highlighted by different colors. The following clusters are the most dominant in academic research regarding research collaboration: brown color (4 authors) has explored environmental policy determinants and how nuclear energy can be integrated within low-carbon energy mix and pollutant emissions strategies [59,60] mint cluster (4 authors) has provided specific discussed nuclear energy sources' implications for climate regimes, low carbon scenarios and global environmental pledges [61–63]; red cluster has researched environmental sustainability, innovation in environmental technologies and policies towards economic sustainability [64]; magenta cluster includes publications with a focus towards reducing carbon footprint and how nuclear energy can substitute as alternate energy source [65] and pink cluster has provided emphasis towards determinants of environmental degradation and role of nuclear energy within environmental sustainability [66,67]. The remaining cluster showcases minimum collaboration with the academic collaboration of two authors, allowing us to emphasize that recent research exploring the impact of nuclear energy within environmental strategies requires further researchers to collaborate and provide novel research contributions.

3.1.1. Key countries, authors, and keywords (CAK) framework

The next section attempts to uncover how researchers have documented different research streams in which countries [37,68]. Hence, we use CAK framework to present novel visualization to depict the integration of authors, research themes, and countries. It is evident from Fig. 6 that China, USA, Turkey, and Pakatan are the most prominent geographical locations. Likewise, Yuan JH, Ozturk I, Radulescu M, and

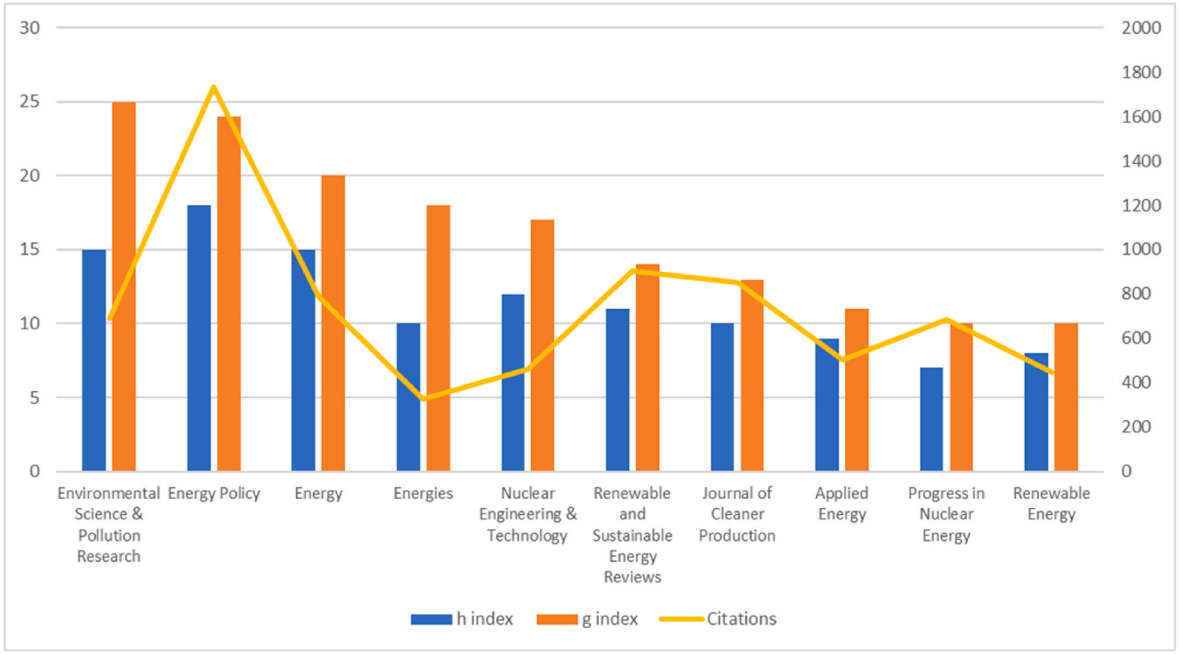

Fig. 2. Source impact.

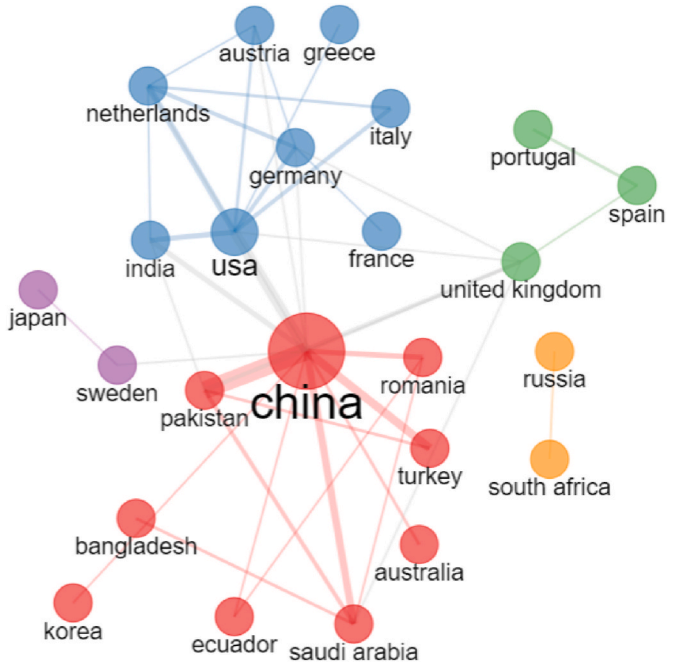

Fig. 3. Countries' collaborations network.

Danish are the most prominent authors. Lastly, the most dominant research themes are nuclear energy, renewable energy, climate change, and carbon emissions. We further conclude that China, the USA, and Turkey have been able to explore nuclear energy consumption from different economic and environmental indicators' perspectives. However, the United Kingdom, Australia, Japan, and India have provided limited research contributions. Most importantly, the nod size of countries with limited contribution indicates that current research is in the elementary stage. Further research, especially from European economies with higher energy demands, must highlight current research discussions from the perspectives of new avenues.

Key findings from Fig. 6 (authors, keywords, and countries) are rather interesting. For example, we can observe that Ozturk, Danish, and Yuan JH have the highest frequency of contribution. Their research has investigated key determinants of how nuclear energy can play an active role in overcoming environmental issues, namely, asymmetries in clean energy [69], dynamic effects of fossil energy [58], nuclear energy consumption's effect over carbon reduction [70] perspective of nuclear energy in China [71] and promoting economic sustainability. Available literature has stressed that economic efforts to eliminate global poverty (SDG 1) would result in a significant increase in carbon emissions [72]. While emissions and energy intensities play an integral role in eliminating global poverty, integrating energy systems towards becoming de-carbonized through clean energy, i.e., nuclear energy can play the most crucial role in creating a balance between economic and climate goals. This suggestion is in line with SDG-7: cleaner and affordable energy for all, and helps us draw policy suggestions to promote clean energy. However, Fig. 6 also highlights the issues of energy efficiency, clean energy, climate change, nuclear power, and energy policy as key determinants in energy debate and calls out academicians and researchers to explore these perspectives further to achieve sustainable development.

3.2. *Intellectual structure - co-citation analysis of authors*

Next, we use co-citation analysis to examine how economic literature has developed in recent decades, as the frequency of citations of studies showcases higher relatedness within economic literature [2,37]. Moreover, co-citation is considered a dynamic matric that evolves and helps recognize paradigms within a aiven sample of academic literature [32]. In the current study, we use Fig. 7 (co-citation analysis), where the number of citations is accounted for by nod size and relatedness of the topic, and academic discussion is highlighted by the distance between these nodes [73].

The visualization of Fig. 7 details two clusters, namely red and blue. The publications belonging to the red cluster have discussed the significance of energy consumption within current economic growth models and discussed the possibility of nuclear energy consumption as a reliable energy source [74,75] or have attempted to determine the factors of environmental degradation [52,67]. Another group of publications by Refs. [55,57] has discussed nuclear energy's role as an alternate

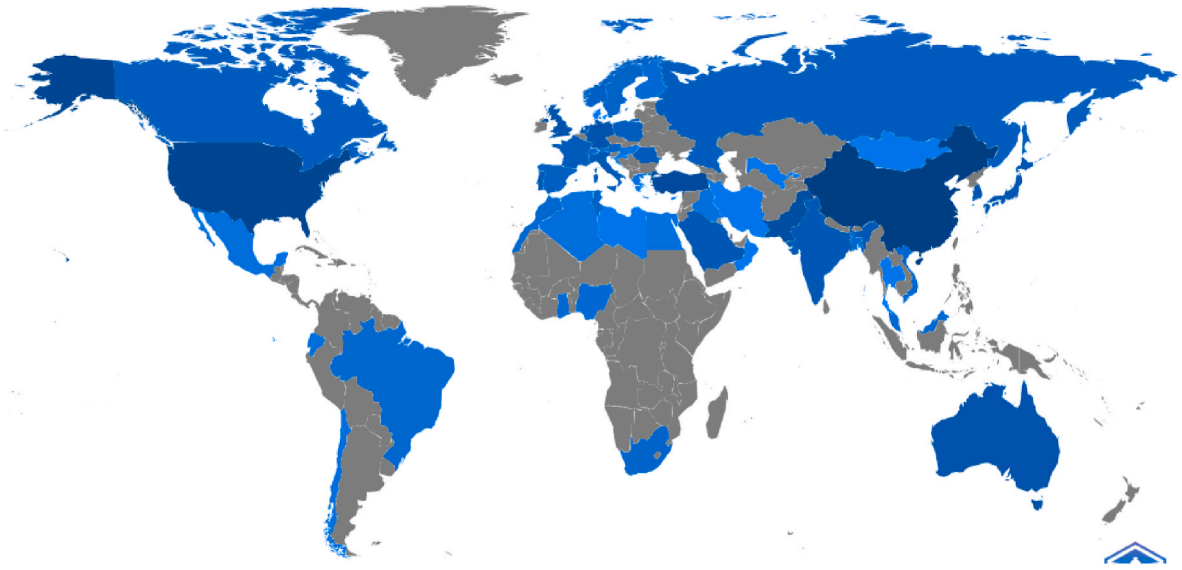

Fig. 4. Country scientific production.

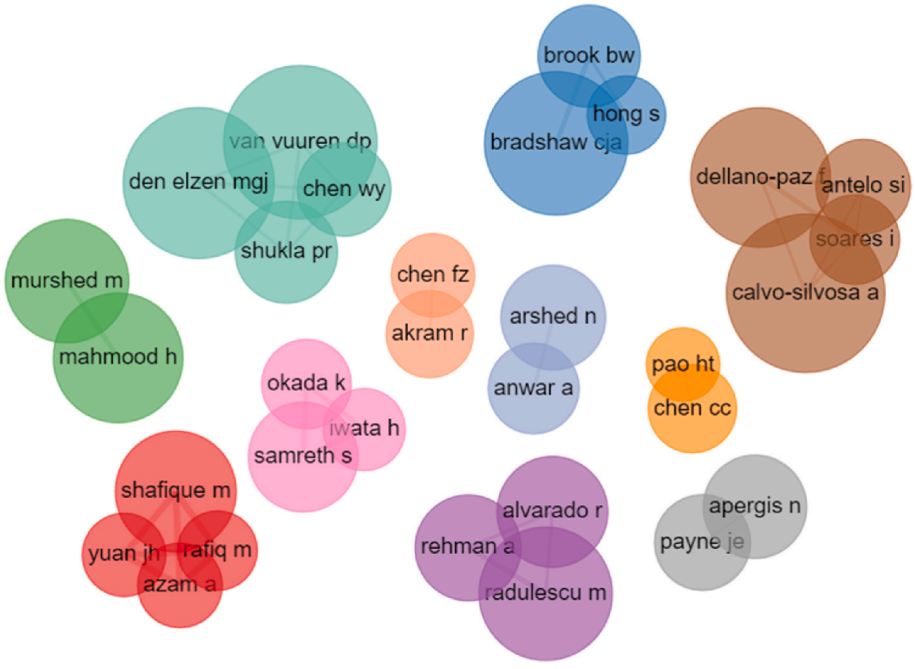

Fig. 5. Author's collaboration network.

energy source and the impact of macroeconomic variables to highlight the role of policymakers and regulatory authorities in laying the foundation for energy standards to assist in developing efficient energy sources. On the other hand, publications from the blue cluster have explored how nuclear energy fits within the concept of clean energy sources and how political and institutional drivers affects development within different geographical regions [58,76]. Sarkodie & Adams [77] researched renewable energy policies to conclude that industrial energy demand, environmental policies, and safety infrastructure through advanced technologies will be the factors behind the acceptance of nuclear energy as a reliable energy source [78].

3.3. Conceptual structure of the publications

In recent years, keyword co-occurrence network has gained popularity within systematic review-based studies to take advantage of knowledge mapping and attempt to reveal association between research themes within a given area of research management [79,80]. This also allows the researchers to fully understand a given domain within cumulative knowledge and use the strengths of keyword association to reveal related insights that materialize within economic literature. For the current study, we select a keyword co-occurrence network approach with the minimum frequency set at five words; consequently, out of 1136 keywords, 113 met the designated criteria (Fig. 8). Keywords like CO_2 emissions, renewable energy, nuclear energy, and economic growth are the keywords with the most occurrences. Furthermore, as it is evident from Fig. 9, the environmental Kuznets curve, ecological footprint, non-renewable energy, foreign direct investment, and electricity consumption have close association; conversely, global warming, greenhouse gases, fossil fuels, life cycle assessment, and climate have

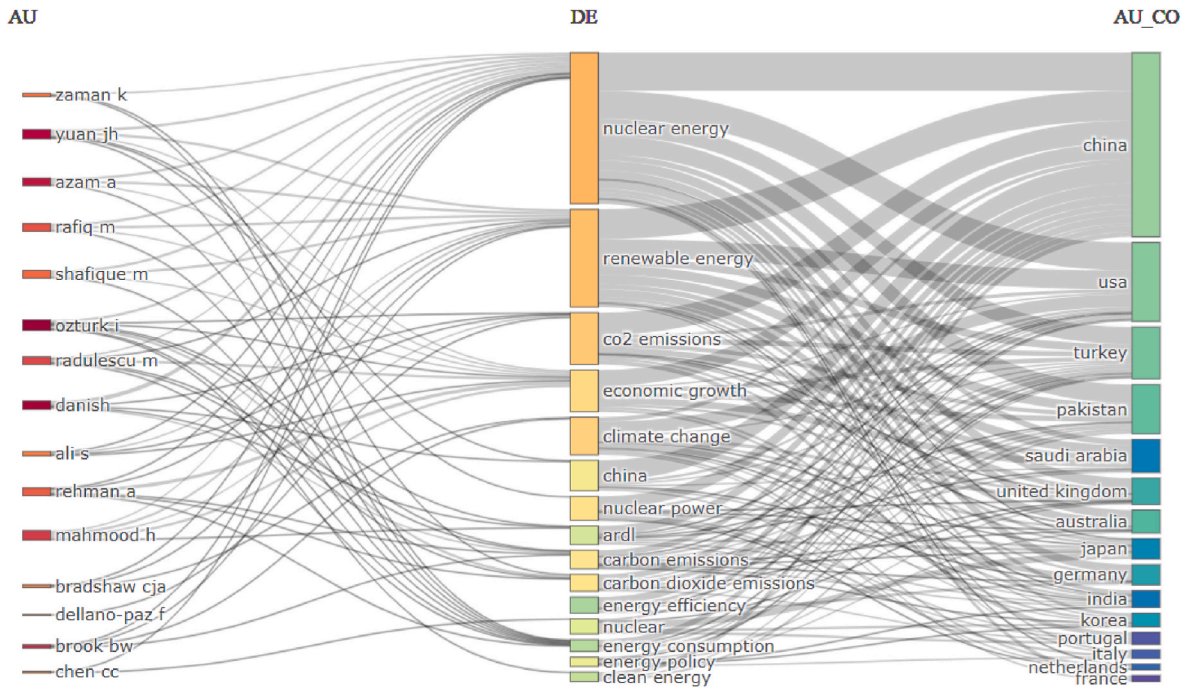

Fig. 6. CAK framework. Authors, keywords, Countries.

smaller node sizes. However, an interesting fact to be observed is that keywords such as clean energy, sustainable development, technology, pollution, and energy policy have small node sizes, but none have disconnection in terms of link [2,25].

Next, we use Fig. 9 to observe thematic mapping from the perspective of four distinct sub-divisions to better comprehend the variability and gravity of sub-components within scientific literature [41,81]. For the current study, we have fixed the maximum number of keywords at 250 and the minimum cluster frequency at 5. The upper right section contains motor themes, which consist of research topics with the highest density and centrality. Sustainability, climate change, and sustainable development are the motor themes. The focus on alternative energy sources, carbon emissions reduction, carbon neutrality, sustainable energy, and energy-environment-economy nexus have been explored to research how nuclear energy can be effective in achieving energy efficiency and allow energy transition from fossil fuels to reduce the threats from global warming [16]. The research themes related to environmental impact, energy planning, pollutant emissions, and life cycle assessment are isolated yet highly developed research areas [82,83]. These research areas are classified as niche themes; the association among these topics has high density (highly developed) but, in comparison to other themes, exhibit weak external links with low centrality. Next, the research themes in the lower-right quadrant due to low density are termed basic themes. These themes have discussed research topics such as climate change mitigation, carbon intensity, low carbon energy, renewable energy consumption, and hybrid energy systems [84,85]. Furthermore, the association between nuclear energy and carbon emissions focuses on clean energy, climate policy, the STIRPAT model, and nuclear energy's role in lowering ecological footprint in industrial economies such as China [26]. These topics are of a traversal nature and have high significance in the research, and they can help general research discussion towards different research directions. Lastly, research topics related to energy policy, alternate and nuclear energy, nuclear energy generation, and energy-economic modeling are categorized as declining or emerging themes [86,87] In general, Fig. 9 and Table 1 help narrate the nature of current academic discussion and nuclear energy's role within energy policies in the near future.

4. Discussion and research agendas

The current study has critically examined existing nuclear energy literature. Our integration of manual, systematic, and bibliometric review approaches [32,37] allows us to map factorial analysis, thematic analysis, keyword analysis, co-citation analysis, research collaboration, leading publications, leading authors, research hotspots, and academic research performances. This allows us to provide novel research contributions in the following ways: first, identification of theoretical contributions by existing publications, which we further segregate into methodological and topical contributions; the second part provides contextual contribution, while the last part provides conclusion and policy implications [2,25].

4.1. Theoretical contributions

Our first main research contribution consists of theoretical contributions, which can be further subdivided into topical and methodological contributions.

4.1.1. Topical contributions

Available nuclear energy literature has attempted to investigate the role of nuclear energy from several dimensions; we offer unique insights and use integrative and analytical overviews to provide detailed summary estimates. We identify that factorial analysis and co-occurrence network indicate that emerging themes have received the least attention. Moreover, energy policies, renewable energy sources, climate change, and sustainable development must be explored further to solve the global energy crisis [10,12]. Also, the thematic map indicates that research on nuclear energy, ecological footprint, and climate policies have been influenced by the generic nature of energy policies and reports that these topics require detailed inspection to extend the scope of energy research.

One prominent discussion within economic literature attempts to identify how different factors have influenced energy vulnerabilities at macro and micro levels, as industrialization requires huge and reliable energy resources [88]. Traditionally, fossil fuels are the major contributor to electricity generation, but these resources have faced significant

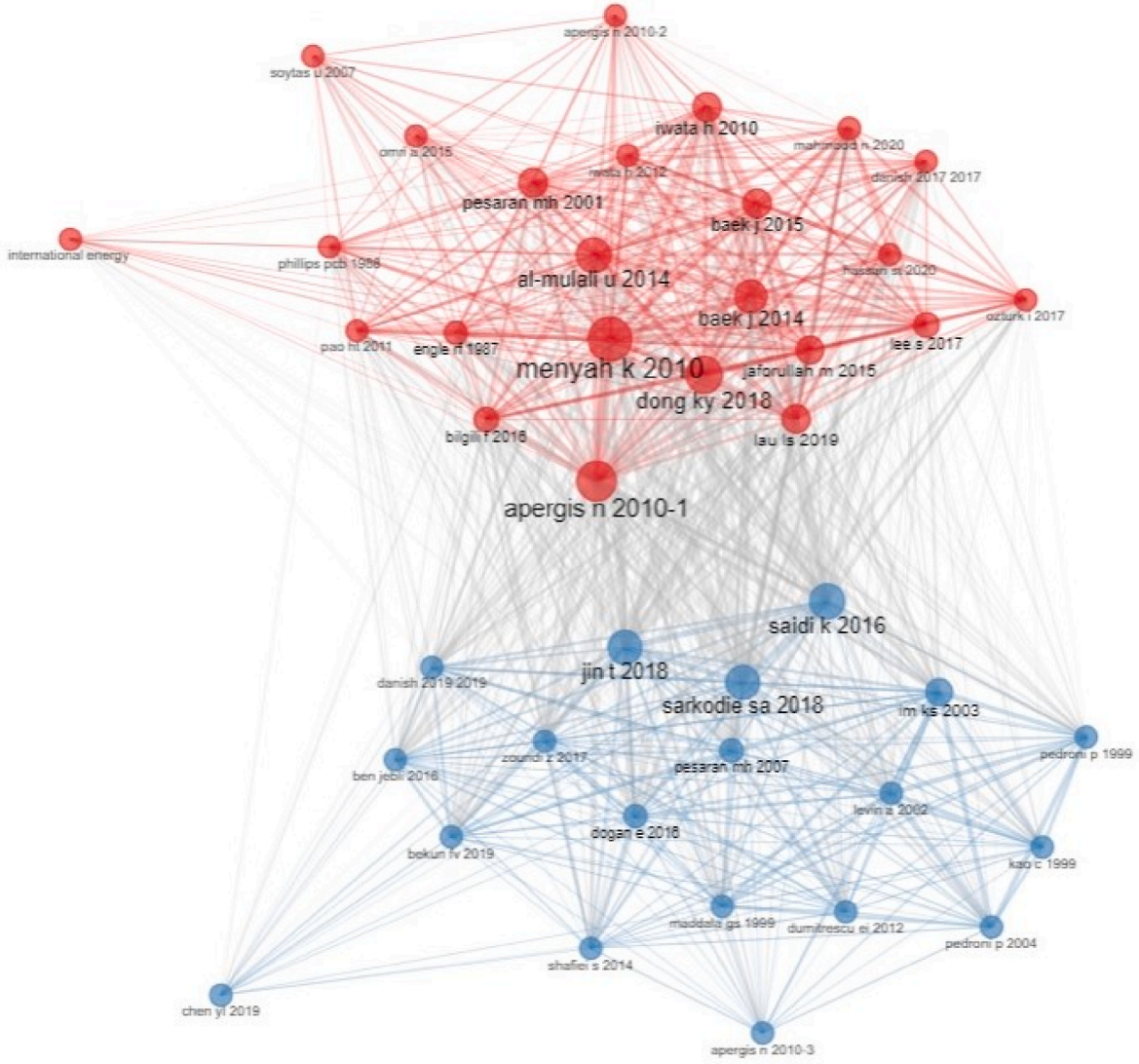

Fig. 7. Co-citation analysis of authors.

resistance due to various socio-economic and political conflicts [89,90]. Consequently, nuclear energy has gained prominence but continues to face safety concerns. However, technological developments have increased the feasibility of nuclear energy to help transformation towards green energy consumption to replace the share of fossil fuels and limit losses from natural disasters. Hence, energy literature has affirmed that careful energy policy considerations would allow nuclear energy to overcome energy vulnerabilities and emerge as a more inclusive indicator of energy injustices [91].

***FRA1*:** further research is critical in examining how nuclear energy can influence green energy developments, energy efficiency, and intuitional changes to extend the scope of environmental strategies and energy policies.

Another emerging issue is energy transition [92–94], where researchers have investigated gradually increasing the share of renewable energy within the existing energy mix [95,96]. This also correlates with efforts to enable energy access, which is fundamental for human development. Hence, an effective process for energy transition would meet energy needs and alleviate energy poverty [97]. However, we suggest that energy transition would decrease toxic contaminations and preserve environmental quality but has varied success rates in terms of acceptability among different world regions [33,78] as global economies struggle to replace fossil fuels. This allows us to suggest that future studies must explore how nuclear energy can facilitate energy transition.

***FRA2*:** A better understanding of the bottom-up approach within the scope of energy transition and environmental strategy frameworks would allow policymakers to universalize the modern energy approach.

Policy literacy is an emerging concept that plays a central role in policy discussion among energy experts and policymakers to influence public acceptance of changes in energy policy [8]. Despite its implications, policy literacy is yet to receive serious consideration in energy policy practices. Rapid urbanization and economic policies have increased the demand for electricity and energy resources. Recently, China announced an increase in electricity capacity from nuclear energy [98]. In contrast, Germany declared a gradual phase-out of nuclear power plants due to safety concerns after the Fukushima nuclear disaster. Likewise, South Korea followed Germany in shutting down nuclear power plants, but such a policy has faced criticism due to indifferent energy policies and a lack of reliable energy alternatives [58] In this regard, energy experts are interested in nuclear energy and how it influences geothermal, wind, and solar energy. Several studies in the energy literature have also investigated the feasibility and disparity of nuclear energy at the regional level [76] to overcome issues related to nuclear policy literacy [99]. In line with this, we suggest that extensive resources must be diverted mainly at the regional level to increase nuclear energy awareness about nuclear energy and related policy

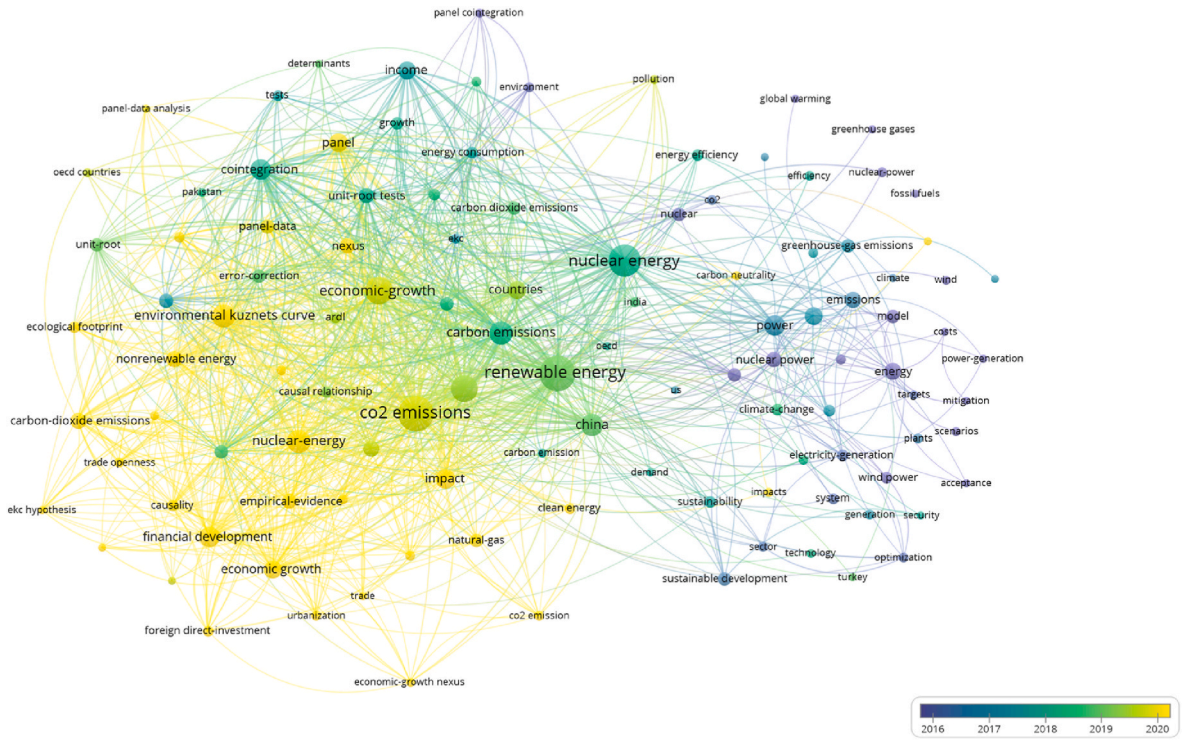

Fig. 8. Keywords co-occurrence network.

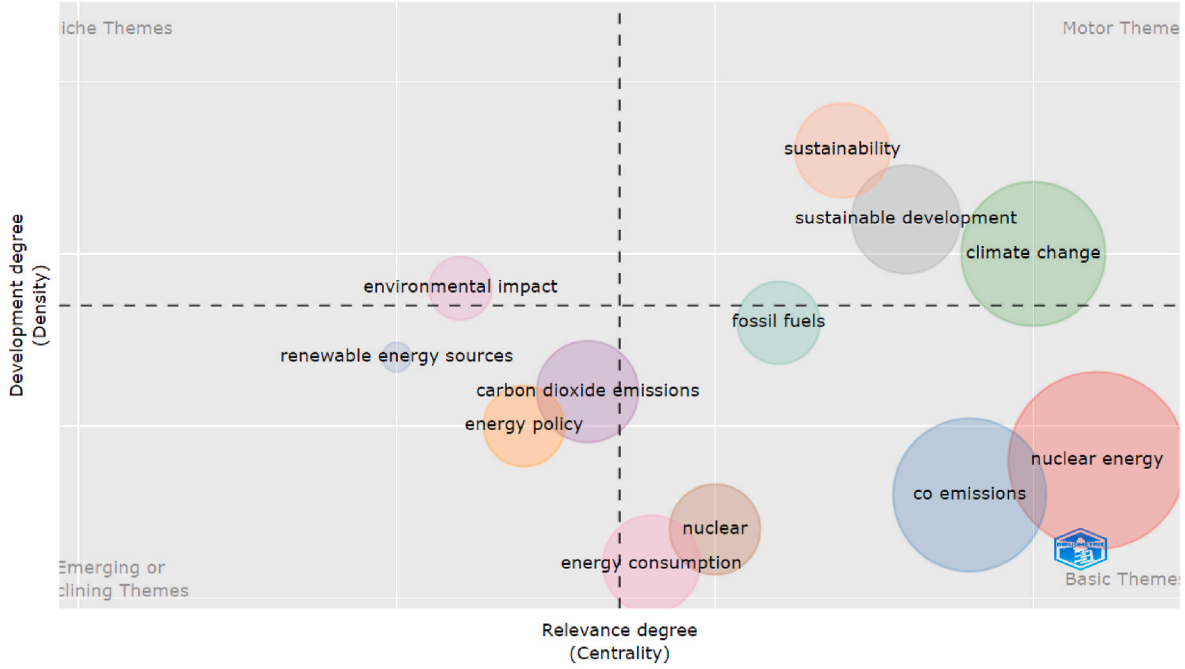

Fig. 9. Thematic map.

perspectives.

FRA3: Using literacy policy approach for nuclear energy within environmental planning and carbon neutral strategies would help achieve a "green environment."

Energy infrastructure is another research area discussed throughout the selected literature [7,11]. Castaño-Rosa and Okushima [100] discussed contextual factors of energy consumption to suggest technological infrastructure will play the most significant role in increasing the share of renewable energy through value chain additions. The complexity in the 21st century of energy systems requires modern infrastructure, which can only function through technological developments [15]. Hence, the energy sector requires further investments in innovation, development, research, and related skills to develop smart power and grid transmission plants to help solve energy crises. Cheng et al. [101] mentioned that energy resourcefulness through environmental technologies will ensure environmental integrity, acceleration of clean energy, and sustainable economic development. In conclusion, a robust technological infrastructure will allow nuclear

Table-1
Main keywords and frequency.

Main indicators	Theme	Keywords frequency
Sustainability	Motor Theme	Sustainability (5), alternative energy (2), carbon emissions reductions (2), carbon neutral (2), carbon sequestration (2), energy transition (2), forecasting (2), fossil fuels (2)
Sustainable development	Motor Theme	Sustainable development (6), sustainable energy (6), energy systems (4), lotka-volterra model (3), Kaya Identity (2), CO2 mitigation (2), competitive interaction (2), energy-environment-economy (2)
Climate Change	Motor Theme	Climate change (24), nuclear power (18), energy efficiency (9), carbon neutrality (6), energy transition (5), global warming (5), carbon capture and storage (4),
Environmental impact	Highly developed and Isolated Themes	Environmental impact (3), power generation (3), energy planning (2), life-cycle assessment (2), pollutant emissions (2), portfolio theory (2)
Renewable energy sources	Emerging Theme	Renewable energy sources (4), emissions (2)
Energy policy	Emerging Theme	Energy policy (10), decarbonization (3), energy mix (3), energy economic modelling (2), energy sector (2)
Carbon dioxide emissions	Emerging themes	Carbon emissions (13), EKC (6), environmental sustainability (4), alternative and nuclear energy (3), energy utilization (2), fossil fuel energy (2), nuclear energy generation (2)
Fossil fuels	Basic Theme	Fossil fuels (5), greenhouse gasses (5), carbon dioxide (3), carbon intensity (2), climate change mitigation (2), nuclear phase-out (2), renewable electricity (2)
Nuclear-energy consumption	Basic Theme	Nuclear (10), renewables (5), energy consumption (9), environment (7), carbon emissions (4), hybrid energy system (2), low carbon energy (2)
Nuclear energy-carbon emissions	Basic Theme	CO2 emissions (32), China (12), clean energy (9), energy (5), GDP (5), climate policy (4), STIRPAT model (4), Nuclear energy (75), renewable energy (58), economic growth (23), carbon emissions (12), ecological footprint (7), financial development (7), renewable energy consumption (5), EKC hypothesis (4)

sector to support higher access to energy services and contribute towards higher economic and environmental improvements [8,9].

***FRA4*: *Advancing environmental technologies' scope and integration within nuclear energy would allow policy institutions to reshape energy mix in favor of renewable energy sources*.**

The 5th research agenda is closely associated with the fourth framework to report that novel econometric methods must be used in research related to evaluating nuclear energy. The existing economic literature has mainly relied on cointegration and panel regression approaches, i.e., panel ARDL, system GMM, etc. However, other approaches, such as wavelet modeling, connectedness, CCE-GMM, NARDL, and CS-ARDL, need further consideration by time series and panel datasets. Building novel empirical, methodological, and theoretical frameworks will allow researchers to highlight practical policy guidelines, policies, and research directions.

FRA5*: *using advanced econometric approaches during data analysis and modeling would allow researchers to draw robust policy implications as recent econometric methodologies are better suitable to deal with spillover effects.

4.1.2. Methodological contributions

The current section outlines methodologies and research strategies within nuclear energy literature and influences future research. Scientific findings for nuclear energy remain inconclusive due to the nature of data, empirical strategies, and belonging to different geographical regions, making policy designing even more challenging. To overcome this, researchers have developed energy indexes to evaluate the role of nuclear energy in energy and environmental issues. Among these indexes, the NTI Index, WANO performance indicators, Nuclear Energy Index, Environmental Performance Index, Energy Sustainability Performance Index of Biodigester have received the most attention [102,103]. However, we argue that novel composite evaluation indicators can increase the relevance of nuclear energy within the renewable energy mix. Despite evaluating energy consumption and demand, most of the above-mentioned indicators are yet to gain global acceptance due to difficulties in implementation. Hence, the identification of key indicators and dimensions will facilitate an accurate comparison to capture key drivers of nuclear energy consumption accurately.

***FRA 6*: *Identification of nuclear energy dimensions and a subset of evaluation mechanisms would allow global comparisons and efforts to evaluate the performance of different nuclear energy strategies*.**

While examining the impact of nuclear energy on energy patterns and environmental sustainability, Danish et al. [99] determined that several factors influence the heterogeneity in the role of nuclear energy within energy mix strategies, as diverse regional characteristics can impact the outcome of sample sizes, data methodologies and require further empirical assessment [16,70].

FRA 7*: *incorporating composite indicators to research nuclear energy's effectiveness by accounting for local and geographical attributes requires further theoretical and empirical analysis.

Furthermore, environmental conditions, human development, socioeconomic conditions, and economic growth are key indicators which can influence the relevance of nuclear energy within energy discussion. Existing studies have attempted to research several determinants which influence the reluctance towards accept/increase in energy generated from nuclear energy, i.e., energy price, technology, public debt, and financial development [78]. There are occasions when practitioners are determined to introduce a 'favourable' technology that ignores the overall contextual aspects and wastes precious resources [84]. Hence, policymakers and practitioners must transit more information about the implications of energy technology [16]. Regardless of technological advances, energy development institutions must consider these principles so that the development of environmental technologies does not suffer from limited effect. Henceforth, we encourage considering every essential factor that might impact nuclear energy's implementation as an energy source.

***FRA 8*: *environmental, technological, and economic factors must be considered while evaluating the effectiveness of nuclear energy within environmental sustainability*.**

4.2. Contextual contributions

In the current section, we identify gaps in the current literature to identify future research directions. We report that research themes related to environmental impact, sustainable development, and climate change [17,39,69] have had the most significant impact on the development of nuclear energy research as they belong to generic themes and have greater interaction with other disciplines. Additionally, we use collaboration and co-author visualization to report that China, USA, and Pakistan have the most collaborations. Furthermore, China, the USA, and Turkey have published most studies to help increase the relevance of nuclear energy consumption within energy economics. We also analyze teamwork and research collaboration significantly differ as researchers from the USA have a higher degree of research collaboration, while the opposite is true for researchers from China. In contrast, Asian and newly industrialized economies have recently emphasized how nuclear energy

can be utilized to overcome energy and environmental issues. Lastly, emerging economies have shared a greater tendency on fossil fuels, which allows us to suggest that energy alternatives and technological developments must be prioritized to achieve environmental sustainability [104].

***FRA9*: The** *use of country-specific framework would provide better contextual evidence and assist in the execution & policymaking of energy policies.*

Our evaluation of authors' collaboration reveals that 84.65 % of sampled studies for the current investigation were multi-authors with an overall collaboration index of 3.05 for each document, where just 15.35 % were single-authored studies. These statistics suggest that research interest in nuclear energy's role in the energy sector and environmental sustainability is growing and that further researchers are expected to extend the discussion.

Our review of current literature also suggests that there is a need to explore how nuclear energy can contribute within the context of South Asia, Oceania, and Middle East regions. Moreover, although most of the research has mainly explored North American and European economies, developing countries still struggle to meet industrial energy needs, and the share of renewable energy has regressed under various environmental agreements. Hence, we encourage researchers to explore how energy policies impact nuclear energy and how such discussion can impact sustainable development.

***FRA10*:** *examining energy needs of emerging economies with collaboration from practitioners and policymakers would overcome the shortcomings of current literature.*

5. Concluding remarks and policy implications

5.1. Policy implications

The continued debate around fossil fuels and renewable energy remains a key hurdle in solving energy access and poverty, especially for developing economies. As more than 125 million people face energy shortages in the European continent alone, there has been growing debate on how to enhance energy affordability, energy accessibility, and comply with SDG-13 and SDG-7 to strengthen the role of clean energy in meeting energy needs and environmental sustainability. Consequently, nuclear energy has emerged as a possible solution to overcome energy and environmental issues, which also has great potential to influence energy and economic dynamics [105]. Recently, several studies have investigated the role of nuclear energy in energy poverty, environmental sustainability, and the share of green energy within energy mix [49,82,105]. Such debate has given prominence in energy literature and allows us to derive novel policy implications. The current study allows us to summarize that concerns about energy accessibility and fossil fuel costs have led to nuclear energy renaissance in recent years.

Based on our comprehensive review, we have provided some novel policy conclusions to address energy and environmental debate. We observe that for nuclear energy to be commercially feasible, there is a need to create novel methodological indexes so that policymakers and researchers can derive policy implications and notions. We further articulate that these policy directives can help developing economies in overcoming severe energy shortages. We also suggest that future studies must urgently explore technological and policy literacy concerns related to nuclear energy as governments remain hesitant to increase the share of nuclear energy despite nuclear energy having the best track record in terms of loss to humans and the environment alike. Moreover, energy dependence on fossil fuels means that organizations such as Climate Action Network, Environmental Defence Fund, and the United Nations have struggled to solve fossil fuels conundrum and sustainable development despite severe threats to our ecological atmosphere. To overcome energy and environmental concerns, we argue that future studies need to extend discussion on (1) how policy considerations would allow nuclear energy to overcome energy vulnerabilities. (2) integrating nuclear energy policy literacy about carbon neutral strategies (3) designing policy frameworks to assist policymakers in developing technological infrastructure (4) developing novel composite indexes to evaluate nuclear energy's role in renewable energy discussion from a wider aspect (5) examining research contribution by developed and developing economies to share scientific research and data to promote research collaboration.

5.2. Conclusion

The basic objective of current research is to extend nuclear energy through a state-of-the-art review of academic literature by focusing on energy practices, needs, efficiency, flexibility & access, and how it can ensure/affect compliance with UN SDGs. For this, we use a novel investigative methodology where we use three-dimensional contributions to investigate policy, contextual, and theoretical contributions by nuclear energy literature. During the research process, we considered all related nuclear energy consumption publications. Our scientific approach allows us to report contextual, methodological, and topical aspects for future policy implications. For instance, we conclude that there is a need to focus on how nuclear energy can influence climate change, carbon emission, energy efficiency, energy consumption, energy policies, and clean energy. As energy is a basic component for industrial and household sectors alike, evaluating socio-economic and policy variables will allow policymaking institutions to balance economic growth and environmental sustainability.

Our contextual and topic research contributions allow us to report innovative policy implications regarding nuclear energy's role in current academic discussion. Our main research contributions are summarized as: (i) future research can focus on integrating nuclear policy literacy among carbon-neutral strategies during environmental planning to shift attention toward the green environment. (ii) designing an efficient technological mechanism would allow the integration of nuclear energy within current energy policies and accommodate growing demands for energy, especially in the industrial sector. (iii) another main research direction would be to categorically analyze nuclear energy's role in energy accessibility and affordability. (iv) Using a bottom-up approach to evaluate nuclear energy's contribution in energy transition can allow policymakers to modernize the energy system compatible with environmental and economic policies.

Moreover, our integrative approach allows us to explore the methodological application of nuclear energy research. We report major indicators used in nuclear energy empirical studies in line with this discussion. The evaluation of methodological application allows us to document that current literature has largely used panel data models, which might be more robust in terms of future researchers to draw policy suggestions in compliance with sustainable development goals. Though, it is worth mentioning that country-wise analysis might also produce interesting findings and overcome panel data constraints. We also encourage future policies to research nuclear energy's role in overcoming energy poverty in emerging economies to report heterogeneous policy conclusions. Such discussion within the parameters of overcoming energy poverty would allow policymakers to assess and better understand the growing problems in developing and developed countries.

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Author contribution statement

Muhammad Farhan Bashir: Data curation, Writing – original draft; Revision; Conceptualization; Resources. Beiling Ma: Resources, data collection, Methodology. Arshian Sharif: Review, language editing. Tong Ao: data collection, Methodology. Kemal Koca: Revision; Conceptualization

Data availability

Data will be made available on request.

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