



# Advances in micro-irrigation and supplementary irrigation in millets of dryland ecosystems

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## Abstract

Dryland ecosystems cover approximately 41 % of the Earth's terrestrial surface and support nearly two billion people. This review synthesises recent advances in micro-irrigation and supplementary irrigation strategies for enhancing millet productivity and resilience in dryland ecosystems. Drylands are characterised by low and erratic rainfall, high evapotranspiration, poor soil fertility and frequent drought stress, making agricultural production vulnerable to climate variability and water scarcity. Millets are drought-tolerant, climate-resilient cereals cultivated in dryland agroecosystems. Despite their resilience, millet productivity remains constrained by increasing rainfall variability, prolonged intra-seasonal dry spells and rising atmospheric aridity associated with climate change. Evidence from semi-arid and arid regions indicates that micro-irrigation systems, including drip, subsurface drip and micro-sprinkler irrigation, significantly improve yield and biomass accumulation compared to conventional surface irrigation methods. These irrigation systems also enhance water use efficiency (WUE) and nutrient use efficiency (NUE), making them highly suitable for millet production in dryland ecosystems. The integration of fertigation further improves nutrient synchronisation with crop demand, reduces leaching losses and supports soil fertility. The review also highlights optimised irrigation scheduling based on evapotranspiration, soil moisture thresholds, deficit irrigation principles and sensor-based automation. Smart irrigation technologies incorporating soil moisture sensors and Internet of Things (IoT)-based control systems show strong potential to enhance precision water management and reduce water consumption by up to 30–35 %. Their adoption, supported by technological innovation, policy frameworks and location-specific research, will promote sustainable water management and resource-use efficiency in millet-based dryland ecosystems. Future research should focus on optimising irrigation scheduling, smart technologies and cost-effective solutions for water-limited environments.

**Keywords:** automation; dryland ecosystem; millets; smart irrigation; water use efficiency

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## 1. Introduction

Dryland agriculture occupies large areas of the tropics and subtropics and is characterised by erratic rainfall, poor soil fertility and frequent moisture stress, resulting in unstable crop productivity. Millets, including pearl millet, finger millet, proso millet and other small millets, are climate-resilient cereals well adapted to these environments owing to their drought tolerance, short growing duration and efficient water-use characteristics. Consequently, millets play a significant role in ensuring food and nutritional security and sustaining livelihoods in marginal and water-limited ecosystems (1). However, increasing climate variability, prolonged dry spells and declining water availability continue to constrain millet productivity, highlighting the need for improved water management strategies in dryland farming systems (2).

Traditionally, millet cultivation has relied predominantly on rainfed agriculture, but supplementary irrigation has been shown to alleviate moisture stress during critical growth stages and improve crop productivity in water-scarce environments (3, 4). Likewise, micro-irrigation technologies such as drip and micro-sprinkler systems have demonstrated considerable potential for enhancing water-use efficiency (WUE), reducing water losses and improving grain yield in cereal-based production systems (5–10). Recent studies have also reported positive responses of millet crops to strategically timed irrigation, although varietal performance varies under different irrigation regimes (11, 12).

Despite the growing importance of millets in climate-smart and sustainable agriculture, information on the application of micro-irrigation and supplementary irrigation in millet-based dryland ecosystems remains fragmented and inadequately synthesised. Most available literature is limited to individual millet species are from major cereals such as wheat and maize, with comparatively fewer studies focusing specifically on millets. Moreover, there is currently no comprehensive synthesis that integrates the effects of these irrigation strategies on millet productivity, WUE, soil processes and resilience under dryland conditions.

Overall, the different research works indicate that, although millets are inherently drought-tolerant-strategically timed supplementary irrigation and efficient micro-irrigation systems can substantially improve grain yield, water productivity and system resilience in dryland ecosystems. At the same time, research on millets under micro-irrigation is still limited and results from wheat and maize must be adapted with care to millet morphology, phenology and rooting patterns (11). These gaps justify a focused review on the effects of micro-irrigation and supplementary irrigation in millets under dryland conditions, addressing not only yield and WUE but also soil processes.

## Research method and literature search

### Review methodology

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure a transparent and systematic literature review process (13). The review evaluates the role of advanced irrigation technologies and water management strategies in improving crop productivity, WUE, nutrient-use efficiency (NUE) and climate resilience in millets cultivated under water-limited environments. Relevant evidence from analogous cereal systems is also included where millet-specific studies are limited.

### Literature search strategy

A comprehensive literature search was conducted using Google Scholar, Scopus, Web of Science, ScienceDirect, SpringerLink and Wiley Online Library. Peer-reviewed articles published in English between 2000 and 2025 were identified using combinations of keywords such as automation; dryland ecosystem; millets; smart irrigation; WUE. Additional publications were identified from the reference lists of selected articles.

Studies related to irrigation management in millets and comparable dryland cereal crops (sorghum, maize and wheat) were included. These crops were considered only to provide supporting information on irrigation mechanisms and water management strategies where millet-specific studies were limited. Findings from analogous cereal systems were critically interpreted and were not directly extrapolated to millet production systems. Studies reporting irrigation methods, crop productivity, WUE and NUE, soil

moisture management, fertigation, smart irrigation technologies and supplementary irrigation practices were included. Conference abstracts, editorials, book reviews, duplicate records, non-English publications and studies lacking relevant irrigation-related information were excluded. Only peer-reviewed scientific literature was included in the review, whereas website sources and non-peer-reviewed online materials were not considered for study selection.

### Study selection and data extraction

All retrieved records were screened based on titles and abstracts and duplicate publications were removed using EndNote. Potentially relevant studies were assessed through full-text evaluation against predefined eligibility criteria. Data extracted included millet species, irrigation methods and scheduling approaches, grain yield, biomass production, WUE and NUE, soil moisture dynamics, fertigation practices, smart irrigation technologies and supplementary irrigation interventions.

### Data synthesis

The selected literature was grouped into thematic areas, including dryland ecosystem characteristics, millet water requirements, critical growth stages, micro-irrigation technologies, fertigation, smart irrigation systems, supplementary irrigation, irrigation scheduling and alternative water sources. A qualitative synthesis was undertaken to identify major advances, limitations and future research needs for sustainable millet production in dryland ecosystems. Following the PRISMA 2020 framework, 157 records were initially identified, of which 18 duplicates were removed. After screening, 77 studies met the eligibility criteria and were included in the final review. The study selection process is presented in Fig. 1.

### Dryland ecosystem: Characteristics and production constraints

Drylands are water-limited regions where annual precipitation is lower than potential evapotranspiration, leading to chronically dry soils, high evaporative demand and frequent droughts (14, 15). Globally, drylands cover about 41 % of the Earth's land surface and support approximately 2–3 billion people. These ecosystems account for nearly 40–44 % of global agricultural land and contribute about 40 % of global food grain production, which includes the cultivation of cereals, pulses, millets and oilseeds while supporting nearly two-thirds of the world's livestock population, highlighting their critical role in global food security and rural livelihoods (16, 17). In Asia and Africa, where drylands each span approximately 23 million km<sup>2</sup>, agricultural production is highly vulnerable to environmental degradation, water scarcity and climatic variability, as well as socioeconomic vulnerability. Despite their contribution to agricultural production, dryland ecosystems remain constrained by limited water availability, poor soil fertility and increasing climate variability, posing major challenges to sustainable crop production (18).



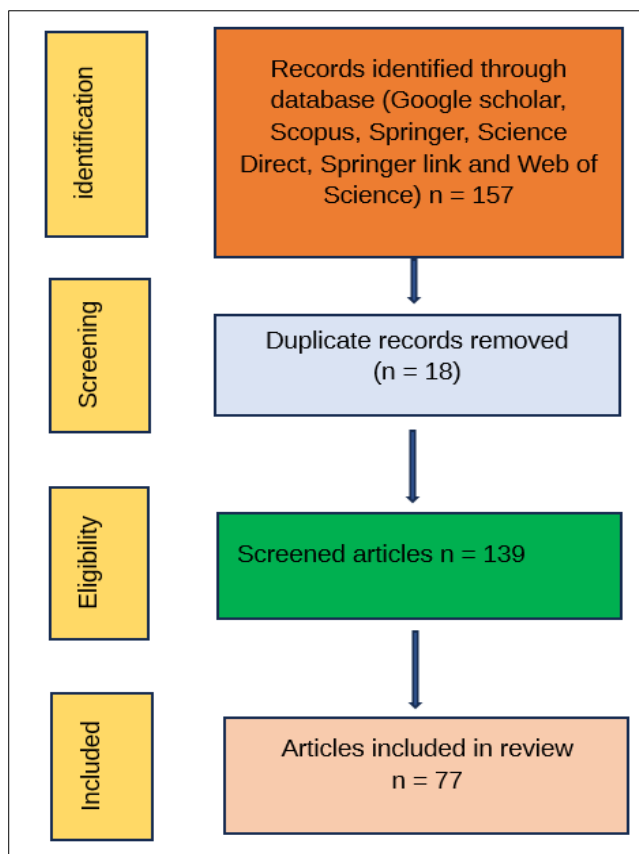


**Fig. 1.** Flowchart of methodology adopted for selection of articles for review considering PRISMA guidelines.

### Biophysical attributes of dryland ecosystems

Dryland climates are characterised by low and highly variable rainfall, high temperatures, intense solar radiation and strong winds, together producing high vapour pressure deficit (the difference between the amount of moisture present in the air and the maximum amount the air can hold when saturated) and evaporative demand (19, 20). Warming-driven increases in vapour pressure deficit accelerate evaporative water loss, deplete surface moisture and intensify atmospheric drying through land-atmosphere feedback (21, 22). Soils are often coarse-textured, shallow or degraded, with low organic matter, poor structure and low nutrient reserves, making them susceptible to water and wind erosion, salinisation, compaction and nutrient loss (18, 22). Vegetation is typically sparse and patchy, forming “fertile islands” beneath plant canopies with higher organic matter, microbial activity and nutrient availability than adjacent bare soil (15).

At the ecohydrological level, drylands show a strong binding between soil moisture, plant function and atmosphere. Plant water stress is governed by critical soil-moisture thresholds that are generally low in drylands, reflecting adaptation to water deficits and efficient extraction from dry soils (23). Ecosystem processes are strongly “pulse-driven”: biological activity and soil respiration respond rapidly to discrete rainfall or irrigation events, then decline during prolonged dry periods (15).

### Climate change, aridity trends and their implications for drylands

Multiple lines of evidence indicate accelerated dryland expansion and rising aridity under climate change (24). Atmospheric aridity (rising VPD and hot-dry extremes) has increased since the 1950s and is projected to intensify, even though soil-moisture and runoff trends can diverge due to plant physiological responses to elevated CO<sub>2</sub> and strong soil-moisture limitation (25).

Climate change has also altered rainfall patterns in dryland ecosystems by increasing rainfall variability, reducing the reliability of seasonal precipitation and increasing the occurrence of prolonged dry spells and extreme weather events. These changes adversely affect soil moisture availability, crop growth and agricultural productivity, resulting in unstable yields and greater production risks in water-limited environments (24).

Dryland ecosystems also face more frequent, longer and more severe droughts, which reduce growing-season length, advance senescence, lower biomass and create multi-year “drought legacies” in soil moisture and plant performance (26). Such climate stresses contribute to declining crop productivity and threaten the sustainability of dryland agricultural systems. These impacts are increasingly observed across dryland regions worldwide, although their magnitude and expression vary by location. For example, ecological drought projections using soil water balance models indicate robust increases in chronic hot–dry stress over large portions of North American drylands, particularly in southern regions, even where precipitation trends remain uncertain (27). Here is Fig. 2, which depicts the Global land area distribution of dryland ecosystems and shows that much of the area falls under Humid, dry-humid, semi-arid and arid regions.

### Water requirement and water use efficiency of millets

Millets are widely recognised as low-water-requiring cereals compared with crops such as rice and are therefore central to dryland and climate-smart agriculture. Pearl millet, finger millet and sorghum are traditionally cultivated in arid and semi-arid regions where intermittent 25–30-day moisture stress is common. Despite these challenging conditions, they continue to produce grain, reflecting their strong adaptation to limited and erratic water supply (28). Pearl millet typically requires approximately 330–380 mm of seasonal water under semi-arid conditions and maintains productivity at considerably lower water inputs than sorghum and maize (29). Similarly, model-based estimates for irrigated rabi systems indicate that modern millet cultivars have lower seasonal water requirements than major cereals grown under comparable agro-climatic conditions (30). Proso millet has been reported to require approximately 579 mm of seasonal evapotranspiration under non-stressed conditions; however, water deficits during sensitive reproductive stages substantially reduce grain yield (31).

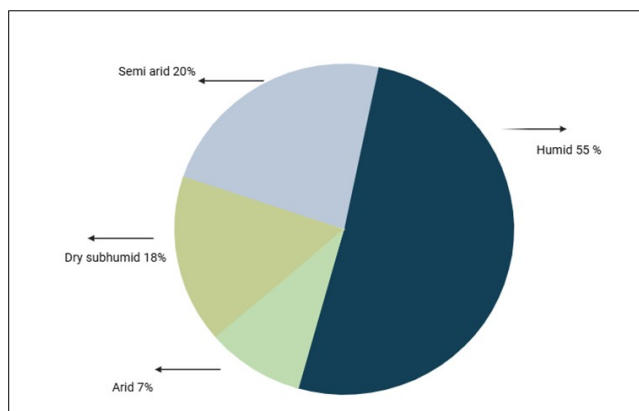


Fig. 2. Global land area distribution (15, 17).

Although millets are inherently drought-tolerant, their water requirements vary across crop growth stages. Moisture stress during early vegetative growth is relatively less detrimental, whereas panicle initiation, flowering and grain filling are considered critical stages that largely determine yield. Water deficits during these reproductive stages adversely affect grain set, grain filling and final productivity, highlighting the importance of stage-specific irrigation management. Consequently, strategically timed supplementary irrigation during critical growth periods can substantially improve water productivity and minimise yield losses under dryland conditions (31).

The ability of millets to perform well under water-limited environments is primarily attributed to their short crop duration, efficient rooting systems, conservative transpiration behaviour, osmotic adjustment mechanisms and superior WUE (32). Comparative studies have shown that pearl millet exhibits greater developmental plasticity under drought conditions than many other cereals, allowing it to sustain physiological activity and maintain yield stability under limited water availability (33). Recent studies further suggest that improved irrigation practices, including deficit and supplemental irrigation, can enhance WUE by increasing biomass accumulation and grain yield per unit of water applied, thereby improving the sustainability of millet production systems (34, 35).

Overall, millets combine relatively low seasonal water requirements with high WUE, making them ideal candidates for sustainable cultivation in water-limited

environments. However, their irrigation requirements are highly dependent on crop growth stages, emphasising the need for precise irrigation scheduling and efficient water management practices, particularly under dryland ecosystems. Table 1 presents the seasonal water requirements of different millet species.

#### Critical growth stages and moisture sensitivity in millets

Critical growth stages in millets play a decisive role in determining crop productivity under dryland conditions, where water availability is often limited and erratic. Although millets are generally drought-tolerant, their sensitivity to moisture stress varies considerably across phenological stages. Timely irrigation during critical stages can substantially improve grain yield, WUE and resource utilisation, particularly when micro-irrigation and supplementary irrigation are employed (36).

Among the various growth stages, panicle initiation, booting, flowering (anthesis) and grain filling are considered the most sensitive to water deficits in most millet species. Moisture stress during these reproductive stages adversely affects panicle development, pollen viability, grain set and grain filling, ultimately resulting in significant yield reductions. In contrast, mild moisture stress during early vegetative growth is relatively less detrimental and can often be tolerated without major yield penalties. Therefore, irrigation scheduling should prioritise the reproductive stages under water-limited conditions (37, 38).

The timing of irrigation is critical for maximising water productivity in dryland ecosystems. Where water availability is limited, supplementary irrigation should preferably be applied during panicle initiation and flowering stages, as these stages have the greatest influence on final grain yield. Under severe moisture stress conditions, a single life-saving irrigation at flowering can substantially improve grain filling and yield stability. In systems where two irrigations are feasible, irrigation at panicle initiation followed by flowering or early grain filling is recommended to achieve maximum yield benefits. Micro-irrigation systems such as drip and micro-sprinklers are particularly advantageous for supplying precise amounts of water during these critical periods while minimising evaporative and percolation losses (36, 37).

Table 1. Water requirements of millets and irrigation methods adopted

| Millet crop     | Botanical name                         | Water requirement | Irrigation methods adopted                                 |
|-----------------|----------------------------------------|-------------------|------------------------------------------------------------|
| Sorghum         | <i>Sorghum bicolor</i> (L.) Moench     | 450–650 mm        | Furrow, sprinkler, drip, supplementary irrigation          |
| Pearl millet    | <i>Pennisetum glaucum</i> (L.) R.Br.   | 350–450 mm        | Drip, subsurface drip, sprinkler, supplementary irrigation |
| Finger millet   | <i>Eleusine coracana</i> (L.) Gaertn.  | 350–450 mm        | Drip, sprinkler, supplementary irrigation                  |
| Foxtail millet  | <i>Setaria italica</i> (L.) P.Beauv.   | 300–400 mm        | Drip, sprinkler, supplementary irrigation                  |
| Little millet   | <i>Panicum sumatrense</i> Roth         | 300–350 mm        | Supplementary irrigation, sprinkler                        |
| Proso millet    | <i>Panicum miliaceum</i> L.            | 250–350 mm        | Supplementary irrigation, sprinkler                        |
| Kodo millet     | <i>Paspalum scorbulatum</i> L.         | 350–450 mm        | Supplementary irrigation, sprinkler                        |
| Barnyard millet | <i>Echinochloa frumentacea</i> Link    | 300–400 mm        | Drip, sprinkler, supplementary irrigation                  |
| Browntop millet | <i>Urochloa ramosa</i> (L.) T.Q.Nguyen | 250–350 mm        | Supplementary irrigation, sprinkler                        |

Different millet species also exhibit varying levels of moisture sensitivity. Pearl millet is comparatively more resilient to intermittent drought owing to its deep rooting system and high physiological plasticity, whereas finger millet is particularly sensitive to moisture stress during flowering and grain development. Proso millet, despite its short duration and drought tolerance, experiences significant yield reductions when water deficits occur during reproductive stages. Small millets generally possess efficient water-use mechanisms but differ in their response to water stress depending on crop duration, rooting characteristics and growth habits. These interspecific differences should be considered while designing irrigation schedules for millet-based production systems (31–33).

Overall, understanding stage-specific moisture requirements and species-specific responses is essential for optimising micro-irrigation and supplementary irrigation strategies in millets. Recent advancements in irrigation scheduling, deficit irrigation approaches and sensor-based micro-irrigation technologies have enabled precise water application during moisture-sensitive growth stages, thereby improving WUE, yield stability and resource-use efficiency in dryland ecosystems. Integrating stage-specific irrigation management with modern irrigation technologies offers considerable potential for enhancing climate resilience and sustainable millet production under water-limited conditions. Fig. 3 illustrates the critical growth stages and moisture-sensitive periods of major millet crops.

### Limitations of conventional irrigation practices in millet cultivation

In dryland ecosystems, millets are primarily cultivated in agro-ecological regions characterised by low and erratic rainfall and high evaporative demand and limited groundwater availability (39, 40). Although millets are physiologically adapted to withstand drought conditions, strategic irrigation is necessary to prevent severe yield loss, particularly during prolonged dry spells and at critical growth stages (41). Conventional methods, including flooding, basin irrigation and furrow irrigation, are employed for their ease of implementation and low cost. These methods are practised in millets due to water scarcity and the crop's low water requirement (40). Under conventional irrigation, water is generally applied at critical crop growth stages such as germination, tillering, ear-head emergence and grain filling, depending on rainfall availability and soil moisture conditions. Irrigation during these stages can significantly improve crop growth and yield under dryland conditions (40, 41). The irrigation requirement for the kharif season ranges between 150–200 mm, with the crop tolerating moisture depletion up to 75 % (40). In dryland regions, conveyance losses can account for 30–40 % of irrigation water before it reaches the field, severely reducing water availability for crops. These losses are particularly critical for millets because even a small quantity of water, if effectively delivered, can significantly increase growth and yield (42). In the case of basin or flood irrigation, it may lead to rapid infiltration followed by deep infiltration losses, leaving insufficient moisture in the active root zone for extended periods (40). Water is commonly transported through unlined earth channels, where substantial losses occur continuously. For these reasons, conventional systems fail to ensure a timely and adequate water supply, limiting their effectiveness under different crop growth conditions.

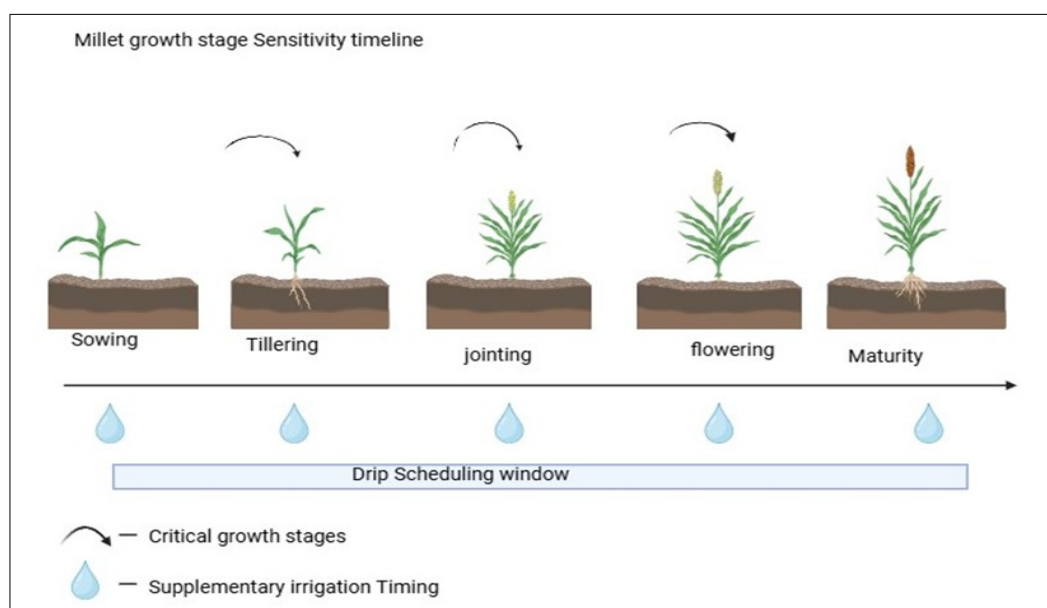


Fig. 3. Millet growth sensitivity timeline.

Despite these limitations, conventional irrigation methods continue to be widely adopted in millet cultivation because they are simple to implement, require low initial investment and are suitable for resource-limited farming systems where advanced irrigation infrastructure is unavailable. When water is available at critical growth stages and fields are properly levelled, conventional irrigation can provide satisfactory crop establishment and acceptable grain yields (41). However, under dryland conditions, their low application efficiency and high-water losses limit long-term sustainability, highlighting the need for improved irrigation technologies.

In dryland regions, soils are coarse, structured red soils or shallow soils with low water-holding capacity, further aggravating the inefficiency of conventional irrigation methods (43). Due to a shallow, fibrous root system, millets cannot efficiently utilise water that moves beyond the upper soil layers (41). Other limitations in conventional irrigation include field-level unevenness, slope variations and poorly formed bunds, which lead to non-uniform wetting patterns by causing uneven water application and distribution across the field, thereby reducing irrigation uniformity and water use efficiency in millet cultivation (40). This uneven distribution results in spatial variability in plant growth, poor tillering and uneven panicle development in millets. Conventional irrigation also generates surface runoff when the application rate exceeds soil infiltration capacity, accelerating soil erosion and land degradation.

#### **Advances in micro irrigation technologies for millet cultivation**

Micro-irrigation has evolved from simple drip lines to an integrated, sensor-guided, precision water and nutrient delivery system, making it particularly suitable for dryland crops such as millets. Micro-irrigation (drip, subsurface drip, micro-sprinkler, bubblers, low-head devices) applies small quantities of water directly in or near the root zone at low pressure and high frequency, wetting only part of the soil volume and sharply reducing evaporation, runoff and deep percolation losses (44). Other benefits include higher WUE, yield and quality, improved fertigation efficiency and reduced weed and pest infestation compared with surface methods (45). Micro-irrigation has emerged as a major water-saving innovation in agriculture, particularly in water-scarce environments such as dryland ecosystems. Micro-irrigation applies water precisely and uniformly to the root zone of crops, thereby significantly reducing water loss through deep percolation, runoff and evaporation. This precision is especially important for millets, which are often grown in semi-arid regions where water resources are limited and erratic rainfall is common. Micro irrigation systems are designed to deliver water at low pressure through valves, pipes, tubing and emitters, which improves water application efficiency compared to traditional methods such as basin and furrow irrigation (5).

Research works on micro irrigation in millets indicate that this technology not only economises water use but also enhances nutrient management by synchronising water and nutrient delivery to meet crop demands (5, 46). Various field-specific experiments have shown that sprinkler-based micro irrigation systems can substantially improve WUE. For instance, drip and sprinklers applied at appropriate reference evapotranspiration (ET<sub>0</sub>) levels in sandy soils have been reported to save significant volumes of irrigation water up to 22–53 % compared with conventional farmer practices-while achieving higher water use efficiency in pearl millet forage production (47). This demonstrates how micro irrigation can help maintain adequate moisture in the root zone even under water-limited conditions, a major advance compared to sporadic surface irrigation in drylands. Advances in micro-irrigation also include technology integration and policy support. Government-supported schemes such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) - “Per Drop More Crop” in India actively promote the adoption of micro-irrigation systems, including drip and micro-sprinkler technologies, to improve water productivity at the farm level. These programmes aim to expand irrigation coverage, enhance water use efficiency and increase crop yields through precision water management practices, particularly in semi-arid and dryland areas where traditional irrigation is inefficient and water resources are scarce.

Despite its numerous advantages, the adoption of micro-irrigation technologies in millet-based dryland farming systems is associated with certain limitations. The initial installation cost of drip and micro-sprinkler systems may limit their adoption among smallholder farmers, particularly in resource-constrained regions (48). Regular maintenance is required to prevent emitter clogging, especially when irrigation water contains suspended solids or salts, thereby increasing operational requirements and costs (49). Recent studies have also reported that farmers often face challenges related to technical knowledge, spare-part availability and system maintenance, which can affect the long-term sustainability of micro-irrigation systems (50). Consequently, the successful implementation of micro-irrigation technologies depends not only on their water-saving potential but also on appropriate policy support, farmer training and location-specific management strategies.

#### **Role of drip irrigation in millet production**

Drip irrigation has emerged as a highly effective and water-saving technology for millet cultivation in dryland ecosystems, offering substantial improvements in yield, WUE and crop quality compared to traditional surface irrigation methods. Numerous studies have demonstrated that drip irrigation, especially when combined with practices like mulching or optimised nitrogen (N) application, significantly enhances the growth, physiological traits and yield components of millets such as foxtail millet and pearl millet (51, 52). For



instance, field experiments reveal that the integration of drip irrigation with mulching and appropriate planting patterns (leads to the highest yields and improved agronomic traits in foxtail millet, with maximum yields exceeding 4600 kg ha<sup>-1</sup> under optimal conditions (51). Drip irrigation not only maintains soil moisture near field capacity but also reduces evaporation losses, resulting in higher WUE and better resource utilisation. Regulating the frequency and amount of drip irrigation, such as maintaining soil moisture at 64–74 % of field capacity, optimises both yield and WUE while minimising N leaching and soil salinity risks (52). Advanced drip systems, including subsurface drip irrigation (SDI), have shown even greater benefits by improving root zone moisture distribution, reducing deep percolation losses and enhancing nutrient uptake in arid regions (53). Studies comparing surface drip, subsurface drip and sprinkler systems consistently find that subsurface drip delivers the highest forage yields and WUE for pearl millet under both full and deficit irrigation regimes (45). The efficiency of drip irrigation and its impact on crop production vary among millet species depending on their growth characteristics, rooting patterns and moisture requirements. Foxtail millet has shown significant improvements in grain yield and agronomic performance when drip irrigation is combined with mulching and optimum planting patterns (51). Pearl millet exhibits superior forage yield and WUE under both surface and SDI systems, particularly under deficit irrigation conditions (46). Similarly, optimised soil moisture management through drip irrigation has been reported to improve yield while reducing nutrient losses and salinity risks in millet production systems (52). These findings indicate that species-specific irrigation management is essential to maximise productivity and resource-use efficiency in millet-based dryland agriculture. However, challenges such as emitter clogging (especially with saline or poor-quality water), initial investment costs, technical skill requirements for installation and maintenance and adaptation for smallholder farmers remain important considerations for widespread adoption (53).

#### **Application of sprinkler irrigation in millet-based systems**

Sprinkler irrigation combined with drip and sub-surface drip irrigation will play a major role in providing water availability in millets in the dryland system. When compared with other pressurised systems, sprinkler irrigation may be more effective in arid and semi-arid regions. It can conserve scarce water resources while maintaining acceptable forage and grain yields, making it a practical option for millet cultivation under water-limited conditions. Sprinkler irrigation can also save scarce water resources while maintaining acceptable forage yields. It is an important consideration where soil moisture is already limited and water availability is somewhat constrained. Sprinkler irrigation helps to adjust irrigation levels relative to crop evapotranspiration, which can maximise WUE and improve crop productivity in millet-based production systems (54).

In an arid-region study comparing surface drip, subsurface drip and sprinkler irrigation for forage pearl millet, subsurface drip produced the highest forage yield and irrigation water use efficiency (IWUE), followed by surface drip, with sprinkler giving the lowest forage yield and IWUE under both full (100 % ET) and deficit 50 % (46). Nevertheless, sprinkler irrigation maintained acceptable forage production under water-limited conditions, highlighting its potential for sustaining millet productivity in dryland ecosystems. Other work in pearl millet emphasises that irrigation level is the dominant factor controlling forage production and WUE, while system type and row spacing are secondary; optimum WUE was achieved under moderate irrigation that maintained adequate leaf area rather than simply maximising applied water (47). Adaptive irrigation scheduling using soil-based sensors in pearl millet showed that treatments receiving higher, well-timed water inputs substantially increased biomass and grain yield while achieving irrigation and water use efficiencies, underscoring the importance of matching sprinkler applications to crop demand in drylands (55). Overall, sprinkler irrigation contributes to improved millet production by enhancing biomass accumulation, sustaining grain and forage yields and optimising WUE when appropriately scheduled under dryland conditions.

#### **Fertigation strategies under a micro irrigation system**

It is a modern agricultural technique that combines irrigation and fertilisers by delivering dissolved fertilisers through irrigation water directly to the plant root through irrigation systems. Fertigation enables precise and timely delivery of nutrients directly to the root zone, thereby minimising losses through leaching, volatilisation and runoff. In millets, fertigation through drip or sprinkler systems was found to improve nutrient uptake efficiency and crop growth, especially under dryland conditions where nutrient uptake and soil moisture are limited (5). Due to fertigation, soil parameters like available N, phosphorus (P) and potassium (K) can also be increased. Fertigation using nutrient-rich liquid sources can improve millet productivity and soil fertility in dryland ecosystems. Moreover, fertigation allows nutrients to be applied in split doses according to crop demand, thereby reducing nutrient accumulation in the root zone and minimising the risk of nutrient toxicity and salt buildup associated with excessive fertiliser application. Nutrient application rates can also be adjusted at different crop growth stages to improve NUE and support optimal crop growth (56). Hence, fertigation can enhance crop growth.

#### **Smart irrigation and automation technologies in dryland agriculture**

Automated irrigation is the process of using technology and devices to automatically water crops or plants without manual intervention. It uses sensors and other devices to monitor the flow of water based on environmental conditions like soil moisture, temperature, humidity and weather conditions. It includes components such as pumps, sprinklers or drippers, controllers, valves, communication modules, sensors and actuators.



Despite the advantages of smart irrigation technologies, their adoption in agriculture is often limited by economic and technical constraints. The initial investment costs associated with smart irrigation systems, including sensors, controllers, wireless communication modules and automated irrigation infrastructure, remain one of the major challenges for their large-scale adoption. The periodic maintenance requirements such as sensor calibration, software updates and replacement of damaged components are essential for ensuring the accuracy and long-term performance of these systems (57). The successful implementation of automated irrigation systems requires adequate technical knowledge, reliable internet connectivity and continuous power supply for real-time monitoring and irrigation scheduling (58).

However, the potential of sensor-based smart farming technologies for real-time monitoring of millet crop growth, environmental parameters and disease prediction is considerable. These technologies can be integrated with micro-irrigation systems to facilitate precise irrigation scheduling during critical growth stages of millet crops. Considering the low water requirements and high WUE of millets, the development of low-cost and farmer-friendly automated irrigation systems specifically tailored for millet-based dryland ecosystems remains an important future research priority (59). Millet-specific applications have also been demonstrated in pearl millet, where sensor-based irrigation scheduling improved biomass production, grain yield and WUE by applying irrigation according to crop water demand (60). These findings indicate that smart irrigation technologies can be effectively integrated into millet-based production systems to improve irrigation precision under dryland conditions.

In terms of crop productivity, smart irrigation technologies have considerable potential to improve millet productivity by optimising irrigation timing and reducing water losses in dryland ecosystems. Sensor-based irrigation scheduling can enhance WUE, maintain optimum soil moisture during critical growth stages and contribute to improved grain yield and biomass production (60). However, their large-scale feasibility in millet-based farming systems remains dependent on factors such as installation costs, technical expertise, internet and power availability and farm size. While these technologies are highly feasible for precision water management, their adoption among smallholder farmers in dryland regions will require cost-effective designs, policy support and farmer-oriented extension programmes (59). Therefore, the successful integration of smart irrigation technologies in millet production systems should balance technological advancement with economic and field-level feasibility.

Automation can significantly reduce operational costs by reducing water use by up to 30–35 %. An automatic irrigation system that integrates the Internet of Things (IoT) with a logic-based control engine automatically decides water application based on environmental data obtained from sensors. This

approach uses historical and real-time inputs to dynamically optimise irrigation schedules, thereby improving WUE and network resource utilisation (61).

Smart irrigation technologies focus mainly on systems such as IoT, machine learning and artificial intelligence. Smart irrigation systems are increasingly incorporating sensors, wireless communications and intelligent control methods to schedule water application based on real-time soil and environmental data. The IoT-enabled systems improve irrigation efficiency and reduce water waste compared to conventional irrigation, supporting the adoption of automated irrigation in both rural and urban agriculture (62).

Internet of Things-based smart irrigation systems monitor soil moisture and other environmental conditions using sensors connected to microcontrollers. Fig. 4. illustrates the working principle of an IoT-enabled smart irrigation system. It can automatically turn irrigation on and off without manual control, thereby maintaining optimum soil moisture levels for crop growth (63). Automated irrigation systems improve WUE by supplying timely irrigation and promoting better plant growth compared with manual irrigation practices (59).

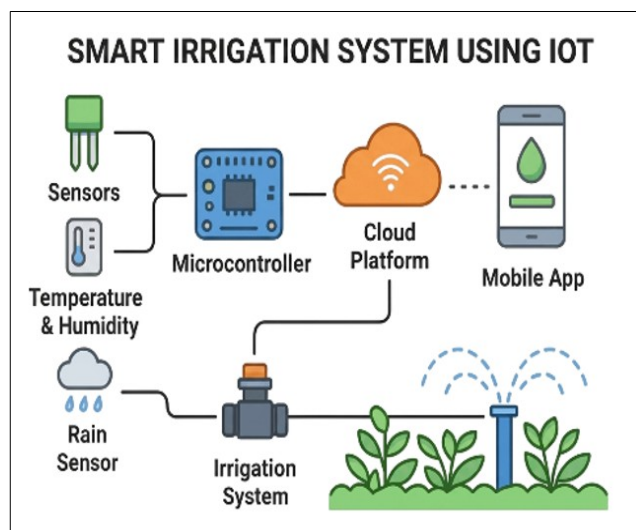


**Fig. 4.** Smart irrigation system using Internet of Things (IoT).  
**Supplementary irrigation for enhancing millet productivity in the dryland ecosystem**

Supplementary irrigation is defined as the application of a limited amount of water to primarily rainfed crops when rainfall fails during critical growth stages. In dryland ecosystems, supplementary irrigation stabilises yields and improves water productivity by alleviating soil moisture stress during dry spells. It is increasingly recognised as a climate-smart water management strategy that enhances crop production and resilience in rainfed agriculture. By focusing on precise irrigation timing rather than total water volume, supplementary irrigation helps optimise scarce water resources and reduce the risk of crop failure under erratic rainfall conditions (64, 65).

In barnyard millet, supplementary irrigation has been shown to significantly increase grain yield, gross

income and benefit-cost ratio compared with rainfed cultivation. The integration of farm ponds for water storage has further improved the effectiveness of supplementary irrigation by ensuring water availability during moisture-stress periods. This demonstrates the value of combining supplementary irrigation with rainwater harvesting and soil moisture conservation practices to enhance both productivity and economic returns in dryland millet production systems (65).

Studies conducted in millet-growing regions have demonstrated that supplementary irrigation has been evaluated in several millet-growing regions and has been shown to increase stem diameter, leaf area index (LAI), dry matter accumulation and, in some cases, soil organic matter. Timely irrigation during critical growth stages helps alleviate soil moisture stress and contributes to improved yield and resource-use efficiency in millet crops. Supplemental irrigation combined with appropriate fertiliser management has also been reported to further enhance grain yield under water-limited conditions (4, 66).

Supplementary irrigation has also been evaluated during the early growth stages of millet crops. Experiments on pre-sowing and seedling-stage supplemental irrigation reported significantly higher seedling emergence rates, improved photosynthetic characteristics and enhanced early vegetative growth compared with water-deficient conditions. These findings highlight the importance of ensuring adequate soil moisture during crop establishment for sustaining millet productivity in dryland environments (4).

The role of soil moisture in regulating crop and soil processes further increases the value of supplementary irrigation in millet-based farming systems. International Center for Agricultural Research in the Dry Areas (ICARDA) has identified supplementary irrigation as a climate-smart practice that significantly enhances production and water productivity in dryland rainfed systems. Supplemental irrigation also enables farmers to optimise limited water resources, maintain stable production under erratic rainfall and improve the resilience of millet cultivation in dryland ecosystems. When strategically applied during moisture-sensitive growth stages, supplementary irrigation offers a practical and sustainable approach for enhancing millet productivity and climate resilience in water-limited environments (66).

#### **Water sources for supplementary irrigation in dryland millets**

Supplementary irrigation (SI) in millets within dryland ecosystems primarily relies on diverse water sources that can buffer the crop against erratic rainfall and intra-seasonal droughts, thereby stabilising yield and improving WUE. Conventional sources include surface water from rivers, canals and reservoirs, but in many dryland areas, these are limited or unreliable. Increasingly, alternative and unconventional water sources such as treated wastewater (greywater) and drainage water are being explored for millet irrigation

(67). Irrigation with treated wastewater has been shown to maintain millet productivity without causing salt stress, although caution is needed to prevent long-term soil salinisation due to salt accumulation. In addition, the suitability of treated wastewater for irrigation depends on its quality, as contaminants such as heavy metals, pathogenic microorganisms and emerging pollutants may adversely affect soil health, crop safety and environmental sustainability if not properly monitored and managed (68). Drainage water mixed with river or ditch water has also been successfully used for repeated millet cropping in alluvial soils, achieving good yields and economic efficiency despite varying mineralisation levels (69). In addition, selecting appropriate irrigation application technology plays a crucial role in improving WUE and crop performance in dryland millet production systems. Micro-irrigation methods, such as drip and micro-sprinkler, are often combined with supplementary irrigation to optimise water delivery directly to the root zone, thereby enhancing WUE and nutrient uptake while reducing water losses. Deficit drip supplementary irrigation has demonstrated improved growth and stable yields in semi-arid systems by mitigating drought stress while reducing nitrate leaching risks compared to conventional flood irrigation (70). In dryland millet production areas like northern Shanxi Province, China, supplemental irrigation strategies involving pre sowing irrigation combined with one or two irrigations during the growing season have been effective in increasing yield and irrigation WUE under future climate scenarios (71). Optimal timing of supplementary irrigation is critical; for instance, late jointing stage irrigation significantly promotes millet growth and yield by improving soil moisture conditions during critical phenological phases (72). Water quality is another important consideration; studies on saline water irrigation indicate that N fertilisation can alleviate salt stress effects on pearl millet, with low-salinity water throughout the crop cycle being more efficient for photosynthesis and water use than saline treatments applied later. Irrigation frequency also influences performance under salt stress: intervals of two to three days between irrigations maintain better agronomic traits than longer intervals regardless of salinity level (73, 74). Overall, supplementary irrigation sources for millets in drylands encompass a range of surface waters supplemented increasingly by treated wastewater and drainage waters, applied through efficient micro-irrigation systems or carefully scheduled deficit irrigations to maximise yield stability and resource use efficiency under challenging environmental conditions.

#### **Impact of supplementary irrigation on growth, yield and water productivity of millets**

Supplementary irrigation has been carried out in major and minor millets in many arid and semi-arid regions due to limited water availability. One research study conducted on millet farmland in a semiarid region found that supplementary irrigation significantly improved crop growth and productivity compared with purely rainfed

conditions. The study found that supplementary irrigation increased key growth indicators, including plant height, stem diameter, LAI and dry matter accumulation from the jointing stage to maturity, where rainfed millet typically experiences moisture stress. Additional water increased soil organic matter and soil biological activity, creating favourable conditions for crop development. Grain yield and WUE were also higher in supplementary irrigation. It shows that supplementary irrigation can boost millet growth under dryland conditions (75). Another experiment was also conducted in foxtail millet under different irrigation schedules, where multiple supplementary irrigations were provided on different days. Growth parameters and yield attributes like plant height, LAI, stem diameter, grain yield and biomass were increased compared to fewer water applications. Grain yield and straw yield were both higher under four supplementary irrigation treatments, showing that even in dryland or limited water settings, timed supplementary irrigation can enhance foxtail millet productivity for canopy expansion and reproductive development (76). Another experiment with summer foxtail millet has been conducted in north China to know about WUE, where results showed that grain yield increased significantly with supplemental irrigation, enhancing both yield and WUE in foxtail millet (77).

#### Comparative effect of different irrigation methods on millet productivity and water use efficiency

Different irrigation methods have a significant impact on millet productivity and WUE. Studies comparing surface

drip, subsurface drip, sprinkler and alternative methods like wick irrigation consistently show that SDI produces the highest forage yield and WUE in pearl millet, followed by surface drip (SD), with sprinkler systems performing worst under both full and deficit irrigation conditions (46).

Irrigation method significantly influences forage productivity and irrigation WUE by affecting root-zone soil moisture distribution and water availability. Subsurface drip irrigation maintained a more favourable soil moisture environment, resulting in greater biomass accumulation and improved crop performance than SD and sprinkler irrigation (60).

Similarly, other reports emphasised that the effectiveness of irrigation methods depends not only on the irrigation system but also on proper irrigation scheduling. Maintaining optimum soil moisture during critical growth stages enhanced biomass production, forage yield and WUE, whereas excessive irrigation reduced irrigation efficiency without proportionate yield benefits (47).

Overall, comparative studies indicate that SDI is the most efficient irrigation method for improving millet productivity and WUE under dryland conditions, followed by SDI, while sprinkler irrigation remains a practical alternative where economic or field constraints limit drip irrigation adoption. Table 2 summarises the comparative effects of different irrigation methods on millet productivity and WUE in millet-based production systems.

**Table 2.** Comparative effect of different irrigation methods on millet productivity and water use efficiency (WUE)

| Irrigation method             | Water saving (%)              | Effect of yield                 | Water use efficiency          | Major advances                                  | Limitations                                          | Reference |
|-------------------------------|-------------------------------|---------------------------------|-------------------------------|-------------------------------------------------|------------------------------------------------------|-----------|
| Conventional flood irrigation | Low                           | Moderate                        | Low                           | Low initial cost                                | High runoff, evaporation and deep percolation losses | (46)      |
| Drip irrigation               | 30–50 %                       | High increase                   | Very high                     | Precise root zone irrigation                    | Initial installation cost                            | (46, 39)  |
| Subsurface drip irrigation    | 40–60 %                       | Very high increase              | Highest                       | Reduced evaporation and nutrient loss           | Emitter clogging and maintenance                     | (39)      |
| Micro sprinkler irrigation    | 20–40 %                       | High                            | High                          | Uniform irrigation and suitable for sandy soils | Wind drift losses possible                           | (78)      |
| Supplementary irrigation      | 10–25 % additional water only | Stabilises yield during drought | High under dryland conditions | Useful during critical growth stages            | Depends on water storage availability                | (65)      |
| Smart/Automated irrigation    | 30–35 % water saving          | Optimised yield                 | Very high                     | Sensor based precise irrigation scheduling      | Technical knowledge required, cost is also High      | (55)      |

### Irrigation scheduling and optimisation in millets

Irrigation scheduling is a critical component of water management in millet-based dryland production systems. It involves determining the appropriate timing, frequency and quantity of irrigation water based on crop water requirements, soil moisture status, climatic conditions and water availability. In millets, irrigation scheduling approaches commonly include soil moisture threshold-based irrigation, growth stage-based irrigation, deficit irrigation strategies and water quality-based scheduling under saline or brackish water conditions. Optimising these scheduling approaches can improve WUE, maintain crop productivity and minimise water losses under water-limited environments. A recent experiment in Northeast China optimised drip irrigation for millet by using soil water threshold. Four lower limits where yield and WUE increased with irrigation up to an optimum, then declined when water was excessive (52). Under saline condition irrigation schedule must consider both frequency and water quality. Using low salinity water early, then switching to more saline water after 65 days, improved WUE and reduced leaf temperature in pearl millet (2). A separate study found that with brackish water, irrigation every 2–3 days maintained better growth, whereas longer intervals reduced leaf area, biomass and panicle traits regardless of water

quality. The recommended irrigation schedule and relative water requirements at different growth stages of major millet crops under dryland conditions are summarised in Table 3.

### Use of marginal / alternative water sources

When fresh water is scarce, mixing drainage or ditch water with river water for millet irrigation can maintain yields while reducing freshwater demand. In grassland alluvial soils of Uzbekistan, comparable millet yields were achieved across treatments using drainage water, river water, mixed water and mixed water with bio solvent, with higher economic efficiency when mixed water was used (69).

## 4. Conclusion

Dryland ecosystems are increasingly threatened by erratic rainfall, rising atmospheric aridity, soil degradation and frequent drought events, making sustainable water management essential for maintaining millet productivity. Although millets are inherently drought tolerant, stable production under changing climatic conditions requires efficient irrigation strategies beyond conventional rainfed cultivation.

**Table 3.** The recommended irrigation schedule and relative water requirements at different growth stages of major millet crops under dryland conditions

| Millet crop     | Growth stage                  | Relative water requirement | Irrigation recommendation                            |
|-----------------|-------------------------------|----------------------------|------------------------------------------------------|
| Pearl millet    | Germination and establishment | Moderate                   | Irrigate only if soil moisture is inadequate         |
| Pearl millet    | Tillering                     | Moderate                   | Irrigation beneficial under prolonged dry spell      |
| Pearl millet    | Panicle initiation            | High                       | Critical stage; supplementary irrigation recommended |
| Pearl millet    | Flowering                     | Very high                  | Most critical stage for irrigation                   |
| Pearl millet    | Grain filling                 | High                       | One irrigation improves grain filling and yield      |
| Finger millet   | Germination                   | Moderate                   | Ensure adequate soil moisture                        |
| Finger millet   | Tillering                     | Moderate                   | Irrigation if prolonged moisture stress occurs       |
| Finger millet   | Flowering                     | Very high                  | Most moisture- sensitive stage                       |
| Finger millet   | Grain filling                 | High                       | Supplementary irrigation improves grain weight       |
| Foxtail millet  | Establishment                 | Moderate                   | Light irrigation if rainfall is inadequate           |
| Foxtail millet  | Booting - flowering           | High                       | Critical stage for yield formation                   |
| Foxtail millet  | Grain filling                 | Moderate - high            | Irrigation improves productivity                     |
| Barnyard millet | Germination                   | Moderate                   | Maintains adequate soil moisture                     |
| Barnyard millet | Panicle initiation            | High                       | Supplementary irrigation recommended                 |
| Barnyard millet | Flowering                     | Very high                  | Critical stage for maximum yield                     |
| Barnyard millet | Grain filling                 | High                       | Irrigation enhances grain development                |

This review demonstrates that micro-irrigation technologies, particularly drip and subsurface drip irrigation, substantially improve grain yield, biomass production, water-use efficiency (WUE), nutrient-use efficiency (NUE) and overall resource-use efficiency compared with conventional irrigation methods. Likewise, well-timed supplementary irrigation during critical growth stages effectively alleviates moisture stress, stabilises yields and enhances water productivity in rainfed dryland ecosystems. Advances in irrigation scheduling based on evapotranspiration, soil moisture thresholds and sensor-based approaches further improve irrigation efficiency while reducing unnecessary water losses.

However, the successful adoption of these technologies depends not only on irrigation methods but also on water availability, soil characteristics, nutrient management, economic feasibility, farmer adoption capacity and climate-specific irrigation strategies. Therefore, integrated and location-specific water management approaches are essential for maximising the benefits of micro-irrigation and supplementary irrigation in millet-based production systems.

Future advancements should focus on integrating smart irrigation technologies, Internet of Things (IoT)-enabled automation, artificial intelligence (AI), remote sensing, decision-support systems and precision fertigation to optimise water and nutrient management under dryland conditions. Greater emphasis should also be placed on developing affordable, farmer-friendly irrigation technologies, validating irrigation strategies across diverse millet species and agroecological regions and strengthening policy support and extension programmes to enhance large-scale adoption. Such integrated advancements will contribute to climate-resilient, resource-efficient and sustainable millet production in dryland ecosystems.

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## Authors' contributions

MM wrote the manuscript draft and NV revised it. GS and PA verified contents. RP helped to align the content. All authors have read and approved the final manuscript.

## Compliance with ethical standards

### Conflict of interest

Authors do not have any conflict of interests to declare.

## Ethical issues

None

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to do corrections. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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