

RETHINKING AGRICULTURAL WATER MANAGEMENT THROUGH AN INCLUSIVE AND HOLISTIC WATER-ENERGY-FOOD NEXUS

REPENSER LA GESTION DE L'EAU AGRICOLE A TRAVERS UNE APPROCHE INCLUSIVE ET HOLISTIQUE DU LIEN ENTRE EAU-ENERGIE-ALIMENTATION

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ABSTRACT

Agricultural water management (AWM) practices are increasingly shifting toward a transformative process that connects the interlinked sectors of water, energy, and food. This shift is prompted by traditional and legacy AWM practices that fail to address current interconnected water insecurities. This mixed-methods study explores both theoretical and practical narratives, aiming to identify pathways to reduce unproductive water losses, optimise crop water productivity, and enhance AWM and agronomic practices by examining the fundamental relationships between water, energy, and food resources. It also considers the opportunities and pathways to transition from traditional agricultural practices to integrated AWM. The research offers a comprehensive overview of an integrated AWM system that improves water-use efficiency through the WEF nexus. It emphasises reducing water consumption, boosting environmental flows, minimising waste, and reusing resources in agriculture. Pathways for transitioning traditional AWM practices toward a water-energy-food (WEF) nexus-informed system are identified to foster an equitable, inclusive, integrated, resilient, and balanced socio-ecological system. This is achieved by viewing the WEF sectors as a unified system that supports sustainable crop production, highlighting trends, opportunities, barriers, and solutions for a smarter AWM system. The recommendations advocate shifting from the current production-focused AWM to a transformative, equitable, sustainable, and resilient process that benefits both people and the planet.

Keywords: Water productivity; climate change adaptation; sustainable food systems; agriculture transformation; water-use efficiency.

RESUME

Les pratiques de la gestion de l'eau agricole (AWM) s'orientent de plus en plus vers un processus de transformation qui relie les secteurs interdépendants de l'eau, de l'énergie et de l'alimentation. Cette évolution résulte de l'incapacité des pratiques traditionnelles et héritées du passé à répondre aux insécurités hydriques actuelles étroitement liés. Cette étude basée sur des méthodes mixtes, explore à la fois les perspectives théoriques et pratiques, afin d'identifier des voies permettant de réduire les pertes d'eau improductives, d'optimiser la productivité hydrique des cultures et d'améliorer les pratiques de gestion de l'eau agricole et les pratiques agronomiques, en examinant les relations fondamentales entre les ressources en eau, en énergie et alimentaires. Elle examine également les possibilités et les perspectives de transition des pratiques agricoles traditionnelles vers une gestion intégrée de l'eau

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agricole. Cette recherche offre une vue d'ensemble complète d'un système intégré de la gestion de l'eau agricole qui améliore l'efficacité de l'utilisation de l'eau grâce au lien entre eau-énergie-alimentation (WEF). Elle met l'accent sur la réduction de la consommation d'eau, l'augmentation des débits environnementaux, la minimisation du gaspillage et la réutilisation des ressources dans l'agriculture. Des voies de transition des pratiques traditionnelles de la gestion de l'eau agricole vers un système fondé sur le lien entre eau-énergie-alimentation (WEF) sont identifiées afin de favoriser un système socio-écologique équitable, inclusif, intégré, résistant et équilibré. Pour réaliser cet objectif, il faut tenir les secteurs de l'eau, de l'énergie et de l'alimentation comme un système unifié qui soutient une production agricole durable, mettant en lumière les tendances, les possibilités, les obstacles et les solutions pour avoir un système de gestion de l'eau agricole plus intelligent. Les recommandations préconisent de passer de la gestion de l'eau agricole actuelle, axée sur la production, à un processus transformateur, équitable, durable et résistante bénéfique à la fois aux populations et à la planète.

Mots-clés : Productivité de l'eau; Adaptation au changement climatique; Systèmes alimentaires durables; Transformation de l'agriculture; Efficacité de l'utilisation de l'eau.

1. INTRODUCTION

Water scarcity and weather extremes, especially the increasing severity and frequency of droughts and floods, combined with the expansion of irrigated land to meet the rising food demands of a growing population, continue to exacerbate environmental degradation and the depletion of the natural resource base. (Ingrao et al., 2023). Agriculture remains one of the main culprits of climate change, both as a source of greenhouse gas (GHG) emissions and a victim of global change, as it is a climate-sensitive sector (Yuan et al., 2024). Agriculture is not only a primary polluter of water resources but also accounts for approximately 70% of global freshwater withdrawals, with the majority used for crop production (Mekonnen & Gerbens-Leenes, 2020). As a result, agro-based economies face acute challenges related to water scarcity and reduced crop yields, contributing to water, food, and nutritional insecurity (Nhamo et al., 2024).

The Food and Agriculture Organisation (FAO) of the United Nations estimates that by 2050, global water requirements for agriculture will need to increase by more than 50% to meet food requirements (FAO, 2014). These changes are compounded by worsening weather extremes, which affect mostly the vulnerable who depend on rainfall for crop growth (Nhemachena et al., 2020). These challenges highlight the need to transition to more efficient water management in agriculture, including innovative solutions to sustainably manage crop water use and produce 'more crop per drop'. Transitioning agricultural water management (AWM) requires technological innovations and smart agricultural practices that optimise water use efficiency in crop production while reducing negative environmental impacts. Smart agricultural practices and technological innovations encompass efficient irrigation techniques and applying water-saving practices such as mulching and cover cropping, capturing and storing water, growing drought-resistant crops, and improving soil health to enhance water retention (Parra-López et al., 2025).

These are meant to enhance crop-water productivity, a foundational concept of AWM that advances the transformational agenda in the agriculture sector. It refers to the simultaneous efficient use of water and maximisation of crop production (Molden et al., 2010). Crop-water productivity essentially quantifies crop yield relative to the amount of water consumed, promoting the idea of producing "more crop per drop." (Nhamo et al., 2016).

Thus, crop-water productivity is the applied science of AWM, as it aims to improve yields and water use efficiency. Increasing crop-water productivity in agriculture is paramount to meet future food demand with limited water supplies. Transitioning AWM is driven by the water-energy-food (WEF) nexus (Nhamo et al., 2024) as trends indicate an increasing global awareness of the interconnectedness of these sectors (Dirwai et al., 2024). The worsening water scarcity challenges, increasing energy demands for both domestic and industrial uses, and food insecurity, in the face of climate change, are prompting a shift towards more holistic and transformative practices that promote efficient water use in agriculture,

integrating renewable energy sources, and adopting circular economy models that minimise inputs (Mabhaudhi et al., 2018). The WEF nexus refers to the holistic management of the complex, intricate, interconnectedness of the three sectors.

All this necessitates a shift from the current conventional legacy resource-intensive AWM practices and single-factor productivity approaches towards integrating resource conservation and the circular economy. This entails reducing water consumption, minimising waste, and reusing resources from a circular economy perspective (Voulvoulis, 2018). Traditional practices often prioritise maximising output at the expense of long-term sustainability, while a circular economy approach emphasises closing resource loops and regenerating natural systems (Velenturf & Purnell, 2021).

As an interdisciplinary subject, AWM cuts across the traditional domains of agronomy, climatology, geology, economics, and sociology (Nhamo et al., 2025; Santos et al., 2023). These disciplines, however, have each developed sector-based empirical models on water management to meet specific needs. However, there is a lack of an integrated model that comprehensively and holistically simulates all major hydrological and crop-growth aspects to tackle current cross-sector challenges. This study explores theoretical and practical approaches to reducing unproductive water losses, optimising crop water productivity, and enhancing agricultural water management (AWM) and agronomic practices. It examines the relationships between water, energy, and food, and explores the trends, opportunities, barriers, and solutions related to integrated AWM.

2. METHODS

This mixed-methods study explores both theoretical and practical narratives aimed at reducing unproductive water losses, optimising crop water productivity, and enhancing AWM and agronomic practices by examining the fundamental relationships of WEF resources. The research highlights the critical need to transition from traditional AWM towards an integrated system that ensures sustainable water resource management, minimises environmental impact, and improves food and water security. The study also highlights the opportunities and pathways that advance the transition to an integrated AWM. It is a comprehensive overview of an integrated AWM system that improves water-use efficiency through the WEF nexus.

It identifies smart practices that reduce water consumption, boost environmental flows, minimise waste, and promote resource reuse in crop production. Pathways for transitioning traditional AWM practices toward a WEF nexus-informed system are identified to foster an equitable, inclusive, integrated, resilient, and balanced socio-ecological system. This is achieved by viewing the WEF sectors as a unified system that supports sustainable crop production, highlighting trends, opportunities, barriers, and solutions for a smarter AWM system.

The methods were aided by a systematic literature review to address specific research questions, including: (a) what are the current AWM practices limiting water-use efficiency in agriculture?, (b) what are the opportunities presented by transitioning to a transformative and integrated AWM practice?, and (c) what are the transitional pathways towards an integrated AWM? These are the guiding questions for literature selection and exclusion, and identification of pathways towards an integrated AWM. The mixed and transdisciplinary methods also facilitated a critical distinction between water-use efficiency (WUE) and water productivity (WP) by distinguishing between technical efficiency, physiological plant responses, and economic/beneficial output. The two concepts are key in understanding and advancing the cause of a transformative AWM.

3. RESULTS AND DISCUSSION

3.1. Use and misuse of water productivity and water use efficiency terms

There should be a consensus among stakeholders on the difference between water-use efficiency (WUE) and water productivity (WP). The two terms are often used interchangeably, yet they are different

altogether (Fernández et al., 2020). This has the risk of confusing policy if left unresolved. Their misuse and confusion are based on whether one is an agronomist or an agricultural engineer. Agronomists consider WUE and WP as the same, yet they are distinct and should be applied differently (Parra et al., 2020). Water productivity is the yield calculated from the water that is used by the plants, and is expressed in weight units of yield (kg or g) compared to the quantity of water consumed (m^3). For example, it can be measured as kg/m^3 (Molden et al., 2010; Nhamo et al., 2016). Yet, in general terms, efficiency refers to the percentage or ratio of output divided by input, both with the same units (Fernández et al., 2020).

For example, in irrigation, if one adds 10 mm of water to the plant and the plant consumes 8 mm through the root water system, followed by transpiration, and 2 mm is lost by drainage below the root zone or via the bare soil evaporation from the surface. The WUE here is 80%. Irrigation efficiency assesses the performance of an irrigation system (Levidow et al., 2014). In irrigation terms, WUE is described as the ratio between the volume of water used by a crop, including the whole evapotranspiration process, and the volume that reaches the irrigated field, and is expressed as (Parra et al., 2020):

$$WUE = \frac{WU}{WS} \quad (1)$$

where WUE represents water use efficiency (dimensionless), WU is water that is eventually used by crops (m^3), and WS is water supplied to the irrigated field (m^3).

The difference between WUE and WP is that WP refers to the yield produced from a unit of input. There are three types of WP: physical, nutritional, and economic productivity (Nhamo et al., 2016). Thus, WP can be defined as the physical mass of production or the economic value of production measured against gross inflow, net inflow, depleted water, process depleted water, or available water, and is expressed as (Molden et al., 2010):

$$WP = \frac{CY}{WC} \quad (2)$$

where WP represents water productivity, CY is crop yield (kg/m^3 or $\$/m^3$), and WC is the water consumed (m^3).

Therefore, WUE and WP are water accounting terms essential for monitoring the efficiency with which water is supplied to the field and the rate at which the plant converts water into food, respectively (Hatfield & Dold, 2019). The concept of WP is critical in both rainfed and irrigated sub-sectors. It monitors and assesses water use efficiency in crop production (Parra et al., 2020). The main aim of WP is to increase crop yield per unit of water used, hence the term “more crop per drop.” (Molden et al., 2010). Attaining the production of more crops with less water is possible through (i) increasing the marketable yield of the crops for each unit of water transpired, (ii) reducing water losses, or (iii) enhancing the effective use of rainfall and the water stored in the soil (Molden et al., 2010).

The first option aims to increase crop yield; the second focuses on enhancing the beneficial use of water through transpiration compared to non-beneficial losses like evaporation; and the third option highlights the efficient use of water resources. All these options associated with WP, coupled with modern irrigation technologies, are essential for improving on-farm crop water management practices as they facilitate the use of less water in both rainfed and irrigated systems, reduce water losses through evaporation, optimise the use of chemicals, minimise energy consumption, and enhance soil conditions (Nhamo et al., 2016).

These practices are important in water-scarce regions, as farmers are always constrained to apply deficit irrigation strategies and to manage water supply in relation to the sensitivity of the crop's phenological stages to water stress (Nhamo et al., 2020). Therefore, improved WUE catalyses WP and both improve economic return from irrigation investments from a water-supply perspective.

Table 1. Difference between water use efficiency and water productivity

Water use efficiency (WUE)	Water productivity (WP)
A dimensionless ratio of the total amount of water used to the total amount of water applied	Relationship between crop yield and water consumed
Applies to the efficiency of water supplied to a field	Refers mainly to the benefits from a system (rainfall or irrigated)
Refers to the performance of crops	Refers to the performance of the production system as a whole
It is an assessment of the amount of water taken up by the plant	It refers to the best returns from applied water
Does not consider losses	Loss accounted for through supply or depletion.

3.2. Opportunities for integrated systems adoption in water management

Integrated AWM offers significant opportunities to improve water use efficiency, enhance crop yields, and promote sustainable farming practices. By combining various technologies, such as smart irrigation, wastewater reuse, integrated farming systems, and holistic approaches like the WEF nexus, farmers can optimise water, energy, and land resources, reduce environmental impact, and increase food production from an informed perspective (Pronti et al., 2024), as shown in Fig. 1. Implementing irrigation technologies, including precision irrigation, alongside water-efficient crop selection, reduces water consumption in agriculture, a sector already consuming over 70% of the available freshwater resources. Innovative technologies enable more efficient water delivery to crops, minimising losses from evaporation and runoff, thereby ensuring that water is used precisely where and when it is needed.

This presents an opportunity to promote indigenous underutilised crops, which are more resilient to harsh local climate conditions and require fewer agricultural inputs. These crops are valuable in the context of climate change, as they offer better nutrition and contribute to water and food security. (Ndlovu et al., 2024). In addition, smart technologies optimise energy use in irrigated agriculture by leveraging renewable energy sources, such as solar power for water pumping, and together with sensor technology and automated systems for precise water delivery (Parra-López et al., 2025).

This reduces reliance on traditional energy sources, lowers operational costs, and improves water and energy efficiency, thereby reducing energy footprint in agriculture. Moreover, adopting smart AWM practices offers opportunities to recover nutrients from wastewater for agricultural reuse, reducing the reliance on synthetic fertilisers and minimising water pollution (Parra-López et al., 2025). This is enhanced by the WEF nexus, which facilitates the formulation of coherent strategies to close the loop by integrating food waste into the resource cycle through circular systems that promote sustainable resource management (Nhamo et al., 2021).

3.3. Transitional pathways towards an integrated AWM

Transitional pathways towards integrated AWM involve moving from fragmented, sector-specific approaches to a holistic, systematic approach that embraces the entire water cycle and its interactions with other sectors. The transition requires addressing key issues, including water scarcity, pollution, and unproductive water losses. It is driven by (a) the growing water scarcity, (b) environmental degradation, and (c) fragmented water management practices (Stringer et al., 2021). The increased competition for and depletion of water resources necessitate more efficient and sustainable water management practices. Traditional and unsustainable agricultural practices dominating smallholder farming contribute to water degradation and pollution by releasing nutrients and pesticides into the environment, endangering human and environmental health (Pandian et al., 2024).

Characteristic	Smart Irrigation	Wastewater Reuse	Integrated Farming Systems	WEF Nexus
Water Use Efficiency	Improved water delivery	Nutrient recovery for reuse	Optimises water resources	Promotes sustainable resource management
Crop Yields	Enables efficient water delivery	Reduces reliance on synthetic fertilisers	Increases food production	Integrates food waste into resource cycle
Sustainable Farming	Minimises losses from evaporation	Minimises water pollution	Reduces environmental impact	Formulates coherent strategies
Energy Use	Leverages renewable energy sources	Reuses nutrients from wastewater	Lowers energy footprints	Optimises energy use
Crop Selection	Water-efficient crop selection	Mainstreams underutilised crops	Improves crop productivity	Promotes sustainable food systems

Fig. 1. Cross-sectional opportunities for integrated systems adoption in water management

Processes driving the transition to an integrated AWM include (a) the identification of existing unsustainable agricultural practices, (b) an assessment of how these practices exacerbate climate change impacts on agriculture, (c) exploration of strategies that support the transition to an integrated water management in agriculture, (d) identification of trends, opportunities, barriers and solutions to achieve sustainable water management, (e) formulation of coherent strategies and recommendations that drive the transition, and (f) implementation and monitoring of integrated, climate-smart AWM practices (Fig. 2).

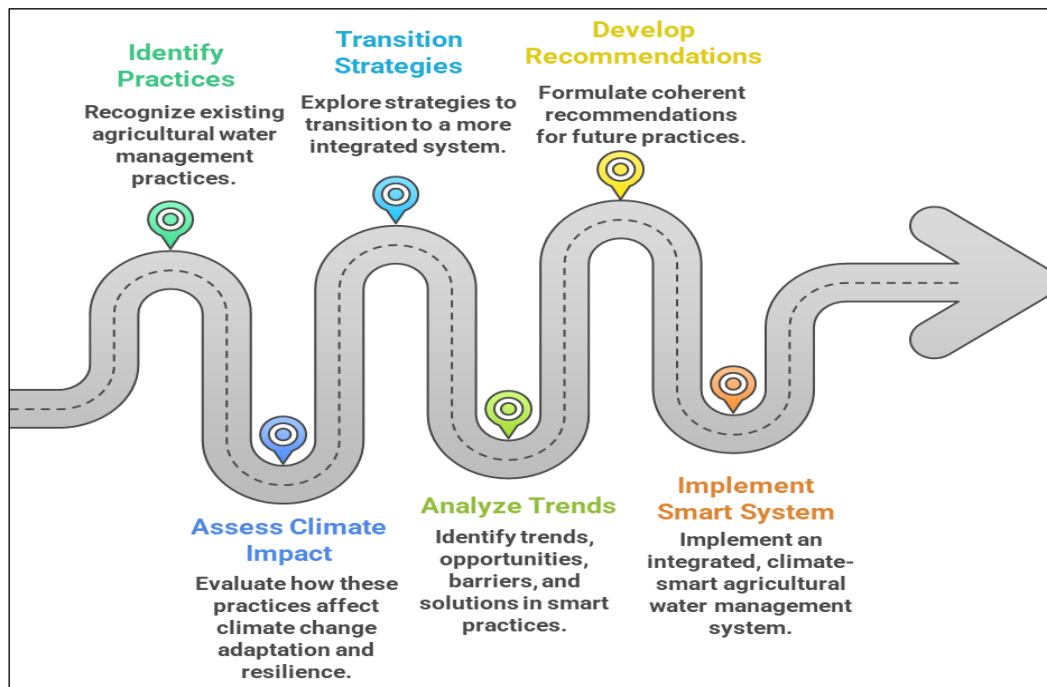


Fig. 2. A roadmap of guiding processes leading the transition towards an integrated water management in agriculture

However, integrated AWM brings together different sectors and actors, including agriculture, industry, urban areas, and the environment, to manage water resources holistically (Cosgrove & Loucks, 2015). It also considers the entire water cycle (precipitation, surface water, groundwater, wastewater) and its interconnectedness with other resources such as land and energy. The integration includes stakeholder inclusivity (farmers, communities, and public and private sectors) in decision-making processes, as it has foresight into long-term sustainability, aiming to balance economic development, social equity, and environmental protection (McGuire et al., 2024). Adopting transitional pathways in agriculture (Table 2) accelerates the transition to integrated AWM. It ensures water and food security while protecting the environment for people and the planet

Table 2. Transdisciplinary and transitional pathways that lead to an integrated AWM

Transitional pathway	Description
Improved irrigation efficiency	Adopting water-efficient irrigation techniques like drip irrigation and sprinkler systems to reduce water consumption in agriculture
Water storage and recharge	Developing infrastructure for rainwater harvesting, groundwater recharge, and water storage improves water availability during dry seasons.
Water reuse and recycling	Treating and reusing wastewater for irrigation reduces freshwater demand and pollution.
Soil management practices	Adopting smart practices such as zero tillage, cover cropping, and crop rotation improves soil health, increases water infiltration and soil moisture retention, and reduces erosion.
Policy and institutional reforms	Strengthening water governance frameworks, implementing regulations for water allocation, and promoting integrated water management across scales to support the transition
Technological innovations	Using technologies like remote sensing, GIS, data analytics, and decision support systems enhances water use efficiency.
Promoting a water-wise culture	Raising awareness about water conservation, promoting responsible water use, and encouraging behavioural changes support water management in agriculture.
WEF nexus approach	Considering the interconnectedness between water, energy, and food leads to more efficient and sustainable water management.
Livelihoods and demonstration farms	Testing and demonstrating innovative water management practices in real-world settings accelerates adoption and implementation.

CONCLUSIONS AND RECOMMENDATIONS

Transforming AWM moves beyond siloed water management, fostering coordinated strategies that optimise resource use, minimise waste, and improve overall sustainability in agriculture. Opportunities lie in increased resource efficiency, improved livelihoods, and enhanced sustainability. Solutions and pathways that guide the transition include developing integrated WEF models with AWM as an entry point, promoting participatory approaches, and strengthening governance structures. Understanding these interdependencies, identifying opportunities for synergies, addressing barriers, and implementing synergistic solutions that promote sustainable resource management could be the missing link between sustainability, climate change, and adaptation. Effective management of water resources in agriculture ensures water resources are used efficiently, supporting food production while safeguarding ecosystems and promoting sustainable development. Key recommendations include implementing smart technologies to enhance water use efficiency and developing strategic, coherent policies that acknowledge the interconnectedness of systems.

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