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Review Paper

Water-Energy Nexus for Global Sustainability: A Comprehensive Review, Challenges, Innovations, and Strategic Solutions

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Abstract

The Water-Energy Nexus (WEN) represents the critical interdependence between water and energy systems (WES), where energy is used to power water extraction, treatment, and distribution. In contrast, water is equally vital for energy generation, industrial processes, and sustaining power production infrastructure. Rapid population growth, urbanization, climate change, and escalating energy demands are intensifying pressure on both resources, posing significant sustainability challenges worldwide. Understanding and addressing the WEN has, therefore, become critical for achieving long-term environmental, social, and economic resilience. This paper presents a comprehensive review of the literature published between 2010 and 2024, synthesizing key technological innovations, policy frameworks, and global case studies that address the complex interlinkages of WEN. The findings reveal persistent gaps, including fragmented governance structures, inconsistent adoption of nexus-based models across regions, limited integration of renewable energy sources, and the absence of a universally accepted framework for implementing WEN strategies. The study highlights the increasing importance of integrating renewable energy into water infrastructure, the adoption of innovative water systems facilitated by digital technologies, and the utilization of data-driven decision-making tools, such as artificial intelligence and predictive analytics, to enhance operational efficiency and resilience. Furthermore, it emphasizes the need for harmonized policy development, robust cross-sector collaboration, and improved institutional frameworks to facilitate coordinated action across the WEN sector. Expanding research on feedback mechanisms between WES is crucial to optimizing resource use and supporting the achievement of the United Nations Sustainable Development Goals (SDGs). This review offers actionable recommendations to promote sustainable and resilient WEN solutions worldwide.

Keywords: Water-Energy Nexus, Climate Change, Sustainable Development, Policy Integration, Resource Management

1. Introduction

The interdependence between WE systems, widely recognized as the WEN, has emerged as a critical area of research and policy focus due to its profound implications for global sustainability [1]. This nexus extends beyond physical and technical infrastructures, influencing ecological balance, socio-economic development, and long-term environmental security. Energy underpins essential water services, enabling the extraction, purification, conveyance, and treatment of wastewater (WWT). In contrast,

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water is indispensable throughout nearly every stage of energy production, including hydropower generation, thermoelectric plant cooling, biofuel cultivation, and various industrial processes [2]. The growing demand for WE, driven by rapid population growth, urbanization, industrial expansion, and economic development, coupled with the intensifying effects of climate change and environmental degradation, is placing record strain on already delicate resource systems worldwide. Increasingly frequent droughts, floods, and other climate-induced extremes further exacerbate this pressure, threatening water availability, energy security, and overall socio-economic stability [3].

Despite their intrinsic interdependence, WE are still managed mainly as separate entities, resulting in inefficiencies, competing allocations, and conflicts that compromise long-term sustainability [4]. While significant progress has been made in understanding and modeling WEN interactions, many frameworks remain fragmented and lack comprehensive integration into regional or national policies. Initiatives such as basin-level nexus assessments by the United Nations Economic Commission for Europe have provided valuable insights into trade-offs and cross-sectoral linkages, but often fall short in addressing infrastructure investment needs, operational feasibility, and socio-political constraints that hinder large-scale implementation [5]. These persistent gaps highlight the urgent need for harmonized approaches that bridge technological, institutional, and governance dimensions to secure sustainable water and energy futures.

This review aims to critically analyze advances in WEN research and practice over the period 2010–2024, with a focus on identifying solutions that strengthen the resilience and efficiency of interlinked resource systems. Specifically, it seeks to synthesize technological innovations, integrated planning models, and evolving policy frameworks; examine barriers that limit coordinated WEN implementation; and highlight successful case studies that demonstrate effective strategies for managing WE interdependencies. The novelty of this study lies in its comprehensive scope, uniting technological, environmental, and governance perspectives to propose a conceptual roadmap for future WEN integration. Unlike prior reviews that focus predominantly on technical or policy aspects in isolation, this work provides a cross-sectoral synthesis that emphasizes resource optimization, harmonized policy development, and collaborative management strategies aligned with the United Nations Sustainable Development Goals (SDGs). Yet, Figure 1 illustrates the conceptual framework of WEN, highlighting its bidirectional flows, interconnected challenges, and sustainability-driven objectives. The literature review is presented in Table 1.

1.1 Knowledge Gap

As water and energy are independent of each other, improving one without considering the other will be a challenging task. The challenges to water resources have been under pressure due to recurrent variations. On the other hand, climate change issues such as temperature increases, floods, and droughts can significantly impact water quality and availability. Climate change, along with population growth, will enhance competition for water resources and could affect energy production [6], [7]. Disclose that most of the research lacks a precise analysis that effectively challenges the WE relation. There is a need for present studies based on WEN to investigate updated data, which mostly looks unsatisfactory for most of the literature, with a focus on. Most studies rely on existing works by WEN and do not explore the historical background of the process that links WE. We recommend that all the gaps regarding WEN issues be addressed at some point. To advance the methodological range, enhance the scope of the sectors, and refine the data used for the literature [8]. Population growth and climate issues are key drivers of water needs. Climate change issues can result in variable precipitation with an increase in temperature [9]. Whenever there is an increase in population, the demand for water also increases.

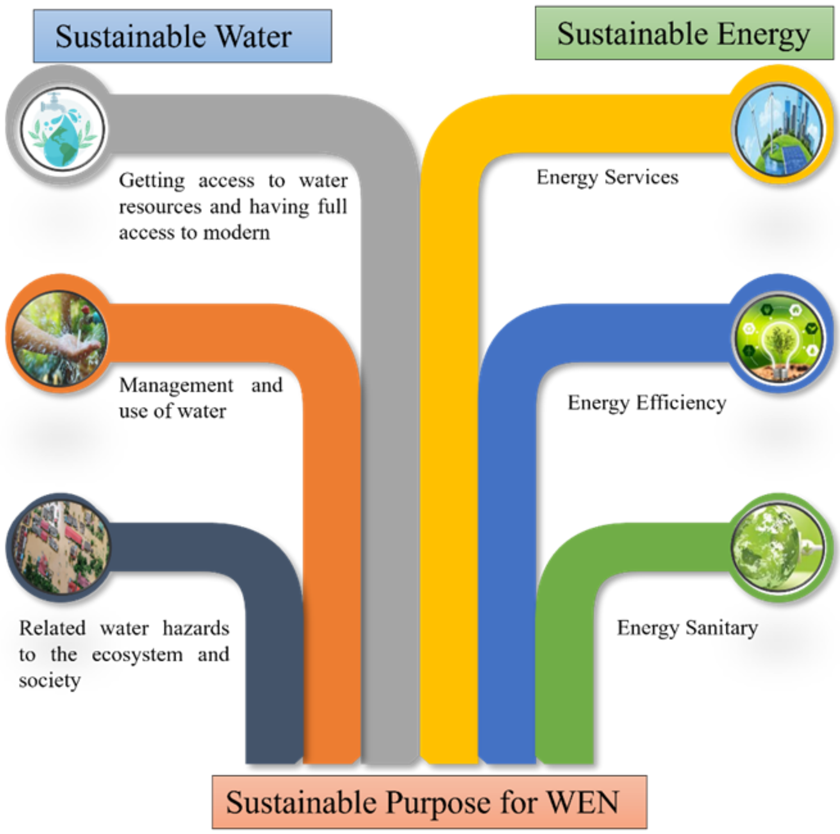

Figure 1: *The conceptual framework of WEN*

2. Literature Review

The reviewed literature reveals three dominant themes in WEN research: (i) Technological Interventions with focus on renewable energy and desalination. (ii) Policy Integration, highlighting challenges in cohesive WEN governance and (iii) Regional Disparities, pointing to high WEN risk in drylands and developing cities. The studies concur with the urgent need for localized, interdisciplinary frameworks to address nexus challenges in the context of climate change. However, Figure 2 highlights (a) the lingo most used in the literature (2002–2024) on the WEN, while (b) the nations that mostly employ the WEN. The theoretical framework of the WEN nexus, as explored in the studies, emphasizes a systems-based approach to understanding and managing the interdependence among water, energy, and food systems, addressing challenges like climate change, resource scarcity, and sustainability. Employing methodologies such as system dynamics and quantitative modeling, as well as frameworks like AQAL, the studies highlight synergies (e.g., resource efficiency through integrated policies) and trade-offs (e.g., economic versus environmental costs), advocating for unified policy frameworks, stakeholder engagement, and context-specific innovations like dry cooling or renewable energy integration. While acknowledging regional variations and barriers, such as technological immaturity and limited policy implementation, the WEN nexus offers a holistic perspective for developing climate-resilient strategies and promoting cross-sector coherence to ensure sustainable resource management.

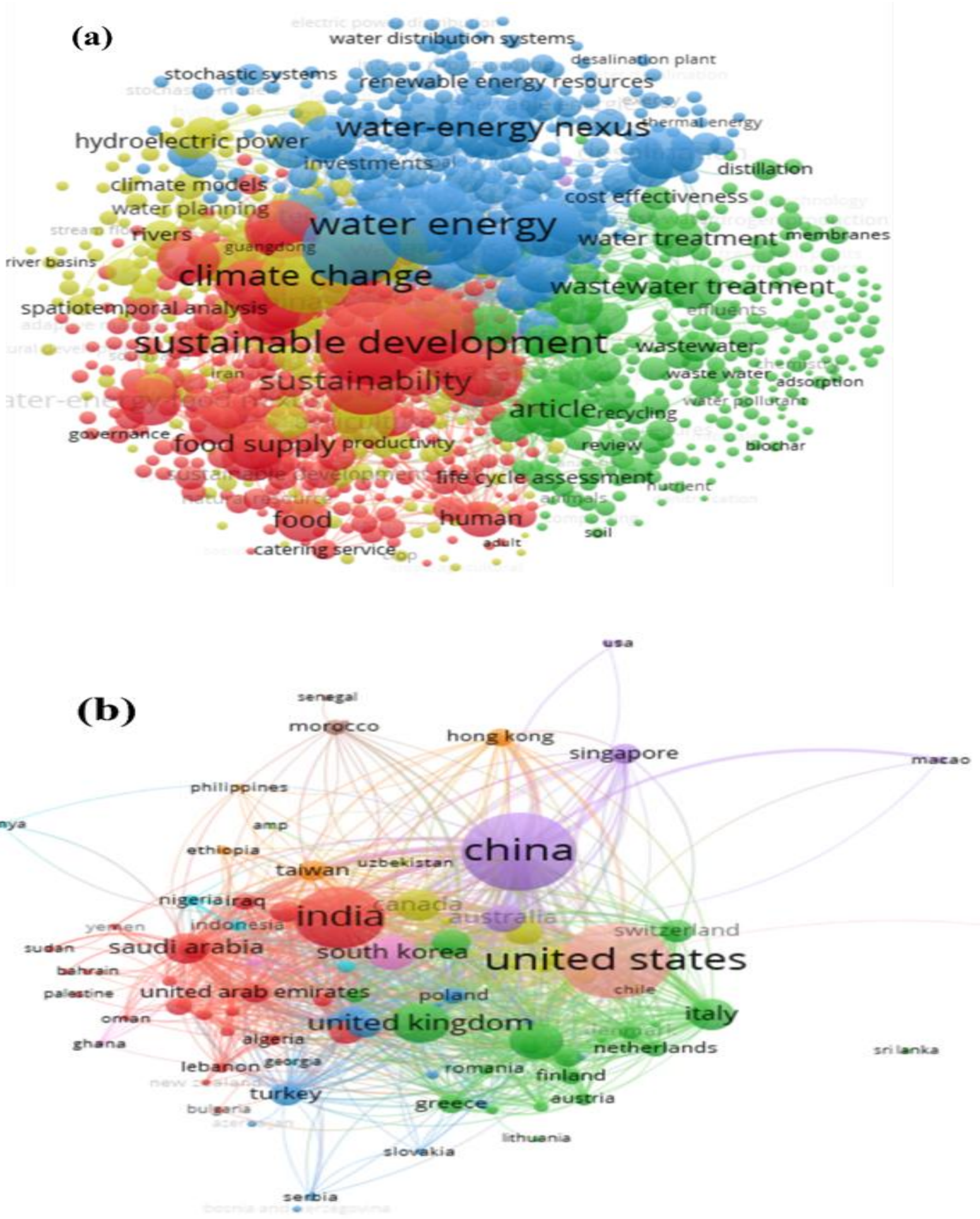

***Figure 2*:** *(a) the lingo most used in the literature (2002–2024) on the Water and Energy Nexus (b) the nations that mostly employ the Water Energy Nexus*

***Table 1**: Present a comparative table summarizing related studies*

S/N	Methodology	Country	Application	Conclusion	References
1	A database-driven review, utilizing Web of Science and Google Scholar, examined over 850 WEN-related approaches that involve climate change, food, and bioenergy. The study conducted outward influence analysis and identified theoretical gaps, highlighting the need for unified policy and modeling frameworks.	China	Examination, outward influence analysis, and assessment of the coupled system.	A critical review based on water energy theory, literature questions, and at least 850 techniques within food, water, and energy concepts.	[10]
2	Using the AQAL framework, this study assessed irrigation modernization and its implications for water-energy efficiency. It found that economic and environmental trade-offs remain key barriers to widespread implementation of modern irrigation strategies	Spain	a technique of modernization and irrigation which aims to improve the relationship between water and energy.	Computer obstacles, which are challenges of the modernization ways from the economic and environmental aspects	[11]
3	This case-based review analyzed regional challenges within the WEN, including environmental tension and conflict escalation. It emphasized the need for coordinated water and energy development strategies across Eastern, Western, and Central U.S. regions.	USA	Developmental aspects between the interlink of the two, environmental tension within the nexus, as well as conflict advancement.	These case studies link to Eastern, Western, and central areas, which are among the efforts to assess energy and water developments.	[12]
4	Quantitative modeling explored energy concentration across water systems. The study suggested specific mitigation pathways to support vulnerable countries facing high WEN risks, advocating for	Africa, Asia, Europe, and North America	techniques on existing water systems within the water cycle, the aim is to help the regions with less access to water	The examination of the work was to support and bring a suggestion to mitigate water issues within those countries that show high risk within their water energy strength.	[13]

	adaptive infrastructure and governance reforms.				
5	A multi-level review combined global and national scales to assess water-energy-environment interdependencies. It proposed WEN-integrated modeling to improve lifecycle assessments and decision-making for sustainable electricity generation and natural gas use.	China	The review work will pave the way for WEN-integrated modelling and even assessment	Using the harmonization technique to existing work will improve electricity generation, conventional natural gas, and renewables to bust a life cycle stages and technology, which is a cost-effective adaptation for making a well-mannered decision	[14]
6	The intertwined water, food, and energy nexus approach solely emphasizes synergies and trade-offs. However, a conceptual framework was employed to explore how the assimilating sectors could contribute to supporting climate change mitigation.	HKH regions	Refining climate change adaptation, whether through resources, water efficiency, energy, or food. Policy coherence among the energy, food, and water nexus can be advanced, which will lead to a well-designed adaptation plan.	Well-mannered techniques are necessary for effective and sustainable adaptation to climate change, integrating the water, energy, and food nexus, and improving techniques to enhance resource efficiency and promote policy strategies with long-term security.	[15]
7	This conceptual study highlighted the synergies and trade-offs among the water, energy, and food sectors. It proposed a climate-resilient adaptation strategy based on cross-sector policy coherence and resource efficiency improvements	China	The WEN nexus techniques are functional in addressing global and economic decisions, as revealed by the World Economic Forum. This approach suggests that the application of the WEN is not only something with limited-income organizations but also to advance the stability of the economy.	Even though WEN is getting advanced with wide attention, which includes funding, different scientific challenges remain in place	[16]
8	The authors projected regional water-related energy consumption for 2020 and 2030 using disaggregated techniques. The findings provided strategic insights for planners aiming to establish low-carbon water supply systems.	China	The results are solely relevant to officials and planners to progress a sustainable low low-carbon water supply system. The projection of water-related energy consumption for 2020 and 2030.	Water disposal, energy use, and carbon radiation must be looked into whenever there is a need to plan a nice water supply system within China.	[17]

9	Focused on dryland applications, the study forecasted that by 2050, water use in manufacturing could increase by 400% and electricity demand by 140%. It emphasized the urgent need for integrated water-food-energy strategies to enhance industrial sustainability.	Morocco	Industry requirements for water and electricity in manufacturing are expected to advance by at least 400% and 140%, respectively, between 2000 and 2050.	The projected advancement in water farming across various industries highlights the need for unified techniques that integrate the interconnection among water, food, and energy to promote sustainability and resilience.	[18]
10	Reviewed the potential of ocean energy for seawater desalination. Despite its promise, the study noted that ocean-based power remains underexplored due to economic constraints and technological immaturity.	Global Regions	Exploring renewable energy options is critical; however, investing in the location benefits of integrating ocean energy desalination techniques is also essential.	Ocean-based power generation has a promising possibility for desalination assembly, which remains underexplored and constrained by technological and economic constraints.	[19]
11	Developed a two-stage optimization model integrating electricity, gas, and water systems. It demonstrated how coordinated operation of distributed energy hubs can improve system reliability under resource and demand uncertainty.	China	The models were used to optimize the coordinated operation of water, energy, and gas, providing an integrated technique to manage the interdependencies within the systems, which are essential for system operation and managing connections between energy systems.	The use of models is an effective tool for managing the interplay between water and energy systems under uncertainty, particularly for system operators who face higher risks associated with renewables.	[20]
12	Analyzed the relationship between energy consumption and greenhouse gas emissions in water distribution. It advocated prioritizing renewable energy, particularly wind, solar, and micro-turbines, to reduce emissions from water pumping systems.	USA	Renewable energy, which includes wind and solar with mini water turbines, should be a priority to tackle the energy needed for water distribution, specifically for activities of water pumping and maintenance of the system.	The link between energy use and greenhouse gas emissions, which relies on water distribution systems, presents a way to mitigate carbon radiation.	[21]
13	Used a system dynamics approach to simulate how climate change and population growth impact water and energy availability. The study underscored the	USA	The models applied to such study explored that change in climate and population hinder interaction between energy and water availability.	A critical understanding of the intertwinement between water and energy enables informed decisions and opportunities for improvement, which can lead to better	[22]

	importance of integrated modeling for long-term planning and decision-making.			results in resource management.	
14	This systematic review of WEN nexus models revealed limited implementation in real-world policy settings. The authors emphasized the importance of innovation, institutional capacity building, and stakeholder engagement in operationalizing nexus frameworks.	USA	There is an emphasis on the need to integrate a technique that encompasses the social, political, and economic aspects of the WEN nexus. However, at least 18 testament studies aligned with the WEN nexus, which in the end, exhibit features for innovation, framework, and implementation.	WEN nexus offers promising procedures for addressing complex challenges within its practical application, which are currently limited by existing methods.	[23]
15	Focused on technological innovations such as dry cooling to reduce water demand in thermoelectric power plants. The study advocated for decoupling water use from energy production to address environmental constraints while supporting energy efficiency.	USA	Achieving the decoupling of water from the energy it requires for thermoelectric cooling is essential. This can be achieved through the technology of dry cooling, which comes between the trade-off between advances in capital cost and energy reduction.	Excellent technological approaches and engineering solutions are needed within the water and energy nexus, which hold promise for environmental improvement and addressing the increasing demand for resources.	[24]

2.1 Scope of the Literature Study

The WEN represents a critical interdependence between WES, where water is essential for energy production, and energy is indispensable for water extraction, treatment, and distribution. This study examines this intricate relationship, focusing on the challenges and opportunities in improving WEN efficiency and sustainability. Despite growing attention to WEN, research remains fragmented, with limited interdisciplinary approaches that combine both qualitative and quantitative techniques. Addressing this gap is crucial for policymakers and researchers aiming to develop integrated solutions that not only enhance power generation and economic growth but also alleviate the challenges faced by water-scarce regions worldwide [25]. The review highlights how climate change exacerbates these challenges, with rising temperatures, prolonged droughts, and shifting precipitation patterns increasing water stress and disrupting energy supply systems. Furthermore, population growth and rapid urbanization place mounting pressure on limited water resources, underscoring the urgency for innovative water frameworks, advanced irrigation methods, the adoption of renewable energy, and water-saving technologies [26]. This review synthesizes findings from global case studies to identify existing knowledge and policy gaps, emphasizing the need for cohesive frameworks that integrate WEN strategies with global Sustainable Development Goals (SDGs). Figure 3 presents a schematic diagram of WEN interconnections, illustrating the dual reliance of both sectors and the potential vulnerabilities arising from uncoordinated management. Ultimately, this study seeks to guide best practices and sustainable solutions by advancing policy evaluation, fostering technological innovation, and promoting cross-sectoral collaboration to mitigate current inefficiencies and enhance resilience in regions most vulnerable to climate change impacts.

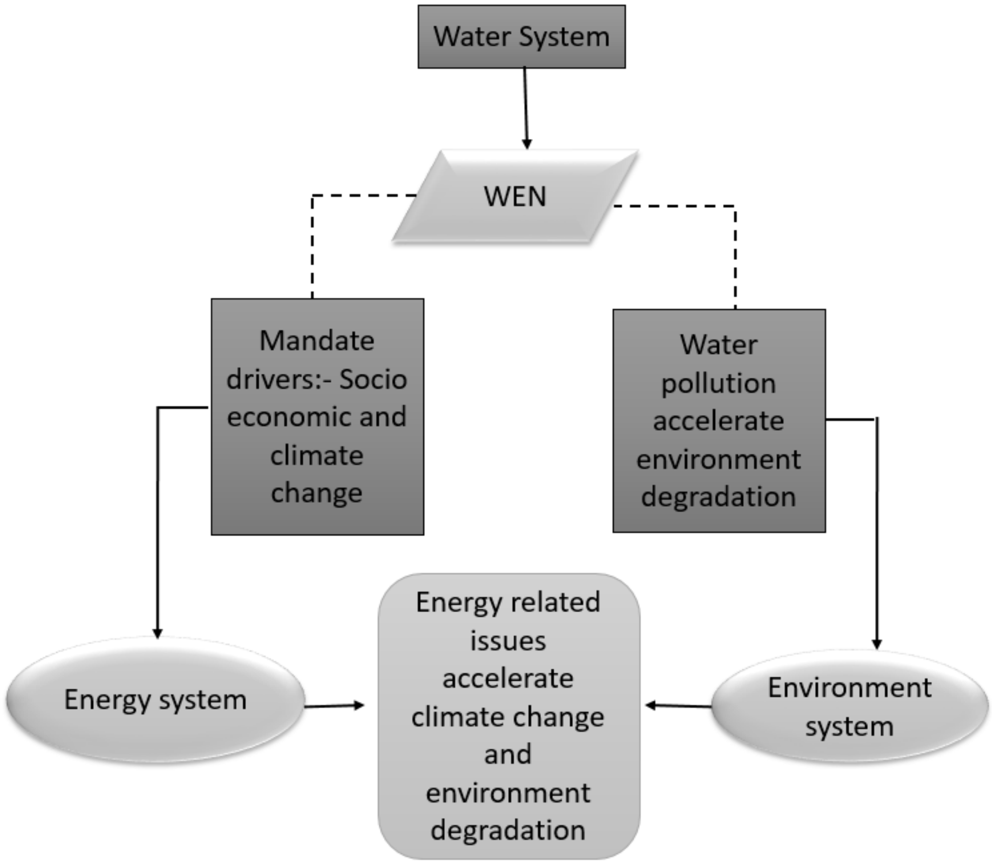

Figure 3. *Schematic Diagram of the Scope of this Study*

2.2 Water for Energy

Water plays a crucial role in energy production, with significant use occurring primarily in two domains: fuel production and electricity generation [27].Multiple technologies involved in energy generation, such as thermoelectric power plants, hydropower systems, and biofuel production, require substantial amounts of water for processes including extraction, cooling, and steam generation. A distinction must be made between water withdrawal and water consumption, as withdrawal refers to water that is temporarily used and later returned to its source, while consumption refers to water that is lost to evaporation, pollution, or transformation into a non-recoverable state [28]. The interdependence of WE is evident across various stages of the energy lifecycle, from mining and resource extraction to processing, refining, and electricity generation, all of which are water-intensive activities. With global freshwater demand projected to rise due to population growth, urbanization, and industrialization, future decades will witness mounting pressure on water resources required for energy production [29].This challenge is particularly pronounced in developing countries undergoing rapid economic expansion, where water scarcity is already a concern, and 20% of global aquifers are reportedly overexploited. Poverty and demographic growth exacerbate water stress, affecting essential uses such as drinking water, sanitation, health, and energy services. Furthermore, Figure 4 highlights the stages of water use in energy production with key phases such as extraction, processing, cooling, and distribution, and underscoring the tight coupling between water availability and reliable energy supply.

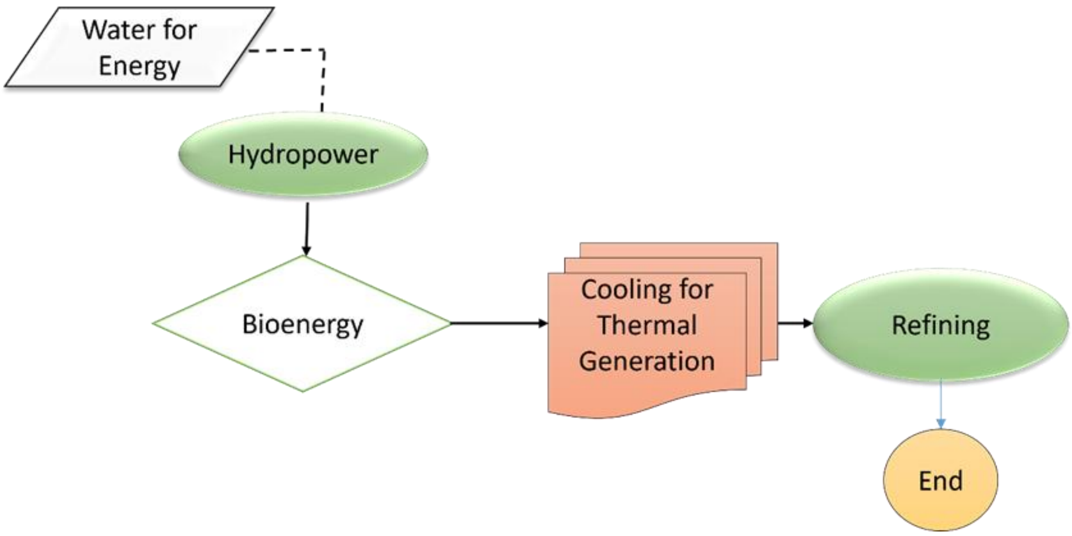

Figure 4: *A Diagram illustrates the process of using water for energy.*

2.3 Energy for Water

Energy plays a crucial role in the water supply chain, encompassing processes such as abstraction, treatment, distribution, and wastewater management. These energy requirements vary significantly depending on the water source, whether groundwater, rivers, or lakes, and are influenced by factors such as population growth, urbanization, climate variability, and regional topography [30]. For example, in Northern China, agricultural and industrial water use largely relies on energy-intensive groundwater pumping due to limited surface water availability[31]. Similarly, water conveyance systems often require substantial energy inputs, particularly when sources are located at lower elevations or far from consumption areas, necessitating long-distance pumping and additional pressure for distribution. Water treatment processes also add to energy demand, with higher requirements for advanced purification technologies that meet increasingly stringent water quality regulations [32]. Desalination plants, in particular, are among the most energy-intensive methods of water production, significantly increasing operational costs and contributing to greenhouse gas emissions. In the United States, water-related energy use accounts for nearly 5% of total electricity generation, with variations depending on regional conditions, water treatment technologies, and infrastructure efficiency [33]. As populations expand and water quality standards become stricter, the energy intensity of water provision is expected to rise further, particularly in water-scarce regions. Opportunities for reducing energy demand in water systems include improved pipeline management to minimize leakage and friction losses, strategic placement of water treatment facilities to exploit gravitational flow, and the adoption of renewable energy sources such as solar-powered pumping systems. However, Figure 5 illustrates the major stages of energy use within the water supply chain, highlighting the interdependence between WES and the importance of improving energy efficiency in water services to ensure long-term sustainability.

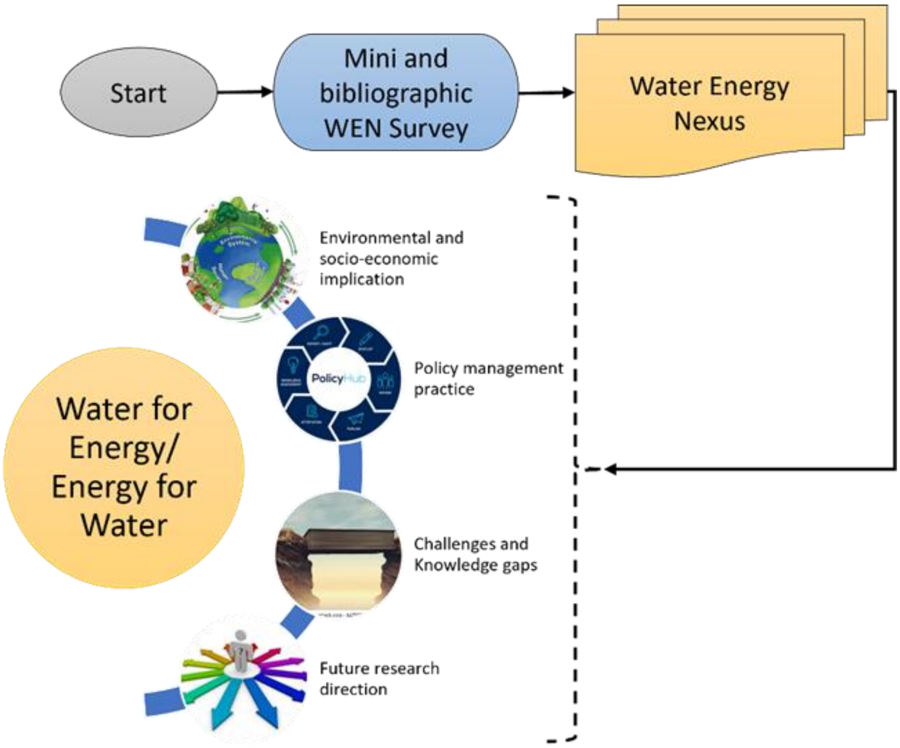

Figure 5: *Demonstrate the step-by-step process of energy for water*

3.0 Methodology

This study adopts a systematic review approach to critically examine the evolution, challenges, and innovations within WEN literature. A structured search strategy was implemented across two major academic databases, Web of Science and Google Scholar, covering the period from 2010 to 2024. Search queries incorporated multiple keywords, including "water-energy nexus," "sustainability," "energy for water," "water for energy," and "WEN policy," ensuring the comprehensive retrieval of relevant scholarly works. Inclusion criteria prioritized research that engaged with policy integration, WES modeling, technological innovation, climate change impacts, and environmental sustainability. Non-peer-reviewed publications, studies lacking methodological rigor, or research tangentially related to WEN were excluded. In addition to academic journal articles, this review incorporated official policy documents, institutional reports, and international frameworks to capture a broader perspective on socio-economic, regulatory, and governance dimensions influencing WE interdependencies [34]. The selection process involved multiple screening stages, including duplicate removal, title and abstract evaluations, and full-text assessments to ensure only high-quality and thematically relevant studies were retained. Ultimately, 89% of the selected literature met the inclusion criteria and made a meaningful contribution to understanding WEN complexities. This rigorous methodology ensures transparency and reproducibility, allowing for the synthesis of evidence that reflects the current state of knowledge on the dynamic interplay between water and energy systems. The study workflow, summarized in Figure 6, outlines the systematic steps undertaken in the selection and review process, laying the foundation for a comprehensive analysis of existing challenges and potential solutions within WEN research.

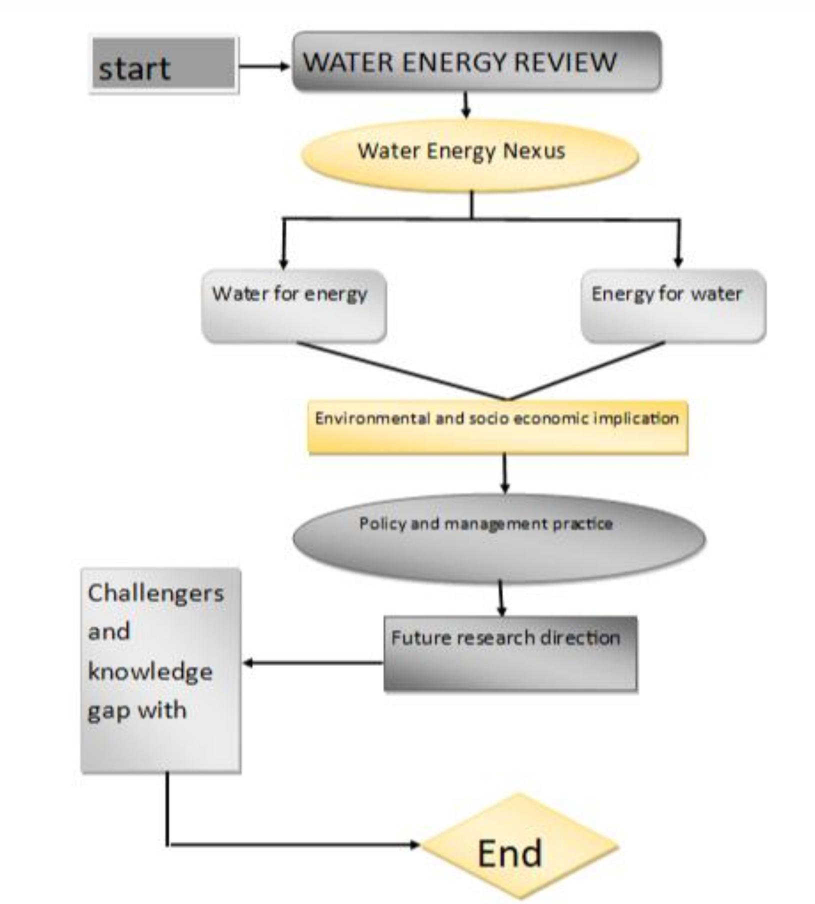

Figure 6: *Methodology flow chart*

3.1 Environmental and Socio-Economic Implications

The socioeconomic implications of water transfers and energy-related infrastructure development can manifest through both direct and indirect impacts, yielding outcomes that may be beneficial or detrimental depending on the context. Direct effects often include changes in labor demand, shifts in government resource allocation, and evolving regional political dynamics influenced by large-scale WEN projects [35]. These projects can alter population distribution, taxation structures, household income levels, agricultural productivity, and industrial activities, thereby reshaping local and regional economies. Indirect effects, though less immediately visible, can influence long-term community stability, social cohesion, and equitable access to essential services, as the redistribution of resources may exacerbate existing inequalities or create new vulnerabilities [36]. Evaluating these implications requires a careful and holistic assessment of the economic costs and benefits associated with each technological or infrastructural option implemented within the WEN. Metrics such as Gross Domestic Product (GDP) are frequently employed to gauge the contribution of WEN-related investments to economic growth, providing a proxy for measuring the success of projects in terms of production and distribution of goods and services (Gold, 2010). However, relying solely on GDP can obscure broader social and environmental trade-offs, highlighting the need to integrate comprehensive socioeconomic indicators into WEN planning and decision-making. Incorporating such indicators enhances the policy relevance of WEN initiatives, enabling more equitable and sustainable outcomes that take into account community livelihoods, long-term resilience, and the multifaceted impacts of resource management strategies.

3.2 Policy and Management Practice Framework for Water-Energy Nexus

Effective integration of the WEN into policymaking requires coordinated efforts from both industry stakeholders and government institutions. Policies must address not only WE use but also interrelated sectors such as agriculture, food security, and climate resilience. While several countries have attempted to implement nexus-oriented frameworks, many policies lack the adaptability and cross-sectoral coordination required to manage interconnected systems effectively [37]. A significant portion of environmental planning failures stems from inadequate enforcement, limited funding, and insufficient technical capacity to evaluate long-term impacts, hindering the development of resilient WES. Policymakers must prioritize integrated planning strategies that account for the dependency of energy production particularly thermoelectric and hydropower, on reliable freshwater availability [38]. Inadequate water sector management often leads to poor health outcomes, economic disruptions, and heightened vulnerability to environmental shocks. It is estimated that poor water infrastructure contributes to a global loss of over $260 billion annually due to disease burden and decreased productivity [39]. Technology can play a transformative role in reducing water demand across sectors. Advancements in irrigation efficiency, wastewater reuse, and household water-saving devices can significantly reduce consumption and increase overall system resilience. Scaling up the use of such technologies offers opportunities to promote shared water use through cooperative and cost-effective safeguarding strategies [20].

4.0 Future Research Directions

Future research must focus on developing robust, interdisciplinary frameworks that effectively integrate WES. Although the WEN is gaining attention in academic and policy circles, significant theoretical and methodological gaps persist. Many existing studies lack comprehensive frameworks that can guide real-world applications or policy development. One of the key areas requiring attention is data interoperability between the WE sector. Improved data sharing can enhance model accuracy, resource planning, and impact forecasting [40]. Additionally, future studies must explore how nexus strategies can be aligned with environmental sustainability while supporting economic development and human wellbeing [23]. Since human activities are central to ecological transformations, addressing global water scarcity and energy stress require both technological innovation and behavioral change. There is also a need for deeper investigation into how changes in production systems and consumption habits can lead to more efficient use of resources. Research must go beyond technical optimization and address social dimensions such as policy adoption, institutional cooperation, and user behavior to make WEN-based approaches practical and scalable [41].

5.0 Conclusion

This review has examined the complex interdependence between WES, commonly referred to as the WEN, in the context of growing global sustainability challenges. The analysis highlights how factors such as climate variability, rapid urbanization, and environmental degradation are intensifying the demand for both WE, particularly in vulnerable regions [42]. While the WEN framework holds significant promise for advancing sustainable development, our findings reveal persistent gaps in governance, policy integration, and implementation [42]. Many existing strategies lack the interdisciplinary coordination needed to address the interconnected nature of WES effectively. Drawing from literature published between 2010 and 2024, this study identifies three core areas of concern: the need for scalable technological interventions, integrated policy frameworks aligned with the SDGs, and region-specific strategies to mitigate risk and improvement [43]. To address these challenges, future research must prioritize the development of adaptive, data-driven models, enhance interoperability between sectors, and promote inclusive planning processes that account for local socio-economic realities [44]. Strengthening cross-sectoral collaboration and investing in institutional capacity-building will be key to unlocking the full potential of the WEN in promoting resource efficiency, climate resilience, and sustainable development.

Competing Interests: The authors declare that they have no competing interests.

Data Availability Statement: The supported data associated with this researcher is available upon request from the corresponding author.

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