PLOS Water

REVIEW

Broadening the dimensions of the Water-Energy-Food (WEF) nexus: A narrative review

Tafadzwanashe Mabhaudhi[1,2,3*], **Nosipho Dlamini**[3,4], **Wendy Geza**[3], **Cuthbert Taguta**[3,4], **Tinashe L. Dirwai**[3,5], **Luxon Nhamo**[3,6], **Sylvester Mpandeli**[6,7], **Tendai P. Chibarabada**[3,8], **Graham P. W. Jewitt**[9], **Rob H. Slotow**[10]

1 Department of Population Health, Centre on Climate Change and Planetary Health, London School of Health & Tropical Medicine, London, United Kingdom, **2** United Nations University, Institute for Water, Environment and Health [UNU-INWEH], Richmond Hill, Ontario, Canada, **3** Discipline of Agricultural Sciences, Centre for Transformative Agricultural and Food Systems, School of Agriculture and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa, **4** Discipline of Bioresources Engineering, School of Engineering Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa, **5** International Water Management Institute [IWMI], Mount Pleasant, Harare, Zimbabwe, **6** Water Research Commission of South Africa, Lynnwood Bridge, Pretoria, South Africa, **7** Department of Environmental, Water and Earth Sciences, Tshwane University of Technology (TUT), Pretoria, South Africa, **8** Agronomy Department, Zimbabwe Sugar Association Experiment Station, Chiredzi, Zimbabwe, **9** Department of Hydrology, IHE Delft Institute for Water Education, Delft, the Netherlands, **10** Discipline of Biological Science, School of Agriculture and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa

* Tafadzwanashe.Mabhaudhi@lshtm.ac.uk

OPEN ACCESS

Citation: Mabhaudhi T, Dlamini N, Geza W, Taguta C, Dirwai TL, Nhamo L, et al. (2026) Broadening the dimensions of the Water-Energy-Food (WEF) nexus: A narrative review. PLOS Water 5(2): e0000516. https://doi.org/10.1371/journal.pwat.0000516

Editor: Alex Godoy-Faúndez, Universidad del Desarrollo, CHILE

Published: February 18, 2026

Funding: This work was funded, in part, by the Sustainable and Health Food Systems - Southern Africa (SHEFS-SA) Programme, which is supported by the Wellcome Trust [Grant No 227749/Z/23/Z]. This work was also funded, in part, by the Water Research Commission [CON2022/2023-00910]. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

The water-energy-food (WEF and its variants) nexus addresses the intricate linkages between human and natural systems to ensure sustainable management of natural resources without compromising economic, social, and environmental well-being. Despite this, the WEF nexus has been mainly approached as a focused biophysical system connecting those three dimensions. This review maps the extent to which the WEF nexus has been conceptualised and the consideration of additional dimensions linked to environmental and social outcomes. The aim is to broaden the WEF nexus concept to enhance its applicability to human, planetary, and sustainable development outcomes. Of the identified nexus frameworks, approximately 50% are sectorally unbalanced, as they centralise one or more resource node(s). Water and energy are key nexus nodes in most frameworks. The second most popular framing is water-energy-food-climate, followed by water-energy-land (WEL) and water-energy-food-land-ecosystems. In addition, the current WEF nexus approach is biased towards input-oriented conceptualisation. It fails to make explicit linkages to outcome- and impact-based dimensions, such as politics, gender, environment, planetary health and the economy. This limits its relevance and practical application in decision-making and policymaking for addressing sustainability and developmental challenges. Models and tools should be improved to be more holistic, including WEF resources and other linked resources, and should be useful for monitoring all

Competing interests: The authors have declared that no competing interests exists.

sustainability outcomes (economic, social, and environmental). We propose a conceptual broadening of the WEF nexus to a WEF+ nexus, with the "plus" representing added outcomes-based dimensions such as environment, climate, people, planet and health. This conceptual broadening balances WEF resource securities with human, planetary and sustainable development outcomes.

Introduction

Population growth, accelerated economic development, global trade, rapid urbanisation, dietary changes, migration, and cultural and technological advances exert pressure on already-depleted water, energy, and food (WEF) resources [1]. Moreover, climate change and sectoral management of the WEF sectors are aggravating the scarcity of water, energy and food, together with other drivers, including pollution, biodiversity loss, rapid urbanisation and the emergence of novel diseases [2,3]. Addressing these multidimensional and interconnected global sustainability challenges requires systems thinking and integrating coupled human and natural components across multiple dimensions to address complex and dynamic interconnections, identify sustainable solutions, and develop effective policies and strategies that promote sustainable development and environmental and human wellbeing outcomes [4].

In its conceptualisation, the water-energy-food (WEF) nexus intends to transcend sectoral management approaches, promising to promote integrated natural resource management through understanding and quantifying the synergies and trade-offs within the WEF sectors [5]. This can be used to formulate coherent policies that are a win-win for all sectors [6]. This will, in turn, improve resource-use efficiency and promote sustainable, inclusive and equitable use of resources to satisfy all demands without depleting natural resources or destroying the natural environment [7].

The WEF nexus is more than just a biophysical system of water, energy, and food, as it is also a multi-scale complex of people, institutions, infrastructure, and the physical environment [8–11]. The three resources are central to sustainable development, as they are vital to socio-ecological, socio-economic, human, and environmental well-being. Consequently, there has been a growth in frameworks and narratives seeking to broaden the WEF nexus approach to include other dimensions such as environment, health, and socio-economic outcomes, shifting the approach from resource-centric to outcome-based [12]. This has resulted in various iterations of the WEF nexus, such as WEFE (including environment/ecosystems/biodiversity) [13,14], WEFL (including land) [7,15], WEFC (including climate change) [16], and WEFH (including health) [17].

Considering the intricate interlinkages between WEF resources, their nexus, and socio-economic and environmental outcomes, it begs the question of whether there is a need to deliberately and explicitly incorporate other dimensions into the WEF nexus conceptualisation, frameworks, and tools to improve the relevance of outcomes across these dimensions. Literature shows that various iterations and nexus themes

have emerged [18,19]; hence, there is a need to map these themes to serve as a starting point on why and how the nexus can be broadened. In addition, it is necessary to identify how framings, frameworks, and tools have incorporated and addressed other social and environmental dimensions, and how they can be improved to promote purpose, adaptability, and implementation. Against this backdrop, this narrative review is aimed at: i) identifying the breadth of existing nexus framings and the extent to which socio-economic (e.g., gender, human health, livelihoods) and environmental dimensions [e.g., climate, biodiversity, ecosystems) are considered, ii) highlighting gaps to broaden the scope of the WEF nexus to address environmental, economic and social sustainability outcomes, and iii) identifying opportunities to aid the transition of the WEF nexus from the current theoretical growth stage to practical implementation and operationalisation, including for the achievement of the environmental, economic and social sustainability outcomes. The review is narrative, and it uses published literature that was not identified systematically, but that is relevant to the water-energy-food nexus and the advancement of the nexus for improved environmental, economic and social sustainability outcomes.

Definition of terms

For clarification, this study has adopted the standard definitions of terms used in WEF nexus research. As this review unpacks the applications of the WEF nexus in research, it draws on three key WEF nexus methodologies: conceptual frameworks, analytical tools, and discourse [20]. WEF nexus conceptual frameworks provide a structured conceptual representation of WEF linkages to promote coherence in policy-making and enhance sustainability, and are typically expressed as diagrams or conceptual models [21]. As an analytical tool, the WEF nexus approach systematically uses quantitative tools and/or qualitative methods to highlight and understand interactions among WEF systems [21]. Decision support tools and systems, which are commonly employed when using the WEF nexus as an analytical tool, are analytical or modelling platforms specifically designed to inform policy and management decisions across nexus dimensions [22]. As discourse, the WEF nexus approach initially facilitates framing of WEF nexus issues, i.e., WEF nexus framing, which encompasses establishing the lens or perspective, as well as setting boundaries, through which WEF nexus issues are understood [20,23]. This framing role, which also serves as a foundation for WEF nexus conceptual frameworks and analytical tools, enables the emergence of new discourses that shape perceptions and the management of WEF interactions (Keskinen et al., 2016).

This research also aims to address the socio-economic and environmental dimensions within the WEF nexus research. According to Marselle, Lindley [24], and Haahtela [25], biodiversity refers to the variety of living organisms within ecosystems, which is fundamental for sustaining WEF systems, as well as human health and wellbeing. Ecosystem services are defined as the benefits obtained by humans from the ecosystem [26]. Planetary health, which is a young, emerging holistic health field, denotes the pursuit of the highest possible standard of global health, wellbeing, and equity through addressing both the human systems (political, economic, and social) that influence humanity's future, and the Earth's natural systems that set the environmental boundaries within which human life can thrive [27].

The case for a broadened WEF nexus – a WEF+ nexus

Since the WEF nexus became prominent in 2011, debates have continued to broaden the configuration and conceptualisation beyond the three sectors of water, energy, and food resources [28,29]. While these three strategic WEF resources and sectors are sometimes presented as the main systems that form an "ultimate" nexus [28,30], there are arguments for deliberate widening to broader nexus framings and frameworks [31–35] to meet certain narratives and interests [11]. According to Wichelns [36], the arbitrary selection of WEF as the key nexus nodes fails to explicitly consider many critical variables and interactions related to soils, plant nutrients, farm chemicals, agricultural land tenure, population, labour, human capital, health, welfare/livelihoods, finance, risk, and uncertainty. From a sustainable development perspective, Qureshi [29] questions the selection of the three main WEF resource dimensions, arguing that other dimensions, such as

climate change, livelihoods, governance, and urbanisation, are equally important for consideration and inclusion in the nexus.

WEF systems and their nexus do not exist and operate in isolation or a vacuum, but rather within global economies wherein they are interconnected to other critical non-WEF systems such as climate change, the environment and human health, among others [37]. For example, geopolitical and health shocks such as conflicts and pandemics disrupt WEF systems and exacerbate WEF resource insecurity [38]. The WEF nexus is an open system supporting integration with additional components, including health, soil, land, climate, nutrients, and waste [39]. Although climate is not considered a resource system, it affects WEF resources. It intensifies their interconnections, while WEF systems impact the climate system through greenhouse gas emissions that exacerbate climate change [40,41]. Consequently, there is a growing focus on climate change, greenhouse gas emissions, and land-use changes in studies relating to the WEF nexus and the environment [42]. The application of WEF tools addressing the link between the WEF nexus and the environment primarily focuses on achieving food security, with environmental sustainability concerns receiving comparatively less attention [43]. This is paradoxical because the environment, ecosystems, biodiversity, and ecology are an irreplaceable foundation that underpins the security of WEF resources [5,28].

The State of Food Security and Nutrition in the World 2020 report defines health as a*" state of complete physical, mental and social wellbeing*" [44]. Human health is not a resource component of the WEF nexus, but a human wellbeing outcome [45] that is intrinsically connected to WEF resources through, among others, (a) access to i) clean water, ii) adequate nutritious food, and iii) reliable, clean and green energy; (b) the efficient use of WEF resources; and (c) the resilience of communities in the face of climate change [45]. Ecosystem health mediates the interconnections between WEF systems and human health [45]. Similarly, water quality is a cross-cutting nexus sub-pillar and indicator of ecosystem services, biodiversity and environmental integrity [46], and it is a key determinant of 'clean' water availability and human health [47]. On the other hand, food, nutrition and environmental integrity jointly affect human health [48].

Although water quality mediates between the WEF systems and ecosystem services and human health [49], broadening the scope of health in WEF nexus research requires thinking beyond just water quality. Firstly, there is a need to integrate more dimensions of water security, such as water availability, access, risk and variability, equity and livelihoods, and water governance [50]. More importantly, there is a significant gap in research on the energy sector's influence on the WEF and health nexus. There is a need for studies that link energy use and production to human and aquatic health, especially from an environmental pollution perspective. Other sectors interconnected with the WEF nexus and health should also be explored. For instance, rising food prices drive people into poverty, hunger and malnutrition [51]. There remains a dearth of research on the economic effects of WEF resources on human health. From a circularity perspective, the impacts of human health on population growth are another avenue in which the WEF nexus and health can be broadened, given the already-proven influence of population growth on urban development and the issues driven by urban development on planetary health [29].

The breadth of existing nexus framings and frameworks

Literature abounds with diverse nexus framings and frameworks: constructs, conceptualisations and configurations depicting nexus dimensions/pillars/nodes and interconnections, sometimes with drivers of change, indicators, inputs, outputs, and processes [52].

Nexus framings consist of the three founding nexus dimensions of water, energy and food, all or in part combined with other interconnected dimensions [53,54]. For water, energy and food dimensions, different sectoral disciplines frame them according to their preferred entry point, i.e., the energy, water and food/agriculture sectors prefer and use energy-water-food (EWF), water-energy-food (WEF), and food-energy-water (FEW) nexus, respectively [29,55], usually from an input-centric perspective (S1 Table). Several frameworks have been developed and used as conceptual models, outlines, skeletons and "organisational diagrams" to highlight, collate, explain and visualise the nexus interconnections and

problems or situations for understanding the complexity of the nexus and assisting with planning, solving and regulating these nexus sectors and resources [53,56]. These frameworks assist in bringing together and summarising nexus information and insights in a standard, logical, and hierarchical way, including system specifics such as the changes in model state, scope/boundary, how the simulated system should work, the entities that it contains, as well as the interactions, and sometimes the rules and equations that govern its behaviour [28]. Existing nexus frameworks have different centrality and focus [39,57] (S1 Table).

The central element in nexus conceptual frameworks is perceived to be highly important in prioritisation, policy development, and implementation [58]. Some key features, including the key and central nodes of 26 major nexus frameworks in the literature, are presented in the S1 Table. Nexus frameworks range from simple conceptualisations with a few elements (e.g., water-energy-food, WEF) to complex conceptualisations with multiple elements [11]. Although the nexus approach is polycentric and seeks to weigh and prioritise the multiple sectors equally [59,60], almost half of the 26 nexus frameworks are sectorally unbalanced as they centralise one or some resource node(s). However, the majority of the 26 nexus frameworks are sectorally balanced from a WEF nexus perspective. While water and energy nodes are key nexus nodes in all 26 nexus frameworks, food is not explicitly a key node in two [61,62]. Similarly, nexus frameworks are solely centred on water [5,63–65] and food [66] but none on energy. The WEF integration is the most popular nexus framing and core or central component in the 26 nexus frameworks [54,67] (Table 1).

The second most popular nexus framework is water-energy-food-climate [79,81,85], followed by water-energy-land (WEL) [61,62] and water-energy-food-land-ecosystems [83,86] (Table 1). The least popular nodal integrations in the 26 nexus frameworks include the combinations of WEF with land and minerals/materials [80], land [66], livelihoods [82] and forests [64,65]. Land, ecosystems, and climate are included in approximately 42%, 33%, and 20% of the 26 nexus frameworks, respectively, while livelihoods are explicitly included in two nexus frameworks [57,59,82]. Only one nexus framework includes explicit nodes for forests [64,65], minerals/materials [80,87,88], and capital and labour [74,75]. The second most popular central components in the 26 nexus frameworks are ecosystems, water, climate, water-energy-land and people (Table 1). Water-centric nexus frameworks focus on water security [64,65] and available water resources [5], ecosystems-centric nexus frameworks focus on resources [76,77] and ecosystem services [78,86], people-centric frameworks focus on livelihoods [57,59,82], stakeholder dialogue [74] and humankind [52,58,60]. Nexus frameworks centred on climate focus on climate change [79] and adaptation [85]. The least popular central components in the 26 nexus frameworks are ecosystems-resources-livelihoods-land [57,59], ecosystems-resources [78], resources [84], WEF-climate [89], food [66], and WEF-land-minerals/materials [80,87,88] (Table 1). Thus, most existing nexus frameworks focus more on biophysical resource dimensions [65%] than the planet [46%], socio-economic and sociopolitical, i.e., people [15%], while few have specific linkages to Sustainable Development Goals (SDGs), targets and indicators [3,53,57,90]. This centrality of biophysical resources in existing nexus frameworks renders them insufficiently integrated and cross-sectoral to improve the integration and coordination of resource-sector policies, create and strengthen synergies, and manage trade-offs across WEF sectors, all key elements of the sustainable development agenda [21].

Placing people and the planet at the centre of the WEF nexus

The founding guiding principles for the WEF nexus approach prioritise sustainable development pillars, namely: (a) the planet through investing in sustaining ecosystem services; (b) prosperity through creating more with less; and (c) people through i) accelerating access, and ii) integrating the poorest [5]. People are the principal drivers within the WEF system through production and growing consumption of WEF resources, and influence on governance and policies that determine how the environment and interconnected resources are managed [60]. People and the planet are core themes and pillars of the sustainable development agenda and its goals and targets [91]. There is a need to base the nexus on people and their basic human rights [92].

Table 1. Nexus framings, central elements and main/key nexus pillars in 26 major WEF nexus frameworks.

Nexus Framing *(Either Explicitly Stated or Presented)*	Central Element(s)	Main/Key Nexus Pillars *(Explicit Interconnections)*
Water-Energy-Food [5,52,59,63,68–78]	Water-Energy-Food [68–73]	Water [5,52,59,61–66,68–86]
Water-Energy-Food-Climate [79,81,85]	Climate [79,85]	Energy [5,52,59,61–66,68–86]
Water-Energy-Food-Land- Minerals/Materials [80]	Water [5,63–65]	Food [5,52,59,61,63–66,68–86]
Water-Energy-Land [61,62]	Water-Energy-Food-Land-Minerals/Materials [80]	Climate [52,78,79,81,85]
Water-Energy-Food-Land [66]	Water-Energy-Land [61,62]	Ecosystems [52,59,71,76–78,83,86]
Water-Energy-Food-Livelihoods [82]	Food [66]	Land [52,59,61,62,66,74–77,80,83,86]
Water-Energy-Food-Land-Ecosystems [83,86]	People [52,74,75]	Minerals/Materials [80]
Water-Energy-Food-Resources [84]	Water-Energy-Food-Climate [81]	Capital [74,75]
Water-Energy-Food-Forests [64,65]	Livelihoods [82]	Labour [74,75]
	Ecosystems [76,77,83,86]	Resources [59,74,75,78,84]
	Resources [84]	People [52,74,75,78]
	Ecosystems-Resources [78]	Livelihoods [59,82]
	Ecosystems-Resources-Livelihoods-Land [59]	Forests [64,65]
		Income [78]
		Environment [52]

https://doi.org/10.1371/journal.pwat.0000516.t001

While it is justifiable that one of the main objectives is to improve resource management and increase efficiency and access, this perspective risks making the WEF nexus input-centric rather than outcomes-based [93]. In this manner, dynamic interactions between society, politics [power relations], economics, technology, and nature are poorly and insufficiently represented and understood, including ownership, property rights, and tenure [11,94]. Failure to embed gender equality and social inclusion considerations, through the recognition and representation of diverse individuals in WEF nexus debates, may lead to an inequitable redistribution of resources. These shortcomings are evident in the relatively abundant existing WEF nexus frameworks, which, in the majority, explicitly include and centralise resource dimensions such as water-energy-food, water-energy-land, and water [5, 61–63] and food [64], but are silent on people and planet dimensions. For example, out of the 26 major nexus frameworks we reviewed, about 65% are centred on biophysical resources, while about a third and a tenth are centred on the planet and people, respectively. A South African study established quantitative relationships among WEF sectors, illustrated sector performance relative to others, and highlighted priority areas for intervention [95]. The study acknowledged that it considered only indicators related to the security of water, energy, and food resources. It fell short of addressing people-related aspects, especially given the high inequality

in South Africa [96]. Similarly, a water-, economy-, and techno-centric hydro-development in Ethiopia's Upper Blue Nile successfully increased food and energy production but led to multiple undesirable socioeconomic and cultural effects on local populations and to the deterioration of wetland and forest ecosystems in the area [31]. As Biggs et al. [82] note, existing nexus frameworks have failed to explicitly or adequately incorporate sustainable livelihoods perspectives, which is counterintuitive and counterproductive given the key role of livelihoods in achieving sustainable development. Among the few WEF nexus frameworks that consider people, they do so through humanity [52,60,97], livelihoods [57,59,82] and stakeholder dialogue [74,75].

To bridge the identified gaps, WEF nexus frameworks should focus on people and planet dimensions, including gender, human, and environmental wellbeing [98]. Where these are implied or embedded as constraints or other externalities [28,30] or external factors [63] or drivers of change [99]. The people and planet dimensions should be made explicit to accentuate their interconnections, including inputs, processes, and outputs in the nexus matrix. Müller-Mahn, Gebreyes [31] call for the broadening of nexus perspectives beyond systemic WEF interconnections to i) better acknowledge social complexities in local contexts, ii) understand the political construction of scarcity, and iii) combine different knowledge at the science-practice interface. Qureshi [29] argues that people should be the primary focus in the WEF nexus because population growth drives challenges to sustainable development, including climate change and environmental concerns. Biggs and Boruff [100] addressed the need for explicit inclusion and centralisation of livelihoods through integration with the WEF nexus within an environmental livelihood security framework.

On the other hand, Beisheim [32] emphasizes that while access to water, food and energy for all must be guaranteed, the nexus must be broadened and widened systemically by integrating planetary boundaries [33,34]. Centralising ecosystem services [regulating, provisioning] in the nexus emphasises and facilitates prioritising the key support functions ecosystems provide for WEF systems [28]. Explicitly including biodiversity in the nexus approach can inform sustainability transitions and increase stakeholder interest in conservation and sustainable management of natural resources towards reversing biodiversity loss [101]. Melo, Parry [102] advocate for 'forest security' to form a fourth, foundational dimension of a novel WEF and forest security nexus framework, given that forest and landscape restoration is a promising strategy for improving WEF securities [102].

Inclusion and accentuation of the planetary dimension in the WEF nexus expands and harmonises the mutual interlinkages among WEF systems to the entire social-ecological systems for the acknowledgement of social-ecological processes that dynamically interact with the WEF nexus [39]. Explicit accentuation and centralisation of people and planet outcome dimensions humanise WEF nexus dialogues [45]. Such people- and planet-centred frameworks add value and purpose to the application of the WEF+ nexus approach across various cases, regions, and scales [103] by translating the nexus into a people-centric and outcome-based approach [104] that builds transformational pathways towards sustainability through the integration of ecological integrity, social equality and security, and human rights and wellbeing [98]. Prioritising people in communities and government as principal actors can potentially strengthen governance of the WEF nexus and amplify stakeholder participation and agency [105]. Policies, governance structures, and finance models should create an environment that enables gender transformation by including women as participants and integrating gender issues into all WEF resource programs, policy conceptualisation, development, implementation, and evaluation.

Developing tools to support a broadened WEF nexus

A WEF tool (model or application) is an intellectual construct of relationships, including mathematical ones, that capture, simplify and represent the reality of WEF spatial and/or temporal dynamics and feedback [106]. Such tools perform integrated nexus assessments through quantification, analysis and visualisation of WEF interconnections [21]. At least 46 nexus tools have been developed worldwide since 2009 [106]. Although nexus framings and frameworks have gradually broadened, nexus tools have remained relatively narrow, and the development of integrated, cross-sectoral, comprehensive quantitative or mixed quantitative/qualitative nexus tools lags [53,107]. Similar to the existing nexus framings and

frameworks, some of which are used to conceptualise WEF nexus tools, the nexus tools tend to be more quantitative than qualitative. Nexus tools have remained in the biophysical and technical realms [14,108] while excluding outcome- and impact-based dimensions such as socioeconomics, politics, gender, environment, ecosystems, human health, economy and livelihoods [29,88]. For example, a review of 46 WEF nexus tools [106] showed that a minority explicitly include non-WEF dimensions of technology, environment, and economics [109–111], land and climate [112–114], and ecosystems and socioeconomics [115,116]. The lack of nexus frameworks and tools with a local governance perspective detaches them from the reality of challenges and implementation, and disconnects the nexus concept from the decision-making and policymaking processes [103].

While there is neither a one-size-fits-all nexus tool nor a single cookbook method for modelling the nexus [28,107,117]. There is room to improve the capabilities of existing WEF nexus tools, mainly by broadening their scope of dimensions and methods. This would include promoting open access to broadened WEF nexus tools in user-friendly formats to increase their application and improve nexus-friendly policies and decisions [118]. The robustness and utility of such tools can be enhanced by integrating environment and development scenario planning to explore the uncertain future supply and use of, and interconnections between, resources [5,53].

Beyond the input- and resource-focused WEF dimensions, incorporating outcome- and impact-based dimensions in WEF nexus tools enables them to centralise people and planet in the nexus approach and reflect the dynamic interactions between society, technology, and nature [14,119]. Integrating socio-economic, socio-political, biophysical, and policy processes into nexus tools would make them more applicable to the real world, while aligning and integrating them with the SDGs, targets, and indicators would accelerate SDG achievement [39,103]. Improved representation of climate interactions in nexus tools at all scales facilitates evidence-based integrated climate action that optimises synergies and co-benefits and minimises maladaptation [120]. This enhancement and broadening of WEF nexus tools can be achieved through cooperation in multi-model frameworks across disciplines, for integrated assessments to make explicit and not implied [e.g., constraints or other externalities] expression of environment/ecosystems, sustainable resource use, socio-politics, equality, human development/wellbeing and governance [5,53]. Integrating qualitative analysis, quantitative modelling, and indigenous and traditional/local ecological knowledge into nexus tools promotes mixed-method research designs and interdisciplinarity that overcome the limitations of disciplinary silos and modelling-based quantitative approaches, facilitating adaptive integrated governance and management processes [11,31,53].

From a methodological perspective, Hejnowicz and Thorn [11] proposed expanding WEF nexus research through transdisciplinary plural methods and community engagement. The continued engagement of stakeholders who live (e.g., communities) and work [e.g., government] in the systems builds relationships, trust and a shared understanding while strengthening methods and processes with increased chances of validation, adoption and implementation of outputs for adapting to alternative states and futures of WEF systems [105,121]. In the same vein, Calder and Grady [122] emphasise the urgent need for enhanced quantitative WEF and health models to address future pandemics from an integrated nexus perspective. Similarly, Slorach and Jeswani [123] proposed a methodology for guiding the interpretation of the environmental impacts of products, technologies, and human activities within the WEF-health nexus. Such improved WEF nexus tools that better represent heterogeneity, policy instruments, and scales would respond to the needs of decision-making, policymaking, and sustainable development [124,125]. While broadening the inputs, processes and outputs in nexus tools greatly increases the number of cross-sectoral interactions and may increase the complexity of nexus tools, balancing the trade-off between simplicity and complexity is a matter of the scale, scope and objective of analysis [11,53]. Thus, broadening the nexus in methods and tools can benefit from a systems approach that seeks to dissect the complexity of interconnected contemporary challenges and develop contextualised and integrated solutions [126].

Combining multiple factors and outcomes increases computational effort and the difficulty of the solution. The field of simulation and modelling is undergoing significant transformations, driven by advancements in technology and increasing computational power. The integration of artificial intelligence (AI) and machine learning (ML) into simulation and modelling

tools now makes it possible to analyse and optimise complex systems [127]. With modern cyber threats on the rise, including in WEF-related systems, a robust, scalable, and reliable solution for securing Internet of Things (IoT) networks, ensuring effective defence against evolving cyber threats has also been developed [128].

Discussion

Ongoing debates question the need and means for broadening and deepening the conceptualisation of the nexus beyond WEF resources [29,36]. While some treat WEF resources as the ultimate nexus wherein other relevant dimensions can be implicitly and vaguely included as external factors, externalities, constraints, or drivers of change [63,99], some argue for explicit inclusion of additional dimensions and their interconnections in nexus configurations and methods [11,31,32,35]. Although WEF nexus framings and frameworks appear relatively abundant, they are diverse and evolving, broadening across multiple dimensions. Still, the inclusion of critical resource, non-resource, people and planetary dimensions related to impact and human wellbeing outcomes in the WEF nexus is in its infancy, including climate, land, biodiversity, soil, ecosystems, environment, human health, socioeconomics, governance, and the SDGs [11,53]. However, this evolution towards a broader WEF nexus is slower in WEF nexus tools, with a relatively narrow set of dimensions, than in nexus framings and frameworks [106]. In addition, the scope of existing WEF nexus framings, frameworks, and tools tends to be narrower than that of the SDG framework. Similarly, existing WEF nexus tools tend to be technocentric and quantitative.

Centrality and prioritisation are unbalanced in WEF nexus framings, frameworks, and tools, with a tendency towards biophysical resources rather than social, livelihood, environmental, and political dimensions. Thus, people and planet dimensions are inadequately considered in WEF nexus conceptualisations. This may contribute to detachment from reality, promoting siloes, misrepresentation, poor conceptualisation, misplaced priorities, mismatched guiding principles, slow adoption and low relevance and utility of the WEF nexus approach in addressing contemporary challenges and human wellbeing outcomes, including inequality, livelihoods and sustainable development. While acknowledging their irreplaceable value in sustainable development, we echo that WEF resources and their inherent interconnections are systems/sub-systems within larger interconnected systems, and advocate for integrative broadening and widening of the WEF nexus, hereon referred to as the WEF+ nexus, as guided by context to deliberately and explicitly include other resource, non-resource, people and planetary dimensions. Preferably, such broadening needs to centralise and prioritise the people and planet, as guided by the founding principles of the WEF+ nexus approach [5,92].

Challenges and opportunities

Broadening the WEF+ nexus comes with challenges and opportunities, and its attainment requires, among others, an enabling environment consisting of governance, technology, innovation, knowledge, and finance [11]. However, as outlined in Fig 1's red reinforcing loop 1 (R1), the gaps in some critical enablers, including broadened WEF nexus tools and frameworks, governance, capacity/knowledge, economics, and finance, continue to hamper the nexus approach's implementation and operationalisation, as well as investments (red R1 in Fig 1) [11,129]. Thus, in translating the WEF+ nexus approach from theory to practice, governance issues such as siloed legal structures, inadequate institutional coordination, weak technological infrastructure and capacity gaps that stifle the development and application of hybrid and linked rules, procedures and processes across the sectors will have to be comprehensively addressed [130]. Excluding the agency of the people as principal actors in WEF systems leads to an incomplete representation of WEF interactions and trajectories of change [105].

To align investments with the WEF+ nexus, circular economy planning and projects that optimise water, energy, and land resources, reducing waste and enhancing productivity, need to be considered [6]. Initiatives that provide cross-benefits across the water, energy, and food sectors are also central to the WEF+ nexus approach and should be considered because they create and strengthen synergies, including system productivity and efficiencies, economies of scale, and cross-sectoral buy-in (blue R2 and stock and flow diagram in Fig 1) [124]. A notable example is

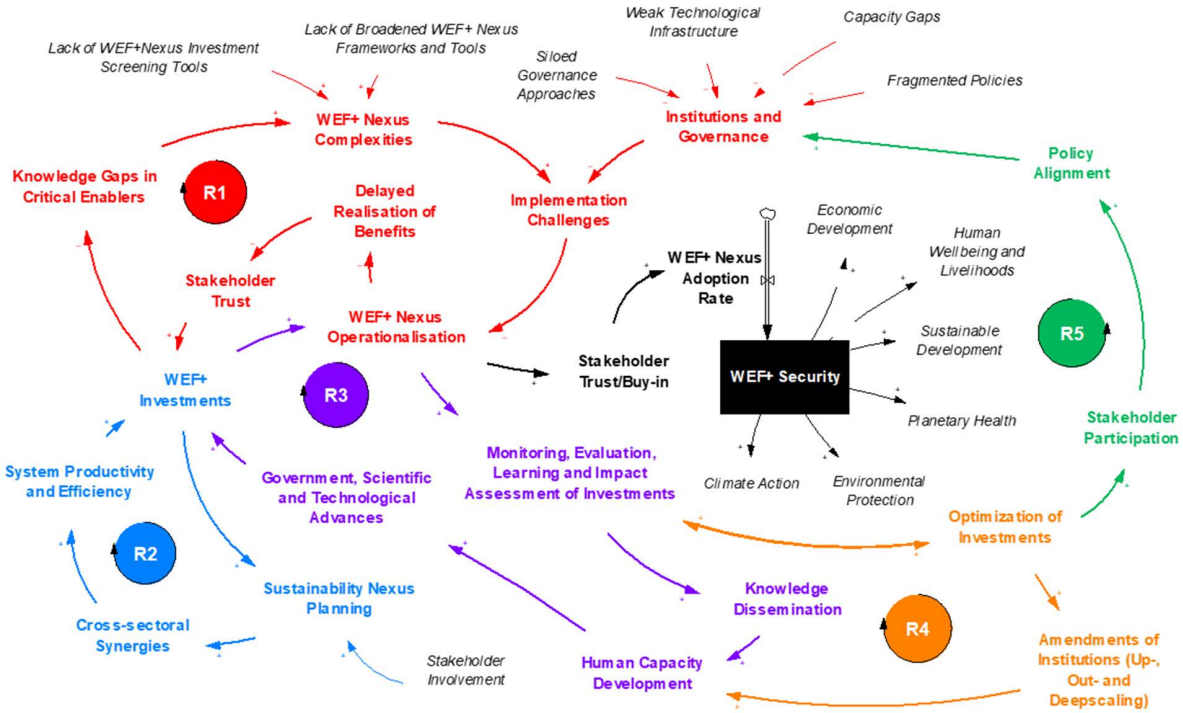

Fig 1. Causal loop and stock-flow diagram of challenges, opportunities and outcomes relating to broadening the WEF+ nexus.

https://doi.org/10.1371/journal.pwat.0000516.g001

hydropower development in parallel with smart irrigation technologies, which decreases agriculture's energy and surface water use, improves agricultural water productivity and access, and increases river flow to downstream users [131]. Ecosystem-based adaptation (EbA) and nature-based solutions (NbS) can simultaneously help achieve climate and biodiversity goals while mitigating duplication of efforts and inefficient utilisation of limited funds [132]. Co-locating solar photovoltaic panels and crops/livestock in agrivoltaics (or agrophotovoltaics), or floating solar photovoltaic panels on surface water bodies, potentially accrue land, water, energy and food synergies and co-benefits [133]. WEF+ nexus projects and investments must also ensure holistic consideration of their implications for promoting long-term sustainable development across all sectors. Also, referring to the R2 in Fig 1, all relevant stakeholders, including local communities and government workers, should actively participate in sustainable nexus planning to capture their agency, foster collaboration, and address potential conflicts [130]. It is worth noting that business models that consider the WEF+ nexus and the circular economy will have a competitive advantage in the near future, especially in international markets, as international standards for promoting sustainability, protecting biodiversity, conserving water and soil, reducing emissions, preventing deforestation, and mitigating climate change are becoming stricter. These standards are increasingly influencing supply and demand [134]. However, there is a reported lack of viable, scalable business models, though the WEF nexus approach can be used to design and screen them from an integrated nexus perspective [129].

Governance is a central enabler of current and future nexus systems [11], and a key challenge to integrated nexus programs and projects is fragmented policies and the silo mentality of institutional and private organisations, which hinder cross-sectoral coordination and cooperation [53,135]. Similarly, inadequate attention has been paid to governance as a dimension of the WEF nexus thinking [136,137]. Siloed and misaligned governance approaches are partly blamed for the slow progress, retrogressions and temporal and spatial variations in the achievement of sustainable development [138]. The institutions and policies of the nexus sectors should be harmonised to achieve the WEF nexus's principal objective

of promoting integrated resource management. Regarding supply and demand management, there is still an imbalance and duplication of effort among the sectors due to the lack of vertical and horizontal linkages between sectoral institutions, which is unsustainable [139]. Thus, there is a need for integration and harmonisation in governance for policy and institutional harmonisation towards coordinated, balanced strategies and collaborative planning and implementation of the WEF+ nexus that can contribute to inclusive development and socio-economic security [140].

The WEF+ nexus approach faces challenges related to inadequate capacities to regulate/supervise and manage integrated implementation and operationalisation [129]. One approach to deep-scale the WEF+ nexus is to incorporate it into the curriculum of higher and tertiary learning institutions (purple R3 in Fig 1). Institutions involved in the implementation of WEF+ nexus-based educational training should be the source of disseminating knowledge, thus playing an important role in up- and out-scaling the WEF+ nexus, as well as participating in the generation of new and up-to-date knowledge to provide the labour market with WEF+ nexus specialists who understand the holistic approach required to solve problems in those sectors [141].

Implementing these transformations across governance, technology, innovation, and human capacity to create an enabling environment for implementing a WEF+ nexus requires significant financial investments [11,142]. There is a belief that the costs of nexus approaches may be generally higher than those of individual silo approaches [53]. However, there is insufficient quantitative evidence to substantiate these claims of additional expertise, time, coordination, and financial resources required [53,143]. Some recent studies have shown that nexus-based investment planning, for example, in the shared transboundary Zambezi River Basin, accrues more intersectoral synergies and identifies relevant trade-offs, risks, uncertainties and externalities than traditional silo sector-centred approaches that under- or overestimate the value of investments [144]. By cooperating in nexus-based multi-sectoral collaborative mechanisms compared to country-focused unilateral approaches in sustainable development investments, countries in the Indus basin countries could accrue multiple biophysical and socioeconomic gains for all including improved water, energy and food security, improved sanitation, reduced costs for development, and reduced pollution (air, land), greenhouse (GHG) emissions, irrigation water intensity (ground, surface), and river depletion [145]. A recent report highlights that an integrated water-energy-food-ecosystem (WEFE) nexus approach to planning water infrastructure multiplied investment returns in Africa, including improved economic benefits, climate resilience, social inclusion, and environmental gains [146]. This was mainly through (i) increased food production and economic returns and reduced conflict among riparian states in the Niger River Basin; (ii) reduced drought vulnerability and flood damage costs [Kenya]; (iii) optimized ecosystem services around major lakes [Upper White Nile Basin]; (iv) job creation, women participation and increased household incomes [urban Senegal]; (v) provision of clean energy for domestic and productive uses [rural Ethiopia]; (vi) water savings, reduced water contamination, treated wastewater irrigation and job creation [Olifants River, South Africa]; and (vii) faster project approvals, mobilization of blended financing, and community engagement [Zambia], compared to conventional single-sector approaches [146]. However, investments and financing instruments for nexus-oriented sustainable resource management projects and initiatives have largely remained fragmented, reactive to emergencies, and complex, making it difficult to provide integrated solutions and cross-sectoral funding streams, for example, in Africa and the Middle East and North Africa Region (MENA) [129,143].

The WEF+ nexus presents opportunities for practitioners and policy- and decision-makers to plan, implement and monitor cross-sectoral investment, harmonize cross-sectoral policies, align strategies across sectors and incentives, and optimise investment portfolios for addressing multiple mutually dependent global resource security concerns in complex socio-environmental systems (orange R4 and green R5 in Fig 1) [53,143]. For example, planning joint WEF+ investments through the nexus approach can systematically analyse interactions between the sectors and sustainable development pillars to reveal and inform the necessary degree of integration [11]. Similarly, a WEF+ nexus approach to investment planning can reveal approaches and business models that consider and utilise interconnections to respond to pressing needs, simultaneously increasing economic productive capacities, improving socio-economic welfare, sustaining the use

of resources, and enhancing local communities' resilience [147]. Other key investment-related benefits of the WEF+ nexus approach include considering multi-tiered institutions, multistakeholder platforms [including public-private partnerships], economically rational decision-making, cost recovery, minimising investment risk, avoiding conflicts, and maximising economic returns [148].

A key challenge is the lack of integrated, systematic, cross-sectoral frameworks and analytical and decision-support tools to inform evidence-based facilitation and screening of investments from a WEF+ nexus perspective [147,148]. Thus, comprehensive tools are required to facilitate the development of policies that optimise all synergies across the nexus sectors and holistically identify investment opportunities in these areas. As the WEF+ nexus is inherently complex, broadening nexus framings, frameworks and tools is perceived to add complexity, which will require advanced methods and techniques, including for data collection, assessment, and integration [11,53]. Similarly, data requirements for nexus assessments may multiply due to increased interconnections, data gaps, and inconsistencies, while new indicators, metrics, and indices may need to be developed [6,54]. Scale heterogeneity and mismatches across sectors, dimensions, pillars, and sub-pillars may present challenges to the WEF+ nexus [6,54].

Recommendations

An ideal starting point for broadening the WEF+ nexus is to expand the dimensions and sub-pillars in nexus framings, frameworks, and tools. These tools provide a basis and foundation for WEF+ nexus understanding, planning, assessment and implementation [52]. In this regard, all contextually critical resource and non-resource dimensions, sub-pillars, and interconnections should be deliberately made explicit and integrated into nexus framings, frameworks, and tools, while ensuring that the latter three centralise and prioritise impact- and outcome-focused dimensions, such as those for people (e.g., gender) and the planet. Here, an open-minded approach is recommended to reconfigure the WEF+ nexus by first placing people and planet at the centre, building on governance and transdisciplinarity, and then adding dimensions in an iterative, context-specific systems/sub-systems manner. People should be central in the WEF nexus as producers and consumers of resources, and custodians of WEF governance and policies [60]. The dimensions to be carefully and contextually considered for explicit inclusion in expanding the resource and non-resource scope of the WEF+ nexus include climate, land, biodiversity, soil, ecosystems, environment, human health, socio-economics, governance and their sub-pillars. Such a cross-sectoral polycentric nexus approach has the potential to distinguish itself from sector-based approaches and succeed. The nexus approach addresses the limitations of other predecessor integrated approaches, such as the water-centric Integrated Water Resources Management (IWRM), by treating all sectors equally [149] and emphasising the role of water as a connector in a system of sectors, interconnections and interdependencies whose enhanced understanding and integrated management can improve outcomes for the people and planet [133,150].

A holistic WEF+ approach can navigate, integrate, and balance multiple objectives, including climate action, environmental protection, economic development, human wellbeing, and livelihoods, through the coordination, integration, and harmonisation of resource-sectoral policies and institutions that create and strengthen synergies and minimise conflicts, risks, and trade-offs [21,54]. Broadening the WEF+ nexus will improve its relevance, applicability, and value for increased adoption, implementation, and purpose in decision-making and policymaking, while prioritising people and planet will reset it to its original guiding principles, including accelerating access and integrating the poorest [5]. The inclusion of dimensions related to drivers of change, including environmental and social, in WEF+ nexus tools will enhance their ability to explore integrated scenarios for planning robust and resilient WEF+ systems [5]. Incorporating integrated mixed qualitative and quantitative methods can break silos and improve institutional coordination. Consideration of environmental justice in broadening the WEF nexus can contribute to environmental livelihood security at multiple spatial scales and institutional levels to achieve equitable and inclusive sustainable development targets, including for marginalised individuals and communities [82].

There is a need to align the WEF+ nexus with global, regional, and national development frameworks. Explicit integrative inclusion of the climate, land, and biodiversity dimensions in WEF+ nexus framings, frameworks and tools can synergistically catalyse and advance the implementation of national biodiversity and climate commitments and strategies [132]. These include the frameworks of the United Nations Framework Convention on Climate Change (UNFCCC), United Nations Convention on Biological Diversity (UNCBD), and United Nations Convention to Combat Desertification (UNCCD), including the Nationally Determined Contributions (NDCs), National Biodiversity Strategies and Action Plans (NBSAPs) and Long-Term Low Emission Development Strategy (LT-LEDS) [132,135]. Deliberate and explicit inclusion of the health dimension in the nexus may facilitate the harmonisation of the WEF nexus with the One Health framework towards improved and balanced collective health for people, animals and ecosystems [39]. Aligning the WEF+ nexus to the 2030 Agenda for Sustainable Development by i) prioritising people and planet and ii) integrating nexus framings, frameworks, and tools (e.g., indicators) with SDGs, targets, and indicators will likely facilitate balancing synergies, co-benefits and trade-offs in the multiple dimensions and pillars of SD towards the accelerated simultaneous achievement of the multiple SDGs [35,53].

Conclusion

The Water-Energy-Food Plus (WEF+) nexus approach aims to systematically manage unsustainable competition for limited resources across multiple sectors by addressing the complex synergies [benefits and co-benefits] and trade-offs [damages and conflicting objectives] that arise between different development pathways pursued under diverse values and interests. Although intricate interlinkages exist between WEF resources, their nexus, and socio-economic and environmental outcomes, the latter two, along with other critical dimensions, are generally missing or implicit rather than explicit in existing nexus frameworks and tools. Over time, the concept of the WEF nexus has evolved, resulting in multiple interpretations and frameworks. Recent efforts have expanded the nexus perspective to include additional pillars, such as climate change, land, environment, economy, and health, reflecting a broader, more integrated approach.

This diversity in nexus framings highlights the approach's ongoing evolution and underscores the interdependencies among WEF sectors. The adaptability of the nexus framework enables tailoring to varying scopes, goals, and stakeholder priorities, making it relevant to both people and the planet in the context of sustainable development. Ultimately, the WEF nexus demonstrates significant utility, versatility, and flexibility, effectively supporting investment screening and decision-making across various contexts and objectives.

We propose broadening the current WEF nexus framing to a WEF+ nexus, with people and planet at the centre. This would allow for the deliberate and explicit incorporation of other dimensions into the WEF+ nexus, including framings, frameworks, and tools, to improve clarity around outcomes on dimensions such as environment, human health, and gender, without the need to create new acronyms at each instance. This broadening must be guided by the context, including location, scope and objectives. An entry point for such broadening is to frame the WEF nexus conceptually, as well as to develop frameworks and tools to address the unbalanced, limited dimensional scope, shifting priorities from biophysical resource dimensions to people and planet dimensions. The planet, people, and their crucial roles should be centralised in the WEF nexus, including people's agency and governance aspects, such as actors, institutions, and actions within water, energy, and food systems. Such contextual broadening of the WEF+ nexus ensures a representative conceptualisation, relevance in implementation, responsiveness to policy- and decision-making needs, and the addressing of contemporary challenges such as climate action, environmental protection, improved livelihoods, and sustainable development in an integrated and balanced manner. This WEF+ nexus and its implementation and operationalisation can only be achieved in an environment that enables governance, finance, technology, and capacity. Thus, more intentional institutional and policy linkages are required to avoid trade-offs, as are increased, jointly planned investments and capacity-building to translate the WEF+ nexus theory into practice.

Supporting information

S1 Table. The 26 major nexus frameworks in literature.
(XLSX)

Author contributions

Conceptualization: Tafadzwanashe Mabhaudhi, Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Tendai P. Chibarabada.

Data curation: Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Tendai P. Chibarabada.

Formal analysis: Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Tendai P. Chibarabada.

Funding acquisition: Tafadzwanashe Mabhaudhi, Luxon Nhamo, Sylvester Mpandeli, Rob H Slotow.

Investigation: Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Tendai P. Chibarabada.

Methodology: Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Tendai P. Chibarabada.

Resources: Tafadzwanashe Mabhaudhi, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Rob H Slotow.

Supervision: Tafadzwanashe Mabhaudhi, Graham P W Jewitt, Rob H Slotow.

Visualization: Nosipho Dlamini.

Writing – original draft: Nosipho Dlamini, Wendy Geza, Cuthbert Taguta, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Tendai P. Chibarabada.

Writing – review & editing: Tafadzwanashe Mabhaudhi, Tinashe L. Dirwai, Luxon Nhamo, Sylvester Mpandeli, Graham P W Jewitt, Rob H Slotow.

References

1. Mahlknecht J, González-Bravo R, Loge FJ. Water-energy-food security: A Nexus perspective of the current situation in Latin America and the Caribbean. Energy. 2020;194:116824. https://doi.org/10.1016/j.energy.2019.116824
2. Expósito A, Beier F, Berbel J. Hydro-economic modelling for water-policy assessment under climate change at a river basin scale: A review. Water. 2020;12(6):1559. https://doi.org/10.3390/w12061559
3. Mabhaudhi T, Nhamo L, Chibarabada TP, Mabaya G, Mpandeli S, Liphadzi S, et al. Assessing Progress towards Sustainable Development Goals through Nexus Planning. Water. 2021;13(9):1321. https://doi.org/10.3390/w13091321
4. Javan K, Altaee A, BaniHashemi S, Darestani M, Zhou J, Pignatta G. A review of interconnected challenges in the water-energy-food nexus: Urban pollution perspective towards sustainable development. Sci Total Environ. 2024;912:169319. https://doi.org/10.1016/j.scitotenv.2023.169319 PMID: 38110094
5. Hoff H. Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm, Sweden: Stockholm Environment Institute (SEI). 2011.
6. Naidoo D, Nhamo L, Mpandeli S, Sobratee N, Senzanje A, Liphadzi S, et al. Operationalising the water-energy-food nexus through the theory of change. Renew Sustain Energy Rev. 2021;149:111416. https://doi.org/10.1016/j.rser.2021.111416 PMID: 37693280
7. Wicaksono A, Jeong G, Kang D. Water, energy, and food nexus: review of global implementation and simulation model development. Water Policy. 2017;19(3):440–62. https://doi.org/10.2166/wp.2017.214
8. Wang X-C, Jiang P, Yang L, Fan YV, Klemeš JJ, Wang Y. Extended water-energy nexus contribution to environmentally-related sustainable development goals. Renewable and Sustainable Energy Reviews. 2021;150:111485. https://doi.org/10.1016/j.rser.2021.111485
9. Ansari A, Wuryandani S, Pranesti A, Telaumbanua M, Ngadisih, Hardiansyah MY, et al. Optimizing water-energy-food nexus: achieving economic prosperity and environmental sustainability in agriculture. Front Sustain Food Syst. 2023;7. https://doi.org/10.3389/fsufs.2023.1207197

10. Lalawmpuii, Rai PK. Role of water-energy-food nexus in environmental management and climate action. Energy Nexus. 2023;11:100230. https://doi.org/10.1016/j.nexus.2023.100230
11. Hejnowicz AP, Thorn JPR, Giraudo ME, Sallach JB, Hartley SE, Grugel J, et al. Appraising the water-energy-food nexus from a sustainable development perspective: a maturing paradigm?. Earth's Future. 2022;10(12):e2021EF002622. https://doi.org/10.1029/2021EF002622
12. Nhamo L, Mpandeli S, Liphadzi S, Mabhaudhi T. Catalyzing sustainable development goals through the water-energy-food nexus. iScience. 2025;28(2):111902. https://doi.org/10.1016/j.isci.2025.111902 PMID: 39995865
13. Canessa C, Vavvos A, Triliva S, Kafkalas I, Vrachioli M, Sauer J. Implementing a combined Delphi and Focus Group qualitative methodology in Nexus research designs-The case of the WEFE Nexus in Apokoronas, Crete. PLoS One. 2022;17(7):e0271443. https://doi.org/10.1371/journal.pone.0271443 PMID: 35834515
14. Jalonen R, Zaremba H, Petesch P, Elias M, Estrada-Carmona N, Tsvuura S, et al. Gender equity and social inclusion in the water-energy-food-ecosystems (WEFE) nexus: Frameworks and tools for moving from resource-centric to people-centric WEFE nexus approaches. Rome, Italy: Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT); 2022. 28 p.
15. Wolde Z, Wei W, Ketema H, Yirsaw E, Temesegn H. Indicators of Land, Water, Energy and Food (LWEF) Nexus Resource Drivers: A Perspective on Environmental Degradation in the Gidabo Watershed, Southern Ethiopia. Int J Environ Res Public Health. 2021;18(10):5181. https://doi.org/10.3390/ijerph18105181 PMID: 34068204
16. Grobicki A. Water-food-energy-climate: strengthening the weak links in the Nexus. In: Dodds F, Bartram J, editors. The Water, Food, Energy and Climate Nexus: Challenges and an agenda for action. 1st edition. London, United Kingdom: Routledge; 2016. p. 127–37.
17. Bwire C, Mohan G, Karthe D, Caucci S, Pu J. A Systematic Review of Methodological Tools for Evaluating the Water, Energy, Food, and One Health Nexus in Transboundary Water Basins. Environ Manage. 2023;72(3):598–613. https://doi.org/10.1007/s00267-023-01841-w PMID: 37269420
18. Brouwer F, Caucci S, Karthe D, Kirschke S, Madani K, Mueller A, et al. Erratum: Advancing the resource nexus concept for research and practice. SNF. 2024;31(1–4):67–67. https://doi.org/10.1007/s00550-024-00536-y
19. Mohtar RH. The WEF Nexus Journey. Front Sustain Food Syst. 2022;6.
20. Keskinen M, Guillaume J, Kattelus M, Porkka M, Räsänen T, Varis O. The Water-Energy-Food Nexus and the Transboundary Context: Insights from Large Asian Rivers. Water. 2016;8(5):193. https://doi.org/10.3390/w8050193
21. Albrecht TR, Crootof A, Scott CA. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environ Res Lett. 2018;13(4):043002. https://doi.org/10.1088/1748-9326/aaa9c6
22. Ghodsvali M, Dane G, de Vries B. An integrated decision support system for the urban food-water-energy nexus: Methodology, modification, and model formulation. Comput Environ Urban Syst. 2023;100:101940. https://doi.org/10.1016/j.compenvurbsys.2023.101940
23. Hoolohan C, Larkin A, McLachlan C, Falconer R, Soutar I, Suckling J, et al. Engaging stakeholders in research to address water-energy-food (WEF) nexus challenges. Sustain Sci. 2018;13(5):1415–26. https://doi.org/10.1007/s11625-018-0552-7 PMID: 30220918
24. Marselle MR, Lindley SJ, Cook PA, Bonn A. Biodiversity and Health in the Urban Environment. Curr Environ Health Rep. 2021;8(2):146–56. https://doi.org/10.1007/s40572-021-00313-9 PMID: 33982150
25. Haahtela T. A biodiversity hypothesis. Allergy. 2019;74(8):1445–56. https://doi.org/10.1111/all.13763 PMID: 30835837
26. Karabulut A, Egoh BN, Lanzanova D, Grizzetti B, Bidoglio G, Pagliero L, et al. Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. Ecosyst Serv. 2016;17:278–92. https://doi.org/10.1016/j.ecoser.2015.08.002
27. Rossa-Roccor V, Acheson ES, Andrade-Rivas F, Coombe M, Ogura S, Super L, et al. Scoping Review and Bibliometric Analysis of the Term "Planetary Health" in the Peer-Reviewed Literature. Front Public Health. 2020;8:343. https://doi.org/10.3389/fpubh.2020.00343 PMID: 32850584
28. Anandhi A, Srivastava P, Mohtar RH, Lawford RG, Sen S, Lamba J. Methodologies and Principles for Developing Nexus Definitions and Conceptualizations: Lessons From FEW Nexus Studies. J ASABE. 2023;66(2):205–30. https://doi.org/10.13031/ja.14539
29. Qureshi WA. An evaluation of the water-energy-food nexus and its alignment with the sustainable development goals. Penn St J L Int'l Aff. 2021;9(1).
30. Rhouma A, El Jeitany J, Mohtar R, Gil JM. Trends in the Water–Energy–Food Nexus Research. Sustainability. 2024;16(3):1162. https://doi.org/10.3390/su16031162
31. Müller-Mahn D, Gebreyes M, Allouche J, Debarry A. The water-energy-food nexus beyond "technical quick fix": The case of hydro-development in the blue Nile basin, Ethiopia. Front Water. 2022;4.
32. Beisheim M. The water, energy and food security nexus: How to govern complex risks to sustainable supply?: SWP Comments; 2013.
33. Weitz N, Strambo C, Kemp-Benedict E, Nilsson M. Governance in the water-energy-food nexus: gaps and future research needs. Stockholm, Sweden: Stockholm Environment Institute (SEI). 2017.
34. Weitz N, Strambo C, Kemp-Benedict E, Nilsson M. Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. Glob Environ Change. 2017;45:165–73. https://doi.org/10.1016/j.gloenvcha.2017.06.006
35. TWI2050. Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. Laxenburg, Austria: The World in 2050 (TWI2050); 2018.

36. Wichelns D. The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? Environ Sci Policy. 2017;69:113–23. https://doi.org/10.1016/j.envsci.2016.12.018
37. Di Martino M, Linke P, Pistikopoulos EN. A comprehensive classification of food–energy–water nexus optimization studies: State of the art. J Clean Product. 2023;420:138293. https://doi.org/10.1016/j.jclepro.2023.138293
38. Behnassi M, El Haiba M. Implications of the Russia-Ukraine war for global food security. Nat Hum Behav. 2022;6(6):754–5. https://doi.org/10.1038/s41562-022-01391-x PMID: 35637299
39. Lucca E, Kofinas D, Avellán T, Kleemann J, Mooren CE, Blicharska M, et al. Integrating "nature" in the water-energy-food Nexus: Current perspectives and future directions. Sci Total Environ. 2025;966:178600. https://doi.org/10.1016/j.scitotenv.2025.178600 PMID: 39923474
40. Dodman D, Hayward B, Pelling M, Castan Broto V, Chow W, Chu E, et al. Cities, settlements and key infrastructure. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, editors. Climate Change 2022: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022. p. 907–1040.
41. IEA, EDGAR. IEA-EDGAR CO2 (v3), a component of the EDGAR (Emissions Database for Global Atmospheric Research) Community GHG database version EDGAR_2024_GHG (2024) including or based on data from IEA (2023) Greenhouse Gas Emissions from Energy, www.iea.org/statistics, as modified by the Joint Research Centre. In: European Commission JRCJ, and International Energy Agency (IEA), editor. 2024.
42. Lee J, Koch M, Alkan-Olsson J. Deliberating a Sustainable Welfare–Work Nexus. Politische Vierteljahresschrift. 2023;64(4):825–44.
43. Mayar MA, Hamidov A, Akramkhanov A, Helming K. Consideration of the Environment in Water-Energy-Food Nexus Research in the Aral Sea Basin. Water. 2024;16(5):658. https://doi.org/10.3390/w16050658
44. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), United Nations Children's Fund (UNICEF), World Food Programme (WFP), World Health Organization (WHO); 2020.
45. Nuwayhid I, Mohtar R. The water, energy, and food nexus: health is yet another resource. Front Environ Sci. 2022;10.
46. Arnbjerg-Nielsen K, Ga K, Marko K, Olli V, McKnight US. To what extent should we ensure the explicit inclusion of water quality within the WEF nexus? Discussion of "Water quality: the missing dimension of water in the water–energy–food nexus". Hydrol Sci J. 2022;67(8):1287–90.
47. Jones ER, Bierkens MFP, van Vliet MTH. Current and future global water scarcity intensifies when accounting for surface water quality. Nat Clim Chang. 2024;14(6):629–35. https://doi.org/10.1038/s41558-024-02007-0
48. Nhamo L, Ndlela B. Nexus planning as a pathway towards sustainable environmental and human health post Covid-19. Environ Res. 2021;192:110376. https://doi.org/10.1016/j.envres.2020.110376 PMID: 33115599
49. Bell A, Matthews N, Zhang W. Opportunities for improved promotion of ecosystem services in agriculture under the Water-Energy-Food Nexus. J Environ Stud Sci. 2016;6(1):183–91. https://doi.org/10.1007/s13412-016-0366-9
50. Mishra SK, Rupper S, Kapnick S, Casey K, Chan HG, Ciraci' E, et al. Grand Challenges of Hydrologic Modeling for Food-Energy-Water Nexus Security in High Mountain Asia. Front Water. 2021;3.
51. Nhamo L, Ndlela B, Mpandeli S, Mabhaudhi T. The Water-Energy-Food Nexus as an Adaptation Strategy for Achieving Sustainable Livelihoods at a Local Level. Sustainability. 2020;12(20):8582. https://doi.org/10.3390/su12208582
52. Simpson G, Jewitt GPW, Badenhorst J. Development of the Water-Energy-Food Nexus Index and its application to South Africa and the Southern African Development Community. Gezina, South Africa: Jones & Wagener Engineering & Environmental Consultants; 2020 February 2020. Contract No.: WRC Report No. 2959/1/19 .
53. Liu J, Hull V, Godfray HCJ, Tilman D, Gleick P, Hoff H, et al. Nexus approaches to global sustainable development. Nat Sustain. 2018;1(9):466–76. https://doi.org/10.1038/s41893-018-0135-8
54. Mabhaudhi T, Chibarabada TP, Taguta C, Dirwai TL, Ndeketeya A. Review of water–energy–food nexus applications in the Global South. Cambridge Prisms: Water. 2024;2:e9.
55. Liu J, Mao G, Hoekstra AY, Wang H, Wang J, Zheng C, et al. Managing the energy-water-food nexus for sustainable development. Appl Energy. 2018;210:377–81. https://doi.org/10.1016/j.apenergy.2017.10.064
56. McGrane SJ, Acuto M, Artioli F, Chen P, Comber R, Cottee J, et al. Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. Geograph J. 2018;185(4):419–31. https://doi.org/10.1111/geoj.12256
57. Mabhaudhi T, Simpson G, Badenhorst J, Senzanje A, Jewitt GPW, Chimonyo VGP, et al. Developing a framework for the water-energy-food nexus in South Africa. In: Diop S, Scheren P, Niang A, editors. Climate change and water resources in Africa: Perspectives and solutions towards an imminent water crisis. Cham: Springer International Publishing; 2021. p. 407–31.
58. Simpson GB. The development of the Water-Energy-Food Nexus Index and its application to the Southern African Development Community. Pietermaritzburg: University of KwaZulu-Natal; 2020.
59. Mabhaudhi T, Simpson G, Badenhorst J, Mohammed M, Motongera T, Senzanje A, et al. Assessing the State of the Water-Energy-Food (WEF) Nexus in South Africa. Pretoria, South Africa: Water Research Commission (WRC); 2018.
60. Simpson GB, Jewitt GPW, Becker W, Badenhorst J, Masia S, Neves AR, et al. The Water-Energy-Food Nexus Index: A Tool to Support Integrated Resource Planning, Management and Security. Front Water. 2022;4.

61. OECD. The Land-Water-Energy Nexus: Biophysical and Economic Consequences. Paris, France: OECD Publishing (Organisation for Economic Cooperation and Development); 2017.
62. Mackie J, ECDPM. Confronting Scarcity: Managing Water, Energy and Land for Inclusive and Sustainable Growth. Maastricht, Netherlands: European Centre for Development Policy Management (ECDPM); 2012. Contract No.: 2011/2012 European Report on Development.
63. Mohtar R, Daher B. Water, energy, and food: the ultimate nexus. In: Heldman DR, Moraru CI, editors. Encyclopedia of agricultural, food, and biological engineering. 2nd edition. New York, USA: Taylor and Francis; 2012. p. 1–5.
64. Bellfield H, Leggett M, Trivedi M, Pareira J, Gangga A. How can Indonesia achieve water, energy and food security without eroding its natural capital? Jakarta, Indonesia: Wildlife Conservation Society (WCS) Indonesia and Global Canopy Programme; 2016.
65. Bellfield H, Leggett M, Trivedi M, Pareira J, Gangga A. How can Indonesia achieve water, energy and food security? Global Canopy Programme; 2016.
66. Ringler C, Bhaduri A, Lawford R. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency?. Curr Opin Environ Sustain. 2013;5(6):617–24. https://doi.org/10.1016/j.cosust.2013.11.002
67. Fernandes Torres CJ, Peixoto de Lima CH, Suzart de Almeida Goodwin B, Rebello de Aguiar Junior T, Sousa Fontes A, Veras Ribeiro D, et al. A Literature Review to Propose a Systematic Procedure to Develop "Nexus Thinking" Considering the Water–Energy–Food Nexus. Sustainability. 2019;11(24):7205. https://doi.org/10.3390/su11247205
68. IBM. Water: a global innovation outlook report. IBM Corporation; 2009 Jan 1.
69. Waughray D, Workman JG. Water security: The water-energy-food-climate nexus: The World Economic Forum water initiative. Washington: Island Press; 2011.
70. WorldEconomicForum. Global Risks 2011. Cologny/Geneva, Switzerland: World Economic Forum; 2011 Sept 27.
71. ICIMOD. Contribution of Himalayan Ecosystems to Water, Energy, and Food Security in South Asia: A nexus approach. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD); 2012. 8 p.
72. Bigas H. Water security & the global water agenda. Ontario, Canada: United Nations University (UNU); 2013.
73. Bizikova L, Roy D, Swanson D, David H, McCandless V. The Water-Energy-Food Security Nexus: Towards a Practical Planning and Decision Support Framework for Landscape Investment and Risk Management. Manitoba, Canada: International Institute for Sustainable Development (IISD); 2013.
74. FAO. The water-energy-food nexus: A new approach in support of food security and sustainable agriculture. Rome, Italy: Food and Agriculture Organization (FAO); 2014.
75. Flammini A, Puri M, Pluschke L, Dubois O. Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative. Rome: Food and Agriculture Organization of the United Nations (FAO); 2014.
76. AboeInga HT, Khalifa M, McNamara I, Ribbe L, Sycz J. The Water-Energy-Food Security Nexus: A Review of Nexus Literature and Ongoing Nexus Initiatives for Policymakers. Bonn: Deutsche Gesellschaft für Internationale (GIZ); 2018.
77. Kabeya PK, Mndzebele D, Ntlamelle M, Samikwa D, Simalabwi A, Takawira A, et al. A regional approach to implementing the WEF nexus: a case study of the Southern African Development Community. In: Mabhaudhi T, Senzanje A, Modi A, Jewitt G, Massawe F, editors. Water - Energy - Food Nexus Narratives and Resource Securities. Elsevier; 2022. p. 145–67.
78. Smajgl A, Ward J, Pluschke L. The water–food–energy Nexus – Realising a new paradigm. Journal of Hydrology. 2016;533:533–40. https://doi.org/10.1016/j.jhydrol.2015.12.033
79. Beddington J. Food, energy, water and the climate: a perfect storm of global events. London, United Kingdom: Government Office for Science. 2009.
80. Andrews-Speed P, Bleischwitz R, Boersma T, Johnson C, Kemp G, VanDeveer SD. The global resource nexus: the struggles for land, energy, food, water, and minerals. Washington, D.C.: Transatlantic Academy; 2012.
81. WBCSD. Co-optimizing Solutions: Water and Energy for Food, Feed, and Fiber. 2014. 2014 May 1.
82. Biggs EM, Bruce E, Boruff B, Duncan JMA, Horsley J, Pauli N, et al. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environ Sci Policy. 2015;54:389–97. https://doi.org/10.1016/j.envsci.2015.08.002
83. UNECE. Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus. New York, USA and Geneva, Switzerland: United Nations Economic Commission for Europe (UNECE); 2015 10 November 2015. Contract No.: ECE/MP. WAT/46.
84. Conway D, van Garderen EA, Deryng D, Dorling S, Krueger T, Landman W, et al. Climate and southern Africa's water–energy–food nexus. Nature Clim Change. 2015;5(9):837–46. https://doi.org/10.1038/nclimate2735
85. Rasul G, Sharma B. The nexus approach to water–energy–food security: an option for adaptation to climate change. Clim Policy. 2015;16(6):682–702. https://doi.org/10.1080/14693062.2015.1029865
86. Karabulut AA, Crenna E, Sala S, Udias A. A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. J Clean Product. 2018;172:3874–89. https://doi.org/10.1016/j.jclepro.2017.05.092
87. Andrews-Speed P, Bleischwitz R, Boersma T, Johnson C, Kemp G, VanDeveer SD. Want, waste or war?: The global resource nexus and the struggle for land, energy, food, water and minerals. 1st edition. London, United Kingdom: Routledge; 2014.

88. Bleischwitz R, Spataru C, VanDeveer SD, Obersteiner M, van der Voet E, Johnson C, et al. Resource nexus perspectives towards the United Nations Sustainable Development Goals. Nat Sustain. 2018;1(12):737–43. https://doi.org/10.1038/s41893-018-0173-2
89. ESCWA. ESCWA Water Development Report 6: The Water, Energy and Food Security Nexus in the Arab Region. Beirut, Lebanon: United Nations Economic and Social Commission for Western Asia (ESCWA); 2015 January 2015. Contract No.: E/ESCWA/SDPD/2015/2.
90. Shannak S, Mabrey D, Vittorio M. Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks. Water-Energy Nexus. 2018;1(1):17–25. https://doi.org/10.1016/j.wen.2018.04.001
91. UNGA. Transforming Our World: The 2030 Agenda for Sustainable Development. New York (NY): United Nations General Assembly (UNGA), United Nations (UN); 2015. 35 p.
92. Salam PA, Pandey VP, Shrestha S, Anal AK. The Need for the Nexus Approach. Water-Energy-Food Nexus. 2017;1–10.
93. Eriksson N, Avellán T, Teutschbein C, Blicharska M. Towards a common understanding of water-energy-food nexus research: A view of the European nexus community and beyond. Sci Total Environ. 2025;967:178775. https://doi.org/10.1016/j.scitotenv.2025.178775 PMID: 39952206
94. Wiegleb V, Bruns A. What Is Driving the Water-Energy-Food Nexus? Discourses, Knowledge, and Politics of an Emerging Resource Governance Concept. Front Environ Sci. 2018;6. https://doi.org/10.3389/fenvs.2018.00128
95. Nhamo L, Mabhaudhi T, Mpandeli S, Dickens C, Nhemachena C, Senzanje A, et al. An integrative analytical model for the water-energy-food nexus: South Africa case study. Environ Sci Policy. 2020;109:15–24. https://doi.org/10.1016/j.envsci.2020.04.010 PMID: 39035455
96. Sulla V, Zikhali P, Cuevas PF. Inequality in Southern Africa: An Assessment of the Southern African Customs Union - Country Brief: South Africa. Washington, D.C.: World Bank Group; 2022.
97. Simpson G, Jewitt G, Becker W, Badenhorst J, Neves A, Rovira P, et al. The Water-Energy-Food Nexus Index: A Tool for Integrated Resource Management and Sustainable Development. OSF Preprints. 2020.
98. Zhang Y. Accelerating Sustainability by Hydropower Development in China: The Story of HydroLancang. Sustainability. 2017;9(8):1305. https://doi.org/10.3390/su9081305
99. Ramos E, Sundin C, Avgerinopoulos G, Howells M, Engström R, Brouwer F, et al. Deliverable 1.7 – Progress of the assessment framework of the Nexus established. KTH, SIM4NEXUS Project. 2019.
100. Biggs EM, Boruff B, Bruce E, Duncan J, Haworth BJ, Duce S, et al. Environmental livelihood security in Southeast Asia and Oceania: a water-energy-food-livelihoods nexus approach for spatially assessing change. Colombo, Sri Lanka: International Water Management Institute (IWMI); 2014. 105 p.
101. Moreno Vargas DC, Quiñones Hoyos CDP, Hernández Manrique OL. The water-energy-food nexus in biodiversity conservation: A systematic review around sustainability transitions of agricultural systems. Heliyon. 2023;9(7):e17016. https://doi.org/10.1016/j.heliyon.2023.e17016 PMID: 37519675
102. Melo FPL, Parry L, Brancalion PHS, Pinto SRR, Freitas J, Manhães AP, et al. Adding forests to the water–energy–food nexus. Nat Sustain. 2020;4(2):85–92. https://doi.org/10.1038/s41893-020-00608-z
103. Yupanqui C, Dias N, Goodarzi MR, Sharma S, Vagheei H, Mohtar R. A review of water-energy-food nexus frameworks, models, challenges and future opportunities to create an integrated, national security-based development index. Energy Nexus. 2025;18:100409. https://doi.org/10.1016/j.nexus.2025.100409
104. Simpson GB, Jewitt GPW, Mabhaudhi T, Taguta C, Badenhorst J. An African perspective on the Water-Energy-Food nexus. Sci Rep. 2023;13(1):16842. https://doi.org/10.1038/s41598-023-43606-9 PMID: 37803054
105. Kliskey A "Anaru," Williams P, Trammell EJ, Cronan D, Griffith D, Alessa L, et al. Building trust, building futures: Knowledge co-production as relationship, design, and process in transdisciplinary science. Front Environ Sci. 2023;11. https://doi.org/10.3389/fenvs.2023.1007105
106. Taguta C, Senzanje A, Kiala Z, Malota M, Mabhaudhi T. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. Front Water. 2022;4.
107. Sušnik J, Staddon C. Evaluation of Water-Energy-Food (WEF) Nexus Research: Perspectives, Challenges, and Directions for Future Research. J Am Water Resour Assoc. 2021;58(6):1189–98. https://doi.org/10.1111/1752-1688.12977
108. Huckleberry JK, Potts MD. Constraints to implementing the food-energy-water nexus concept: Governance in the Lower Colorado River Basin. Environ Sci Policy. 2019;92:289–98. https://doi.org/10.1016/j.envsci.2018.11.027
109. Davies EGR, Simonovic SP. ANEMI: a new model for integrated assessment of global change. IER. 2010;11(2/3):127. https://doi.org/10.1504/ier.2010.037903
110. Bekchanov M, Lamers J. The Effect of Energy Constraints on Water Allocation Decisions: The Elaboration and Application of a System-Wide Economic-Water-Energy Model (SEWEM). Water. 2016;8(6):253. https://doi.org/10.3390/w8060253
111. Reimer JJ, Babbar-Sebens M, Rivera SJ. WEST: Water economy simulation tool to predict impacts of economic and environmental shocks. Adv Water Resourc. 2020;142:103648. https://doi.org/10.1016/j.advwatres.2020.103648
112. Sušnik J, Chew C, Domingo X, Mereu S, Trabucco A, Evans B, et al. Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. Water. 2018;10(2):139. https://doi.org/10.3390/w10020139
113. Ramos EP, Howells M, Sridharan V, Engström RE, Taliotis C, Mentis D, et al. The climate, land, energy, and water systems (CLEWs) framework: a retrospective of activities and advances to 2019. Environ Res Lett. 2021;16(3):033003.

114. Sušnik J, Masia S, Indriksone D, Brēmere I, Vamvakeridou-Lydroudia L. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. Sci Total Environ. 2021;775:145827. https://doi.org/10.1016/j.scitotenv.2021.145827 PMID: 33611179

115. Colloff MJ, Doody TM, Overton IC, Dalton J, Welling R. Re-framing the decision context over trade-offs among ecosystem services and wellbeing in a major river basin where water resources are highly contested. Sustain Sci. 2018;14(3):713–31. https://doi.org/10.1007/s11625-018-0630-x

116. Lee K, Khanal S, Bakshi BR. Techno-ecologically synergistic food–energy–water systems can meet human and ecosystem needs. Energy Environ Sci. 2021;14(7):3700–16. https://doi.org/10.1039/d1ee00843a

117. Daher B, Mohtar RH, Lee SH, Assi A. Modeling the Water-Energy-Food Nexus: A 7-Question Guideline. In: Salam AP, Shrestha S, Pandey VP, Anal AK, editors. Water-Energy-Food Nexus: Principles and Practices. New Jersey, USA and Washington, D.C., USA: American Geophysical Union (AGU) and John Wiley & Sons, Inc.; 2017. p. 55–66.

118. IRENA. Renewable energy in the water, energy and food nexus. Abu Dhabi: International Renewable Energy Agency (IRENA); 2015.

119. Hoolohan C, McLachlan C, Larkin A. 'Aha' moments in the water-energy-food nexus: A new morphological scenario method to accelerate sustainable transformation. Technol Forecast Soc Change. 2019;148.

120. Vinca A, Riahi K, Rowe A, Djilali N. Climate-land-energy-water nexus models across scales: Progress, gaps and best accessibility practices. Front Environ Sci. 2021;9.

121. Johnson OW, Karlberg L. Co-exploring the Water-Energy-Food Nexus: Facilitating Dialogue through Participatory Scenario Building. Front Environ Sci. 2017;5. https://doi.org/10.3389/fenvs.2017.00024

122. Calder RSD, Grady C, Jeuland M, Kirchhoff CJ, Hale RL, Muenich RL. COVID-19 Reveals Vulnerabilities of the Food-Energy-Water Nexus to Viral Pandemics. Environ Sci Technol Lett. 2021;8(8):606–15. https://doi.org/10.1021/acs.estlett.1c00291 PMID: 34373838

123. Slorach PC, Jeswani HK, Cuéllar-Franca R, Azapagic A. Environmental sustainability in the food-energy-water-health nexus: A new methodology and an application to food waste in a circular economy. Waste Manag. 2020;113:359–68. https://doi.org/10.1016/j.wasman.2020.06.012 PMID: 32585558

124. De Strasser L, Lipponen A, Howells M, Stec S, Bréthaut C. A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. Water. 2016;8(2):59. https://doi.org/10.3390/w8020059

125. van Soest HL, van Vuuren DP, Hilaire J, Minx JC, Harmsen MJHM, Krey V, et al. Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. Glob Transit. 2019;1:210–25. https://doi.org/10.1016/j.glt.2019.10.004

126. Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, et al. Sustainability. Systems integration for global sustainability. Science. 2015;347(6225):1258832. https://doi.org/10.1126/science.1258832 PMID: 25722418

127. Mansouri SS, Sivaram A, Savoie CJ, Gani R. Models, modeling and model-based systems in the era of computers, machine learning and AI. Comput Chem Eng. 2025;194:108957.

128. Addula SR, Meesala MK, Ravipati P, Sajja GS. A Hybrid Autoencoder and Gated Recurrent Unit Model Optimized by Honey Badger Algorithm for Enhanced Cyber Threat Detection in IoT Networks. Security and Privacy. 2025;8(6). https://doi.org/10.1002/spy2.70086

129. Decoppet J-B, Guzzo D, Traini L, Gambino V, Roncallo F, Bagnara GL. Designing innovative solutions for the water, energy and food nexus: A comprehensive review of business models for the WEF nexus. Rome, Italy: RES4Africa Foundation and Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ); 2023.

130. Olawuyi DS, Oche A. WEF Nexus and Sustainable Investments in West Africa: The Case of Nigeria. In: Lazaro LLB, Giatti LL, Valente de Macedo LS, Puppim de Oliveira JA, editors. Water-Energy-Food Nexus and Climate Change in Cities. Cham: Springer International Publishing; 2022. p. 243–58.

131. Wada Y, Vinca A, Parkinson S, Willaarts BA, Magnuszewski P, Mochizuki J, et al. Co-designing Indus Water-Energy-Land Futures. One Earth. 2019;1(2):185–94. https://doi.org/10.1016/j.oneear.2019.10.006

132. Mabhaudhi T, Elias M. Applying WEFE nexus approaches for synergistically advancing the implementation of national biodiversity and climate commitments under the UNCBD and UNFCCC. Rome, Italy: Alliance of Bioversity International (CIAT); 2024.

133. Smith MD, Sikka A, Taguta C, Dirwai TL, Mabhaudhi T. Embracing complexities in agricultural water management through nexus planning. Irrig Drain. 2024;73(5):1695–716. https://doi.org/10.1002/ird.3041 PMID: 40092646

134. Wilkinson J. Fair Trade: Dynamic and Dilemmas of a Market Oriented Global Social Movement. J Consum Policy. 2007;30(3):219–39. https://doi.org/10.1007/s10603-007-9036-3

135. Bakhtary H, Rynearson A, Morales V, Matheson S, Zapata J. Breaking silos: Enhancing synergies across NDCs and NBSAPs. Gland, Switzerland: WWF International; 2023.

136. Pahl-Wostl C, Gorris P, Jager N, Koch L, Lebel L, Stein C, et al. Scale-related governance challenges in the water–energy–food nexus: toward a diagnostic approach. Sustain Sci. 2020;16(2):615–29. https://doi.org/10.1007/s11625-020-00888-6

137. Scott A. Making governance work for water-energy-food nexus approaches: Climate and Development Knowledge Network (CDKN); 2017 June. 2017. 20 p.

138. Fuso Nerini F, Mazzucato M, Rockström J, van Asselt H, Hall JW, Matos S, et al. Extending the Sustainable Development Goals to 2050 - a road map. Nature. 2024;630(8017):555–8. https://doi.org/10.1038/d41586-024-01754-6 PMID: 38886551

139. Adom RK, Simatele MD, Reid M. Addressing the challenges of water-energy-food nexus programme in the context of sustainable development and climate change in South Africa. J Water Clim Change. 2022;13(7):2761–79. https://doi.org/10.2166/wcc.2022.099

140. Carmona-Moreno C, Crestaz E, Cimmarrusti Y, Farinosi F, Biedler M, Amani A. Implementing the water–energy–food–ecosystems nexus and achieving the sustainable development goals. Paris, France: UNESCO, European Union and IWA Publishing. 2021.

141. Tsvuura S, Senzanje A, Mudhara M, Mabhaudhi T. Report on integrating WEF Nexus into teaching and learning and on the outcome of the short training programme. Pretoria, South Africa: International Water Management Institute (IWMI); 2022.

142. Nhamo L, Ndlela B, Nhemachena C, Mabhaudhi T, Mpandeli S, Matchaya G. The Water-Energy-Food Nexus: Climate Risks and Opportunities in Southern Africa. Water. 2018;10(5):567. https://doi.org/10.3390/w10050567

143. Mutanga SS, Mantlana BK, Mudavanhu S, Muthige MS, Skhosana FV, Lumsden T, et al. Implementation of water energy food-health nexus in a climate constrained world: a review for South Africa. Front Environ Sci. 2024;12. https://doi.org/10.3389/fenvs.2024.1307972

144. Payet-Burin R, Kromann M, Pereira-Cardenal S, Strzepek KM, Bauer-Gottwein P. Nexus vs. silo investment planning under uncertainty. Front Water. 2021;3(44).

145. Vinca A, Parkinson S, Riahi K, Byers E, Siddiqi A, Muhammad A, et al. Transboundary cooperation a potential route to sustainable development in the Indus basin. Nat Sustain. 2020;4(4):331–9. https://doi.org/10.1038/s41893-020-00654-7

146. Zemadim B, McCartney M, Matchaya G, Cofie O. The Water-Energy-Food-Ecosystem Nexus approach to water infrastructure in Africa: integrated planning, climate resilience, and inclusive growth. Colombo, Sri Lanka: International Water Management Institute (IWMI); 2025.

147. Decoppet JB, Guzzo D, Traini L. Financing the water, energy and food nexus: A comprehensive review of financing mechanisms for the WEF nexus. Rome, Italy: RES4Africa Foundation and Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ); 2023.

148. Liu J, Yang H, Cudennec C, Gain AK, Hoff H, Lawford R, et al. Challenges in operationalizing the water–energy–food nexus. Hydrol Sci J. 2017;62(11):1714–20. https://doi.org/10.1080/02626667.2017.1353695

149. de Loë RC, Patterson JJ. Rethinking water governance: Moving beyond water-centric perspectives in a connected and changing world. Nat Resourc J. 2017;57(1):75–99.

150. Sušnik J, Masia S, Teutschbein C. Water as a key enabler of nexus systems (water–energy–food). Cambridge Prisms: Water. 2023;1:e1.