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Advancing sustainable water use across the agricultural life cycle in the USA

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Water scarcity presents an ever-growing challenge in global agriculture, with major implications for food security. In the USA, the scale and complexity of the agricultural system magnify these challenges, calling for an integrated and adaptive approach to water management. Hence, we reviewed six key strategies aimed at sustainable agricultural water management — crop distribution optimization, soil management, modern irrigation technologies, water treatment and reuse, reduction of water demand in animal agriculture, and minimizing food loss and waste — identified based on their prominence in recent literature and potential to address water scarcity. In examining these strategies through a multidimensional lens, several challenges have emerged, including gaps in the current structure of incentives, psychological barriers, lack of awareness, reluctance to alter existing farming practices and consumption habits, and insufficient data on the effectiveness of certain water conservation measures. By offering actionable insights into potential areas of improvement, this Review aims to contribute to the ongoing discourse on agricultural sustainability amid changing climate dynamics.

Being an essential human enterprise and by far the largest consumer of freshwater resources, agriculture stands at the heart of the global water sustainability challenge. Agriculture is a major consumer of both ground and surface water, demanding the bulk of freshwater diversion worldwide[1]. Population growth and rising per-capita food consumption necessitate a continued increase in crop production[2], intensifying reliance on already depleting freshwater resources. This dilemma is further compounded by climate change disrupting the water cycle[3,4], and addressing it requires a paradigm shift. Thus, the need for sustainable agricultural water management becomes imperative: an approach centred on efficient and effective utilization of water resources while minimizing adverse environmental impacts and ensuring long-term water availability.

Water scarcity in agriculture is a universal challenge, and its primary issues, such as growing competition for water across sectors[5–9], diminishing water quality[6,7,9–11], over-abstraction of groundwater[6–10] and emergent risks from climate change[5–8], are shared globally. However, the drivers and solutions of agricultural water scarcity are deeply influenced by unique local geographic, climatic and socio-economic conditions. In the USA, water management challenges are amplified by the scale and complexity of its agricultural system, which spans 157 million hectares of cropland and 267 million hectares of grassland

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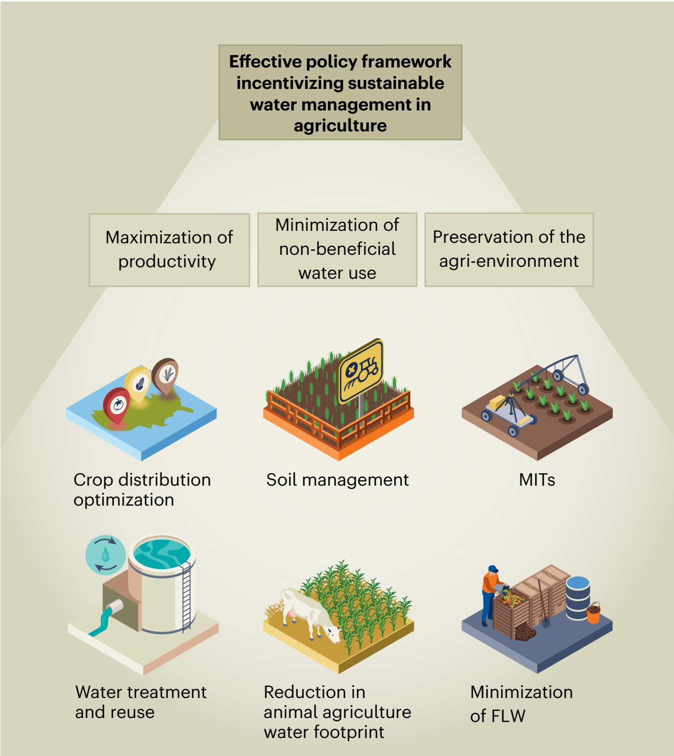

Fig. 1 | Strategies for sustainable agricultural water management. The aims of these strategies include maximizing water productivity, minimizing non-beneficial consumption and preserving the agri-environment. Policies to achieve these objectives should promote and incentivize adoption of the recommended strategies.

pasture and range[12] spread over a multitude of climate zones, from desert to subtropical. These translate to a substantial weight in the global food arena: in 2023, the USA produced over 30% of the world's corn and soybean crops and was the largest exporter of rice, cotton and almonds and the second to largest exporter of corn, soy and chicken meat[13]. Water resources are regulated through several tiers, including federal, state and private entities, leading to varied approaches to pricing, subsidies and allocation[14]. The legal landscape further complicates water management as the coexistence of riparian and prior appropriation doctrines across states reflects the historical and geographical diversity shaping US water law[14]. Hence, given the unique complexities of the US water management system and its substantial role in the global food market, this Review primarily focuses on the USA, while incorporating relevant insights from other regions.

Traditionally, water conservation in agriculture has been largely focused on enhancing irrigation efficiency, but there is now a growing recognition of alternative approaches to alleviating water stress. The entire food supply chain is under scrutiny to highlight inefficiencies that exert avoidable strain on agricultural water resources. Hence, this Review explores a broader range of strategies aimed at sustainable agricultural water management, encompassing key components along the food production pathway. These strategies follow the agricultural life cycle through the lens of water preservation, starting with optimizing crop selection to local conditions, implementing soil management practices, adopting efficient irrigation methods, utilizing alternative water sources, conserving water in crops used for animal feed, and finally, minimizing food waste. Collectively our recommended strategies aim to achieve the shared objectives of maximizing water productivity (value per unit consumed), minimizing non-beneficial consumption and preserving the agri-environment. This Review also emphasizes that achieving these objectives depends on policies that effectively promote and incentivize adoption of the recommended strategies (Fig. 1).

In this Review, we not only explore the potential of these strategies for enhancing water management in agriculture, but also summarize critical factors limiting their implementation or casting doubts on their utility in the USA. Upon reviewing these strategies, several recurring challenges have emerged, highlighting areas for targeted policy efforts and further research.

Crop distribution optimization

In the USA, water shortages are exacerbated by the spatial mismatch between precipitation and agricultural water consumption, which can differ substantially between crops and regions. Altering crop geographic distribution (also termed crop shifting) could therefore considerably reduce total agricultural water consumption. Differences in evapotranspiration rates between crops arise due to variability in phenology, leaf area, canopy cover, stomatal conductance and crop height[15]. Crop management, including fertilization[16], planting density[17] and frequency of fallow[18], also alters evapotranspiration. Within a given crop type, different cultivars can vary in their water use[19], and the development and adoption of limited transpiration cultivars could decrease water use during periods of high evaporative demand to increase yields in drought-prone regions[20,21].

A growing body of literature investigates the effects of optimizing crop distribution to decrease water use (Table 1), showing that it may be possible to decrease water consumption while simultaneously increasing caloric outputs and farmer incomes. For instance, global studies show that redistributing crops (under current climate conditions) could reduce rainwater (that is, green water) and irrigation (that is, blue water) consumption for agriculture by 14 and 12%, respectively[22], while also feeding an additional 825–866 million people[22,23]. National studies show similar trends—redistributing the 13 most common crops in China could reduce blue and green water consumption by between 4 and 19%, while also increasing farmer incomes, curbing greenhouse gas emissions and reducing the need for fertilizers and pesticides (which additionally require water for production)[24]. In the USA, redistributing crops could increase calorie and protein production by 46 and 34%, respectively, double economic value and decrease water consumption by 5%[25]. Notably, many of these optimization models indicate the need for a reduction in wheat and rice production and an increase in soybean and potato production to improve water conservation. For western US states, a study identified alfalfa and other cattle feed crops as the major irrigation consumers that could be replaced to reduce irrigation volumes in these water-stressed regions[26].

Although many optimization studies have examined crop shifts under static climate conditions[22–25], crop redistribution and crop water use will be influenced by climate change. The direct effects of climate change on evapotranspiration arise from the interacting effects of elevated CO_2 concentrations, increases in evaporative demand and plant physiological responses, and the net effects of these mechanisms are uncertain and a topic of substantial debate[27]. However, the availability of irrigation water under climate change is a major concern. Irrigation water originating as snowpack, for example, has decreased and is projected to do so further in the coming decades due to changes in the volume and timing of snowmelt runoff[28,29]. In the USA, almonds, apples, rice, tomatoes and walnuts face severe risk of water scarcity due to climate change, despite many regions already shifting away from water-intensive crops and reducing irrigation water consumption[26]. Similarly, crop geography has changed in many other regions of the world, in some cases exhibiting poleward shifts consistent with adaptive crop migration[30,31].

Despite the potential benefits of crop shifting, there are many barriers that may deter farmers from switching crops. For instance, although crop redistribution could help farmers to avoid future income losses due to water shortages, switching crops involves

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Table 1 | Summaries of existing studies on crop redistribution optimization

Article and geographic extent	Summary	Optimization conditions	Water reductions	Other environmental and social impacts
Beyer et al.[142]; global	Reallocate 25 major crops	Maintain: crop production (for each crop) Do not exceed: crop area Minimize: carbon emissions and biodiversity impacts Eliminate: irrigation	Irrigation consumption: −100%	Carbon emissions: −71% Biodiversity impacts: −87% Crop area: −48%
Davis et al.[22]; global	Reallocate 14 major crops or crop groups (optimization performed separately for rainfed and irrigated croplands)	Maintain: crop diversity and crop area Meet or exceed: calorie and protein production and crop value Minimize: green and blue water consumption	Irrigation consumption: −12% Rainwater consumption: −14%	Calorie production: +10% Protein production: +19% Feed production: +51% Additional people fed: 825 million
Xie et al.[24]; China	Reallocate 13 major crops (including altering crop rotations); optimizations were run multiple times, putting different weights on optimization conditions	Maintain: crop diversity, crop area and geographic appropriateness Meet or exceed: crop production (for each crop) and farmer incomes Maximize: farmer incomes Minimize: water consumption, GHG emissions, fertilizer use and pesticide use	Irrigation consumption: −4.5 to −18.5% Rainwater consumption: −4.4 to −9.5%	GHG emissions: −1.7 to −7.7% Fertilizer use: −5.2 to −10.9% Pesticide use: −4.3 to −10.8% Farmer incomes: +2.9 to +7.5%
Davis et al.[143]; India	Replace rice with alternative cereals (maize, wheat, finger millet, pearl millet and sorghum); optimization performed separately for rainfed and irrigated croplands; this study ran several other scenarios not represented here	Meet or exceed: calorie production (or crop replacement had to be finger millet, pearl millet or sorghum) Minimize: blue water consumption	Irrigation consumption: −33%	Protein production: +1% Iron production: +27% Zinc production: +13% Calorie production: modest reduction
Damerau et al.[144]; India	Reallocate 36 major crops	Maintain: crop diversity and geographic appropriateness Meet or exceed: calorie production Maximize: micronutrient production Minimize: crop area and irrigation consumption (for water-stressed regions only)	Irrigation consumption: −40% (optimizing to only reduce irrigation) or −16% (optimizing to reduce both irrigation and crop area)	Dietary GHG emissions: − 26 to − 34% (optimizing to only reduce irrigation) or −26 to −34% (optimizing to reduce both irrigation and crop area) Crop area: −20% (optimizing to reduce both irrigation and crop area)
Richter et al.[26]; six regions in the USA	Reallocate 30 major crops, allowing varying amounts of land fallowing	Maintain: crop diversity and geographic appropriateness Meet or exceed: farmer income Do not exceed: total irrigated area and 30% reduction in crop-specific area loss Minimize: irrigation consumption	Irrigation consumption: −28 to − 45% (allowing 30% land fallowing) or −7 to −24% (not allowing land fallowing)	NA
Davis et al.[25]; USA	Reallocate 11 major crops	Maintain: crop diversity and geographic appropriateness Meet or exceed: calorie production, protein production and farmer incomes Minimize: water consumption	Combined irrigation and rainwater consumption: −5%	Calorie production: +46% Protein production: +34% Economic value: +208%

We only list studies that included water savings in their optimization conditions. The optimization conditions listed here refer to how variables were treated in the models. For example, maintain means that the value of this variable could not change; meet or exceed means that the model output for this value needed to be equal to or greater than its current value; do not exceed means that the model output for this variable needed to be less than or equal to the current value; minimize means that the model sought to find the lowest possible value for this variable; and eliminate means that the model was finding outcomes where the value of this variable equalled zero. Geographic appropriateness refers to efforts to distribute crops in areas with a history of growing. Major crops refers to the crops with the greatest production in that region; examples of common major crops include rice, corn, wheat, soybeans and tuber crops. GHG, greenhouse gas; NA, not applicable.

substantial financial investment (for example, crop-specific infrastructure, machinery and training) and inherent risk[32]. Also, although climate change or the desire to help conserve water can be a factor in farmer decision-making[33,34], other factors, such as income[35] and available markets[36], may play a larger role in determining farmers' crop choice. Finally, it is important to consider that specific crops may relate to farmers' livelihoods, familial or cultural identities, and generational knowledge systems[37].

Achieving crop switching on a large scale would be extremely complex and expensive, requiring an organized effort across the USA to incentivize behaviour change and exchange knowledge. Financial incentives, such as payment for ecosystem service programmes or grants, would probably be necessary to encourage farmers to alter their cropping systems[38]. It is also possible that water conservation or regulatory programmes, such as California's Sustainable Groundwater Management Act or Kansas's Local Enhanced Management Area programme, would motivate crop switching. The Local Enhanced Management Area programme, for example, reduced groundwater use by 31% between 2013 and 2017, with 19% of these reductions resulting from farmers switching to less water-intensive crops[39]. In addition to this, educational programmes, technical assistance and outreach, such as through agricultural extension programmes, would be essential to ensure that farmers have the skills and knowledge to successfully grow new crops in their specific geography. Research has shown the particular value of farmer networks and organizations in driving the adoption of new behaviours[40]. Finally, expanding or subsidizing crop insurance is also important to buffer farmers' risk after switching crops[41].

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Soil management

Water preservation can be further promoted through soil management practices. Techniques such as cover crops, conservation tillage and application of soil amendments may improve soil texture, elevate soil organic matter content and limit evaporation, contributing to higher water retention and increased irrigation efficiency[42–44]. Wider adoption of water-conserving soil management regimens could ease the strain on farmers and the environment brought about by current and projected water shortages. Thus, understanding the benefits and challenges of implementing these practices is essential.

Cover crops can reduce soil erosion and loss of soil organic carbon (SOC), improving soil water retention[42,45]. By utilizing excess soil nutrients, cover crops improve runoff quality; for example, full implementation of cover crops could reduce nitrate leaching by 20% in the Mississippi River Basin and by 69% globally[46,47]. However, despite the documented advantages, only 3–7% of US farmers incorporate cover crops into their crop rotations[48]. Recent studies found that farmers' decisions to adopt cover crops are predominantly influenced by concerns over management complexity and economic viability[49,50]. The impact of cover crops on primary crop yield varies, with some reports finding a positive effect on primary crop yield and quality, whereas others describe negligible or even negative effects[42,51]. Furthermore, in arid regions where agricultural activity heavily depends on irrigation, cover crops might use more water than they conserve, making them less practical[45]. Incentive programmes directly addressing these concerns by providing guidance and funding for the initial implementation steps have been instrumental in increasing adoption rates in the USA over the past 15 years[52].

No-till farming improves both runoff quality (which translates to better irrigation water quality downstream) and soil water retention[43]. No-till field studies in Australia and Spain have shown marked increases in soil water content (~7%) and available water content (25%) compared with conventional tillage[53,54]. For the major cash crops in the USA, the use of no-till farming ranges from about 20% of the planted acreage of cotton to approximately 40% for soy, wheat and corn; another 20–40% is farmed using other conservation tillage methods[55]. Despite the gradual increase in these numbers over the past two decades and proven long-term economic benefits over conventional tillage, no-till farming is still met with some reluctance[56,57]. Common barriers to adoption include increased herbicide use, lack of trust or eligibility restrictions pertaining to government incentives, and farmers' belief that conservation tillage is not advantageous for their specific operations[56,57]. Governmental programmes developed with farmers to reflect their needs, and increasing farmers' awareness of the monetary and soil health benefits may help to increase acceptance of the practice.

Soil amendments are commonly carbon based, such as biochar, water-absorbing polymers and raw or composted waste. Inorganic additives—often clays and zeolites—are also used, separately or mixed with organic substances[44,58,59]. Amendments increase the soil water holding capacity and plant-available water by introducing properties that keep water in the root zone (apt porosity, high surface area and polar functional groups), as well as through increased SOC and microbiome development[44,58,60]. Thus, their beneficial effect is more substantial in soils with low SOC and/or sandy or coarse texture: biochar, for instance, has been found to increase plant-available water by an average of 45% in coarse-textured soils versus only 14% in fine-textured soils[58,61]. Expanding the use of amendments for water conservation is complicated by the large variety of amendment types, physicochemical properties, application costs and agricultural outcomes. Moreover, a thorough comparison of amendments focusing specifically on their water conservation potential is needed. A field study conducted in the Lao People's Democratic Republic concluded that high-cost amendments such as bentonite and biochar normally take 5–7 years to be economically viable, whereas low-cost additives—usually raw or processed waste—can return the investment in one year[44]. With water scarcity projected to increase, this calculation may shift to give higher weight to amendment-related drought resilience.

In addition to soil management methods that affect soil texture and percolation, water consumption can be directly reduced through rotational fallowing, where agricultural land is deliberately left unirrigated or uncultivated between growing cycles. The two largest fallowing programmes in the western USA include the Palo Verde Irrigation District and Imperial Irrigation District in southern California, where approximately 20 and 4% of cropland are fallowed, respectively, saving an average of ~2,100 $m^3\ yr^{-1}$ of water per hectare fallowed[62]. The loss of income associated with not cultivating crops for a growing season is a considerable barrier to adopting rotational fallowing. However, farmers can be financially compensated by selling the water saved during fallowing to public water supply municipalities. For example, ~40% of the water supply in San Diego County is derived from the Imperial Irrigation District rotational fallowing programme[62]. Such programmes could be applied elsewhere in western USA to address water scarcity. For example, meeting the demand management goal of reducing water consumption by 123,000,000 $m^3\ yr^{-1}$ to avoid water shortages in the Upper Colorado River Basin could be achieved with temporary, rotational fallowing of 20% of cattle feed crops[62].

Modern irrigation technologies

Irrigated cropland contributes 54% of the US$400 billion value of US crops[63]. The 17 western US states, which hold 46% of the national harvested cropland[64], accounted for 82% of the irrigation volumes applied in 2023[65]. Being dominated by semi-arid and Mediterranean climates and lower precipitation averages, enhancement of irrigation efficiency and productivity is imperative to sustaining agricultural activity in these regions.

Traditional irrigation systems are characterized by inefficiencies, with 50–75% of appropriated water failing to reach the intended crops[66]. To address this, modern irrigation technologies (MITs), such as pressurized irrigation systems (sprinkler and drip), canal lining and sealing, remote monitoring and control, and other advancements, are often promoted as effective solutions for improving water conservation in agriculture. By delivering water directly to the root zone and minimizing losses through evaporation and runoff, these technologies have the potential to optimize water application and improve crop water productivity. However, their impact on overall water conservation is not straightforward, as it depends on a multitude of complex and interrelated factors, which are discussed later in this section.

In recent decades, irrigation efficiency in the USA has improved notably, particularly with the widespread transition from gravity-fed or surface irrigation to pressurized systems[5]. According to the US Department of Agriculture, water applied to the total irrigated land area across the western states decreased substantially over time as the proportion of land irrigated by pressurized systems increased[67]. Although the USA has seen a 21% decrease in nationwide irrigation water withdrawals since 1980 with increased MIT adoption[68], a study found that the primary drivers of reduced water consumption (+0.5 to −45%) in six study areas across the western USA were a decrease in irrigated area (3–44%) and changes in crop mix[26].

Pressurized irrigation has also facilitated the adoption of precision irrigation, which utilizes advanced technology, including proximate and remote sensing systems, along with specialized equipment to optimize water and nutrient use. These benefits have been observed in the US Great Plains[69], Mississippi River Basin[70], Southeastern Coastal Plain[71] and California[72]. Precision irrigation has benefited from the rise in artificial intelligence and machine learning algorithms capable of processing large amounts of data to acquire insights, recognize patterns and make predictions automatically. These tools have been demonstrated to predict water demand and identify water stress in real time to help control irrigation for various crops[73–75] (Box 1). Adoption of precision irrigation, however, is hindered by a lack of effective

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BOX 1

Artificial intelligence, machine learning and big data

Currently, three types of data are used for machine learning applications in agricultural water management: sensor based, remote sensing based and traditional[73]. Sensor-based data, collected from soil, meteorological and crop sensors, provide information on soil properties, meteorological parameters and crop physiology, respectively. Remote sensing data focus on meteorological, canopy and hydrological conditions, whereas traditional data are manually gathered in the field, including crop growth, yield and photosynthesis measurements. The availability of these data types facilitates machine learning applications in various irrigation areas of agricultural water management, with a key focus on predicting irrigation water demand, particularly soil water content and reference crop evapotranspiration.

The literature has shown the effectiveness of machine learning algorithms in predicting soil moisture. One study used neural network, random forest and support vector machine (SVM) algorithms to effectively predict soil water content in potato fields with low-cost sensors[159]. Another combined whale optimization with SVM prediction to predict soil moisture in maize fields in the USA using climate data[160]. Moreover, a study in China demonstrated machine learning algorithms predicting soil moisture at various depths in maize fields using RGB, multispectral and thermal sensor data[161].

Furthermore, machine learning-based research on crop evapotranspiration aims to achieve reasonably accurate predictions with fewer parameters. A study from China[162] showed that extreme machine learning and generalized regression neural network models, using only temperature data, outperformed the established Hargreaves model for estimating reference evapotranspiration. Other recent work[163,164] also confirmed that machine learning methods surpass traditional models such as the Shuttleworth–Wallace, Priestley–Taylor and Penman models, in terms of estimation accuracy.

Water scarcity diagnosis in agricultural farms, essential for irrigation scheduling, is another area that has attracted considerable artificial intelligence interventions from researchers. Machine learning algorithms applied to visible and thermal infrared images help to assess soil moisture, water stress, drought stress and canopy water content, enabling real-time water stress detection in crops such as maize, spinach and wheat[165–168]. In irrigation scheduling, machine learning models (artificial neural network, SVM, random forest regression and recurrent neural network models) can optimize water requirements, with numerous studies using meteorological and crop sensor data to enhance decision-making[75,169–172].

Despite promising growth in machine learning-based technology for agricultural water management, certain challenges remain. The biggest hurdle is data availability, as acquiring large-scale irrigation data is costly and time intensive. Since machine learning model advancement depends on data quality and quantity, this remains a major barrier. Additionally, improving model interpretability and transferability is crucial. Researchers suggest that a unified framework for future machine learning models in irrigation should be developed to address these challenges[73].

policy[76,77] and current technological limitations, such as the availability and interpretability of data to train machine learning models and the transferability of these models[73] (Box 1). Nonetheless, the rapid developments in artificial intelligence and machine learning show great promise for facilitating precision irrigation implementation.

Moreover, MIT advantages extend beyond the field level across watershed scales, especially in irrigated alluvial valleys[78–80]. Shallow groundwater created by excessive deep percolation and canal seepage can be mitigated by MITs, thereby reducing waterlogging and salinity under irrigated lands[81]. MITs can also diminish the solute loading of nutrients, pesticides and mobilized salts and trace elements, and can reduce gradients that drive these pollutants into receiving streams[79,82].

However, the shift to MITs has raised concerns that the resulting increase in irrigation efficiency may paradoxically increase water consumption at the watershed scale[83], prompting debate about their effectiveness for achieving tangible water savings[66,84]. Although agencies may promote MIT adoption to encourage water savings, farmers often prioritize maximizing profits[85,86]. As increase in farm-level profit from adopting MITs fails to account for the costs of subsidies and environmental externalities[66], farmers may view MITs as tools to expand irrigated acreage, cultivate water-intensive crops or increase water application to boost yields[66]. For example, a study analysing 221 basins in the western USA observed an increase in irrigation water use across much of the region, contradicting officially reported government statistics[87]. As a result, irrigation intensification has been reported to impact streamflow sustainability in the western USA[84,87]. Such environmental implications are often overlooked when irrigation subsidy programmes are developed[66], as seen in Australia's Murray–Darling Basin, where subsidized conversions to MITs faced criticism for encouraging reduced return flows and ecosystem degradation[88].

It should be noted that this is not an inherent flaw of MITs, but stems from the current structure of incentives pertaining to irrigation. It is also not an unavoidable failure of the subsidy system—subsidizing irrigation technologies carries important benefits, such as food security and reduced poverty—but a guideline to improve related policy-making. One potential solution is to implement water quotas while subsidizing irrigation technology, which can help to maintain positive social benefits while reducing environmental impacts[89]. However, in the USA, any reforms regarding water quotas are particularly complex due to regional variability in water prices, sources and institutional frameworks[14]. The banding together of irrigators in collaborative water users' associations, rather than government-mandated quotas, can contribute to enhanced water management, but has shown mixed success worldwide[90–92]. A recent examination of historical and present-day irrigation advances in the Great Plains region showed that MITs could allow sustainable farm economies with reduced water consumption when public policy was coordinated with effective technology transfer[93]. Such policies have been implemented in Kansas[94,95] and Nebraska[96] with varying levels of success.

Another important factor to consider is the hydrological properties of the individual river basin. In the western USA, MITs can be beneficial in areas where water is lost through avoidable non-beneficial consumptive uses, whereas less efficient irrigation systems may benefit regions where irrigation increases the sub-annual flows despite climate aridification[6].

Hence, the potential benefits of MITs for crop productivity and irrigation hydrology depend on their implementation within an appropriate policy framework. Customized solutions should be tailored to the specific social, economic, environmental, legal and climatic needs of each region.

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Table 2 | Key challenges associated with the poor quality of TWW

Challenges	Negative impact	Current solutions and available technologies	Main gaps towards implementation	References
High salinity	Salinity causes osmotic stress, which hinders water uptake by crops. High Na^+ and Cl^- concentrations suppress the uptake of essential nutrients. The high SAR causes clay swelling, dispersion and pore clogging.	Setting regulations regarding the SAR and salinity with respect to the type of crop, soil and duration. Mixing TWW with fresh or desalinated water. Ion exchange columns and membrane separation.	Cost efficiency related to the treatment of saline water (mainly membrane separation technologies). Technologies that target specific monovalent ions are missing.	Refs. 100,145–148
Contamination by heavy metals and EOCs	Reduction in soil fertility and health. Reduction in crop yield Uptake by plants, digestion by animals and humans and consequently negative health effects. Leaching and contamination of ground and surface water.	Tertiary treatment before irrigation: current technologies for EOCs are advanced oxidation processes (mainly ozonation) or adsorption by activated carbon. Setting regulations regarding safe levels for irrigation with respect to the type of pollutant, crop and soil.	Cost efficiency of the tertiary treatment. The diversity and plentitude of EOCs makes them difficult to remove with one technology. A knowledge gap exists regarding the fate of EOCs in WWTPs and the agri-environment. Lack of legislation regarding safety levels in TWW.	Refs. 103,145,149–152
Biocontaminants: pathogens, ARGs and ARBs	Breakout of disease through plant consumption. Increased risk of spreading ARGs and bacteria. Deterioration of soil microbiome health	Disinfection and membrane filtration reduce the risk of pathogen infection. Implementing physical barriers that minimize direct contact of the crop with TWW (such as drip irrigation and plastic mulch).	Disinfection does not eliminate the threat of ARGs and ARBs and the extent of their survival, and dissemination in the agri-environment is unknown. Lack of legislation regarding ARGs and ARBs.	Refs. 145,147,148,151,153,154
Plastic contamination	Soil and groundwater contamination by microplastics.	No regulatory or technological solutions are currently implemented.	The fate and related health risks are largely unknown. No specific technologies are available. No legislation is in place.	Refs. 155–157

ARBs, antibiotic-resistant bacteria; ARGs, antibiotic-resistant genes; EOCs, emerging organic contaminants; SAR, sodium adsorption ratio; WWTPs, wastewater treatment plants.

Water treatment and reuse for irrigation

Treated wastewater (TWW) is a crucial water resource, playing a pivotal role in addressing the needs of arid regions by satisfying agricultural demands, preserving freshwater reservoirs and facilitating the reuse of organic matter, nitrogen, phosphorous and other indispensable ions[64,97–100]. Globally, an estimated ~1.7% of municipal wastewater is treated and reused, but this practice is widespread in regions with severe water scarcity. In Israel, over 87% of the TWW is reused, accounting for approximately 50% of agricultural demand[97,101]. In the USA, approximately 10% of TWW is estimated to be directly recycled, increasing by about 5% per year; the rest is typically discharged into natural waterways, often indirectly reused as water is withdrawn downstream for irrigation and potable use[102–104]. Reusing TWW from the 16,000 existing plants (~63 billion gallons per day) could fulfil over 30% of US agricultural requirements[98]. Specifically, local TWW supply varies across the USA, with eastern states experiencing a greater excess of reclaimed water compared with western states in terms of irrigation needs. Nonetheless, examination on a sub-watershed scale indicated that a non-negligible demand could be offset by TWW generated within reasonable distance[104]. Direct recycling of TWW for irrigation also allows efficient utilization of residual nutrients by irrigated crops, whereas indirect reuse after discharge into surface water may compromise environmental health.

Recent survey data highlight three primary drivers for direct water reuse in the USA: water scarcity; environmental constraints on wastewater effluent; and state-level mandates to develop and implement integrated water resource plans[102]. The leading states where these practices have been developed are Florida, California and Texas. In Florida, approximately 48% of TWW is directly reused for industrial needs, agriculture and irrigation of public areas. The high direct water reuse is supported by relatively few irrigation restrictions on reclaimed water during droughts and no reported illnesses related to its agricultural uses[103]. Similarly, California has high direct TWW reuse rates for application in agriculture (37%) and landscape and golf course irrigation (24%)[103]. Still, public perception, the cost of water treatment to mitigate reuse risks, lack of consistent regulatory frameworks and legal restrictions impede the expansion of directly recycled water use across the country[99,102,105,106]. Challenges still exist concerning TWW quality, as detailed in Table 2, affecting both costs and farmers' perception. A survey from 2019 found that growers were apprehensive about irrigation with reclaimed water, especially for edible crops, although acceptance increased when they were provided with information on the quality of TWW compared with their primary water sources[107]. Implementation of more stringent treatment policies is also expected to increase the share of TWW that meets quality criteria for irrigation[104,108]. The cost of TWW may be inhibitive as well, in part because current water prices do not reflect true costs or scarcity[98,109]. Allocating resources to develop cheaper and more efficient water treatment techniques may help to balance this disparity over time[98]. Moreover, attaching value to reclaimed wastewater may reduce water treatment expenses and promote efficient irrigation techniques[110,97]. In the short and medium term, incentivizing optimized selection of crops based on local water supply and/or adjusting irrigation water prices (both from alternative and traditional sources) could promote the incorporation of TWW into irrigation schemes. For example, direct TWW use in Israel is integrated into a variable water tariff system that incentivizes irrigation with non-potable water and takes into account local water availability[101]. Several European countries have instituted water pricing mechanisms and policies as well[111].

Lastly, many of the setbacks limiting the use of TWW apply to other non-traditional water sources, such as produced water and agricultural drainage and runoff[64,98]. In addition to quality and treatment cost

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concerns, reuse of such waters may require modifications in the current water rights systems established in the western US states. These systems are mainly based on the prior appropriation doctrine, but in some cases groundwater may also be treated as a mineral right tied to land ownership. The legal landscape is exceedingly complex and varies from state to state. For example, some downstream water rights are based on historical irrigation practices that produced substantial volumes of runoff directly to streams and/or drainage to riparian aquifers that provided base flow to streams. These water volumes of streamflow were in some cases appropriated by users downstream whose water rights may preclude upstream farms from instituting irrigation practices that reduce drainage and runoff[93].

To overcome the obstacles and increase the use of TWW and other alternative water sources in the USA, technical, legislative and social factors should all be addressed to increase public acceptance and trust[105]. This includes setting ambitious water reuse goals, increasing research and oversight on the environmental and health risks, advancing research and implementation of remediation technologies that meet both water quality and quantity standards, introducing water quality criteria that are tailored to the end user and allocating appropriate funding. Although difficult, the severity of water scarcity requires us to make the necessary adjustments and properly harness this invaluable water resource in a sustainable way.

Even with better utilization of alternative water sources, the western US states represent a disproportionate fraction of the national agricultural water demand, in part due to the needs of animal agriculture[62,98]. Reducing the water footprint of animal agriculture is therefore an important aspect of overall minimization of agricultural water demand.

Reduction of the animal agriculture water footprint

A large fraction of agricultural output is not consumed directly but dedicated instead to animal husbandry. Globally, animal production accounts for 29% of agricultural water usage, 98% of which is consumed in animal feed irrigation[112]. Cattle feed crop irrigation is the greatest consumer of western US river water, accounting for 23% of total water consumption nationally and 55% of water consumption within the Colorado River Basin[62]. Thus, curbing animal agricultural water demand could effectively decrease agricultural water usage.

In addition to optimizing crop distribution and rotational fallowing, prioritizing less water-intensive feed crops can reduce animal agricultural water demand. For instance, total water demand for feed concentrates (for example corn, cereals and pulses) is five times higher than that of roughages (that is, pastures and straw)[113–115]. In Brazil, the water footprints of beef production for two separate cattle feedlots using 90 and 80% concentrates in feed were 6,685–9,673 $m^3\,kg^{-1}$ and 4,628–5,236 $m^3\,kg^{-1}$ of meat, respectively[115], highlighting the water-saving benefits when concentrates are substituted for roughages. Within North America, concentrate constitutes 5.1, 26.9, 72.8, 77.4 and 55.2% of the total feed for beef cattle, dairy cattle, broiler chickens, layer chickens and pigs, respectively[112]. Thus, there is substantial room for improvement in shifting away from concentrates. Although decreasing reliance on feed concentrates in favour of roughages would help to minimize feed crop water demand, the efficacy of this change depends on where roughages are grown, highlighting the importance of optimized crop distribution[116]. For example, wildrye hay (a roughage crop) requires more water compared with other feed crops in Northern China dairy farms since the hay is grown in a water-scarce region of Northeast China[116]. Lastly, while roughages are more water-efficient crops compared with concentrates, a substantial amount of water is still used to produce roughages for livestock feed: 28% of total water consumption in the western USA is used for alfalfa hay, grass hay and other haylage irrigation[62]. Consequently, other practices beyond feed type selection are required to decrease agricultural water demand.

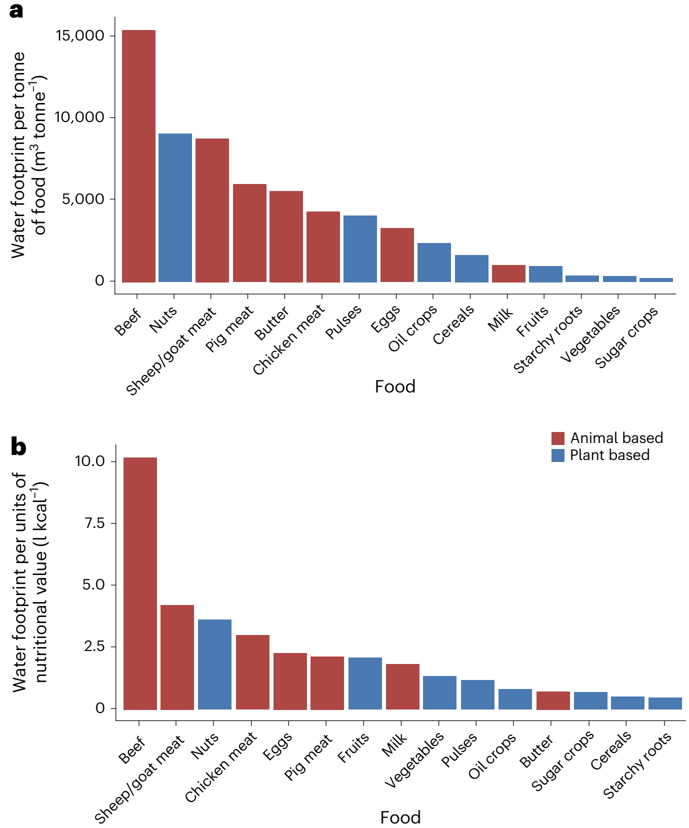

Fig. 2 | Comparison of the water footprints of animal- and plant-based foods. **a**, Volume of water required to produce one tonne of food. **b**, Volume of water required to produce one kilocalorie of food. Foods using a lower number of litres per kilocalorie are more water resource efficient from a caloric standpoint, requiring less water to produce the same number of calories. Data from ref. 112.

Beyond agricultural practices, overconsumption of animal-based foods exacerbates animal agricultural water demand. Consumption of animal-based foods is increasing globally[117] and US meat consumption exceeds the global average by almost threefold[118], contributing to 37% of the food-related water footprint of an average American[112]. Different animal-based diets have varying resource demands; for instance, beef production requires eight and 11 times more feed per kilogram of meat compared with pork and poultry, respectively, increasing the comparative water footprint of beef[112]. Thus, simply switching to a less water-intensive animal-based diet without reducing overall consumption could help to alleviate some of the water demand. Moreover, producing animal-based foods generally requires more water compared with producing plant-based foods (Fig. 2a), and producing animal-based calories is less water efficient compared with producing plant-based calories (Fig. 2b). Replacing meat with equivalent quantities of plant-based foods, such as pulses and nuts, would decrease the average American food-related water footprint by 30%, reducing agricultural water demand and allowing more food to be produced to feed an additional 1.8 billion people[112,119]. Additionally, alternative protein sources, such as insects, merit consideration given that producing one kilogram of crickets requires ten times less water than beef and its amino acid content exceeds requirements provided by the Food and Agriculture Organization and World Health Organization[120]. Barriers to adopting more sustainable diets include factors such as affordability, deeply ingrained habits, lack of incentives and limited consumer knowledge[121,122]. Community-based initiatives (such as the 2020 Meatless Monday campaign in Bedford, Massachusetts), disseminating plant-based recipes and subsidizing plant-based foods can help to address these limitations[121,122]. Nevertheless, additional

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Table 3 | Sample of policy efforts in the USA to reduce food waste

Policy focus area	Policy category	Legislation/statue title	Legislation description	Jurisdiction
Prevention	Date labelling	California Food and Agricultural Code 82000-1	Mandates the California Department of Food and Agriculture to promote use-by and best-if-used-by labels to indicate safety and quality, respectively	California
Rescue and recovery	Tax incentive	California Revenue and Taxation Code 17053.12	Agricultural product businesses are eligible for a tax credit equivalent to 50% of transportation costs for donating crops to eligible non-profit organizations	California
	Food safety	Title 25 Texas Administrative Code 228.64	Detailed safety protocols for food donations, including storage temperature, shelf life, labelling, product damage and distressed food	Texas
	Liability protection	Good Samaritan Food Donation Act (amended by the Food Donation Improvement Act)	Provides legal protection to food donors and non-profit organizations against civil and criminal liability claims related to the condition of donated foods	Federal
Recycling	Organic waste bans	Title 10 Vermont Statutes Annotated Code 6605k (Act 148: Universal Recycling Law)	Individuals and businesses are required to separate and recycle organic waste	Vermont

Data from ref. 158.

behavioural changes from consumers, such as minimizing food loss and waste (FLW), are needed in conjunction with decreasing meat intake to further drive down agricultural water consumption.

Minimizing FLW

The endpoint of the agricultural endeavour is the harvest, trade and consumption of its products. Here, too, opportunities arise to reduce agricultural water demand through the minimization of FLW. Food loss refers to the reduction in food quantity or quality from harvest through processing, whereas food waste primarily occurs at the retail and consumer levels[123].

FLW contributes to a substantial loss of resources, including the water used in production, highlighting the urgency of achieving Sustainable Development Goal 12.3, which calls for halving per-capita global food waste by 2030[123]. Worldwide, an estimated 1.3 billion tonnes of food is lost or wasted annually[124], with the USA alone accounting for approximately 10% of this total[125]. Additionally, the USA has the highest annual per-capita blue water footprint linked to FLW at 54.9 m^3, whereas the global average is 21 m^3 (ref. 126). Globally, FLW is responsible for 24% of freshwater used in food production[127], whereas in the USA uneaten food accounts for 22% of all water use in the country[128]. Reducing global FLW by only half could decrease the water footprint of food production by 12–13%, benefiting over 720 million people by alleviating water scarcity[129].

As the cause and extent of FLW vary based on the production stage, countries' income levels and technological development, consumers' socio-economic status and dietary patterns, there is no one-size-fits-all solution, and various approaches have been adopted to address it[130–132]. For instance, in developing countries, food loss is driven by limited resources for harvesting, storage and transportation infrastructure, leading to higher post-harvest FLW[124]. In contrast, in high-income countries such as the USA, substantial FLW occurs at retail and consumer levels because of the higher purchasing power of consumers[124].

Countries differ widely in their progress towards enacting FLW regulations. For instance, supermarkets in France have a legal obligation to donate unsold food or repurpose it as animal feed, with potential fines for non-compliance[133]. In Italy, regulations encourage FLW mitigation by providing tax benefits to supermarkets engaged in donations[133]. The UK is the only country with data confirming a 27% reduction in FLW, attributed to its focused FLW reduction efforts[134]. Despite the USA setting a goal in 2015 to reduce half of its FLW by 2030, progress towards this target has considerably lagged, as is evident by increased per-capita food waste since 2015[135].

Greater federal involvement is needed to standardize FLW policies. Currently, US federal laws aimed at FLW reduction are limited and inadequate[136]; however, several state-level legislations have been enacted (Table 3). In the absence of federal regulations, states exercising their discretion to regulate food date labels results in inconsistent regulations nationwide[137]. This lack of uniformity contributes to confusion over product safety or selling regulations, resulting in 7% of all food waste in the USA[137].

Another seemingly effective solution to reducing FLW is federally funded, national-level awareness campaigns, such as Love Food Hate Waste, launched in the UK (https://lovefoodhatewaste.com/), Too Good for the Bin, started in Germany[133], and the Clean Plate campaign (2020) in China[138]. The USA could benefit immensely from similar consumer education campaigns considering that households contribute to nearly 50% of all food waste generated in the country[128].

An alternative strategy could be to involve dominant companies in specific food sectors to participate in FLW reduction efforts through government regulations or societal pressure. For instance, with three companies controlling over 50% of the chicken and pig market and 75% of all cattle in the USA, the implementation of FLW reduction policies by them could influence the entire supply chain[131].

Furthermore, in the USA, meat and dairy account for the highest water footprint linked to FLW, whereas fruits and vegetables constitute the largest portion of wasted food. Therefore, shifting to a plant-based diet in isolation could increase the volume of wasted food and its associated water footprint. However, combining dietary changes with FLW reduction strategies could potentially be more effective in reducing the water footprint of an average American[132].

Although all of the above-mentioned solutions to curbing FLW are available, there are several constraints and barriers to adoption. For instance, inconsistencies in definitions and measurement methodologies of FLW among various entities hinder accurate estimation and comparison, affecting FLW policy development[130]. Another challenge is the inadequate monitoring of the progress of FLW reduction policies, making it difficult to gauge their effectiveness. Information about current FLW policies also needs to be disseminated more effectively. For example, in the USA, despite the liability protection available through the Good Samaritan Act for food donors (Table 2), companies still fear consequences related to the condition of donated foods and prefer disposal over donation[136]. Other barriers to adoption include insufficient collaboration between different stakeholders, handling costs of food donations, and extremely low landfill disposal fees[139].

A recent study discussed the possibility that lower food prices resulting from reduced FLW could potentially increase consumption, offsetting some of the benefits of reducing FLW, a phenomenon known as the rebound effect[140]. Therefore, it is crucial to acknowledge that a major reduction in water usage tied to FLW can only be achieved by avoiding surplus food production[141], which may have implications for food security. These complex trade-offs must be considered in policy-making aimed at FLW reduction.

Outlook

Although the challenges of water availability in agriculture present a pressing concern, there exists no silver bullet solution, as is the case for many contemporary sustainability issues. Instead, a multifaceted approach integrating strategies across food production and consumption is required. The key to achieving sustainable water management through these strategies lies in policies that effectively incentivize progress towards their implementation. The development of such policies must adopt a multidimensional context-dependent approach with consideration of competing uses and potential caveats. Therefore, although this Review explores global strategies for water conservation, it specifically addresses their caveats and implementation challenges within the USA, highlighting areas for further development and research.

Here, policy reform is constrained by the cognitive inertia, where actors and stakeholders favour familiar perspectives over emerging evidence challenging the status quo. Additionally, failing to account for and communicate the full cost of irrigation subsidies, including their externalities, such as reduced return flows, limits public awareness of the broader social and environmental impacts, thereby hindering demand for change. Psychological barriers due to insufficient awareness and education, such as negative public perception of TWW-irrigated crops and reluctance to modify farming practices or consumption habits, pose additional limitations. Another major challenge is the lack of adequate data assessing the efficiency of some water conservation measures, such as FLW mitigation programmes and soil amendments. Government and regulatory bodies should prioritize efforts to overcome these obstacles and incentivize change.

Although water-preserving measures, such as water treatment, water-efficient irrigation equipment, soil amendments, long-distance produce transport and artificial intelligence and machine learning integration, can optimize water use, they may also increase greenhouse gas emissions. To mitigate this, energy-efficient designs or incentive programmes may be needed. Therefore, it is critical to conduct life-cycle analyses of proposed strategies to comprehensively assess their environmental and societal impacts and identify measures for mitigation.

As the global water crisis deepens, there is a need to develop more sophisticated models that incorporate operational costs, educational requirements, technical support mechanisms and data collection strategies to sustainably maximize productivity per drop of water in agriculture. If effectively applied, the diverse and interconnected strategies reviewed here, which combine efforts from various stakeholders, can establish a more sustainable and water-efficient agricultural system in better synergy with the hydrologic environment.

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