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Research and innovation in agricultural water management for a water-secure world

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Abstract

There is increased awareness that the current food system is unsustainable and that transformative research, development and innovation in agricultural water management (AWM) are needed to transform water and food systems under climate change. We provide an overview of research efforts, challenges, opportunities and innovations to improve water resource management and sustainability, especially in the agricultural sector. We highlight how sustainable AWM is central to balancing the needs of a growing population and increasing food demand under increasing water insecurity and scarcity, with environmental and socio-economic outcomes. Innovative technologies are being developed to optimize water use and productivity through sustainable irrigation technologies, irrigation modernization and smart water management. However, these innovations still need to fully address equity, inequality and social justice concerning access to water, infrastructure and the delayed technological advances in the global South. This requires adopting transdisciplinary approaches, as espoused by the water–energy–food (WEF) nexus, to better anticipate and balance trade-offs, optimize synergies and mitigate risks of maladaptation. Through such transdisciplinary approaches, AWM innovations could better consider local socio-economic, governance, institutional and technological constraints, thus allowing for more contextualized and relevant innovations that can be scaled.

KEYWORDS
sustainable development, transformation, water security; WEF nexus

Résumé

Il existe une prise de conscience croissante du fait que le système alimentaire actuel n'est pas durable et que la recherche transformatrice, le développement et l'innovation dans le domaine de la gestion de l'eau agricole (AWM) sont nécessaires pour transformer les systèmes hydriques et alimentaires dans le

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contexte du changement climatique. Nous fournissons une vue d'ensemble des efforts de recherche, des défis, des opportunités et des innovations pour améliorer la gestion et la durabilité des ressources en eau, en particulier dans le secteur agricole. Nous soulignons que la gestion durable de l'eau est essentielle pour équilibrer les besoins d'une population croissante et l'augmentation de la demande alimentaire dans un contexte d'insécurité et de pénurie croissantes de l'eau, avec des résultats environnementaux et socio-économiques. Des technologies innovantes sont développées pour optimiser l'utilisation et la productivité de l'eau grâce aux technologies d'irrigation durables, à la modernisation de l'irrigation et à la gestion intelligente de l'eau. Cependant, ces innovations doivent encore tenir compte de l'équité, de l'inégalité et de la justice sociale en ce qui concerne l'accès à l'eau, les infrastructures et les avancées technologiques retardées dans les pays du Sud. Cela exige l'adoption d'approches transdisciplinaires, telles que celles préconisées par le lien entre l'eau, l'énergie et l'alimentation (WEF), afin de mieux anticiper et équilibrer les compromis, d'optimiser les synergies et d'atténuer les risques d'inadaptation. Grâce à ces approches transdisciplinaires, les innovations en matière de gestion de l'eau agricole (AWM) pourraient mieux tenir compte des contraintes socio-économiques, de gouvernance, institutionnelles et technologiques locales, ce qui permettrait des innovations plus contextualisées et plus pertinentes qui peuvent être mises à l'échelle.

MOTS CLÉS

développement durable, transformation, sécurité de l'eau; lien WEF

1 | INTRODUCTION

Freshwater resources cover only 0.8% of the global surface area; over 70% is extracted for agricultural use (Garcia-Moreno et al., 2014). However, although renewable, fresh water remains a limited and threatened natural resource, a situation which is compounded by climate change and climate variability and their impact on hydrometeorological interactions (Garcia-Moreno et al., 2014; Mall et al., 2006; Ngcobo et al., 2013; Ovink et al., 2023; Rockström et al., 2023). Projected warmer climates and further anthropogenic influences will have a catalytic effect on the hydrologic cycle, impacting the timing and distribution of rainfall, rainfall intensity and variability (Mall et al., 2006; Rockström et al., 2023; Smith et al., 2023). Mismanagement of freshwater resources often has catastrophic consequences for the agricultural, health, food and nutrition sectors (Malakar & Lu, 2022; Ovink et al., 2023).

Water scarcity and insecurity, especially in the drylands of the global South, are accelerating under climate change (Ahmed et al., 2022; Crawhall et al., 2012; Rosa et al., 2020). Urbanization, changes in land use patterns, population, and socio-economic growth are driving freshwater demands to exceed freshwater supplies by over 40% by 2030 (Garcia-Moreno et al., 2014). Increased water demands driven by socio-economic growth have also facilitated the accelerated decline in the quality and quantity of fresh water as a result of overexploitation of freshwater resources for human needs and the alteration of natural water systems (Garcia-Moreno et al., 2014; Rockström et al., 2023). The vulnerability of freshwater resources is a pressing and ongoing challenge because water plays a central and vital role in main global economic and developmental activities, including agricultural production and ensuring the realization of health, food and water-focused Sustainable Development Goals (SDGs), particularly SDGs 1, 2, 3, 6, and 8 (Bjornlund et al., 2023; Cofie & Amede, 2015; Rejekiningrum et al., 2022; Smith et al., 2023).

Considering the scale of the challenge, we must find innovative solutions for sustainable freshwater management, particularly agricultural water management (AWM). Decision makers must and have encouraged investment in innovations as solutions for water management efforts and water technologies (Bjornlund et al., 2023; Garcia-Moreno et al., 2014). These innovations come with an emphasis on implementing water-related mitigation and adaptation solutions in anticipation of variable but definite climate change impacts (Bjornlund et al., 2023; Garcia-Moreno et al., 2014; Ovink et al., 2023; Smith et al., 2023). These solutions need to be contextualized, equitable, innovative and strategic management channels for freshwater resources, acknowledging local socio-economics and institutional structures (Bjornlund et al., 2023; Garcia-Moreno et al., 2014; Malakar & Lu, 2022; Smith et al., 2023).

Research and innovation in AWM are central to transforming existing solutions as they inform an understanding of what actions need to be taken to transform water, land and food systems. Demand-driven research has led to holistic approaches to enhance AWM across scales. This work aims to provide an overview of research efforts, challenges, opportunities and innovations to improve water resource management and sustainability, especially in the agricultural sector. The specific objectives include: (i) taking stock of historical research and innovation in AWM, highlighting their impacts, particularly their effectiveness, synergies and trade-offs; (ii) proposing integrative nexus approaches for harmonizing multiple objectives and holistic performances in agricultural production systems; (iii) emphasize need for cautious and just paradigm shifts in bridging the inequality and justice gaps in AWM research and innovation. This study was guided by a water–energy–food (WEF) conceptual framework that integrated siloed approaches for achieving effective AWM across multiple scales (Figure 1).

The inner core of the conceptual framework represents AWM research and innovations across scales which have historically and currently focused on improved performance and outcomes in water productivity or energy use efficiency or production/yield, or water productivity and production/yield, or energy use efficiency and production/yield. However, the improvements in each or two of these silos sacrifices performance in the other dimension. The realization of consequential risks and trade-offs arising from pushing sectoral performance motivates a paradigm shift in AWM whereby interlinkages across dimensions/sectors are acknowledged, and if possible, quantified and simultaneously optimized. Thus, the outer core of the conceptual framework emphasizes integrative approaches towards AWM for optimizing performance and outcomes of multiple objectives from a system nexus perspective.

2 | THE FUTURE OF AWM ACROSS SCALES

Bespoke AWM practices promise to boost food production and mitigate risks associated with crop failure and

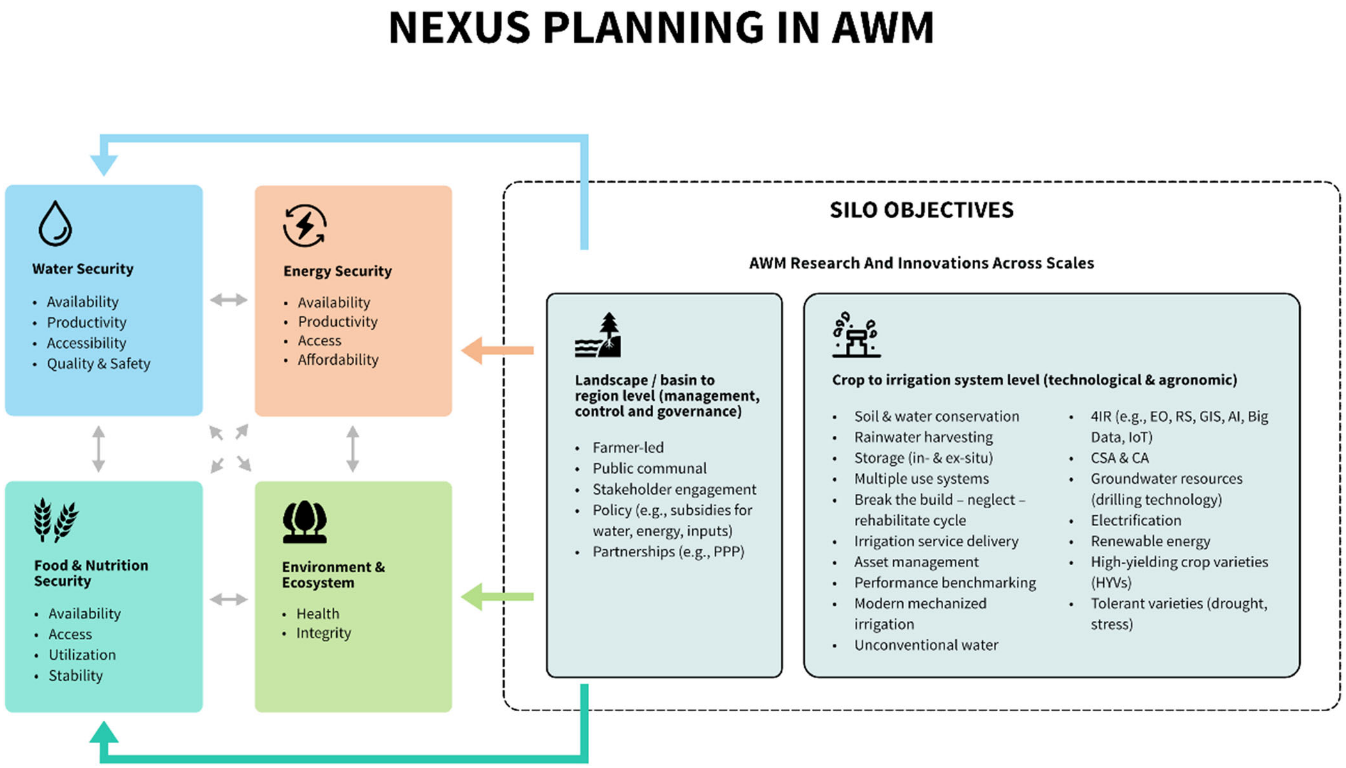

FIGURE 1 Study conceptual framework. *Source*: authors.

yield penalties. Irrigation is one of several AWM strategies being advanced as a key strategy for boosting food and water productivity under climate change in the global South. However, freshwater resources are increasingly threatened by growing competing demands; however, agriculture already accounts for ~70% of global freshwater withdrawals and calls are to reduce the share of water allocated to agriculture.

While agricultural water withdrawals already reach as much as 95% in some developing countries (Food and Agriculture Organization of the United Nations [FAO], 2017b), freshwater withdrawal has been increasing at ~1% per year over the last four decades, mainly in middle- and lower-income countries, and due to population growth, socio-economic development and changing consumption patterns. The business-as-usual projections for 2030 and 2050 relative to 2012 predict demand increases of 35–70% for food, which will require 20–55% more water and 10–30% more agricultural land (World Energy Council [WEC], 2013; International Renewable Energy Agency [IRENA], 2015; High Level Panel of Experts on Food Security and Nutrition [HLPE-FSN], 2017; FAO, 2022). However, water and arable land resources are already scarce and limited resources, and the competition for them is intensifying. For instance, accelerated urbanization due to high population growth has altered land use patterns, sometimes encroaching on fertile land, a situation which will intensify when urbanization rises from 53% (2020) to 70% by 2050 (FAO, 2017a; FAO, 2018; Ritchie & Roser, 2018; United Nations Economist Network [UNEN] and United Nations Department of Economic and Social Affairs [UNDESA], 2020; Organization for Economic Cooperation and Development [OECD] and FAO, 2022). Therefore bridging this growing gap in water demand in the agricultural sector requires consideration of all facets of sustainable management of agricultural water including biophysical and socio-economic factors (Chartzoulakis & Bertaki, 2015; Molden et al., 2010).

To optimally benefit from irrigation as an AWM strategy, the heterogeneous spatial scales of operation must be understood. Different irrigation modernization and improvements can be employed for effective AWM across scales. Additionally, the issues of typologies, as presented in the African Union (AU) (2020), equally determine the contextual and regional innovations required for optimal AWM. Thus, scale and typology are important considerations for designing bespoke AWM interventions (Figure 2).

The future hinges on contextualized and fit-for-purpose interventions that balance multiple considerations across social, economic and environmental dimensions. For example, a need exists to systematically appraise irrigation technologies and assess their performance at the field, farm and irrigation command scales, not just from a water perspective, but including energy, environment and economic considerations to inform sustainable transitions. For example, a study by Taguta, Dirwai, et al. (2022) used an integrated WEF nexus approach to assess the potential benefits of transitioning among furrow, sprinkler and trickle irrigation technologies in different agro-climatic zones. The results showed that shifting from flood irrigation to sprinkler and drip systems improved water productivity (WP). Although siloed, that is, neglecting and sometimes sacrificing other resources involved in irrigation, such as energy to drive water conveyance, the results presented an opportunity for pragmatic appraisal of irrigation systems to sustainably support food production processes with optimal WP. The study also presented an entry point for applying holistic approaches, such as the WEF nexus, to critically appraise irrigation technologies and practices for effective AWM.

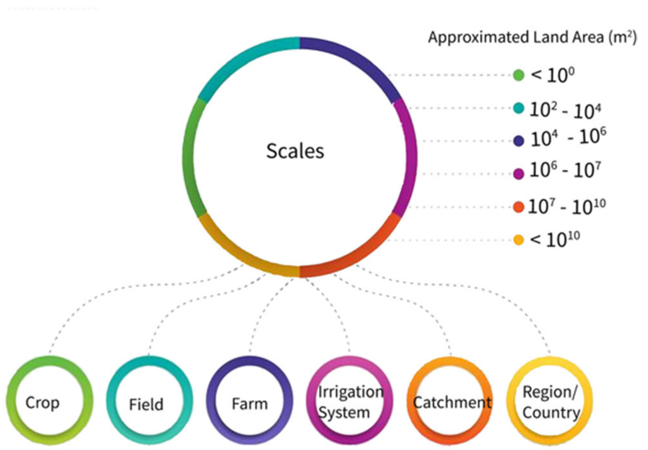

FIGURE 2 Representative operational spatial framework (adopted from Uhlenbrook et al., 2022; designed by the authors).

Unconventional water sources can reduce pressure on freshwater resources. At crop and field scale, peri-urban vegetable production in African cities relies on wastewater for irrigation. Irrigation technologies (hardware) should incorporate mechanisms that withstand emitter clogging for effective operation and minimize the risk of contamination (human and produce) and pollution (environment). Newly developed energy smart emitters such as Moistube irrigation (MTI) (Niu et al., 2017) significantly save water. Still, they are prone to hydraulic clogging under low-quality irrigation water (suspended and dissolved solids) (Kanda et al., 2018). The African Union recognized the socio-economic and biophysical importance of using unconventional water in agriculture. It was included as a key pillar and pathway (number 4) in its framework for Irrigation Development and Agricultural Water Management (IDAWM) (African Union [AU], 2020).

3 | TECHNOLOGIES AND APPROACHES FOR IMPROVED AWM: A SOFT PERSPECTIVE

In recent years, a significant amount of research has been undertaken in AWM, which has led to several innovations, including technological and institutional or management or governance (Velasco-Muñoz et al., 2019). Demand-driven research seeks to develop technologies and management systems that will help to increase water productivity (WP) in agriculture and reduce non-beneficial use for water security across scales. Of late, WP is the preferred metric used to measure the effectiveness of irrigation for informing irrigation performance at various system levels. Depending on the prevailing development objective and degree of water scarcity, the units of water productivity are kg m^{-3}, US$ m^{-3} or nutritional value m^{-3} and it links the production (or benefits) to water consumption (Beekma et al., 2021).

The demand-driven technologies, for example, should consider the cross-cutting water pillars (Figure 3); this brings context and fit-for-purpose utility across multiple scales. The pillars provide sectoral lenses in assessing demand-driven water use; for example, water policy influences governance, which regulates institutions, regulations, procedures and by-laws that influence water use. If properly implemented, the bottom-up and top-down interlinkages can benefit the hydrology of irrigation, where water demands meet water adequacy, reliability and dependability and subsequently support environmental flows (e-flows) for ecological services.

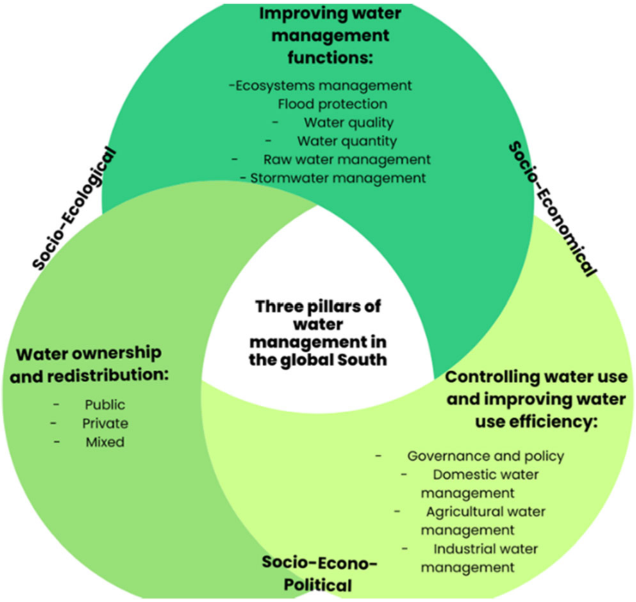

FIGURE 3 Three pillars of water management to be considered to achieve water security. Information extracted from Akhmouch et al. (2018) and the content of this document. The authors designed the figure.

Implementing inclusive thinking and research-informed advances will significantly impact AWM practices, especially for farmers, helping them increase their yields and drastically reducing water usage. This will also help farmers improve food sovereignty and security, especially in marginalized settings. However, there is a need for regulation to ensure that improvements in WP at the farm level are transferred to the system level, and reallocated. This would ultimately ensure that we meet the goal of reducing water use in agriculture.

3.1 | Unconventional water resources

Unconventional water resources are non-traditional sources of water that can be used to augment traditional water supplies. These resources include rainwater harvesting, recycling of municipal and industrial wastewater, seawater and brackish water desalination, and recharge (Lin et al., 2021). In the global South, where water scarcity is a critical concern, systematic re-evaluation and optimization of water systems through the use of unconventional water resources can play an important role in meeting the water needs of communities and promoting socio-economic development (Lin et al., 2021).

Wastewater recycling can provide an alternative water source for irrigation, industry and other non-potable uses while helping to reduce environmental pollution and improve sustainability. Desalination can offer a sustainable solution to the lack of fresh water but can be expensive and energy-intensive because it is still privatized; this calls for public–private partnerships to ensure that the technology becomes more affordable and feasible. However, this industry has the potential to be a sustainable option for solving water challenges, provided that cost-effective measures, such as using renewable energy, are implemented to enable water mining from aqueous solutions such as seawater (Lin et al., 2021).

The socio-economic importance of unconventional water resources in the global South lies in their potential to alleviate poverty, improve public health, secure food and create economic opportunities. Many communities in the global South are in water-scarce environments and do lack access to clean water, which can lead to water-borne diseases and hinder socio-economic development. Utilizing unconventional water resources can provide a more reliable water source, reduce the burden on traditional freshwater resources and promote sustainable development.

Niche-specific opportunities for mining economically valuable resources are also presented by resource recycling and mainstreaming unconventional water use (Lin et al., 2021). Because of the different processes that go into recycling and repurposing unconventional water resources, this process is highlighted to have the potential to aid in overcoming numerous challenges relating to the interlinked WEF nexus, particularly in the global South in an environmentally responsible way (Lin et al., 2021).

Despite the benefits of using unconventional water resources, the subject is still fraught with complex challenges that require careful planning and management to ensure sustainable and cost-effective reclamation of resources (Lin et al., 2021). While these resources can address water scarcity and improve socio-economic conditions, their implementation must be guided by technical, social, capacity and environmental considerations.

3.2 | Control and management of irrigated agriculture

Key research and innovation in AWM include the governance, management and control of irrigation schemes, with particular emphasis on 'who does what and how' and the consequences of these on the success of irrigated agriculture. Some case studies have shed light on how productivity in irrigation schemes depends on the levels of management and control of production processes by different actors, especially the farmers, including women, and government. This has also highlighted the contrast between large collective communal government-controlled irrigation schemes and private individual-controlled small- to medium-scale farmer-led irrigation schemes.

Farmer-led irrigation development (FLID) is a promising AWM practice in which farmers drive investment in irrigation technologies (International Water Management Institute [IWMI], 2021), and it is a key pillar and pathway (number 2) in the AU's IDAWM framework (AU, 2020). FLID has been found to be more productive than government-led collective irrigation schemes (e.g. in southern Tanzania; Osewe et al., 2020), while total government control over production in major large collective irrigation schemes (e.g. Gezira scheme in Sudan and the Office du Niger scheme in Mali) have resulted in trade-offs, including a decline in farmer participation and productivity, among other things (Bjornlund et al., 2020). When farmers take irrigation into their own hands, they innovate to increase production by supplementing rainfed crops with irrigation water and growing an additional harvest during the dry season. Thus they accrue increased benefits in better nutrition, higher incomes and greater climate resilience (IWMI, 2021).

According to Mutiro and Lautze (2015), the descending order of success in 100 irrigation schemes in southern Africa was as follows: (i) private sector (commercial) schemes; (ii) joint ventures between farmers and the private sector; (iii) irrigation schemes managed solely by governments. The failures of the latter, for example in southern Africa, can be attributed to multiple factors, including poor yields, the inadequacy of budgetary allocations due to lack of credit, lengthy government turnaround times due to onerous bureaucracy, inadequate institutional support, lack of maintenance of facilities and lack of ownership (Mutiro & Lautze, 2015). A recent study on the impacts of irrigation by the World Bank found the need to (i) expand attention to irrigation benefits and costs and (ii) explicitly consider direct and indirect impacts in investment planning (Giordano et al., 2023).

3.3 | Nexus approaches for thinking beyond water in AWM

Approaches to AWM research and innovation have traditionally been water-centric and focused at the field and scheme scales (Scheierling et al., 2014, 2016; Scheierling & Treguer, 2018; Taguta, Dirwai, et al., 2022). While this proved essential for producing 'more crop per drop' at a local scale, there is potential for trade-offs at larger scales such as landscapes and river basins due to the efficiency paradox (Grafton et al., 2018) or the rebound effect as farmers are tempted to expand their area or by switching to high-value water-intensive crops using the saved water (Hamidov, Kasymov, et al., 2022). Thus, improvements in WP at the field and scheme level have not always translated to system-level benefits and the reallocation of water to other users. Similarly, the importance of water cannot be overemphasized as a connector between sectors such as food/agriculture and energy (United Nations Economic Commission for Europe [UNECE], 2018; United Nations Educational, Scientific and Cultural Organization [UNESCO] and UN-Water, 2020).

Water, energy and food (WEF) are inextricably linked in a WEF nexus. Actions in one sector influence the others, synergistically or adversely, at different levels and scales (Beekma et al., 2021; Hoff, 2011; Hoff et al., 2019). Processes and activities in agricultural production require water and energy, among other inputs (Belaud et al., 2020). Agriculture consumes ~70% of freshwater abstractions globally, while food production and supply chains consume ~30% of energy (Avellán et al., 2018; Cui et al., 2022). The ever-increasing annual global withdrawals are large and contribute at least 43% of global irrigation as driven by the availability of enabling technology, including smaller, cheaper pump sets and tube well technology (Ringler et al., 2013). All irrigation systems require and are driven by energy for conveying and pressurizing water (sometimes with fertilizer/nutrients) from the source to the plants (Daudin et al., 2022). Different irrigation systems require different amounts of energy, mainly due to their design, operation and maintenance. For example, traditional systems may use only gravity to convey water to the fields. In contrast, modern systems generally require external energy sources for filtering water and creating (lifting) the required flow rate and pressure head for uniform application (Belaud et al., 2020). Average hydraulic power requirements for gravity-fed, localized sprinkler irrigation schemes are 0 (zero) bar, 1–3 bars and 1–8 bars. Similarly, their hydraulic efficiencies are 40–70, 85–95 and 70–95%, respectively (Daudin et al., 2022).

In recent decades, there has been increased promotion and development of water-efficient agriculture. However, irrigation innovation and technology consume significantly more energy (Belaud et al., 2020). Similarly, we have witnessed increases in energy prices (Ringler et al., 2013). The combination of rising energy consumption and prices have pushed energy costs to be the new threat to the sustainability of irrigated agriculture (Díaz et al., 2011). This is one of the key drivers for using renewable energy and the polycentric and holistic WEF nexus approach, or broadly, nexus planning in agriculture.

Because of the cost, greenhouse emissions (carbon footprint) and pollution effects of energy and water use in agriculture, the nexus in agriculture goes beyond WEF to include the economic, socio-economic, ecosystem, climate, environmental and health dimensions, which share some forward and backward loops with agriculture (Avellán et al., 2018). Ecosystems, land and the environment, underpin the provision, production and security of nexus resources (Carmona-Moreno et al., 2021). Agriculture, for example, irrigated, typifies the complexity of the WEF nexus, which requires a better understanding of the risks, trade-offs and synergies for designing effective and harmonized natural resources policies (Cremades et al., 2016; Hamidov, Daedlow, et al., 2022).

AWM has witnessed initiatives geared towards improved WP in food production. However, it was later realized that these water- and food-centric initiatives led to negative trade-offs with other significant costs and dimensions. Table 1 presents an overview of previous AWM interventions and their supposed impact(s) on the nexus.

From a nexus perspective, it is often worth while prioritizing rainfed agriculture more than irrigation. Findings from Morocco support that investment in rainfed agriculture is more profitable for the national economy, and agricultural development should favour rainfed agriculture. AWM and energy management, among other things, are closely linked to saving water and energy and reducing costs (Belaud et al., 2020). In summary, the examples presented here (Table 1) show that sectoral policies and initiatives (e.g. access to energy) meant to increase the capacity of agricultural production (e.g. irrigation) and resource use efficiency and productivity may have a rebound effect on the unsustainable consumption of other linked resources. They create a vicious cycle, circle and trap. More research needs to be done to inform the sustainable implementation of potentially nexus-friendly interventions.

For example, the environmental and health impacts of irrigation and artificial recharge with unconventional water resources, such as wastewater and drainage effluent (Avellán et al., 2018), must be understood regarding water, energy, food, environmental and health tradeoffs. If the unconventional water is to be treated, we need to remember that the process is more energy intensive (0.3–2.1 kWh m^{-3} for wastewater; 0.951–1.942 kWh m^{-3} for brackish water; 4.0 kWh m^{-3} for seawater) than raw fresh water (0–0.198 kWh m^{-3}) (Gandiglio et al., 2017; IFI, 2020).

Other initiatives that need similar scientific investigation and consideration of AWM from a nexus perspective include co-generation of renewable energy in crop fields, canals and water bodies, including agrivoltaics, photovoltaics, micro-hydro and pumped (hydraulic) storage hydropower for optimizing resource use efficiency. Thus, planning, appraisal and implementation of AWM initiatives, technical and management, should be informed by the local context of challenges and priorities from a nexus planning perspective. As we wait for or work on the development of better tools to plan and appraise agriculture from a nexus perspective, existing tools for integrative analysis and visualization include indices and sustainability polygons/radar charts/spider diagrams (FAO, 2021a, 2021b; Taguta, Dirwai, et al., 2022).

3.4 | Think the future: AWM and disruptive 4IR technologies

Emerging digital technologies such as the Internet of Things, virtual reality, remote sensing, 3D printing, big data and artificial intelligence are gaining traction in agricultural production systems. Remote-sensing techniques, such as drones, have been used extensively to monitor crop health status and soil water use/depletion

TABLE 1 Previous AWM-related initiatives, and their synergies and trade-offs on nexus dimensions.

What happened?	Where?	Effects and implications on the nexus?
• Advent of diesel and electric motors • Development of pressurized irrigation systems	• Global	• Intensive use of groundwater
• Irrigation modernization from canal gravity-fed surface systems to pumped pressurized (drip and sprinkler) irrigation systems	• Spain	• Change to water-intensive crop rotations • Decrease in water use at the national level • Increase in energy demand and consumption for pumping • Increase in costs for amortization, operation and maintenance
• Invention of centre-pivot irrigation systems • Rural electrification • Improved well drilling and pump technologies	• US Great Plains	• Decline of the water table as pumping exceeded recharge
• Agrarian policies • Irrigation projects • Subsidies for diesel fuel	• Syria	• Increased agricultural production • Overabstracting water resources • Political unrest
• Heavy subsidies for water (sometimes free), energy (flat tariffs, sometimes free), irrigation and agro-chemicals (including fertilizer) • Exponential growth of the number of wells and energised pump sets • Electrification • Irrigation mechanization through diesel or electricity pumps • Expansion of irrigation • Policy support for the adoption of high-yielding varieties (HYVs), particularly for rice, wheat and maize	• South Asian countries, Indo-Gangetic Plain: • India (West Bengal, Punjab, Haryana and Andhra Pradesh) • Pakistan • Nepal •Bangladesh	• Increase in irrigation efficiency and flexibility • Increased agricultural production • Agricultural and economic development • Decline of the water table due to groundwater overabstraction • Intensification of the cropping pattern • Increased income • Increased water and energy consumption • Accelerated degradation of natural resources and environment (waterlogging, soil salinization, water pollution, contamination and biodiversity loss) • Increased area under irrigated rice and wheat • Increased greenhouse gas emissions (GHGs) • Replacement of traditional food crops and legumes, narrowing of both crop and dietary diversity, with a resultant negative impact on nutritional security • Distorted agricultural input markets • Unstable power grid due to overusage (tripping and power outages) • Prevalence of waterborne diseases (human health) • Weakened long-term sustainability of agriculture and food security
• Policies subsidizing agricultural and irrigation water and energy • Policies and investments targeting 'water-saving' irrigation techniques	• Morocco	• Increased use of subsidized butane for private irrigation • Rapid growth of agriculture • High energy consumption and costs
• Use of micro-irrigation (drip and sprinkler) systems	• India	• Increased total energy (30–40%) and energy per area planted
• High subsidies for water (surface and ground) and energy	• Iran	• Increased water use for agronomic crop production • Increased food (staple) production • Water bankruptcy • Significant groundwater table decline • Increased energy consumption
• Subsidy for installing solar pumps • Adoption of the solar water pump	• India (Rajasthan, Bihar, Maharashtra, Gujarat)	• Apprehension about increased groundwater abstraction • Reduced diesel and electricity consumption • Increased food security • Increased cropping intensity and gross cropped area • Improved water productivity • No change in the total quantity of water used

TABLE 1 (Continued)

What happened?	Where?	Effects and implications on the nexus?
		• Switch from deficit to full irrigation • Higher crop yields, savings and profits • Reduced production costs
• Solar-powered drip irrigation	• Sudano-Sahel region of West Africa (Benin)	• Improved household income and nutritional intake
• Replacing gravity-fed traditional surface irrigation with high-efficiency irrigation systems (HEIS, e.g. drip and sprinkler irrigation systems) • Substantial investment in energy development and the national energy grid	• Vietnam	• Improved access to electricity, even in rural areas • Reduced irrigation water demand per hectare per year • One area reported higher energy use under the HEIS system
• Electrification • Reduction in night-time tariffs • Subsidies for daytime pumping	• Mexico	• Aquifer depletion
• Increased access to and affordability of rural electricity, diesel pumps and fuel • State energy subsidies	• Morocco	• Proliferation of private tube wells and unregulated groundwater pumping • Depletion of aquifers
• Subsidies to support drip irrigation	• Morocco	• Improved water and energy efficiency
• Drip irrigation	• Australia	• Water savings • Increased energy consumption where the source was surface water • Reduced energy consumption where the source was groundwater
• Shift from furrow irrigation to drip and sprinkler irrigation system	• Australia (Murray–Darling basin)	• Water savings • Increased energy demand and consumption • Increased GHG emissions
• Irrigation modernization	• Mediterranean region	• Water savings • Increased energy demand and consumption • Increased GHG emissions
• Shifting from rainfed to irrigated production	• Mediterranean region	• Increased irrigation demand • Increased GHG emissions
• Switching from sprinkler irrigation to surface irrigation	• Turkey	• Reduced energy requirement for irrigation • Increased irrigation demand
• Expansion of sprinklers and micro-irrigation	• China	• Increased GHG emissions from agricultural water use, with decreases in those provinces using groundwater and planned expansion of low-pressure pipes

Sources: ADB (2017), Ahmad and Khan (2017), Avellán et al. (2018), Beaton et al. (2019), Beekma et al. (2021), Belaud et al. (2020), Burney et al. (2010), Cremades et al. (2016), Daccache et al. (2014), Gupta (2019), Hagerty and Zucker (2019), Jackson et al. (2010) Jackson et al. (2011), Jobbins et al. (2015), Lawford et al. (2013), Lee et al. (2020), Mirzaei et al. (2019), Rasul (2016), Rasul and Neupane (2021), Reinhard et al. (2017), Scott (2011), Shah et al. (2012), Siddiqi and Wescoat (2013), Singh et al. (2022), Siyal and Gerbens-Leenes (2022), Tarjuelo et al. (2015), Topak et al. (2005).

at different spatial scales. Some countries in the global North have applied these emerging technologies in monitoring food processing; for example, augmented reality has been applied to monitor poultry production lines to maintain meat quality. Virtual reality can be leveraged in assessing fluid flow in piped systems for improved hydraulic friction analysis in piped irrigation systems. Improved hydraulic efficiencies improve water conveyance and application efficiencies, subsequently improving energy use in piped irrigation systems. Energy use efficiency ties in with improved WP, consequently; leading to a balanced WEF and fibre production nexus (WEF nexus). The different technologies can be harnessed to improve resource use efficiency while minimizing trade-offs. Figure 4 summarizes the holistic WEF nexus approach in a disruptive 4IR environment.

The technologies mentioned above could be far-fetched for low- and middle-income countries (LMICs) because of the capacity and wealth gap. However, to improve water use in LMICs, there is a need to leverage and mainstream social innovations such as indigenous knowledge systems with emerging and existing technologies. There has been a surge in the development of GIS-enabled water productivity decision support tools (WP-DSTs), which facilitate monitoring water use at varied spatial and temporal scales. These WP-DSTs have been applied extensively, and there is an opportunity to collate all the data for big data and artificial intelligence utility. Artificial intelligence can improve the accuracy and precision of WP-DSTs.

For shifting AWM paradigms from individual silos to the integrative nexus, Fourth Industrial Revolution (4IR) technologies have the potential to usher in the required disruption in AWM research and innovation, especially in the case of development of new metrics/indices/tools for integration, quantification and visualization, for better and precise decision support in space and time. For example, 4IR innovations can be used to integrate

WP-DSTs with energy accounting tools and spatial tools (GIS, remote sensing) to get a complete picture of the performance of agricultural systems from a nexus perspective at scale. These tools can be used *ex post*, or in conjunction with scenario planning to conduct *ex ante* irrigation nexus planning for robust and cost-effective agricultural systems that factor in efficient and productive use of resources, not only water, but a wider spectrum that can be meaningfully captured. However, only the global North is well placed to benefit from 4IR research and innovation in AWM because the global South still lags in digital innovations and there is a risk of digital exclusion and widening existing inequalities. For example, only 2 out of 46 WEF nexus tools that were reportedly developed by mid 2021 were from Africa (Taguta, Senzanje, et al., 2022).

4 | REDRESS AND SOCIAL JUSTICE

The concepts of water security and AWM often meet with existing and diverse challenges relating to inequality and inequity, some of which are racial and gender-based, when it comes to accessibility and management of the

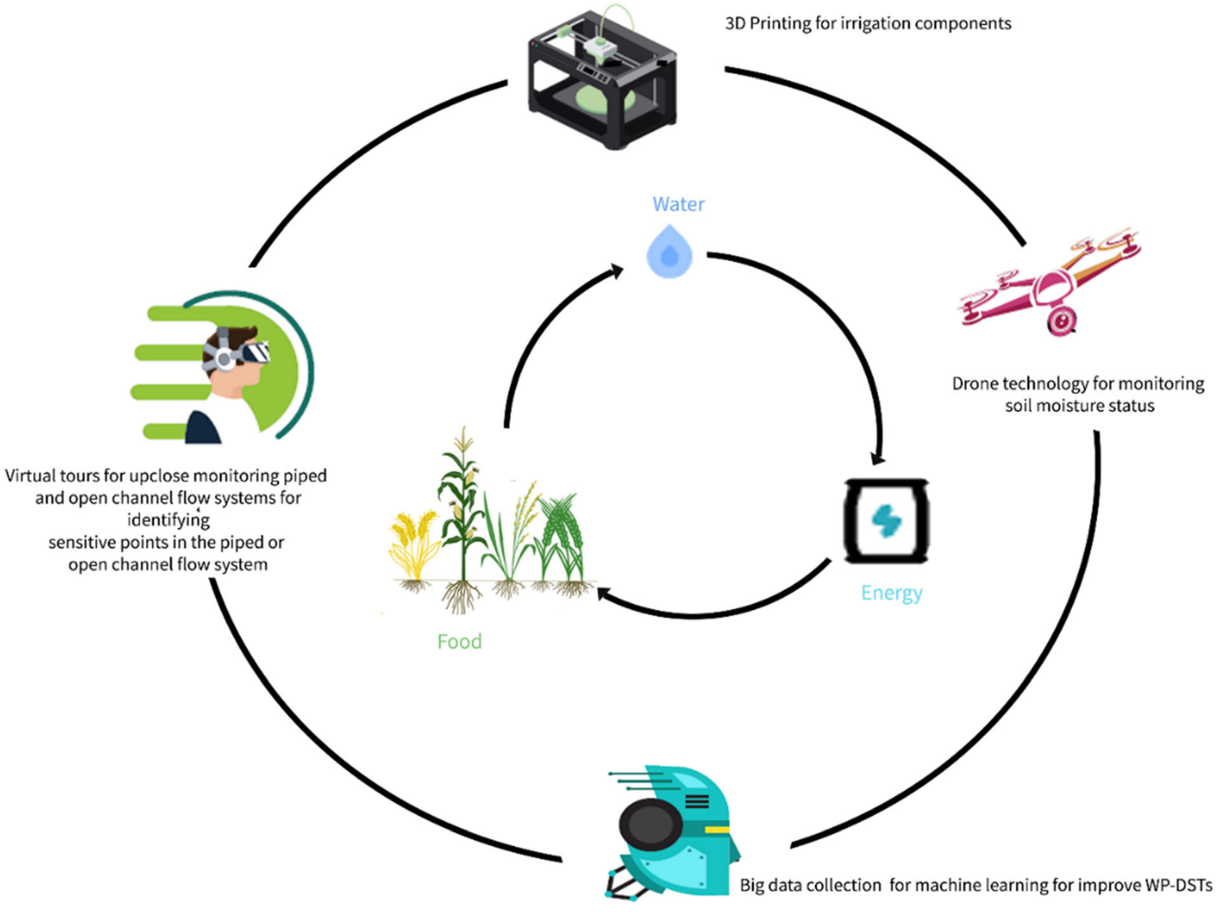

FIGURE 4 Emerging technologies and the potential interactions from a WEF nexus perspective. The WEF nexus exists in the innovation ecosystem. This interaction can be employed at appropriate scales. *Source*: authors.

resource at national and local levels, especially in the global South (Rockström et al., 2023; Smith et al., 2023). Sometimes AWM, water and ultimately food security are closely linked to land and water tenure in these regions. For example, black farmers own less than 30% of commercial farms in South Africa and use only 5% of the water allocated to the agricultural sector (Department of Water and Sanitation [DWS], 2018a); this situation is broadly representative of other countries in Africa that share a similar colonial history with South Africa. Thus in such cases, AWM innovations need to be contextualized so that reallocation for equity has to be pursued in parallel with strategies for improving efficiency and productivity (DWS, 2018b). Failing to address these underlying factors perpetuates inequality and inequity in water access and management at different scales (Bjornlund et al., 2023; Ovink et al., 2023; Rockström et al., 2023; Smith et al., 2023).

Before achieving sustainable water management, some localities, especially in the drylands of Africa, still need to address issues relating to water rights and freshwater resource decentralization and distribution to encourage the decentralization of water management (Cofie & Amede, 2015). However, home to over 3 billion people, dryland agriculture in the global South remains challenged by biophysical, agroclimatic and resource shortages and struggles to support their production and productivity (FAO, 2022). Optimizing AWM in the drylands to increase crop productivity under climate change is a global challenge that demands holistic and inclusive solutions (Bjornlund et al., 2023). However, it is an essential step to be taken towards resource-sensitive, environmentally friendly, adaptable and sustainable agricultural practices, especially in marginalized environments.

Organizational structures at different levels must enable inclusive and sustainable water resource management in the agricultural sector (Ahmed et al., 2022). This can be achieved through collaboration between different sectors, institutions, policies and regulations, and locally implemented programmes (Ahmed et al., 2022; Cofie & Amede, 2015; Rejekiningrum et al., 2022). Nexus planning in AWM could be a starting point because it strives to bring everyone to the table and co-plan for balancing conflicting interests among different actors. All AWM solutions must account for local access to developmental agents, including capacity, infrastructure, engineering and technology (Bjornlund et al., 2023; Rockström et al., 2023; Smith et al., 2023). Applications of single-factor innovation, particularly technological innovations that are not locally feasible, will continue to undermine sustainable water management efforts in agriculture (Bjornlund et al., 2023). Nexus planning seeks to design and implement interventions that minimize risks and trade-offs and optimize synergies across multiple interlinked sectors and resources. Principles of good governance at different water governance levels must ensure that integrated approaches that honour different perspectives and enabling environments are considered when addressing water-related challenges (Bjornlund et al., 2023).

5 | CONCLUSIONS AND RECOMMENDATIONS

International development trajectories focusing on water resources management need a comprehensive, contextualized and inclusive approach to achieving water security sustainably and equitably across different localities. Developmental innovations in AWM and agriculture water practices need to account for existing inequalities such as socio-economics, technological development and engineering advances, access to resources and different capacities between the global North and the global South. Development trajectories in the global South first need to account for underlying factors such as food poverty and widespread food and nutrition insecurity to promote innovations that support agricultural water practices that solve local challenges and enhance local systems to improve differentiated struggles in so doing, providing opportunities for local economic development, livelihood options and circular agricultural and economic systems. Water management and governance are politicized, and radical transformations in how things are currently done are needed to achieve equitable management and water security. Innovations in water management technology and systems must be deployed with ethical leadership, policy changes and incentives to ensure equitable access to resources and speed local capacity development and adoption of solutions and systems.

Management styles affect the biophysical and economic performance of irrigation schemes. There is a need to rethink the roles and level of participation of external actors in irrigation schemes, limiting them to facilitative and supportive so that farmers retain more control and have more room to innovate towards productivity and water and food security.

Research and innovation are crucial in fresh and unconventional water resource management, including AWM. The challenges of climate change and a growing global population require sustainable solutions addressing water scarcity and quality. We can overcome water constraints by adopting and implementing innovative perspectives and technologies, such as exploring unconventional water, smart agriculture, resilient AWM practices, integrated water management systems and nexus planning while increasing crop yields and profitability. With continuous research and innovation, the agricultural sector can become more sustainable and make great strides in global food and nutrition security. Therefore, stakeholders must continue to support research and innovation in AWM for a secure and resilient future.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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