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Key Points:
- The water-energy-food "nexus" is increasingly used to frame and examine sustainable development challenges in the Global South
- Nexus research spans 23 focal domains of activity, with relations between theory and practice improving but still disjointed
- Challenging current narratives, improving equitability and the salience of nexus theory and practice are key to future utility

Supporting Information:
Supporting Information may be found in the online version of this article.

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Appraising the Water-Energy-Food Nexus From a Sustainable Development Perspective: A Maturing Paradigm?

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Abstract The water-energy-food (WEF) nexus is a prominent approach for addressing today's sustainable development challenges. In our critical appraisal of the WEF, covering different approaches, drivers, enablers, and applications, we emphasize the situation across the Global South (Africa, Asia, Latin America and the Caribbean). Here, WEF research covers at least 23 focal domains. We find that the *nexus* is still a maturing paradigm primarily rooted in a physical and natural sciences framing, which is itself embedded in a neoliberal securities narrative. While providing insights and tools to address the systemic interdependencies between resource sectors whose exploitation, degradation, and sub-optimal management contribute to (un)sustainable development, there is still insufficient engagement with social, political, and economic dimensions. Progress related to climate, urbanization, and resource consumption is encouraging, but while governance and finance are central enablers of current and future nexus systems, gaps remain in relation to implementation and operationalization. Harnessing the nexus for sustainable development across the Global South means recognizing that it is more than a biophysical system, but also a multi-scale complex of people, institutions, and infrastructure, affected by history and context. Addressing this complexity requires alternative and possibly challenging perspectives to counter dominant narratives, and manage problems associated with policy integration, trade-offs, and winners and losers. We outline 10 emergent research areas that we think can contribute to this endeavor and enable the nexus to be a stronger policy force.

Plain Language Summary The sustainability of water, energy, and food systems, especially in the Global South, is one of the grand challenges of the 21st century. The water-energy-food (WEF) nexus provides a framework and an approach to help address these multifaceted issues. Although the WEF paradigm has evolved, experiencing rapid policy uptake, with encouraging applications in understanding climate change, urbanization, and resource consumption impacts, it is yet to achieve its full potential. Unfulfilled promise is evident in the failure to fully harness "nexus thinking" to enhance the implementation of WEF-based policies and governance of WEF systems. Simultaneously, research on WEF systems remains largely the preserve of the natural and physical sciences, with much less critical attention received from the social and political sciences. Ensuring the WEF paradigm achieves policy and research salience and improved implementation across the Global South, to effectively contribute to sustainable development, means rectifying such imbalances. This will require expanding beyond some of the innovative WEF research already undertaken, emphasizing interdisciplinarity, plural methods, and a focus on communities in the dynamics of nexus systems. We identify 10 emergent priority areas that can contribute to this endeavor and enhance the capacity of the nexus to positively influence policy change for sustainability.

1. Introduction

Since the mid-20th century, the world has witnessed profound, inter-related changes in human societies and ecological systems, leading to large-scale shifts in planetary processes (Steffen et al., 2015, 2018) and the transition into a new geological era—the Anthropocene (Lewis & Maslin, 2018; Malhi, 2017). Between 1950 and 2018 the world's population tripled, growing from 2.5 to 7.6 billion, whilst also becoming predominantly urban,

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quintupling from 751 million to 4.2 billion urban dwellers (UN, 2019). Alongside these astonishing demographic shifts, the global economy grew tenfold from US$ 9.25 to 108 tn (UN, 2014, 2017). In conjunction, consumption of food, energy, and water resources skyrocketed (Schlör, Venghaus, Fischer, et al., 2018), leading to a reconfiguration of Earth's matter-energy balance (Williams et al., 2016) and living biomass (Bar-On et al., 2018; Elhacham et al., 2020).

Notwithstanding significant progress and improvements (e.g., in health, science and technology, education, wealth), these rapid developments represent an existential threat to human survival and planetary health (IPCC, 2021). Our actions have altered the planet's climate, and caused extensive biodiversity loss, deforestation, resource depletion, land use change, and air, soil, and water pollution (CBD, 2020; IPBES, 2019; IPCC, 2019), pushing us beyond several planetary boundaries (Lade et al., 2020; Rockström et al., 2009). At the same time development processes are uneven; 770 million people lack access to electricity (IEA, 2022b), 2.1 billion to safe and readily available water (UNICEF & WHO, 2017), malnutrition remains a leading cause of ill health globally (GNR, 2018), 1 billion people live in informal settlements (UN, 2019), and by 2050 water shortages are predicted to affect almost 5 billion people (UN-Water, 2018).

It is against this background that the concept of the water-energy-food (WEF) nexus (from here on referred to as the "nexus") emerged in 2009–2011 (Hoff, 2011; WEFWI, 2011) and has continued to evolve and be operationalized and implemented. Water, energy, and food resources are conceived as linked "systems" and "sectors," with the growing demands on them often viewed through the lens of "security" (Bizikova et al., 2013). Here, human development and natural resource management converge as issues of health and wellbeing, equity and justice, and sustainability is understood as the social foundation of the planetary ceiling (Friedman et al., 2018; Raworth, 2017), and a "safe and just corridor for people and the planet" (Rockström et al., 2021). Consequently, the nexus has been increasingly used to assess potential systemic drivers of change and synergies and trade-offs across sectors (De Laurentiis et al., 2016; Dodds & Bartram, 2016), improve governance through coherent planning and management (Weitz et al., 2017), organize research (Keskinen et al., 2016; Pueppke et al., 2018), and inform sustainability pathways for Agenda 2030 (Albrecht et al., 2018; Liu et al., 2018).

With the nexus establishing itself as a credible boundary spanning framework, prominent in research and policy, but still emergent, we reassess its evolution and theoretical and practical applications in relation to sustainable development. Research (e.g., Glass & Newig, 2019; Güney, 2017) has highlighted the significance of governance (especially in the form of coordination, integration, and policy coherence), and social and political science perspectives (UNESCO & ISSC, 2010, 2013, 2016) for achieving sustainable development. Within that context, broadly stated, our two principal aims are to: (a) appraise the development and current trends of nexus research, with particular emphasis on the Global South and (b) outline a future nexus research agenda that goes beyond current domains of activity. This provides our entry point to pursue a social science- and governance-engaged assessment of nexus discourse, which emphasizes a neglected perspective that facilitates a more critically reflective narrative. This approach differentiates our analysis from other more quantitative reviews of the nexus, many of which either describe methods and approaches for assessing the nexus (e.g., Albrecht et al., 2018; Endo et al., 2020; Kaddoura & El Khatib, 2017; Kling et al., 2017; C. Zhang et al., 2018; X. Zhang et al., 2018) or provide a purely bibliometric consideration at global (e.g., Endo et al., 2017; Sarkodie & Owusu, 2020) or regional scales (e.g., Botai et al., 2021). Adopting this approach affords the opportunity to consolidate a body of discourse whilst helping to shape the next stage of its evolution. Moreover, a sustainable development lens provides opportunities for policy relevant insights applicable to global development contexts, where key nexus challenges in the coming decades will play out. We therefore seek to jointly advance nexus research and nexus applications in the real world. We accomplish this task by reviewing the literature focused on low- and middle-income countries across Africa, Asia, and Latin America, and from that basis extend our remit to a broader critical analysis of nexus discourse. We do this through a reflexive question-led interrogation of the evidence base.

The rest of the article is structured as follows. Section 2 outlines the literature review methodology. In Section 3, we look at the evolution of the nexus, focusing on conceptual framings and characterizations and their examination from a research perspective drawing on insights provided by a regional bibliometric synthesis of the literature (Text S2–S4 in Supporting Information S1). After which, in Section 4, we look at system-wide drivers of nexus dynamics, and in Section 5 we outline key areas necessary for managing nexus systems sustainably. In Section 6 we offer recommendations for future research in the context of supporting the sustainable development agenda. We finish with some final concluding insights.

2. Materials and Methods

Literature searches used the abstract and citation databases Scopus and Web of Science (core collection). Searches were conducted on 10 May 2021. The search strategy focused on "title, abstract, and keywords," with no date or document limitations. The following search strings employing Boolean logic and wild cards were used: ("water energy food" OR "food water energy" OR "food*" AND "water*" AND "energy*") AND ("nexus*") AND ("Africa" OR "Latin America" OR "South America" OR "Asia") (Tables S1.1 and S1.2 in Supporting Information S1). This yielded 579 records, which when combined and duplicates removed, reduced to 236 records (Table S1.3 in Supporting Information S1). These unique records were then screened at title and abstract level to ascertain whether studies met the following inclusion/exclusion criteria: study is concerned with nexus matters in Latin America (Central and South America), Africa (including the Middle East) or Asia; study considers one or more of the economic, social, governance and environmental aspects of the nexus; study highlights a nexus model or technology and its application; study is published in English or Spanish (due to linguistic capacity of the review team); the article is a peer-reviewed article published or in press, a review, a conference proceeding, note, survey, book, book chapters, but excludes theses, editorials; and studies lacking an abstract. We excluded global assessments, comparative case studies including countries and regions outside the remit of interest, as well as studies that report on a nexus model or technology and its specifications, parameterization, and operationalization rather than its application to a nexus problem domain. Applying these criteria resulted in a final sample of 138 unique records (Table S1.4 in Supporting Information S1 and Table S1.5). We then extracted the following data to form the basis of the bibliometric analysis: source date and title; document type; geographic focus of nexus research; author affiliations; institutional type and location; author keywords; and funding sources. We used these results to inform a wider critical analysis of nexus discourse.

3. The Nexus: An Evolving Picture?

3.1. Framings and Characterizations

Clearly, the nexus has evolved since its inception (Lazaro et al., 2022). Described as a policy "buzzword" (Cairns & Krzywoszynska, 2016), during its adolescence the nexus has birthed multiple variations, leading to a variety of interpretations and the charge of having no universal definition (Endo et al., 2017). Nevertheless, the nexus is commonly described as a physically interconnected, interacting, and multi-layered set of resource systems comprising water, energy and food sectors with socio-economic and governance dimensions. The fact that the nexus is evolving and not singularly defined adds to its versatility. Sectoral elements are often substituted or added, providing a number of new nexus configurations such the "water-energy-land-food" (WELF) (Ringler et al., 2013), "water-land-energy-carbon" (WLEC) (Zhao et al., 2016), "water-energy-food-land use-climate" (WEFLC) (Laspidou et al., 2019), "climate-land-energy-water systems" (CLEWs) (IAEA, 2009; Ramos et al., 2021) or the "food-energy-water-ecosystem services" (FEWES) (Uden et al., 2018) nexus. In these instances, a social-ecological approach is useful to avoid "rigidity traps" when emphasizing connections between system components such as land use and climate change. Further variants include the food-water-energy-biodiversity (FWEB) nexus which strengthens the link between biodiversity and food production (Subedi et al., 2020); the water-energy-food-ecosystem (WEFE) nexus which highlights the centrality of healthy ecosystems (Carmona-Moreno et al., 2019); and the food-energy-water-health (FEWH) nexus which stresses the relationship between resource use and human health and wellbeing through a circular economy lens (Slorach et al., 2020). The recent emergence of the water-food-labor (WFL) nexus attempts to recognize the social and labor consequences of production and consumption from a poverty and income perspective (Distefano et al., 2022). The widespread utilization of the nexus may arguably lie in the fact that it is a flexible construct, allowing many disciplinary fields, sectors, and policy domains to find resonance with it.

Whilst nexus typologies have grown, the full understanding of non-biophysical aspects remains more rudimentary. Overall, physical and natural science approaches are the most commonplace conceptual lenses (Albrecht et al., 2018; Dodds & Bartram, 2016). As a result, these often ignore or discourage consideration of social and political processes, limiting our assessment of the nexus to a broadly quantitative viewpoint. These approaches also fail to facilitate a holistic understanding of how nexus systems function and are embedded within political economies. From a development perspective, this means that sectoral elements are primarily non-politicized; matters in relation to food and land, like ownership, property rights, and tenure are typically not considered in examinations of the nexus. Consequently, some have suggested that nexus discourse is too firmly entrenched within a scientific, managerial, and technocratic framing that masks important social conditions, power relations and inequalities (Wiegleb & Bruns, 2018).

The increasing application of mixed-method research designs and interdisciplinarity may help to redress this imbalance (Albrecht et al., 2018). For instance, while a wide range of journals across regions was identified here—Africa (n = 47); Asia (n = 28) and Latin America and Caribbean (n = 9)—most nexus research was published in interdisciplinary environmental journals, notably *Energy*; *Frontiers in Environmental Science*; *International Journal of Water Resources Development*; *Journal of Cleaner Production*; *Land Use Policy*; *Nature Sustainability*; *Renewable and Sustainable Energy Reviews*; *Resources, Conservation and Recycling*; *Science of the Total Environment*; *Sustainability*; *Water*; and *Water Alternatives*. This trend suggests that while the foundation remains natural science-oriented, nexus research is beginning to go beyond the traditional biophysical modalities to connect with other disciplines. Nonetheless, very few of the journals identified here were purely from the fields of social or political science.

To some extent this situation is paradoxical, given that the nexus concept was birthed out of political arguments centered on the imperative to address water, energy, and food security issues, which are primarily framed as significant social and economic development challenges. The security narrative emerged as a policy response to address growing threats to natural resources (WEFWI, 2011) such as those in the Mekong Region (Lebel & Lebel, 2018). This narrative argues that these threats influence so-called "nexus insecurities," that is, the risk-based profiles of water, energy and food related to long-term sector stability, functioning and development in the context of wider uncertainty (de Fraiture et al., 2014; Dodds & Bartram, 2016; Finley & Seiber, 2014; Garcia & You, 2016; Olsson, 2013). These effects are manifest mainly through impacts on sector sustainability (Pittock et al., 2015; Tian et al., 2018); resource scarcity (De Laurentiis et al., 2016; Dodds & Bartram, 2016; Helmstedt et al., 2018); disruptions of connections between sectors and across systems (Y. Chang et al., 2016; Hoff, 2018; Kling et al., 2017); and the intensification of urban nexus (see Section 4.2 for definition) system challenges (Schlör, Venghaus, & Hake, 2018).

The securities vision of the nexus remains strong, although it is increasingly seen as controversial. The dominant securities contextualization has attracted criticism because of its reductionist, neoliberal capitalist language (Allouche et al., 2015), making economic productivity the referent of interest rather than individuals, organizations, or countries (Liebenguth, 2020) and overlooking the functional importance of the environment and associated processes (de Grenade et al., 2016). This approach shifts the loci of authority away from state-centric institutions toward private organizations as the principal agents of nexus security and governance, while increasing technocratic responses to risk management (Liebenguth, 2020). Some argue that securities framing is unfit to address embedded social injustices, because it privileges the economic interests of developed economies and relegates considerations of the poorest to a secondary position, thereby undermining North-South relations (Leese & Meisch, 2015), while promoting vested interests and obscuring underlying socio-environmental inequalities (Allouche et al., 2015; Liebenguth, 2020). As such, there have been increasing attempts to expand the purely economic and scarcity notion of security to include aspects such as diversity of access and system resilience (Beck & Walker, 2013). Oddly, the role of financial instruments in managing nexus issues has been neglected, even though these instruments are central to its implementation and are increasingly used in approaches to sustainability, rather than public models (Schmidt & Matthews, 2018).

Even though the nexus is a physical system, adopting a "nexus approach" or "nexus thinking" indicates that the nexus is also a heuristic and analytical tool for conceptualizing problems and solutions from a complex systems perspective. Focus on the interconnections, interrelations and interdependencies among nexus sectors provides the foundation to develop coherent and effective policy and planning strategies (Ahuja, 2015; Finley & Seiber, 2014; Lee, 2016; Machell et al., 2015; Pittock et al., 2015; Ringler et al., 2013; Von Braun & Mirzabaev, 2016; Wicaksono et al., 2017; Yillia, 2016). Addressing interconnections clarifies how drivers of change simultaneously and differentially impact system and sectoral behaviors and responses (Y. Chang et al., 2016; de Fraiture et al., 2014; McGrane et al., 2019; Olsson, 2013), and it improves governance efficacy (de Loë & Patterson, 2017) through better vertical (between sector) and horizontal (within sector) coordination (Kurian et al., 2018). The interlinked nature of nexus sectors requires cross-disciplinary, -sectoral models of investigation (Pueppke et al., 2018) to be "nexus appropriate" (Leck et al., 2015).

Associated with connectivity is the notion of integration, which is considered to deliver more coherent policy and management by bringing together the biophysical and socio-economic elements of the nexus (Kling et al., 2017).

Integrated management has the potential to address water, energy, and food insecurities (de Fraiture et al., 2014) including in urban contexts (Artioli et al., 2017), whilst enabling ecological, economic, and social outcomes that deliver on the Sustainable Development Goals (SDGs) (de Fraiture et al., 2014; Finley & Seiber, 2014; Helmstedt et al., 2018; Yillia, 2016). Factors highlighted as critical to determining the effectiveness of integration include: closed-loop learning; obtaining sufficient information about resource sectors and their interactions (Pahl-Wostl et al., 2018); addressing complementarities and trade-offs, and power relations between resource sectors and actors (Artioli et al., 2017; Kaddoura & El Khatib, 2017; Pueppke et al., 2018); capturing the spatial changes and continuities in nexus sectoral interactions across scales (Abulibdeh & Zaidan, 2020); and addressing the metabolism of nexus resources (i.e., material throughput, flows and use) (Serrano-Tovar et al., 2019).

The concept of striving for integration across the nexus, however, is not always clear. Integration can be conceived as "incorporation," where all sectors are brought together under a system view, "cross-linking," where practical, crystallized links between sectors highlight priority areas for action, or "assimilation," where strategies for managing one sector are applied to another (Al-Saidi & Elagib, 2017). This ambiguity has led some to question the nexus approach, suggesting that it fails to offer any meaningful advantage over other widely known framings such as integrated water resource management (IWRM) (Kurian, 2017; Muller, 2015; Wichelns, 2017). Others counter this view by arguing that the nexus attempts to move beyond a purely resource-centric position to promote a multi-resource and multi-sector governance account of key management challenges (Roidt & Avellán, 2019).

Linked to these relational networked elements, scale and boundaries are also fundamental to nexus systems and approaches but are not easy to capture. The traction of the nexus to tackle global issues occurs across several different types of scales (e.g., spatial, temporal, institutional, and jurisdictional), and is inextricably linked to both the drivers and enablers of the nexus, particularly at local scales where "nexus practice emerges" (McGrane et al., 2019). Boundary delineation and scale are thus key for any application of the nexus, with studies evaluating nexus interlinkages from the household to the global scale (Dargin et al., 2020; D'Odorico et al., 2018). Boundaries in this sense are fluid and plural—nexus systems are embedded within overlapping and intersecting social-ecological and technical systems, which create complex pathways between different embedded nexuses and locations of impact and outcomes (Fontana et al., 2021). This becomes increasingly important in regions like the Gulf Cooperation Council (Kuwait, Qatar, and Saudi Arabia), where a domestically delineated boundary would reveal a modest requirement for food and water compared to energy. Yet, when the boundary is extended internationally, the compensatory need for energy exports to make up for low food production, scarce water availability and the impacts on those regions is revealed (Siderius et al., 2020). However, the inherent complexities of defining any boundary, and the number of different nexus tools used for analysis, makes teasing out these details and making cross comparisons challenging (Endo et al., 2020). Some promising attempts to solve these difficulties, though limited in the breadth of what they consider, include Dargin et al. (2020) and their method for evaluating the complexity and costs and benefits of nexus tools, and Sušnik (2018), who use shared economic indices (e.g., GDP) to examine relations between sectors.

3.2. Modeling the Nexus

Metrics, modeling, data analytics, and decision-support tools are the most popular approaches to examining the nexus, and these have seen rapid developments over recent years (Bian & Liu, 2021; Borge-Diez et al., 2022; Y. Chang et al., 2016; Dai et al., 2018; Garcia & You, 2016; King & Carbajales-Dale, 2016; Kurian et al., 2018; Liu et al., 2017; Mcgrane et al., 2019; Miralles-Wilhelm, 2016; Mohtar & Lawford, 2016; Stylianopoulou et al., 2020; Tian et al., 2018; Wicaksono et al., 2017; Wolfe et al., 2016; C. Zhang et al., 2018; X. Zhang et al., 2018). Indeed, the most recent assessment suggests that there are at least 46 nexus models and tools (Taguta et al., 2022). Readers wishing to know more about the particularities of these models and tools should consult Albrecht et al. (2018), C. Zhang et al. (2018), X. Zhang et al. (2018), and Taguta et al. (2022).

Modeling is most frequently used to quantify biophysical nexus relationships (Schull et al., 2020), including trade-offs, interdependencies, and uncertainties across the Global South. In China, simultaneous equation modeling (a type of statistical model) has shed light on the interactions and magnitude of local-level nexus sectors (Huang et al., 2020), assessment-optimization modeling has revealed synergies between nexus sectors (T. Zhang et al., 2020), and multi-level interval fuzzy credibility-constrained programming methods (allocation models) have identified uncertainties concerning regional-scale planning (Yu et al., 2020). The WEFSiM model has unraveled feedback relationships to optimize alternative forms of national resource management under South Korea's

Energy 2030 Plan (Wicaksono et al., 2020), while the NExus Solutions Tool (NEST), which integrates resource optimization and hydrological modeling, has also been used to demonstrate key interlinkages across system-level development pathways toward the SDGs and the centrality of transboundary cooperation in achieving those outcomes in the Indus River basin (Vinca et al., 2020, 2021). In Central Asia, the technique for order of preference by similarity to ideal solution (TOPSIS) approach (a multi-criteria decision analysis method) combined with indicators to measure resource security (accessibility, availability, self-sufficiency and productivity) has been used to develop an integrated framework for evaluating nexus security at a sector and whole system level (Hao et al., 2022). In Africa, spatial analysis using the Pardee Rand FEW Index shows that 87% of Sub-Saharan African countries are at high risk for food, energy and water insecurity (Nkiaka et al., 2021). Further, in Ghana and Burkina Faso, the utilization of MAXUS, a spatially explicit nexus model, has enabled the geospatial integration of electric grid development and food security (Burger & Abraham, 2020), while in Tanzania's Rufiji River Basin, multisector spatial modeling has been employed to assess WEF trade-offs across infrastructural development scenarios (Geressu et al., 2020).

Significant insights behind nexus modeling are supported by complex adaptive systems approaches (Y. Chang et al., 2016; Dai et al., 2018; Kurian et al., 2018; Li et al., 2019; Liu et al., 2017; Pereira et al., 2017; Tian et al., 2018). For example, ontology engineering (an approach for examining methods for building ontologies) has been used to develop nexus domain maps to identify causal linkages between resource sectors and key actors (Endo et al., 2018); agent-based models (computational simulations) have been exploited to examine possible impacts of water infrastructure developments on local human wellbeing (Bazzana et al., 2020); Bayesian network analysis (a probabilistic graphical model) has made it possible to qualify the causal relations between nexus sectors, economy and society (Chai et al., 2020); circular economy and life cycle assessment approaches have been employed to assess nexus interdependencies (Del Borghi et al., 2020); and participatory scenario planning (a futures approach focused on vulnerability and adaptation) has helped to deal with the challenging complexity and uncertainties that exist across nexus sectors in support of sustainable development (Hoolohan et al., 2019). Others have combined resilience thinking and nexus approaches within a single framework to account for social justice in managing social-ecological systems (Stringer et al., 2018). Increasingly, there are calls for nexus applications to take advantage of rapidly advancing frontier technologies (e.g., Artificial Intelligence, Big Data analytics) to improve sectoral agility and adaptivity; measure success and failure; and improve multiscalar assessments (Pitts et al., 2020; Taylor, 2020). Despite the variety of tools available to investigate the nexus, conspicuously absent is the utilization of different forms of knowledge and perspectives, especially indigenous and traditional/local ecological knowledge. This absence perpetuates the domination of "Western" science and subjugates and erodes the legitimacy and value placed on other knowledge systems and practices, this is despite the increasing emphasis placed on both indigenous and local ecological knowledge contributions to sustainability (Mistry & Berardi, 2016; Tengö et al., 2017).

Although much progress has been made in creating useable decision support tools and software, their complexity can be a barrier to assessing nexus interactions and translating findings into diverse decision support arenas. This suggests that more needs to be done to integrate diagnostic, guidance, and capacity building applications and critique model assumptions (Dargin et al., 2019). Several challenges remain, including data accuracy, availability and curation, the ability to describe nexus spatial dynamics, and providing appropriate metrics for policymaking (Purwanto et al., 2021; Taguta et al., 2022). For instance, most (61%) nexus applications are not available in the public domain (i.e., some form of authorized access is required, or they are located on an internal network), while only 30% have geospatial capabilities (Taguta et al., 2022). The lack of appropriate data hampers the realization of more sophisticated models capable of teasing out social-ecological interactions.

Increasing calls have been made for new collaborative ventures between sectors, institutions, disciplines and across scales to collect more robust, accessible data (Y. Chang et al., 2016; King & Carbajales-Dale, 2016; Liu et al., 2017; McGrane et al., 2019; Pueppke et al., 2018; C. Zhang et al., 2018; X. Zhang et al., 2018). In this context, there are opportunities to escalate south-south and north-south cooperation to improve knowledge exchange and technology transfer in an equitable way. Indeed, the sustainable implementation of a nexus approach requires open access tools and greater availability to analysts in developing countries (Taguta et al., 2022). Evidence from expert surveys emphasizes the importance of technological solutions (Mayor et al., 2016), human behavior and risk, and regional differences in the functioning of the nexus (Faeth & Hanson, 2016). Kurian (2020) goes further, arguing that place-based observatories are needed to bridge science-policy gaps and connect global environmental

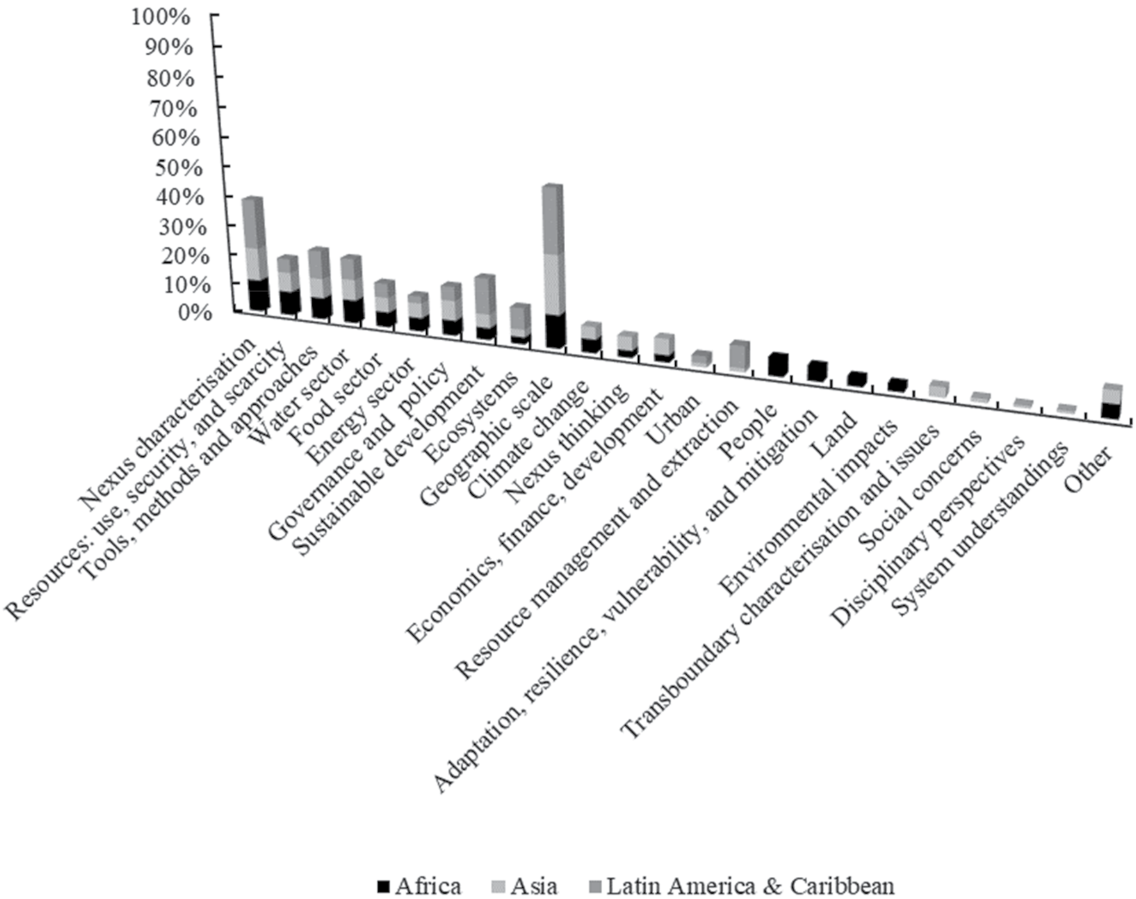

Figure 1. Focal domains of nexus research based on an inductive thematic analysis of 646 keywords across Africa, Asia and Latin America & Caribbean regions. Twenty-three focal domains were established (excludes other). Percentages indicate the importance of these nexus focal areas for each region.

models with local development interventions and assessment tools. This accords with the observation that many nexus tools have not been practically applied and lack appropriate case-based examples (Taguta et al., 2022).

Ultimately, there are no standalone methods or tools for delivering a nexus approach; so rather than attempting to engineer a silver bullet, what is needed is a combinatorial approach that harnesses interdisciplinarity and mixed methods (Endo et al., 2020). Critical to the success of that process however is recognizing that nexus tools need to consider "utility, transferability and scalability across uses and users" (Taguta et al., 2022, p. 1).

3.3. Development Geographies of Nexus Research

Across the Global South, nexus literature demonstrates a variety of research domains of interest. The most common focal domains (Figure 1) are clustered around nexus characterization; resources: use, security, and scarcity; tools, methods and approaches; water sector; food sector; energy sector; governance and policy; sustainable development; and ecosystems collectively viewed across multiple geographies. Other important areas include climate change; economics, finance, and development; people; resource management and extraction; and urban issues. Although many themes are shared across all regions (43%), a significant percentage are shared across two regions (21%) or are regionally specific (35%). Many of these map onto the nine keyword cluster themes of Zhou et al. (2022): "uncertainty"; "risk analysis"; "bioenergy"; "food-energy-water nexus"; "transport"; "integrated water resource management"; "water footprint"; "infrastructure investment" and "energy efficiency"; the five research trends underpinning the temporal evolution of the nexus identified by Lazaro et al. (2022): "nexus for water management and natural resource security"; "linkages between the nexus, sustainable development goals and green economy"; "application of the nexus concept at different scales" and "climate change and urban nexus

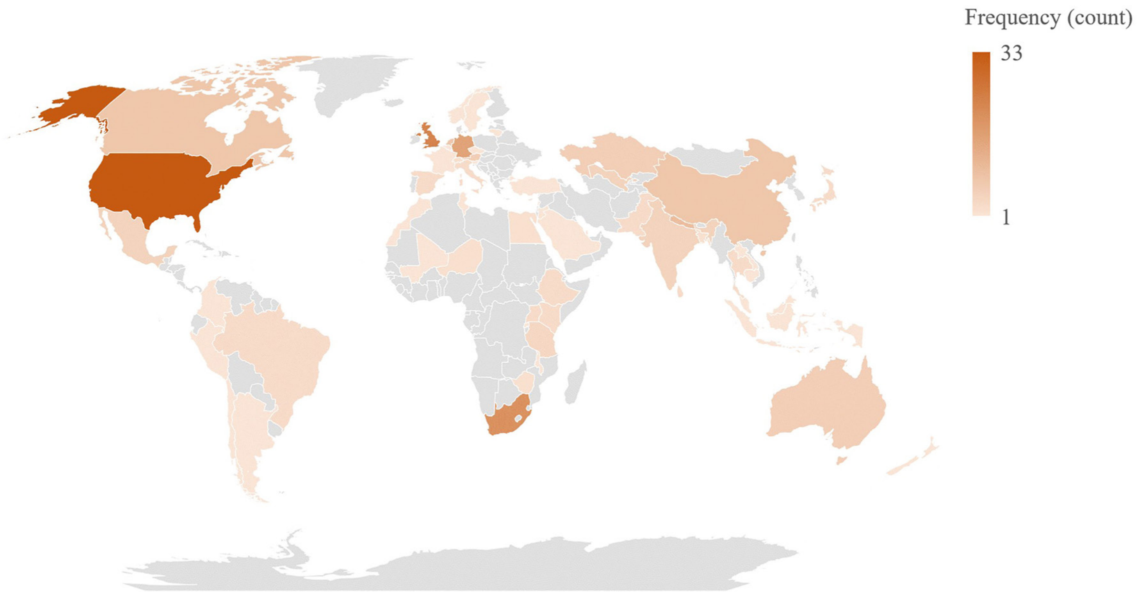

Figure 2. Global map of countries active in nexus research based on author institutional affiliation. Darker shades of orange indicate more intensive areas of nexus research.

challenges"; and the four cluster themes of Bian and Liu (2021): "sustainable development and water management"; "water and food intake"; "water and food" and "environmental impact."

The term "Global South" can, and is, often employed to equalize and homogenize. However, countries within and across continents captured by that term exemplify a huge diversity of "southern realities"; they face a variety of development challenges and are themselves subject to different socio-economic and political pressures and phases of development (Haug et al., 2021). As an example, recent analysis of WEF nexus projects in Africa by Muhirwa et al. (2022) indicates that projects are distributed according to the context and circumstances of each region, such that in North Africa there is an emphasis on energy-focused projects whereas in East Africa food security-focused projects predominate. To a large extent, countries that are the focus of nexus research display this broad-spectrum developmental reality (Table S6.1). However, certain areas and countries are more heavily favored than others. In the case of Africa, research in South Africa and Tanzania dominates, while in Latin America and the Caribbean it is Argentina, Brazil, Colombia, Mexico, and Peru that loom large and in Asia areas such as the Mekong, Aral Sea and Hindu Kush Himalaya, Central Asia and China are dominant.

Fifty-nine countries, based on author institutional affiliation, are active in nexus research (Figure 2). Institutions spearheading nexus research originate mainly from a small coterie of Northern countries, especially the USA, UK, Germany. Only South Africa figures as prominently. Other developing countries of note are China and Nepal, but these are at a lower frequency.

Global North institutions drive the publication landscape across all regions. Universities are the most represented and dominant institutions in the nexus research ecosystem (Figure 3). Other sectors add diversification to the institutional landscape, particularly research institutes, think tanks, and government and related entities. Less prevalent, overall, are third sector organizations, private companies, development agencies and inter-governmental organizations (IGOs). In funding terms, overall universities and governments are the dominant sources of finance, whilst development agencies are comparatively more important in the Latin America and Caribbean nexus context with IGOs more prominent in Asia (Figure 3).

4. Systemic Influences on Nexus Dynamics

A set of system-wide drivers influences nexus dynamics (Kurian, 2017; Mohtar & Lawford, 2016), which includes, amongst others, transboundary trade in goods and commodities, climate change (D'Odorico et al., 2018), rapidly increasing urbanization and other demographic changes, and geopolitics (Dalin & Outhwaite, 2019;

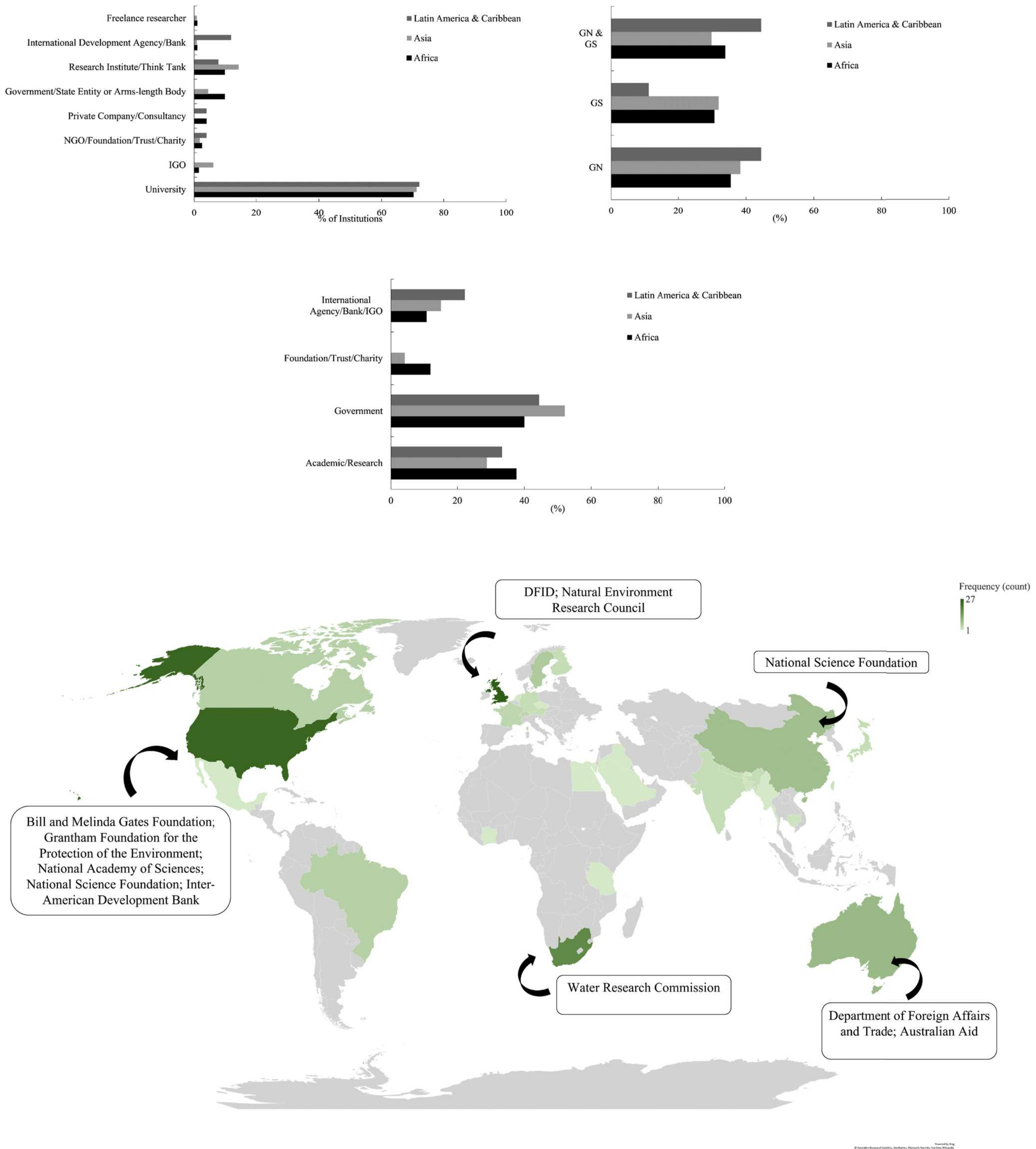

Figure 3. Top panel: Institutional contributors to nexus research publications in Africa, Asia, and LA & C according to sector domains. Upper middle panel: Indicates the percentage Global North and Global South institutional composition of research publications on the nexus across Africa, Asia, and LA & C. GN, Global North; GS, Global South; GN & GS, Global North & Global South. Lower middle panel: Sectoral funding patterns of nexus research across Africa, Asia, and LA & C regions. Values refer to percentages. Bottom panel: Global map of countries contributing to nexus research based on an analysis of institutional financial contributors to published nexus research. Text boxes indicate some of the most prominent funders associated with the most intensive nexus research countries: USA, UK, South Africa, China, and Australia.

Hogeboom, 2020; Jackson, 2017; Ramaswami, 2020). The combination of these drivers, operating across spatiotemporal scales, is argued to have generated a "perfect storm" around the nexus (O'Neill et al., 2018; Schlör, Venghaus, et al., 2018), such that global food production, water resources and energy provision will all have to increase between 50% and 70% by 2050 to meet our demands (FAO, 2012; Reilly et al., 2018). Other scenarios suggest that human activities will lead to the doubling of material resource use over the next 30 years (IRP, 2017).

These drivers will hit the Global South especially hard. Expectations are that water consumption, food demand and electricity requirements in Africa will increase by 238%, 60%, and 70%, respectively, between 2005 and 2030 (RES4Africa, 2019). In LA & C, the projected escalation in water demand, primary energy production, and food production is 75%, 50%, and 31%, respectively, between 2020 and 2050 (Mahlkneckt et al., 2020). Similarly, in Southeast Asia, energy demand is expected to grow by 60% by 2040 to accommodate an extra 120 million people (IEA, 2019). This will almost certainly influence energy availability for agriculture, which currently accounts for up to 20% of the total in South Asia (Rasul & Neupane, 2021). The rise in energy demand and supply, and its regional variation, has significant implications for poverty reduction, social cohesion, long-term economic development, and environmental sustainability (GEA, 2012).

The role of price shocks as a driver of nexus vulnerability in this domain is acute. Current global food prices are high, and part of a broader trend in the cost-of-living crises experienced in developing and emerging economies as well as advanced economies too (FSIN, 2022). This has been exacerbated by Russia's invasion of Ukraine, which has destabilized global wheat supply generating shortages and raising wheat prices by 40%, and related to these geopolitical events, energy costs (e.g., gas and oil) have also soared, increasing by 40%–50% between 2021 and 2022 (World Bank, 2022). Delinking demand from fossil fuel consumption will be important because volatility in oil and gas prices undermines long-term energy as well as food security by affecting agricultural production choices, markets, and water consumption (Ringler et al., 2016; Su et al., 2019; Taghizadeh-Hesary et al., 2019). Under these conditions fossil fuel (carbon) taxes imposed under the UNFCCC may be helpful in buffering food security against energy price shocks (Ringler et al., 2016).

Zooming out, overlapping climatic and non-climatic drivers (e.g., trade, globalization, land use change) are placing added burdens on local and global food systems (e.g., Béné et al., 2020; FSIN, 2020), undermining the four key pillars of food security (i.e., availability, access, utilization, and stability). This is expected to be especially acute for regions such as dryland Africa and mountainous regions of Asia and South America (Mbow et al., 2019) where nexus research to date has been very sparse.

Rapid rises in population and associated economic development over short timeframes can also strain resources, especially when resources are already under pressure and unfairly distributed, and in situations where long-term planning and preparedness for such outcomes is poor. Sub-Saharan Africa (SSA) is particularly vulnerable to this, with 52% of the population currently suffering food insecurity and 14 countries expected to see their populations double by 2050 (IEP, 2020). The story of population growth increasing pressure on land and promoting widespread land cover and land use change, from subtle modification to large-scale radical conversion, has been documented in West Africa (Herrmann et al., 2020) and East Africa (Bullock et al., 2021). The high population density (495/km^2) and growth rate (3%) in Rwanda, for instance, is escalating nexus-land pressures, with land stress jointly undermining nexus security and future ecologically driven sustainable development (Imasiku & Ntagwirumugara, 2020). Similar patterns have also been observed in South America (Zalles et al., 2021) and Asia (Vadrevu et al., 2019).

The consequences of food and energy driven land-use change (e.g., land extensification, infrastructure development) on water supply and stress will also be considerable, with SSA, South Asia, and the Middle East North Africa (MENA) regions being the worst affected. Staggeringly, 90% of freshwater withdrawals in South Asia is for agriculturally based activities (Rasul & Neupane, 2021). Since 1960, the global availability of freshwater per person has been reduced by 60%, and of 157 countries surveyed by the Ecological Threat Register, 34% are predicted to succumb to "catastrophic water stress" by 2050, with the majority located in the Global South (IEP, 2020). Whilst there is a strong emphasis on water availability as part of nexus discourse, water quality is often underappreciated; however, water quality can exacerbate water scarcity issues through additional impacts on human health (IFPRI & VEOLIA, 2015). At the same time, climate-related hazards, which have increased substantially over the last 30 years, will put increasing burdens on nexus resources for the poorest populations, through impacts on infrastructure (e.g., damaged sanitation systems or flooded sewer pumping stations), energy generation disruption, migration, the loss of traditional livelihoods (e.g., pastoralism), and increased frequency of vector and waterborne diseases (UNESCO & UN-Water, 2020). The severity of these events depends to a large extent on several different socio-economic factors associated with water, land, forest, and agricultural management (Lange et al., 2020). Below, we discuss further three key system-wide factors that strongly influence nexus dynamics and are a central focus of nexus research, namely, production and consumption activities, urbanization, and climate change.

4.1. Production and Consumption

4.1.1. Agricultural Systems

Agriculture, which accounts for almost 85% of current water consumption (D'Odorico et al., 2020), will almost certainly have access to less water in the future, as this resource is re-allocated for competing uses (World Bank, 2020). Enhancing agricultural system sustainability is thus critical for ensuring sufficient levels of food production and minimizing water consumption in economies where primary production is a central component of GDP and water stress is significant. For example, irrigated agriculture is essential to meet current and future food demands, but, in water scarce regions such as MENA, irrigation creates unsustainable trade-offs with uses such as drinking and sanitation, and it often exacerbates soil salinization (Besbes et al., 2019; Hamidov & Helming, 2020; Sposito, 2019). A nexus approach focuses attention on how precision agriculture can reduce water consumption and evaporative losses while maintaining yields (Narayanamoorthy, 2004; Rijsberman, 2006). Of course, improving irrigation efficiency on its own is insufficient, this needs to be accompanied by improved management systems, a better understanding of uncertainties, farmer behaviors, and trade-offs (Grafton et al., 2018). Nexus applications also need to be wary of precipitating the so-called "efficiency paradox," in which "saved water" from improved irrigation measures creates demand for water uses elsewhere in the system leading to an overall reduction in water availability (Scott et al., 2014). More comprehensive efforts, such as those of Das et al. (2020) in India, are based on a nexus-sustainability index to reduce the intensity of water, energy, and labor investments in agricultural productivity using crop allocation models. The nexus has also been used to clarify the role of institutions in establishing how agricultural technologies (e.g., upgraded irrigation systems, water harvesting, soil moisture conservation) can be optimized. Management of common pool resources, changed incentives, leveraged financial capital, investments in infrastructure, and more participative engagement are all important in this regard (Jobbins et al., 2015).

4.1.2. Renewable Energy

The energy transition, and the drive toward decarbonization and net zero ushered in by the Paris Agreement, is significantly influencing the traditional nexus configuration and the geopolitics of energy production and consumption, including the scaling up of renewable energy sources to substitute for conventional fuel resources (Hafner & Tagliapietra, 2020). About 3,700 major hydropower dams are currently being planned or under construction, mainly in emerging economies, at a projected cost US$1.9 trillion between 2005 and 2030 (IEA, 2020; Moran et al., 2018); this will raise global hydroelectric output by 73% by the end of the current decade (Zarfl et al., 2015), and it has important implications for the Global South, where opportunities to dam underexploited rivers are substantial and where the potential for nexus synergies and tradeoffs is significant. The Mekong Region continues to be the global hub for hydroelectric projects, mainly due to Chinese investment (Moran et al., 2018). In South America, the Amazon region is expected to see an additional 151 large dams constructed over the next two decades, increasing renewable power generation by 300% (Castillo & Crisman, 2019). It is nevertheless Africa that will likely experience the greatest increase in hydropower generation by 2040, simply to keep pace with the predicted three-fold increase in electricity demand (IHA, 2020). Hydropower already constitutes more than 75% of electricity generation in countries as diverse as Malawi, Ethiopia, and the Democratic Republic of the Congo.

Harnessing rivers to generate hydropower is a globally extensive and significant infrastructure development strategy with considerable nexus-relevant social, economic, and environmental impacts (Moran et al., 2018; Pokhrel et al., 2018). Just in India, increasing the share of renewable energy whilst raising the efficiency of cooling technologies could reduce water withdrawals, water consumption, and carbon intensity by 84%, 25%, and 43%, respectively by 2030 compared to 2014 levels (IRENA & WRI, 2018). It is therefore critical that these installations operate effectively in the context of widespread global environmental change, which poses considerable challenges for large-scale projects to deliver on their energy provision potential (e.g., Jirau and Santo Antonio

Dams on the Madeira River in Brazil only produce a small percentage of the 3 GW originally intended) (Moran et al., 2018). Tackling such issues is an urgent matter if resources are to be utilized sustainably and local needs met (Berga, 2016; IHA, 2019). Here, a nexus approach looks systemically at interdependent factors and can augment strategic approaches by investors and donors to minimize climate risks (Siderius et al., 2021).

Biofuel provision has been expanding rapidly in recent years. Between 2013 and 2019, half of the increase in biofuel production originated from middle income economies in South America and Asia such as China, India, Thailand, Philippines and Brazil (Subramaniam & Masron, 2021). These dynamics have generated several nexus controversies (Benites-Lazaro et al., 2020; Moioli et al., 2018; Wouters & Nagpal, 2016)—many of which concern the conversion of food crops into first generation biofuels—fostering competition for land and water resources, degrading natural habitats and biodiversity (Martinez-Hernandez & Samsatli, 2017), promoting monocultural production, and incentivizing the (over)use of subsidized fertilizers (Rulli et al., 2016). For instance, in Brazil, biofuels produced from oil palm, sugarcane and soy plantations will likely increase as a proportion of the energy economy from 16% to 18% by 2030 to meet both domestic and international energy demands (Sabogal et al., 2016). Government reports suggest that 68% of the Cerrado, an environmentally fragile region of Brazil, is considered suitable for sugarcane biofuel expansion (Benites-Lazaro et al., 2020). Similarly, in China, significant areas of cultivated land have been earmarked for biorefinery feedstocks, with the prospect of significant water consumption (Martinez-Hernandez & Samsatli, 2017). The nexus is finding application to address conventional bioenergy sector silos (Benites-Lazaro et al., 2020), optimize bioenergy supply chains through a whole system approach (Martinez-Hernandez & Samsatli, 2017); and to evaluate the efficiency and sustainability of bioenergy production (Moioli et al., 2018). Although these applications are framed from a technological perspective, they represent important first steps toward a more inclusive approach that incorporates the social-ecological dimensions of bioenergy provisioning.

Of growing importance is solar energy. For example, given the abundance of solar radiation reaching Africa's surface (3.4–6.9 kWh/m^2/day), and following the 82% global decrease in photovoltaic solar panel costs over the past decade (IRENA, 2020), solar electricity generation is forecast to increase across the continent. Micro-solar technology and solar mini-grids present a significant opportunity to power the half a billion people across the continent currently without affordable and reliable electricity access, while utility scale solar parks could add much-needed low-carbon electricity to existing grid networks that primarily rely on fossil fuels. It is forecast that standalone and mini-grid connectivity will contribute 58% of electrification between 2022 and 2030 (IEA, 2022a), emphasizing the importance of decentralized electricity sources. Yet, installing solar infrastructure is not without its challenges. Due to the diffuse nature of solar radiation, significant areas of land are required for ground-mounted solar parks, and this may conflict with existing land uses such as food production (Nerini et al., 2018). Rooftop solar can provide electricity at household levels without requiring such land use change, however ground mounted mini-grids that power entire communities do require this change. As well as the loss of existing land productivity, land ownership and tenure can create conflicts between communities and government bodies (Lomax et al., 2021). These conflicts are often greater in poorer, rural regions compared with wealthier urban regions, where electrification can expand rich-poor divides (Falchetta et al., 2020).

Conflicts between renewable energy and other socio-environmental needs are also prevalent in other parts of the world, for example, Central and East Asia (IEA, 2022c). Meeting the current 2022 renewable energy goal of 175 GW installed renewable energy capacity in India will have required 55,000–125,000 km^2 of land use change (Kiesecker et al., 2020), and the goal for 2030 is almost triple this capacity (Government of India, 2020). Water consumption is another potential source of conflict, particularly in arid regions where solar park managers clean panels with water that may urgently be needed by local farmers for irrigation (Santra et al., 2017). Socio-technical factors are therefore critical when implementing solar infrastructure to ensure maximum nexus benefits and to avoid as many trade-offs as possible between social needs and development goals.

4.1.3. Resource Extraction

Resource extraction is ramping up across the world, especially the mining of non-renewable minerals and metals, much of which is bound up with the global (and Northern driven) energy transition and reconfiguration of the "global socio-economic metabolism" (POST, 2022; Voskoboynik & Andreucci, 2022). For instance, the move toward electromobility will require a 40-fold increase in lithium use by 2040 (IEA, 2022d). Large amounts of minerals and metals from Latin America flow to Europe to support those developments. As such, there continues to be heavy investment in mining infrastructure, particularly in Bolivia, Chile, and Argentina—the so-called

"Lithium Triangle." However, lithium mining has a variety of socio-environmental impacts. Lithium extraction consumes huge volumes of water, whilst also producing chemical residues that negatively affect the environment and the land-based livelihoods of rural and indigenous communities living within the triangle (Agusdinata et al., 2018; Voskoboynik & Andreucci, 2022). This is just one example of an up and coming globally significant nexus development challenge.

However, exploring the social-ecological costs and benefits associated with extractive industry impacts on nexus resource sustainability—via a nexus approach—is still nascent, even though it may be gaining traction. Examples include: examining the impacts of unconventional oil and gas extraction on water scarcity and irrigated agriculture in Argentina (Rosa & D'Odorico, 2019); investigating the socio-economic and environmental impacts of mining on communities and surrounding ecosystems in Suriname (Roy et al., 2016); highlighting how the costs (e.g., increased surface and groundwater withdrawals, heavy metal contamination of watercourses, heighten energy demand) and benefits (e.g., transportation, communication, employment and sanitation and waste infrastructure) of mining extend across sectors and differ over the lifetime of a mine (Huppé et al., 2015), and in Mpumalanga, South Africa, addressing key trade-offs between coal mining and food production (Simpson et al., 2019). In China, the nexus approach has revealed unseen linkages among water, energy and food resources embedded within upstream production and downstream consumption processes for agricultural, manufacturing, construction, power, mining, transport, and services supply chains (Deng et al., 2020), whilst also demonstrating the spatial interconnections between these sectors at the level of provincial supply chains (Liang et al., 2020). Arguably, these examples demonstrate a positive progression in the utilization of the nexus, though equally, they also reveal considerable scope for wider and more extensive applications. For instance, they continually downplay or ignore the value choices underlying industrial extraction activities, or indeed, the social and environmental value consequences of those decisions, even though values—their diversity, synergies and trade-offs—are central to improving sector security (Jenkins et al., 2021).

4.2. Urbanization

Today, more than ever, urban residents are an increasingly influential class of transboundary consumers (Brekke & Brugmann, 2016; You, 2016). The demands of dense concentrations of people generate supply chains that extend well beyond urban administrative boundaries to influence the nexus, giving rise to the concept of the "transboundary environmental footprint" (Ramaswami, 2020; Schulterbrandt Gragg et al., 2018; Sukhwani et al., 2020). Indeed, the strong telecoupling of nexus resource flows from surrounding hinterlands serves as the lifeblood that sustains urban development (P. Zhang et al., 2019). Delhi, India, where 90% of food, 76% of energy, and 86% of water are derived from transboundary sources, is a case in point (Newell & Ramaswami, 2020). At the same time, nexus interdependencies heighten risks for generalized disruptions. For example, heavy erratic rains can trigger a breakdown of transportation infrastructure, resulting in energy generation failure, and hindering the provision of food and water (Romero-Lankao et al., 2018).

Nexus thinking can help manage the heterogeneous impacts of planned and unplanned urbanization across time, space, social groups, and sectors (Heard et al., 2017). This is particularly the case in large watersheds such as the Otun River Watershed and the Pereira/Dosquebradas urban area in Colombia, both of which service urban regions (Torres et al., 2020). Consequently, there have been calls for an "urban nexus" to assess social and material flows between sectors, understand how actors mediate system interconnections, and enhance design, innovation, learning and communication (Covarrubias, 2019; GIZ & ICLEI, 2014). By incorporating material flows and waste into the classic nexus trinity, the urban nexus attempts to improve links between urban planning and the development of a circular economy (Lehmann, 2018). The urban nexus also allows for a more nuanced appreciation of resilient institutional arrangements to encourage social cohesion, stability, good governance, justice, and equality (Schlör, Venghaus, & Hake, 2018), and incorporate health and wellbeing related to "liveable" and "inclusive cities," as highlighted by the World Health Organization's "Healthy Cities Initiative" (Newell & Ramaswami, 2020; Ramaswami, 2020).

The nexus has found wide application in guiding new infrastructure investments, climate-smart development models, low-carbon urban management, green building monitoring programs and reducing fragmented land use planning (Brekke & Brugmann, 2016; IPCC, 2019). Examples include the Carbon Bank System in Gwangju, South Korea, which encourages households to reduce greenhouse gas emissions by saving energy and water; and Estidama in Abu Dhabi, which is focused on smart green urban technological design to reduce energy and water usage (You, 2016). In this context, the role of green and blue infrastructure in mediating nexus interactions within cities to foster inclusive pathways for development will be increasingly important, especially in urban Africa and Asia (Bellezoni et al., 2021).

Initial approaches to combine nexus sector analysis with urban growth models are now underway (N. B. Chang et al., 2020; Li et al., 2017), as are efforts to characterize urban nexus indicators for resilience and sustainability in relation to resource flows, efficiency, cross-city supply chains, and environmental impacts (Arthur et al., 2019; P. Zhang et al., 2019). The development of smart cities also promises to improve the efficient utilization of nexus resources through enhanced data coverage, granularity, and analytics. For example, in Nagpur, India, city-wide data gathering has enabled administrators to better understand demand and consumption dynamics (Sukhwani et al., 2020), whilst in Rio de Janeiro, Brazil, Big Data analytics and cross-city data sharing have enhanced integrated risk management and action (You, 2016). The nexus can help foster preemptive planning for informal settlements, drive in-situ upgrading, and legitimate multiple forms of iterative, adaptive, and collaborative multilevel governance (Chirisa & Bandauko, 2015). Nonetheless, there has been a tendency for the urban nexus to focus on the physical resilience of urban systems, paying less attention to social vulnerabilities at the household and user levels, especially of marginal communities, and everyday practices such as cooking, heating and recycling. Projects such as the ResNexus program counter this trend by emphasizing a bottom-up perspective on the urban nexus (Mguni & van Vliet, 2020).

4.3. Climate Change

Climate change is arguably the world's most serious 21st century challenge, as Rasul and Sharma (2016) state: "Effective adaptation to change requires the efficient use of land, water, energy, and other vital resources, and coordinated efforts to minimize trade-offs and maximize synergies" (p. 682). Such studies are also vital to avoid, as Lazaro et al. (2022) put it, "future conflict and how political and social stability are significantly correlated with food-water-energy security" (p. 5). The use of nexus thinking to reveal vulnerabilities and risks and enhance resilience to shocks triggered by climate change is consequently growing.

Conway et al. (2015) observe that the connections between nexus sectors and climate are especially strong in Southern Africa, particularly with regards to spatial interdependencies and physical and socio-economic exposure. These connections are visible as decreases in crop yields, livestock deaths, rising incidences of vector and waterborne diseases (e.g., malaria, dengue, cholera) and a myriad of knock-on effects on rural livelihoods, health, and wellbeing. Across Africa more generally, the application of the nexus to climate change has been used to inform long-term water availability strategies in the Niger River Basin (J. Yang et al., 2018); examine the vulnerability and resilience impacts of the confluence of climate, oil, and food price shocks on water institutions and initiatives in Kenya (Wakeford, 2017); demonstrate how different priorities and pressures placed on the energy sector undermine efforts to climate proof water and agriculture sectors in Tanzania (Pardoe et al., 2018); and assess how hazards, such as chronic droughts, may affect the long-term viability of infrastructure developments in Tanzania and Malawi (Siderius et al., 2021). In an international comparative manner, the nexus has also been employed to assess the adaptive capacity of ecological networks to climate change in South Korea and Southern Africa (Holtermann & Nandalal, 2015), and used to improve risk-based decision-making in ecosystems as disparate as the Himalayan mountains and Southeast Asian coastal mangroves (Stringer et al., 2018). In these contexts, but with particular reference to Africa, the nexus approach has been hailed as a means to harmonizes priority intervention areas and encourage policy convergence, resource mobilization and the mitigation of trade-offs (Mabhaudhi et al., 2019; Mpandeli et al., 2018; Nhamo et al., 2018).

5. Sustainably Managing WEF Systems for 21st Century Development Challenges

Sustainable development is an increasingly central pillar of nexus discourse (Bhaduri et al., 2015; de Andrade Guerra et al., 2021), which intertwines SDGs for food, water and energy and integrates them across environmental goals for climate action, life below water and on land, and socio-economic goals related to industry, innovation, infrastructure; cities and communities; and responsible production and consumption (Fabiola & Dalila, 2016). The connections between the nexus and SDGs are increasingly manifested through a variety of metrics. These include mapping the nexus onto the SDGs to assess research, innovation, and policy impacts on resource management (Saladini et al., 2018); assessing synergistic or antagonistic interactions between economic development and basic resource needs (Fader et al., 2018); correlations between the WEF Security index and key SDGs (Cansino-Loeza et al., 2020), imbalances in sectoral structure and upstream/downstream basin level resource flows (Qin et al., 2022). That said, whilst these approaches have strong utility, they remain largely quantitative and technocratic in orientation.

Nexus and sustainable development relationships have nevertheless been expressed in relatively diverse ways, for instance, in terms of sustainability-security interactions (Gallagher et al., 2016; Mayor et al., 2016); trade-offs and synergies between nexus SDGs (Fader et al., 2018; van Zanten & van Tulder, 2021); the exploration of social, economic and environmental co-benefits (Carmona-Moreno et al., 2019); material resource nexus interlinkages between SDGs (Bleischwitz et al., 2018); or developing sustainability indicators for mapping interactions (Cansino-Loeza et al., 2020; Nhamo et al., 2020; Saladini et al., 2018). In other cases, the nexus is combined with other frameworks, such as planetary boundaries for sustainable resource consumption (Hua et al., 2020); a sustainable livelihood's approach (Biggs et al., 2015) or circular economy and life cycle approaches (Bleischwitz et al., 2018; Davis et al., 2016).

These exploratory modalities articulate the nexus as a site of dynamic social innovation and indicate its potential for radical social change. However, the success of the nexus in these contexts is very much dependent on broader societal uptake (Tevar et al., 2016), as well as legal structures and architectures that modulate incompatibilities between sectoral objectives, institutional capacities, resource constraints, and rule linkages (Olawuyi, 2020). Considering other developmental agendas, there is strong resonance between the nexus and the African Union's Agenda 2063. For example, in 2017, the African Union, together with the New Partnership for Africa's Development, the African Development Bank, and the UN Economic Commission for Africa, launched the US$10 billion water fund for infrastructure projects which foster a WEF nexus approach by building robust, competitive, and climate-resilient economies, inclusive socioeconomic development, and better livelihoods (Paul, 2018). However, suitably managing nexus systems within a development context is highly challenging. Reflecting on that fact, via our engagement with the literature, we summarize seven "challenge areas"—distilling their core arguments—where the nexus is and should continue to engage to deliver sustainable nexus systems.

5.1. Developing Credible Governance Architectures to Support Nexus Systems

A core focus of sustainable development, as exemplified by SDG 16, is governance. Indications are that "nexus governance" is starting to be addressed along eight major thematic lines: water and basin; environmental and systems; risk and resource security; economic governance; global; urban; integrative and cooperative; and epistemic and transdisciplinary (Urbinatti, Benites-Lazaro, et al., 2020). Theoretical discussions of nexus governance have advanced innovations, nonetheless progress is slower than expected and practical applications are not commonplace. Although effective governance is a precondition for responsible development and environmental sustainability, the "governance gap" persists (Abbott et al., 2017; Al-Saidi & Elagib, 2017; Leck et al., 2015; Oliver & Hussey, 2015). There remains a need to break institutional silos to ensure more integrated management and policymaking, centered on collaboration, regular communication, centering on complementarity and trade-offs (Artioli et al., 2017). There have also been calls for a "meta-governance approach" to coordinate governance across different sectors and jurisdictions, ensure coherence and enable a deliberative approach (Oliver & Hussey, 2015). However, this continues to be hampered by sectoral barriers, regulatory frameworks, and competing institutional interests, especially those represented by the state and the market (Al-Saidi & Elagib, 2017; Leck et al., 2015; Pahl-Wostl, 2019; Weitz et al., 2017). Systematic approaches to governance are necessary, particularly for water, which is frequently seen as the lynch pin in the nexus system, where availability, access, quality, and quantity are inextricably linked to and embedded within land, food, and energy systems (de Loë & Patterson, 2017; Rasul & Neupane, 2021; Rasul et al., 2021).

Nexus literature often reflects a simplified and technocratic view of governance that emphasizes how policy and regulatory instruments can be wielded to achieve desired goals. More deliberative forms of governance, participatory pluralism, power and inequalities are usually downplayed (Weitz et al., 2017). Attention is consequently shifted away from issues related to resource scarcity, food security, access to and distribution of other nexus commodities and ownership rights to collective resources, especially those transferred or shared across borders (Allouche et al., 2015; Dombrowsky & Hensengerth, 2018; Liu et al., 2018). Jurisdictional, power and policy issues all play into these dynamics, which tend to generate undesirable tradeoffs by creating winners and losers (Ringler et al., 2013). Williams et al. (2014) have commented on these issues, criticizing the technocratic nature of existing analyses and calling for a social and political science perspective to resolve interactions between different sectors that are "hotly contested, reflective of struggles between interest groups, and always develop through the exercise of political and economic power" (1). Nevertheless, the role of good governance in modulating resource outcomes (Galaitsi et al., 2018) to avoid winners and losers or reinforce prevailing interests, and achieve desirable change across the nexus, is far from the norm (Keskinen et al., 2016).

Simply stated, there is still scant evidence that nexus principles are being advanced from theory to practice. In part, this flows from overlooking the socio-political and economic features of the nexus in favor of physical and natural science dimensions (Albrecht et al., 2018; Artioli et al., 2017; Srigiri & Dombrowsky, 2022). This has led some to argue for greater "epistemic pluralism" and a need to shift away from quantitative, technocratic formulations and a "scientific managerialist" approach (Urbinatti, Benites-Lazaro, et al., 2020; Wiegleb & Bruns, 2018). Moving beyond a "positivist" approach and refocusing on the political dimensions of the nexus can strengthen the linkages between science and public policy (van Gevelt, 2020). As Fontana et al. (2021) remark, "critical social science researchers have a key role to reveal power dynamics" (p. 6). This argument is further bolstered by suggestions that nexus governance needs to undergo a complete reconfiguration, due largely to its history of underplaying the need to redistribute centers of power and overstating the validity of certain knowledge perspectives (Urbinatti, Fontana, et al., 2020).

Responsive governance regimes are critical for managing nexus systems at all levels, although in many contexts this is far from the case. Four factors seem significant: property rights; policy design; financing; and scale. Collectively, these are considered necessary for enabling appropriate institutional management, technological innovation, and community development (Davis et al., 2016). A fifth factor is mitigating against the risks posed by highly interconnected and integrated resource systems, where problems are often confounded by international boundaries (Ho, 2018) and can easily spread from one sector to the next (de Amorim et al., 2018; Taherzadeh et al., 2018). This is essential for developing evidence-informed, robust public policy geared towards sustainability (de Andrade Guerra et al., 2021; Smajgl, 2018).

The above issues have motivated a push to understand nexus governance through a polycentric or multi-level lens (Pahl-Wostl, 2019). This focuses attention on four key attributes of governance, namely: scale of fit (appropriateness of planning and management architectures to nexus temporal and spatial sector dynamics); scale of strategies (the degree of contestation or negotiation in arenas where actors are engaging); institutional interplay (the extent of influence of different sector rules and norms on each other) and scale of uncertainty (uncertainties in governance outcomes arising from the complexity of nexus systems) (Pahl-Wostl et al., 2021). This argument has been further bolstered by the polycentric analysis of nexus systems by Srigiri et al. (2021) in Ethiopia's Awash River Basin and Dombrowsky et al. (2022) in Jordan's Azraq Basin, culminating in the development of a polycentric conceptual framework for nexus governance (Srigiri & Dombrowsky, 2022). Based on Ostrom's Institutional Analysis and Development framework (Ostrom, 2005) and the idea of networked action situations, Srigiri and Dombrowsky (2022) argue that these concepts improve the ability to "understand the relations and interactions among constituent decision centers" and "to investigate the conditions under which different types of interactions emerge among the decision centers" (p. 11).

5.2. Addressing Power and Agency Imbalances in Nexus Systems

Politics, power and social justice are central to shaping the sustainable and equitable management and governance of nexus systems in support of human livelihoods and prosperity. Power, influence, and agency of nexus actors, as well as the externalization of human and environmental impacts, are essential to address sustainable resource management and livelihoods, but they remain poorly described (Allouche et al., 2019; Wiegleb & Bruns, 2018). The development of polycentric nexus governance analysis, with its focus on actor interactions, behaviors and the multifaceted context in which decisions are made and unfold, offers a powerful means to reveal underlying power dynamics at play (Srigiri & Dombrowsky, 2022).

The political and economic dimensions of "power-in-knowledge" can be especially challenging (Urbinatti, Fontana, et al., 2020), but as shown by Johnson and Karlberg (2017), one tool to try and tackle these dimensions is participatory scenario planning. This approach was successfully employed in Ethiopia and Rwanda to co-produce future development pathways to achieve joint social-ecological sustainability across nexus sectors, making explicit synergies and tradeoffs, and a forum to explore opportunities to mitigate risks and flexibly adapt to changes. Crucially, the stakeholder-owned process enhanced the quality and legitimacy of the outputs, whilst the deliberative elements facilitated more effective co-decision-making. More often, however, as illustrated by construction of the Xayaburi dam in Lao PDR, private investors are not hesitant to use their power to reconfigure the dynamics of cross-border river basin management. The case further highlights how actor networks are shaping the "hydro-hegemony" of the Lower Mekong Basin through the exercise of authority and exploitation of power asymmetries (Dombrowsky & Hensengerth, 2018; Hensengerth, 2015).

Power politics and political gaming usually benefit actors that can build political alliances, sidestep weak governance systems, and leverage significant financial pressures (e.g., foreign exchange reserves, foreign direct investment, and trade packages). The result often decimates local livelihoods, circumvents social justice, and compromises environmental quality. Unfortunately, there seems to be no shortage of examples of these dynamics, as illustrated by Thai investments in hydropower in Lao PDR (Mathews, 2012), Chinese state-owned enterprise investments along the Upper Mekong River (Mathews & Motta, 2015), and Chinese hydropower investments more broadly across Asia and Africa (Siciliano et al., 2019). Work in Colombia, on payment for ecosystem service programmes, also highlights these types of power dynamics and has led to calls for the "politicizing" of the nexus "to trace both the flows of resources and the flows of power" (Rodríguez-de-Francisco et al., 2019, p. 1).

The combination of power and influence need not to be hard and direct; it can also be soft and persuasive. The Mekong River Commission has shown itself to be adroit at deploying a nexus security narrative to curtail unilateral decision-making by its member states. It does so by framing uncoordinated and non-cooperative economic development in the basin as the progenitor of potential calamities to regional nexus systems (Gerlak & Mukhtarov, 2016). In this regard, narratives can be both pro- and anti-development, but are most frequently shaped in the Mekong Region through an individualistic pro-development lens. This stance attempts to "de-politicize the nexus" and advocates a neoliberal position of free markets, business innovation and top-down technocratic managerialism (Lebel & Lebel, 2018). Chinese policies toward hydropower developments in the Mekong exemplify this approach, by deliberately crafting narratives that undermine nexus interconnections and associated trade-offs in the hope of securing future preference for Chinese investments (Mathews & Motta, 2015).

Purposeful action and transformative change are necessary to overcome entrenched positions and centers of power (Pahl-Wostl, 2019). The "nexus of humility" framework provides one avenue for addressing some of these difficult and sensitive political challenges. This framework focuses on framing (considering assumptions, cross-sectoral challenges, resource and environmental interconnections, and actor assemblages); vulnerability (historical legacies and path dependencies of resource access, perceptions of marginalized groups, and social connectivity of the resource chain); distribution (costs and benefits of how water energy and food can impact lives and livelihoods, emphasizing transparency and accountability); and learning (reflexive and collective dialogs) (Urbinatti, Fontana, et al., 2020). The reality, however, is that it remains untested in any meaningful political and decision-making arena concerning nexus governance, and so as yet it is difficult to foresee the extent to which it will be used beneficially.

5.3. Advancing Community Involvement in Nexus Resource System Decision-Making

Prioritizing and incorporating local community actors and voices in the governance of nexus systems is central to assuaging their marginalization, improving livelihood security, and enhancing decentralized and representative decision-making processes. Understanding the lived and embodied experiences of nexus realities is essential (Bruns et al., 2022). This lies at the heart of the central principle of the SDGs, namely, "leave no one behind." Local communities are underrepresented in nexus research and practice and are not central to nexus decision-making, while ultimately bearing the brunt of nexus resource management decisions that inevitably influence community livelihoods, social cohesion, and cultural and social capital (Biggs et al., 2015).

In the Upper Blue Nile basin of Ethiopia, large-scale water infrastructure developments have accelerated social disintegration, further undermining the livelihood security of already marginalized communities (Gebreyes et al., 2020). In Brazil, 56 hydropower plants constructed between 1991 and 2010 did not significantly improve key social indicators, suggesting that the original developmental justification for these large-scale and substantive investments was not fulfilled (de Faria et al., 2017). At the same time, the socio-economic, cultural, and political impacts of water and energy infrastructure developments on those living nearby are routinely underestimated. Dam and reservoir construction, by modifying land systems, which may include land submergence,

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shrinks productive farmland, reduces the availability of fish used for food, and may trigger other deleterious shifts in the nexus (Dorber et al., 2020; Rufin et al., 2019; Winemiller et al., 2016; Zarfl et al., 2019). Millions of people are frequently resettled or have their livelihoods disrupted due to dam construction and operation, without adequate compensation or recourse to influence planning (Moran et al., 2018). An international analysis of dam-related conflicts found that assassinations, repression, and criminalization were commonplace activities affecting local communities (Del Bene et al., 2018). Similar logic applies to other types of large-scale infrastructural developments (Juffe-Bignoli et al., 2021; Thorn et al., 2021).

The connection between livelihoods and nexus resources is sometimes narrowly defined. Local community perceptions of nexus resources in the Ethiopian Rift Valley, for example, are framed through specific lenses, such as food (Wolde et al., 2020). Similarly, in the Mekong basin, the influence of dam construction on local livelihoods is often framed in terms of food resources (Pokhrel et al., 2018) - thereby missing the interconnections between other resource elements. However, drawing inspiration from political ecology, Bruns et al. (2022) argue the need to understand peoples' everyday practices in relation to nexus infrastructure (i.e., their agency and how they create, stabilize or alter nexus configurations). Here, the nexus is continually in the making, and inequalities and insecurities are revealed and shaped by the entanglement between the social and material worlds of peoples' lived experiences.

Although nexus impacts have commonly been viewed in terms of rural livelihoods, rapid urbanization, especially in the Global South, is shifting this perspective. Again, the Mekong Region is a case in point. Rapid urbanization has radically transformed environmental resource flows, ecologies, demographics, and socio-economic outcomes (Friend et al., 2015) and increased strain on resources in coastal China (Niva et al., 2020). These transformative processes are dependent upon interlinked WEF systems that shape key risks and vulnerabilities faced by local and poorer urban communities (Friend et al., 2015).

Reprioritizing local community involvement in nexus decision-making, while strengthening decision-making capacities and engagement is a means to address discontinuities of power, agency, and representation (Laohasiriwong & Oishi, 2020). The reality, however, is not always straightforward, especially where purposeful community disruption is employed to repress opposition to infrastructure developments (Moran et al., 2018). Public participation and consultation processes are often orchestrated as technical exercises that eschew local concerns (Thorn et al., 2021). Growth in alternative participatory spaces and external accountability, as precipitated by civil society and activist movements such as the Save the Mekong Coalition, holds promise to counteract these forces (Yong, 2019).

5.4. Managing Transboundary Nexus Resource Systems

Developing effective transboundary governance regimes is central to the future management of large-scale cross-national nexus systems, but coordination and collaboration across political and economic divides continues to pose fundamental challenges. The potential for conflict and competition is most acute when resources transcend administrative boundaries (Nunan, 2018). The shared Mekong River basin, which spreads across portions of China, Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam, provides a clear example of such complexity. "Waterscapes" of the Mekong are highly contested due to the multiple conflicting interests and worldviews of intra-and inter-nation state actors, further crystallized by differences in wealth, resource endowments, environmental integrity, regulatory enforcement and political openness - despite an increase in cooperative rhetoric emphasizing poverty alleviation and benefit-sharing (Dore et al., 2012). For instance, medium-to large-scale water infrastructure projects have illuminated several problems including simplified state-level planning; poor ministerial coordination; ineffectual, often energy-specific development plans; and the general exclusion of marginalized groups from decision-making processes which are themselves highly opaque (Keskinen et al., 2016; Lebel et al., 2020). There remain incompatibilities between and within China and the Lower Mekong Basin countries; and communities and "development" interests (Laohasiriwong & Oishi, 2020). Incompatibilities mediated by physical exclusion and economic constraints can significantly undercut the possible benefits of energy supply gains for intended beneficiaries - as shown from agent-based modeling of hydropower infrastructure construction on rural population wellbeing (Bazzana et al., 2020). In this vein, the nexus is an adept device for exposing systemic fault-lines along the Mekong, but this has not yet led to effective coordination across the basin.

Coordinating a diverse assemblage of actors operating at different scales and subject to differing drivers and vulnerabilities is challenging (Nunan, 2018). Accounting for both the geographic resource features (e.g., a river basin) and the operational and legitimized domains (e.g., economic, governance, legal, jurisdictional, business) of all actors is critical to the successful utilization of the nexus in transboundary contexts (Abulibdeh & Zaidan, 2020; Olawuyi, 2020). Effectively utilizing a nexus approach requires ownership by relevant actors to drive implementation, while overcoming resource constraints that dis-incentivize collaboration due to issues around cost recovery, free-riders and ensuring future budgets (Pardoe et al., 2018). Advancing from coordinated to collaborative forms of country-level cooperation and engagement between Ethiopia and Sudan improved economic gains across nexus sectors in the Blue Nile Basin (Basheer et al., 2018). In the Mekong, transboundary nexus water governance, in contrast to integrated water resource management, provided clearer management entry points, more comprehensive perspectives on key resource issues, and expanded opportunities for interdisciplinary and multi-sector deliberations (Dore et al., 2012; Keskinen et al., 2016). Nonetheless, transboundary nexus issues in the Global South still represent a small portion of the literature and discussions are often limited in geographical scope.

Frequently, narratives connect to the idea of the nexus as having "transformative potential," which advocates trans- and interdisciplinary approaches to foster collaboration, cooperation, and improved governance (Cai et al., 2018; Dodds & Bartram, 2016; Kurian, 2017; Pahl-Wostl, 2019; Scanlon et al., 2017). One means of enhancing cooperation and coordination, whilst reducing conflict, is co-creating an operating landscape under an approved set of principles (e.g., legitimacy, transparency, accountability, inclusiveness, fairness, integration, capability, adaptability) (Nunan, 2018). Equally, such moral principles need to be embedded within legislation, rule linkages, and information sharing networks (Olawuyi, 2020). This can be seen as part of a move toward bringing together nexus governance and so-called "water diplomacy" to address transboundary complexities (Salmoral et al., 2019). For example, the Mekong River Commission exemplifies the development of a principles-based approach to intergovernmental cooperation for water resources (Dore, 2014). That said, as Dombrowsky and Hensengerth (2018) demonstrate, the effectiveness of such organizations can nevertheless be undermined by unilateral state investment decisions, mixed information on project impacts, and donor and private investor funding requirements.

5.5. Supporting the Integrity of Social-Ecological Systems

A nexus approach provides decision makers for social-ecological systems (SES) with practical insights into the impact and importance of global drivers of change (e.g., climate change), especially on watershed management (e.g., Masood & Takeuchi, 2016; Piao et al., 2010; Shrestha, 2014). The assumption, valid in some instances and not in others, is that these insights are synergistic and will lead to socially equitable outcomes (Lawford et al., 2013). The nexus has shown promise in illuminating conflicting priorities across SES at the level of various competing sectors: hydropower versus irrigation (Zeng et al., 2017), food versus water (Terrapon-Pfaff et al., 2018), upland farmers versus downstream fishers in the Philippines (Spiegelberg et al., 2017), and proposing sugarcane for food *vs.* biofuel in Brazil (Benites-Lazaro et al., 2020) and Ethiopia (Mekonnen et al., 2017). The social elements of SES are important, as, for example, in the Pangani Basin (shared by Tanzania and Kenya), where farmers self-organize into co-operatives to address issues such as marketing, welfare, education and social work. Here, the notion of the WEF "complex" has been introduced to denote the idea of communities as organizational structures and social entities that continually engage with the nexus in an ongoing recursive fashion (Harwood, 2018).

Nexus approaches can focus attention on mitigating the degradation of SES. Examples include improving resource use efficiency via less carbon-intensive energy systems in Southeast Asia, the Pacific region (Lehmann, 2018; Taniguchi et al., 2017) and Taiwan (Chen et al., 2020), and more generally with respect to hydropower (Lawford et al., 2013; Ringler et al., 2013; Y. C. E. Yang et al., 2016; C. Zhang et al., 2018; X. Zhang et al., 2018) and geothermal energy (Wakeford, 2017). In other resource management contexts, it has also been used to articulate inefficiencies (Cremades et al., 2019), and highlight resource stress co-dependencies and environmental degradation (Mukuve & Fenner, 2015) in relation to agricultural irrigation systems (Hamidov & Helming, 2020; Mabhaudhi et al., 2018; Ngammuangtueng et al., 2019), fertilizer runoff (Reddy et al., 2018), livestock production and waste (Neto et al., 2018), soil salinization (Lawford et al., 2013), and land use trade-offs within and between rural and urban systems (Loy et al., 2017).

Crucially, as the demand for natural resources grows, nexus thinking has the capacity, if properly applied, to help identify potential thresholds and tipping points and internalize externalities to improve resource efficiency (Simpson & Jewitt, 2019; Waughray, 2011). The benefits of this approach, pertinent to agricultural intensification and sustainable water use in the Global South, are expected to be considerable (Holtermann & Nandalal, 2015; Y. C. E. Yang & Wi, 2018). Consider the application to water provision technologies such as desalination to reduce water insecurity in the face of climate change, particularly in the MENA region (El-Sadek, 2020; Pistocchi et al., 2020). In Saudi Arabia, 80% of drinking water is estimated to be supplied via desalination (Grobicki, 2016), whilst in Qatar it is 99% (Wouters & Nagpal, 2016). Taken at face value, this would seem a straightforward path to follow. However, the deployment implications of new technological infrastructure has to be evaluated in the wider context. For instance, desalination is costly, energy-intensive with the potential to contribute to higher GHG emissions, vulnerable to volatile energy markets, disturbs the environment and can lead to tensions when rolled out (Wouters & Nagpal, 2016). In this and other contexts, as Smajgl et al. (2016) argue, the nexus offers a "new paradigm" to shift away from a hydro-centric approach of water management, to what "water can do for society." From this perspective, the synergies necessary to catalyze regional development through joint investments in energy projects, resource sharing and water conservation, as exemplified by the Southern African Development Community (Conway et al., 2015; Nhamo et al., 2018), are consequently unlocked whilst also driving trans-boundary benefit-sharing (Saidmamatov et al., 2020).

5.6. Unveiling the Globalization of Nexus Resource Systems

Many food, energy, and manufacturing industries and supply chains are global in nature, utilizing and transforming capital assets, such as human and natural capital, from different countries and geographies across the world. Focusing on value chains, a nexus approach can improve equity and distributional access by helping to determine the spread of costs and benefits from producer to consumer across the supply chain. It may reveal differences in consumption patterns and resource use intensity within and between countries, alongside material resource flows across sectors and interactions between SDGs (Bleischwitz et al., 2018). For instance, in Sub-Saharan Africa, a nexus approach was applied to the charcoal value chain to demonstrate that the production cycle has different nexus impacts, whilst also identifying possible solutions across technical, political, and institutional domains (Hoffmann et al., 2017).

Combining nexus thinking and global production network approaches makes it possible to identify extra-regional and international environment-society interactions via nexus trade linkages (Franz et al., 2018). This is particularly important in the context of water scarcity and the trade in virtual or embedded water, especially for water stressed developing countries. The movement of water from water-abundant regions to water-scarce regions can be instrumental in managing the lack of available water. Work by Kashifi et al. (2022) has shown that for Saudi Arabia, importing certain crops (maize, wheat and rice) could significantly reduce the local water footprint, energy costs and greenhouse gas emissions. Indeed, virtual water trade in maize from Argentina has helped other water scarce nations meet their water security and water-dependent food security needs (Arrien et al., 2021). Human labor and social wellbeing are also a significant component of these trade networks. In Colombia, a WFL nexus configuration has been used to assess the domestic trade connections between virtual water trade and virtual informal labor flows across administrative units and economic sectors, in order to examine the consequences of food production on water use, food security and social outcomes (Distefano et al., 2022). This analysis revealed both significant income inequality and fragile informal work conditions within the food production sector, and the reliance of rich departments such as Antioquia and Bogotá on the supply of food and virtual water from rural departments at the cost of exposing those regions to increased water stress.

This raises questions of fairness. Nexus approaches offer opportunities to address equity, access, transparency, and differentiated demands among public, private, and civil society in green growth initiatives and ethical value chains that attempt to link smallholders to markets. Such approaches help to enhance cooperation among actors and institutions, collective governance, policy coordination and cross-resource optimization from production to consumption (e.g., land-based utilization, virtual water trading) (Koulouri & Mouraviev, 2019; Sharma & Kumar, 2020). Together with transdisciplinary and ecological modernization approaches, the nexus provides a pathway to develop more sustainable supply chains (Bergendahl et al., 2018). However, this requires more discussion regarding the hegemonic globalizing forces shaping trade and supply chains that influence considerably developmental outcomes across the Global South. For instance, Northern acquisition of Southern resources and labor, sometimes referred to as "imperialist appropriation" or "plunder," which has a long colonial history and a legacy that weaves its way through the post-colonial era, stems mainly from processes of unequal exchange underwriting global commodity chains (Hickel et al., 2021). Shockingly, during the period 1990–2015, the appropriation value of resources and labor moving from South to North has been estimated at around US$242 trillion (Hickel et al., 2022). Today, some argue such "imperialist" appropriation continues and not only via North-South pathways but increasingly through South-South relations. The impact of Chinese foreign direct investment in Africa, driven by the belt and road initiative, observed in large scale linear infrastructure projects in Kenya for example, on both biodiversity and local communities, is colossal (Thorn et al., 2021). These issues, however, which are hugely significant for nexus sustainability and uneven development, continue to remain on the fringes of mainstream nexus research.

5.7. Financing and Capacitating Nexus Systems

Financing is key to addressing future nexus infrastructure needs, irrespective of the institutional approach. It is nevertheless difficult to segregate these costs from those associated with more general infrastructure requirements, which are substantial. The Asian Development Bank estimates that by 2030 Asia will need to invest US$1.7 trillion/yr just to maintain present growth trends, and concerted efforts to tackle poverty and climate change. China and India account for over 50% of required global infrastructure investment by 2040 (GIH, 2017). Lack of sufficient public infrastructure investment means that Latin America and the Caribbean will need to spend 5% of the region's GDP over the next 30 years (US$100 billion/yr) (Izquierdo et al., 2018). In Africa, the nexus has a significant contribution to make to achieve universal electricity access by 2030 which will require c. US$30 billion/yr in energy infrastructure (RES4Africa, 2019), with US$35 billion/yr to secure safe drinking water, sanitation, and hygiene (Hutton & Varughese, 2016). In the MENA region, by 2050 water infrastructure is estimated to require between US$27 and 112 billion—depending on the climate scenario. In these circumstances, the planning of joint water, energy and food investments would benefit from the systematic analysis of interactions between the different sectors to determine the necessary degree of integration required (Payet-Burin et al., 2021).

Although required nexus investments are often estimated geographically, globalization is triggering important international ramifications. For instance, several MENA state-capital alliance entities have bought farmland abroad to offset growing water and land scarcity; China and Singapore (Akyeampong & Fofack, 2019; B. Yang & He, 2021) have also taken this approach, promoting land grabbing that displaces local farmers and leads to hydro-political conflicts (Hanna, 2020). These issues are especially acute in Africa and Asia, which account for 47% and 33% of the global grabbed area respectively, with major implications for energy and water sector security (Rosa et al., 2021; Rulli et al., 2013). If water-energy-food resources are used inefficiently this can lead to key knock-on vulnerabilities in systems, for instance, in transport and manufacturing. This can have severe implications on the bankability and creditworthiness of projects, the brand reputation of companies, servicing and monitoring requirements, the social license to operate—all which affect the ability to mitigate risks in the future (UNEP, 2021b). Plainly, nexus investments need to take these factors into consideration to ensure they deliver, rather than undermine, equitable sustainable development. Climate finance is starting to recognize this, with associated safeguard measures and new metrics, financial flows of the World Bank are aligning with the Paris Agreement. Sustainable Finance is another tool for raising capital in support of private sector climate goals on emerging markets, through use-of-proceeds, such as green, social, or sustainable bonds, or through target-driven instruments, such as sustainability-linked bonds (UNEP, 2021a). While these initiatives are promising, the scale of funding currently committed to such mechanisms is far from what is needed, and the interconnections between the nexus factors continues to be side-lined in infrastructure planning and design.

6. Future Research Directions

To maintain momentum and maximize the positive contribution of the nexus to sustainable development across the seven challenge areas outlined in Section 5, we offer 10 emerging and underexplored avenues that we believe are necessary to undergird those developments and should be an increasing focus of nexus research going forwards:

1. Address the impacts of nexus developments on human rights, environmental justice and just transitions (da Silva et al., 2020);

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2. Identify more inclusive stakeholder participatory and deliberative decision-making processes to provide plural insights and shared understandings (Cabello et al., 2021; Fontana et al., 2021; Lazaro et al., 2022; Naidoo et al., 2021);
3. Configure nexus systems to aid a green recovery as part of the "build back better" narrative from the COVID19 pandemic (Al-Saidi & Hussein, 2021; Durodola et al., 2020);
4. Define nexus interventions that emphasize system interconnectedness and lead to long-term and sustainable human and environmental health (Nhamo & Ndlela, 2021);
5. Investigate the probabilities and consequences of compounding nexus shocks on human migration and displacement (Daher et al., 2021), broadening the scope of the nexus to intersect with what has been termed the "disaster risk, global change, and sustainability nexus" (Peduzzi, 2019);
6. Understand how nature-based solutions and green infrastructure and associated green finance can enhance the climate resilience and adaptive capacity of nexus systems (Bellezoni et al., 2021; Hogeboom et al., 2021; Muthee et al., 2021);
7. Institutionalize nexus thinking into governance systems at multiple scales, advancing a polycentric approach, for improved policy integration, cross-sectoral planning and coordination for sustainable development (Lazaro et al., 2022; Mabhaudhi et al., 2021; Rasul & Neupane, 2021; Rasul et al., 2021; Srigiri & Dombrowsky, 2022);
8. Explore how to close the gender gap in access to nexus resources and their management, decision-making capabilities, and social relations (Purwanto et al., 2021; Villamor et al., 2020);
9. Seek insights from retrospective forms of nexus management or "ancient WEF," that can be adapted to our modern-day nexus challenges (Pueppke, 2021);
10. Utilize frontier data science technologies, such as Big Data and AI, and expand the use of geographic information systems (GIS) and remote sensing, to fully integrate multi-source, multi-temporal, and multi-scale georeferenced data into nexus planning and implementation (Pitts et al., 2020; Taguta et al., 2022).

7. Conclusions

Little more than a decade after it was first conceived, the nexus is still finding its feet. While it has grown, it remains to some extent an immature and contested paradigm. Contributory factors include its multi-dimensional character, the variety of circumstances to which it is applied, its primarily natural and physical science treatment, definitional and conceptual ambiguities, and its patchy application from local to global scales in policy and governance arenas (Purwanto et al., 2021). This has led some to suggest that the nexus is still not fully realizing its potential, and instead continues to offer more of a partial framing that is insufficiently holistic, policy-relevant, and inclusive (Endo et al., 2017; Liu et al., 2018; Pandey & Shrestha, 2017). For others, the lack of empirical data that sufficiently captures the diversity of resource-use dynamics across sectors (Endo et al., 2015; C. Zhang et al., 2018; X. Zhang et al., 2018) has called into question the usefulness of the concept and approach altogether (Wichelns, 2017). Although we would not go this far, our analysis nevertheless corroborates many of the above criticisms as they relate to the Global South. It is in the Global South and developing nations where the nexus arguably has its greatest utility - bringing much-needed attention to overlooked regions with more acute nexus problems and offering locally relevant recommendations and solutions (Sušnik, 2022). We strongly concur that a conscious effort must be made to pluralize the debate and encourage multi-perspective voices via participatory practices that focus on empowerment, citizen participation and accountability, and deliberation (Alsop et al., 2006; Dryzek & Pickering, 2017; Kenter et al., 2016).

In parallel, harmonization of technical perspectives with socio-economic approaches will be required. Using the Global South as exemplar, we have spotlighted nuance in the evolution of the nexus concept, the increasing growth in and sophistication of tools applied to its examination and the broadening focal domains to which nexus concerns are being articulated (Purwanto et al., 2021). Indeed, the nexus has shown itself to be an adept and powerful bridge between research and policy (Albrecht et al., 2018), functioning as a "boundary concept" in a way not too dissimilar to "landscape" (Opdam et al., 2015) or "ecosystem services" (Schleyer et al., 2017). This underappreciated nuance originates from the nexus's chimeric nature, which embodies an actual system and an approach to thinking about systems, their interactions, and interdependencies.

Nexus research has made inroads across all three geographies of the Global South examined here, although it is much more advanced in Asia and Africa than in Latin America and the Caribbean—with most research concentrated in Central Asia, the Mekong, the Nile Basin, the MENA area, and Southern Africa. This patchiness reflects underlying asymmetries in institutional composition and funding landscapes which, by and large, are shaped by Global North organizations, especially in the USA and Europe. What is and is not reported on affects our understanding of the nature of nexus challenges and their possible sustainable development solutions. Hence, greater South-South cooperation, human resourcing and funding is essential to ensure that the continued theoretical developments and applications of the nexus are sufficiently cognizant of "non-Western" values, perspectives, priorities, and contexts.

A multiplicity of local, national, and transboundary nexus challenges is emerging at the interface of social-ecological resource and technical systems. This, too, is a nuanced part of the maturation of the paradigm involving inextricable linkages and tensions between WEF sectors and current and future social, economic, and environmental development. They also expose how nexus-based developments can create inequalities where there are stark differences in power, non-inclusive decision-making, or top-down implementation. Under these circumstances, adopting nexus approaches that emphasize the role of governance and policy coordination will produce a more comprehensive and robust framing.

In the Anthropocene, the often widespread and disruptive systemic changes we encounter mean that ongoing nexus analyses must account for new information, assumptions, and provide the detail necessary to effectively inform policy and practice (Mabhaudhi et al., 2021; Shannak et al., 2018; Varis & Keskinen, 2018). In the years ahead, in the next stages of its evolution, the nexus must become a much stronger force for policy change if it is to succeed in contributing to a sustainable future. This is no mean task, but it is nonetheless necessary, if we are to move from "thinking" to "action," to enhance operationalization, and deliver "actionable knowledge" which, simultaneously, considers the purpose that knowledge will serve, whose and what knowledge is being privileged and which voices remain absent or under-represented and, finally, how it may support the transformation of current systems or further entrench present paradigms (Fontana et al., 2021).

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

As this is a review, we did not generate any primary data, nor do we employ any models, simulations, or software. All data connected to our literature search and bibliometric analysis that is not present in the main manuscript can be found in the online Supporting Information. Data in support of this paper has been deposited and is freely available on ReShare, the UK Data Service's online data repository, with the following data citation: Hejnowicz et al. (2022, https://reshare.ukdataservice.ac.uk/856076/).

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