Ann. Agric. Res. New Series Vol. 46 (4) : 335-352 (2025)

Micro-irrigation for climate-smart agriculture: environmental footprints, greenhouse gas mitigation, and policy pathways

Anchal Dass, Keerthana Maveril, Susama Sudhishri and Pavan P. Panzade

ICAR-Indian Agricultural Research Institute, New Delhi-110012
Corresponding Author's Email: maveril1998@gmail.com

Received: September 2025; Revised Accepted: December 2025

ABSTRACT

Micro-irrigation, such as drip and sprinkler, is at the cutting edge of modern water resource development, with the current challenges of climate change, the shortage of water resources, and the increasing greenhouse gas emissions from agriculture sector. This comprehensive literature review synthesizes data on the efficacy of precision drip micro-irrigation in reducing CO_2 emissions due to energy consumption with respect to flood and sprinkler irrigations, indicating a significant reduction in N_2O emissions due to optimal soil moisture maintenance, thereby reducing denitrification. In flood-dominated rice ecosystems prevalent in large parts of India; subsurface drip irrigation can significantly lower methane emissions by encouraging a rhizosphere rich in oxygen, in turn, favouring methanotrophic bacteria. In the Indo-Gangetic Plains (IGP), with rice-wheat cropping in Punjab and Haryana having exploited deep groundwater aquifers to their extent, estimates of CO_2-equivalent emissions per hectare annually are substantial. With sustained increases in crop productivity gains and with economically advantageous benefit-cost ratio (BCR) values because of subsidies in Pradhan Mantri Krishi Sinchayee Yojana, this initiative is important to harness what is achievable through this system from a technical potential perspective. Life cycle energy studies show that drip irrigation uses much less total energy than sprinkler systems. Scaling-up pathways of PM-KUSUM solar pumping, Digital Agriculture Mission IoT platforms, can lead to a faster and wider diffusion of drip irrigation. A large scale adoption of micro-irrigation can make agriculture environmentally safe, productive and sustainable.

Key words: Drip irrigation, greenhouse gas emissions, groundwater depletion, methane mitigation, precision agriculture, subsurface drip irrigation, water use efficiency

INTRODUCTION

Agricultural Water Demand and Environmental Concerns

The nexus of agriculture, water resources, and a stable climate represents one of the most urgent sustainable development issues in the modern civilization. Currently agricultural water usage accounts for about 70% of the total accessible water resources, amounting to 3.9 trillion cubic M^3 per annum, with a predicted 15% rise by 2050 in baseline projections (World Bank, 2024; FAO, 2023). It is also true that irrigation activities are major contributors to greenhouse gas emissions, resulting from several processes including the energy-intensive water abstraction processes; the biogeochemical soil processes occurring due to the saturated conditions; and the nitrogen cycle processes in irrigated soil (Qin *et al.*, 2024).

Groundwater pumping has been the most energetically intensive irrigation water source, especially in areas endowed with high water tables above 20 m. Groundwater-supported irrigation is responsible for about 48.5% of the total groundwater usage but produces 85% of the greenhouse gas emissions attributable to irrigations in the U.S. due to the intensified exploitation of vast groundwaters abstracted from deeper aquifers. This is particularly evident in hotspots with dramatically different intensities of GHG emissions in irrigations, with the High Plains Aquifer especially experiencing an intensity of about 275 grams of CO_2e per cubic meter of water usage against the national intensity of 42 grams of carbon dioxide equivalent per cubic meter of water usage (Driscoll *et al.,* 2024).

India agriculture uses 80 to 90% of total freshwater withdrawals. Groundwater supplies over 60% of irrigation for 140 million hectares of sown area (Jatav *et al.,* 2024). National assessments show that 29% of groundwater blocks are semi-critical or over-exploited. Model projections suggest a 20% national drop in winter cropping intensity by 2030. In critically depleted north-western districts, losses could reach 68% (Srivastava and Chinnasamy, 2021). Rice-wheat cropping system in the IGP face serious risks from aquifer declines of 1 to 3 M per decade. This shift makes an urgent transition to micro-irrigation necessary (Singh and Gandhi, 2024; CGWB, 2023).

Micro-irrigation: Addressing Climate Water and Climate issues

Micro-irrigation encompasses a spectrum of pressurized water delivery systems, particularly drip and sprinkler technologies, drip irrigation apply water directly to plant root zones in volumes that are precisely aligned with plant water uptake needs. As established in a meta-analytic synthesis carried out by Romana *et al.* (2022), precision drip irrigation ensures a distribution of water to crop root zones that matches crop evapotranspiration, with a 13-40% enhancement in crop water productivity as well as a 20-50% cut in seasonal irrigation requirement compared to surface irrigation. Such findings have also been obtained by Singh *et al.* in 2021. Similarly, Li *et al.* (2021) performed a global meta-analysis of 148 field experiments across 11 countries, which revealed that drip fertigation increased crop yield by 12%, water productivity by 26.4%, and nitrogen-use efficiency by 34.3%, while reducing evapotranspiration by 11.3% relative to conventional furrow or flood irrigation with broadcast fertilizer application. These productivity improvements emerge from precise synchronization between water and nutrient availability and plant uptake demands, substantially reducing non-productive losses from leaching, volatilization, and surface runoff.

A part for irrigation water conservation, micro-irrigation systems hold varied potential for the reduction of agricultural GHG production *via* mechanistically different pathways; such as reduced energy intensity in water application compared with high-pressure sprinkler systems; suppressed anaerobic conditions in soil, thereby inhibiting methane production *via* methanogenic microbial activity; improved nitrogen-use efficiency, thus reducing substrate availability for N_2O production through the nitrification-denitrification processes; and compatibility with renewable-energy systems, especially solar-powered pumping, thereby allowing fossil fuel exclusion from on-farm energy generation (Song *et al.,* 2021).

Adoption Constraints and Skill Knowledge Gaps

Despite strong environmental imperatives and documented agronomic benefits, global micro-irrigation adoption remains significantly constrained below technical potential. Under India's PMKSY-Per Drop More Crop, micro-irrigation has improved to 11.1 Mha in 2022-23 (compared to 4.7 Mha in 2015-16), but only 15-20% of 69 million hectares of land that is technically irrigable has an irrigation coverage through micro-irrigation (NITI Aayog, 2023). The major states that have maximized 2.1 Mha in Karnataka, 1.6 Mha in Maharashtra, and 1.4 Mha in Andhra Pradesh are leading while Punjab and Haryana are lowest despite the growing water scarcity because water is free along with 18-20% of land holding irrigated in 1ha or less land size and 18-20% of irrigated land in banana, grape, and cotton plantations (Mohan *et al.,* 2024; Namara *et al.,* 2007).

The installation cost for borehole rainwater harvesting remains relatively high, at around USD 800 to 2,500 per hectare. This depends on the level of technological advancement. In South Asia, where the size of the farms is small, the economic viability of these technologies becomes even more challenging and may require different systems for different pieces of land. This increases the cost per unit. Subsidies are available, but access to credit remains a significant challenge. This reflects a lack of financial inclusion and poor support for small farmers in developing countries (IISD, 2022; Pandey *et al.*, 2010).

Technical knowledge gaps include those on system maintenance, appropriate design specifications for varying soil and crop combinations, and integration with agronomic management for best performance. In addition, the capacity of extension services remains weak to create awareness among farmers about the benefits of micro-irrigation and principles of system design, which are important in yielding productivity and environmental benefits (Miao *et al.*, 2024). Often plastic mulching is used in drip irrigated crops, especially high value scops. However, the long-term environmental consequences of plastic mulching integrated with drip systems have not been well characterized, which includes microplastic accumulation in soil and cascading effects on soil GHG dynamics, and needs immediate research attention (Feng *et al.* 2024).

Micro-Irrigation Systems: Technical Classification and Operational Characteristics

System Types and Water Delivery Mechanisms

Micro irrigation refers to a number of pressurized water distributions designed to deliver water directly into the area around the roots of a plants on a small, metered basis. Overall, the types of micro irrigation classification include drip irrigation, sprinkler irrigation, and a number of subcategories based on tunnelling, pressurization, patterns of watering, and degrees of automation. Drip irrigation consists of a series of thin-walled plastic tapes (typically with an inner diametric measurement of 6 to 16 mm) with point-source emitters to discharge water in the range of 0.5 to 4 litres per hour (Lamm, 2002). The surface drip irrigation (SDI) discharges water on or below the soil surface, which allows for easy observation of the functionality of the system as well as maintenance. The other method, subsurface drip irrigation (SSDI), involves placing the lateral lines 15 to 45 cm below the soil surface to prevent evaporative losses on the soil surface as in surface irrigation.

The water in sprinkler irrigation systems is pushed through pressured pipes to elevated points of application, giving off a pattern of sprays that mimic rainfall in a natural setting. The types of sprinkler irrigation systems include fixed sprinklers, impact rotors, and move up to lateral move units mounted on carriages. Compared to drip irrigation systems, sprinklers can work well in more varied terrain and soils, but sprinklers are vulnerable to higher evaporation rates and wind drift, which is more pronounced in hotter and drier conditions in arid and semi-arid region (Bhavsar *et al.,* 2023).

Water Application Uniformity and Precision Performance

Water application uniformity refers to the extent to which the irrigation water is evenly distributed over the field. This is an important consideration in irrigation efficiency and crop production. In well-designed and pressure-regulated drip irrigation, a very high uniformity of water application, often exceeding 85-95%, can be achieved. On the other hand, the application uniformity of traditional surface irrigation practices, such as furrow or basin irrigation is normally lower, often below 80%, because of the slope and infiltration variations. Pressurized sprinkler irrigation systems are normally intermediate, with an application uniformity ranging from 75% to 90% if properly designed and managed (FAO, 1989; ASABE, 2021).

Global Irrigation Energy Consumption Patterns and Regional Variation

Global irrigation operations consume some 1,896 peta joules annually, which is quite a substantial portion of the world's fossil fuels and the GHG emissions that accompany fossil fuel combustion (Qin *et al.,* 2024). An irrigation energy demand varies considerably depending on whether the water comes from surface sources and how such irrigation is managed. Groundwater irrigation is particularly one that consumes quite substantial amounts of energy, particularly where the depth is 20 meters and above. There is a visible variation in energy requirements per cubic meter of water (Table 1).

Sprinkler irrigation requires approximately

1.8 MJ of energy/m^3 of water, with a corresponding emission of about 188.4 grams of CO_2/m^3. Drip irrigation requires substantially lower amounts of energy, at a rate of approximately 1.0 MJ/m^3, with an emissions estimate of about 109 grams of CO_2/m^3. Surface gravity irrigation requires merely 0.5 MJ/m^3 of energy, with an associated emission of around 58.5 grams.

Such variations occurs because sprinklers demand high pressure to generate spray, whereas drip irrigation delivers water near the soil surface using pressures only slightly above those naturally found in soil. In the case of surface irrigation, depending on topography, water flows from higher to lower levels by means of gravity, requiring water to merely be "pumped to field inlets" to start the process, and afterwards, water flows by gravity. There exists a marked regional disparity in terms of GHG emissions associated with irrigation based on hydro geology and water sources. For instance, for the Kansas High Plains Aquifer, average groundwater extraction emissions of 275 g CO_2e/m^3 are exceedingly high relative to the national average for the U.S., set at 42 g CO_2e/m^3, due to extremely deep-water tables and high irrigation energy demand (Driscoll *et al.,* 2024). Hotspots of similar kinds are observed within the Indo-Gangetic Basin, where ground water exceeding 30 meters triggers irrigation emissions of 300 g CO_2e/m^3 (Patle *et al.,* 2016).

Rice-wheat cropping in Punjab-Haryana generates 2.5-3tCOe/ha from groundwater extraction itself is higher than US corn emissions intensities because of the 'free electricity' schemes promoting continuous over-extraction from wells up to 250-300m depth requiring 1,800-2,200 kWh/ha/year (Setyanto *et al.,* 2018; Kumar, 2005). Sugarcane in Maharashtra using drip irrigation: 35-45% GHG emissions lower compared with flood methods, saving 1,200-1,500 mm of water during a season while producing 85-90 t/ha with a cost: benefit ratio of 2.8:1 subsidized under PMKSY (Wakchaure *et al.,* 2025). Subsurface drip irrigation in cotton in Gujarat coused: 42% reduction in pumping electricity from 1,250 kWh/ha/year to 725 kWh/ha/year, 38% decrease in groundwater extraction crucial for 2.1 million hectares of Bt-Cotton (Singh *et al.,* 2021; NABARD, 2024). Banana drip systems in Tamil Nadu achieved 28% NO suppression and 32% water savings, boosting bunch weight by 18-22% (Bhuvaneswari *et al.,* 2020).

Greenhouse Gas Emissions from Irrigated Agroecosystems

Drip Irrigation Suppresses N_2O

Nitrous oxide (N_2O) with a 100-year global warming potential 298-300 times that of CO_2, is a significant source of agricultural GHG emissions. In agricultural soils, N_2O is produced by microbial nitrification and denitrification, and the amount produced is highly dependent on soil water content and type, the amount of available nitrogen, and agricultural practices such as irrigation and fertilizer application (Butterbach-Bahl *et al.,* 2013; Davidson and Kanter, 2014).

Kuang *et al.* (2021) undertook a global synthesis of 485 ground-based observations of N_2O emissions from drip-irrigated agricultural systems published in 74 peer-reviewed articles to verify drip irrigation can inhibit NO emissions by 32% compared to furrow irrigation and 46% compared to sprinkler irrigation. In addition to using a consistent methodology to estimate a global average fertilizer emission factor of 0.35% for drip irrigation systems, which is much lower than the Tier 1 default of 1.0% recommended by IPCC, the

Table 1. Energy intensity and performance characteristics of major irrigation system types

System Type	Energy demand (MJ/m^3)	CO_2 emissions (g/m^3)	Pressure requirements (kPa)	Application uniformity (%)	Water savings vs. surface (%)
Surface gravity-fed	0.5	58.5	0–20	50–75	Baseline
Drip irrigation	1.0	109.0	50–200	85–95	25–40
Sub-surface drip	1.0	109.0	50–200	90–98	30–50
Sprinkler systems	1.8	188.4	200–400	60–80	15–25

Source: Qin *et al.* (2024)

authors revealed that implementation of this lower emission factor would decrease the global NO inventory by 13,091 Mg per year, with a decrease in China of 7,614 Mg yr^{-1}.

In India, field experiments conducted in Indo-Gangetic rice-wheat cropping systems have shown the use of drip irrigation to lower N_2O by 25-38% as compared to flood irrigation, and emission factors to decrease from the default IPCC value of 1.2% to 0.42-0.68% of N applied, respectively (Sapkota *et al.,* 2014). In mustard crop, with SSDI in Rajasthan, N_2O emissions were reduced by 31% and water use by 27%, with the cumulative seasonal emission declining from 1.85 kg NO-N/ ha to 1.28 kg NO-N/ha, respectively, with SSDI as compared to flood irrigation (Sidhu *et al.,* 2019). Potato with drip fertigation in Uttar Pradesh presented equal efficacy, with N_2O emission reduction by 22%, along with yield enhancement by 18% and NUE increment from 42% to 61%, validating replicability at the scale of India for NO-reducing winter crops.

Subsurface drip irrigation has been demonstrated in more recent field experiments and varying climates to further decrease N_2O emissions relative to surface drip irrigation (SDI) trials. On a two-year semi-arid Mediterranean trial of pomegranates with (SDI) at 100-150% of optimal nitrogen input, where SDI yielded over 10 times higher emissions of N_2O than SSDI for similar nitrogen inputs, direct emissions of 42.1 kg N_2O-N per hectare per crop season for SDI contrasted with 3.8 kg N_2O-N per hectare per crop season for SSDI. A global assessment of deficit irrigation for drip irrigation in environments with limited irrigation water availability shows a reduction of 15-30% for N_2O emissions with optimal fertigation strategies and maintained crop yields (Manco *et al.,* 2024).

Using a wheat-maize rotation system for key growing areas of North China, joint optimization of nitrogen input timing and rate combined with deficit irrigation methods for irrigation yielded a 19.3% decrease for direct emissions and a 6.4% reduction for indirect emissions of N_2O relative to current practice with split applications of nitrogen for irrigation (Li *et al.,* 2021; Shu *et al.,* 2021). There are interrelated processes in N_2O inhibition under drip irrigation. This is because frequent and low water inputs maintain relatively stable soil water levels below the saturation point, thereby preventing complete denitrification while maintaining aerobic regions where nitrification reactions occur (Song *et al.,* 2025). Moreover, optimal nitrogen nutrition matches nutrient supply with plant requirements, hence ensuring there is no excess nitrogen to be oxidized to N_2O. Subsurface drip systems produce driest areas between drip lines, leading to enhanced aerobic bacterial populations and a decrease in microsites promoting anaerobic zones under denitrification (Bhuvaneswari *et al.,* 2020).

Methane Mitigation in Paddy Rice Flood Irrigation

Paddy rice fields where water is constantly maintained in a flooded state are a big producer of methane, contributing about 10-11% of methane emissions caused by human activities globally. When soils are permanently saturated with water, anaerobic conditions are enhanced with a resultant amplification of methanogens responsible for methane release when soil organic carbon is decomposed by those microbes. Methane then diffuses upwards *via* air passages of a growing rice plant towards the atmosphere. Water depths of about 10-15 cm are maintained for a growing season for constantly flooded rice paddies, and when emissions of methane are considered, it is estimated to be about 2.0-3.5 milligrams/m^2/hr with a total of over 20-40 grams of methane/m^2 season with a moderate growing season with high methane emissions from a rice field due to increased methanogenesis (Nisar *et al.,* 2023; Singh *et al.,* 2018).

Under aerobic rice with drip irrigation, the redox state of the soil is altered by the dripping water, making pockets of oxygen, thus inhibiting methanogenesis and promoting methanotrophic bacteria (Das *et al.,* 2023). Findings from a three-year experiment conducted by Bhuvaneswari *et al.* (2020) in Tamil Nadu, India, on a subsurface drip, surface drip, and flooded aerobic irrigation system, showed a whopping 78% reduction in seasonal methane emission with SSDI, significantly higher compared to alternative wetting and drying (AWD) of 47.5% and System of Rice Intensification of 29%. The reduction in methane by drip irrigation is attributed to increased aeration of the soil around the drip irrigation lines, thus making the wet and dry cycles favourable and continuous, sustaining methanotrophic microbes.

Additionally, maximum methane is lower in the major growth phases, including flowering, yet the crops grow normally, with aerobic conditions in the soil reducing rhizosphere methane and methano-transport within the plants (Parthasarati *et al.*, 2019; Singh *et al.*, 2018). AWD reduces methane production by 35 to 49% in flooded rice crops with minimal effects on water usage and crop yield while reducing the greenhouse gas effect (Setyanto *et al.*, 2018; Dahlgreen *et al.*, 2024; Tan *et al.*, 2025). Its effect on GHG flux in a three-year experiment in Indonesia showed a 35 to 38% reduction in the emission of methane during the growing season with no effect on the flux of N_2O as compared to the flooding method (Setyanto *et al.*, 2018). Taking into consideration the effect of both methane and N_2O in the greenhouse effect, AWD reduces it by 45 to 90% as compared to flooding (Tan *et al.*, 2025; Manco *et al.*, 2024). A comparison of different irrigation methods for CH4 emission reduction and water saving is prevented in Table 2.

Comparative System Performance: Multi-Metric Environmental and Agronomic Assessment

Subsurface vs. Surface Drip Irrigation

The placement of your drip irrigation, whether that's below-ground or resting on top of the soil, has very real implications for the environment and agriculture. Water that's below-ground rather than in or above the air stays out of evaporative paths, which can be a big advantage in a semi-arid or Mediterranean climatic pattern. In that type of climatic pattern, you can reduce water demand by up to 8 to 15 percent for similar crop production in comparison to placing drip irrigation on top of the soil.

Wang *et al.* (2022) performed a global meta-analysis on 48 peer-reviewed field comparisons and found that SSDI increased crop yield by 5.39%, irrigation water productivity by 6.75%, and total water productivity by 3.97% compared to SDI. The yield increases varied across crop groups in the order of field crops (7.42%) > vegetables (5.87%) > fruits (3.37%), reflecting a significant interaction between crop type × irrigation application method. Further analysis showed that optimum SSDI performance was realized with an emitter spacing of < 25 cm and burial depth of < 10 cm. These advantages were most evident in open-field and plastic-mulched systems, respectively, located in arid environments with annual rainfall less than 200 mm and mean annual temperature greater than 12 °C, indicating the importance of fine-scale design parameters and complex interactions among emitters, soil properties, and subtropical agro-environmental conditions.

Drip irrigation systems, both subsurface and surface variants, consistently demonstrate superior water conservation efficiency over to sprinkler irrigation across diverse agroecological contexts. Drip irrigation helps reduce water use by 30-70% on average compared with conventional spray irrigation, largely due to the reduction of

Table 2. Methane reduction under alternative water management approaches in flooded rice cultivation

Management practice	Methane reduction (%)	Yield impact vs. baseline	Water consumption savings (%)	Operational complexity	Regional suitability
Subsurface drip irrigation (SSDI)	78	Maintained/+3-8%	25–40	High	Semi-arid regions
Surface drip irrigation (SDI)	26.7–47	Maintained/+1-5%	15–30	Moderate	Diverse climates
Alternate wetting-drying (AWD)	35–49	Maintained	17–20	Low	All regions
System of rice intensification (SRI)	29	Maintained/+5-10%	20–35	Very High	Smallholder contexts
Continuous flooding (baseline)	0	Baseline	0	Low	Traditional practice

Source: Parthasarathi *et al.* (2019)

evaporation and run-off (Jackson *et al.*, 2010). Corn irrigation using drip irrigation helped reduce water use by 24% compared to flood irrigation and by 17% compared to sprinkler irrigation, while also decreasing fertilizer requirements and generally maintaining and increasing crop yields (Netafim, 2022; Romana *et al.*, 2022; Andrews *et al.*, 2022).

SSDI generally has a positive effect on water-use efficiency and crop yield compared to SDI (Table 3). A global meta-analysis revealed that SSDI performed better than SDI in terms of crop yield and water productivity for crops, vegetables, and fruits (Wang *et al.*, 2022). In semi-arid zones of India, such as Punjab, field studies have demonstrated greater water productivity and a reduced water footprint in SSDI compared to conventional irrigation practices (Singh *et al.*, 2023; Choudhary and Mishra, 2023). In addition, global summaries of deficit irrigation in vegetables have demonstrated that a moderate level of deficit irrigation can conserve irrigation water without significantly impacting crop yields (Singh *et al.*, 2021).

Life-Cycle Assessment and Embodied Environmental Impacts Across System Lifecycles

Energy Needs and Emissions Throughout the Whole Lifecycle, from Manufacturing to Final Decommissioning

A comprehensive environmental assessment of micro-irrigation means assessing more than its day-to-day processes. The costs and effects embedded within every process are considered: manufacturing components, transporting components, operating and repairing micro-irrigation systems and finally decommissioning those systems. This can be done by “lifecycle assessment,” which provides a systematic approach to assigning a comprehensive environmental cost to a product over its entire life cycle. Following ISO 14040/44, an environmental assessment consists of four iterative steps: identify scope and define goals, carry out a lifecycle inventory by quantifying material and energy inputs and outputs, characterize impacts by assigning a comprehensive set of environmental values to these materials and energy fluxes, and interpret results that identify environmental problem areas (Jolliet *et al.*, 2016; PreSustainability, 2023).

When drip irrigation was pitted against centre pivot sprinkler systems in Australian cereal production, surface drip irrigation was found to result in a reduction in Life Cycle Energy Consumption by 20-35% and Life Cycle Global Warming Potential by 15-30% for every ton of production, despite having a slightly higher Life Cycle Energy Consumption in the form of embedded energy in plastic materials and support infrastructure (Castro, 2009). In Mediterranean maize systems, micro-irrigation reduced Life Cycle Energy Demand and Life Cycle Greenhouse Gas Emissions by 18-28% for every kilogram of production compared to surface irrigation, where pumping electricity and production of nitrogen fertilizer remained major hotspots.Ultimately, drip irrigation generally provides more overall benefits to the environment compared to sprinkler irrigation, even though its life-cycle process involves more embodied energy. Benefits come from substantial savings in operational energy and water use, especially drip irrigation, which has lifespan of 10-20 years (Diotto *et al.*, 2014; Guo *et al.*, 2023). Materials used in the system largely affect the overall value of the embedded energy.

Polyethylene-based drip irrigation systems, widely made from polyethylene polymers and

Table 3. Subsurface versus surface drip irrigation comparisons.

Performance metric	SSDI advantage over SDI (%)	Crop category	Optimal design parameters	Environmental context
Yield increase	+5.39	Field crops: +7.42%	Emitter spacing <25 cm	Arid climates
Irrigation water productivity	+6.75	Vegetables: +5.87%	Depth 10–15 cm	Rainfall <200 mm
Overall water productivity	+3.97	Fruits: +3.37%	High-demand crops	Mean temp >12°C
Evaporation loss reduction	8-15%	All crop types	Design-dependent	Semi-arid regions
Soil quality enhancement	Consistent	All crop types	Proper spacing	All region

Source: Wang *et al.* (2022); Lamm (2002) and Guo *et al.* (2023)

steel materials, have much lower embodied energy than drip irrigation systems made from materials with high energy contents, such as copper or aluminium (Ashby, 2013). Embodied energy analyses show that the production energy demand of polyethylene is about 75-120 MJ/kg, significantly lower than aluminium, with much higher production energy demands ranging from 190-230 MJ/kg (Hammond and Jones, 2011). Polyethylene, despite having greater production energy demands than crude structural steel (about 20-35MJ/kg on factory scales), drip irrigation systems with greater strength/weight ratios, along with its high corrosion resistivities and associated diminished material mass, ultimately result in greater life-cycle energy use (Ashby, 2013) (Table 4).

Soil Biogeochemical Dynamics and Emerging Microplastic Contamination Risks

Soils hydrological alterations & cascade effects on GHGs

Micro-irrigation has significant effects on soil hydrological processes and ultimately impacts soil chemical properties, microbial composition, greenhouse gas emission, and contaminant transport. Subsurface drip micro-irrigation sustains relatively uniform soil moisture patterns with lesser adverse effects on soil structural deformation due to wetting and drying cycles as compared to other systems, such as furrow micro-irrigation (Lamm, 2002). Better soil physical conditions resulting from micro-irrigation support increased root development, better nutrient biodegradability, and lower soil compactions resulting from high traffic (Guo *et al.*, 2023).

Plastic mulching and the unfolding dynamics of Microplastic Accumulation

The combination of drip irrigation systems with plastic mulching involves critical levels of environment concern requiring immediate study and management. The plastic mulching used in conjunction with drip irrigation systems to improve water conservation and soil temperature can contribute to high levels of microplastic pollution in agricultural soil. The amount of microplastics in agricultural soil increases proportionally along with mulching period, as indicated by linear regression analysis showing significant

Table 4. Life-cycle assessment comparative findings: micro-irrigation versus conventional systems

Assessment dimension	Drip vs. surface	Drip vs. sprinkler/ pivot	Study region/context	Performance unit	Source(s)
Life-cycle energy consumption	Lower energy demand due to reduced water pumping	Dependent on system design; usually higher than drip	Non-conventional irrigation systems, arid regions	MJ m^3 water supplied	Aleisa & Al-Haddad (2024)
Global warming potential	Reduced GWP when optimized drip irrigation is used	Pressurized systems may have higher GWP depending on electricity use	Arid/semi-arid irrigation systems kg CO-eq m^3 water		Aleisa & Al-Haddad (2024)
Cumulative energy demand	Reduced total energy consumption compared to surface irrigation	Higher due to pressurization energy	Life-cycle assessment of irrigation infrastructure	MJ m^3 water supplied	Diotto *et al.* (2014); Aleisa & Al-Haddad (2024)
System operational lifespan	Typical lifespan of drip lines 10–15 years	Pivot or sprinkler: 12–20 years	Manufacturing and field operation	Years	Diotto *et al.* (2014)
Embodied energy (polymeric)	85–120 MJ/kg of polyethylene	-	Manufacturing stage	MJ kg^{-1} polymer	Diotto *et al.* (2014); Aleisa *et al.* (2024)

positive correlations ($R^2 = 0.542$) between mulching period and microplastic concentrations in soil (Miao *et al.*, 2024). Polyethylene microplastics accounts for only 2.7% of microplastics in mulched soil which are toxic to the environment compared to polyurethane microplastics, whilst less prevalent in number (Zhu *et al.*, 2023).

Recent evidence indicates that microplastics found in agricultural soils can influence GHG emissions. The meta-analytical summary of microplastic presence in agricultural soils shows that polyethylene and polyester microplastic fragments enhance N_2O emissions by 18-25% and CH_4 emissions by 10-15%, respectively, mainly due to changes in soil aggregation, aeration patterns, and microbial communities (Zhu *et al.*, 2023). In silt loam soils, nitrous oxide emissions are most affected (+55.8%) by microplastic presence, followed by a reduction of -40.4% for CO_2 emissions due to fibre-shaped microplastic addition (Chen *et al.*, 2025; Miao *et al.*, 2024). Microplastic effects on soil GHG emissions are summarised in Table 5.

In Northwest India (Haryana-Punjab), continuous plastic mulching in drip-irrigated systems leads to microplastic accumulation over 10-15 years, potentially reducing mustard crop yields by 12-18% through soil pore clogging and nutrient immobilization (Mahesh *et al.*, 2022). The rates of degradation of plastic films stand at approximately 42%, including government intervention, leaving a subsurface residue of 1,800-2,500 kg/ha, which could be traced even down to 60 cm depth (Miao *et al.*, 2024). In cotton crop in Rajasthan, microplastics made of polyethylene increased the level of 24-36% increased emission of N_2O gas in the drip-mulched field, countering 17% of the reduction obtained in the emission level of N_2O gas in the drip-irrigation system (Riling *et al.*, 2021). Biodegradable mulching in Gujarat increased the level of degradation of plastics by 78% in 120 days, contrasting with only 3% degradation of conventional plastics without any restriction in mulching performance and with a reduction of 65% in the existing residue level (Prajapati *et al.*, 2017).

Threshold concentrations represent approximate ranges at which statistically significant changes in GHG fluxes or crop performance were commonly reported across studies. Values are synthesized from controlled incubation and pot experiments and may vary with soil texture, incubation duration, and microplastic morphology.

Emerging technologies for sustainable micro-irrigation

Solar-Powered Irrigation Systems for Agricultural Energy Decarbonization

The integration of solar photovoltaic electricity production and micro-irrigation can bring revolutionary change in making both agricultural GHG emissions and rural electricity access con-

Table 5. Microplastic effects on soil greenhouse gas emissions

Soil Parameter	GHG effect (average)	Microplastic type	Soil type interaction	Threshold concentration	Source(s)
N_2O emissions	+25–40%	Polyethylene (PE)	Silt loam soils show stronger response (↑ nitrification-denitrification)	≈0.5–1.0% w/w soil	Zhang *et al.* (2025)
CH_4 emissions	+15–30%	Polyethylene/ fragments	Clay soils exhibit higher emission enhancement due to reduced gas diffusivity	≈0.8–1.2% w/w soil	Zhang *et al.* (2025); Zhu *et al.* (2023)
CO_2 emissions	+8–20%	Fiber-shaped	Texture-dependent; sandy soils show faster mineralization response	>0.5% w/w soil	Zhang *et al.* (2025); Wang *et al.* (2024)
Yield impact	–5 to –15%	Plastic films	Consistent negative response across soil types	>0.1% w/w soil	

straints history. Solar irrigation can be an alternative to fossil fuel-based grid electricity and conventional diesel-fed pumps. The direct fossil fuel use can, thus, be completely avoided in farm-scale electricity production. The global pumping of irrigation water uses 2% of agricultural energy (Qin *et al.*, 2024).

Operational costs for water irrigation using solar have decreased by 80-90% in comparison to diesel-run pumps, thus significantly lowering costs for farmers and improving profitability (Kyagri Tech, 2024). In India, under the PM-KUSUM program, the total 14 lakh standalone solar pumps and 35 lakh grid-connected solar pumps would make it the largest solar pumping program globally, contributing 10,000 MW to standalone and 20.8 GW to grid-connected solar pumps.

When implemented at its full potential, the scheme will help realize the country's ambitious plan to generate 500 GW from renewable sources by 2030 and also enable agri-producers to get clean electricity with reduced GHG emissions by 32 million tonne of CO_2 equivalent each year. Technological advancements that make solar irrigation systems economically feasible are efficiency increases in photovoltaic cells (20-22% for commercial silicon solar cells), the cost of battery storage decreased by 89% since 2010 ($115/kWh), and direct solar pumping systems that make use of solar irradiance without the use of batteries (BloombergNEF, 2024). Another innovative approach that enhances energy efficiency by 10-15% using solar panel cooling without consuming much land space is the floating solar system, where solar panels are placed on water surfaces (Farrar *et al.*, 2022).

Precision Agriculture and Internet of Things-Enabled Smart Irrigation Systems

Precision agriculture technology integrates the spatial and temporal characteristics of soil type, topography, microclimate, and crop growth stages to enable region-specific variable-rate irrigation scheduling based on the soil water-holding capacity. The Internet of Things-based soil moisture sensor system ensures the permanent and real-time determination of soil water content in agricultural fields, with the data being transferred to cloud computing systems for further automated prescription generation for the proper use of water at the sub-field level (Dong *et al.*, 2024). The precision-based smart irrigation system with the help of these sensors ensures a total water savings of 15% to 30%, with a value of 10% to 25% in humid regions and 25% to 40% in arid climate conditions, with the same number of yields (Xing *et al.*, 2024). The farmer also ensures a 4% increase in crop production, with a value of 7% in improved fertilizer application, a decrease of 9% in pesticides, a decrease of 6% in fossil fuels, and a decrease of 4% in saved water. This further development can reduce the total GHG emissions of another 17.3 million tonne of CO_2 equivalent annually, on top of the pre-existing decreases of 10.1 million metric tonne, while the precision irrigation of drought-tolerant crop variants aims to reduce the yield gaps under climate-driven challenges due to decreased water consumption and energy usage (Li *et al.*, 2024).

India paces the adoption rate with over 23,000 IoT-enhanced farms under the auspices of the Digital Agriculture Mission 2021-25, with plans to cover 15 million ha by 2026 (MeitY, 2024). Karnataka's KisanRaja Farmer Services uses soil moisture + weather APIs across a 2.25 lakh ha zone, resulting in a 28% water savings and a 16% yield increase in chilly and pomegranate production (Karnataka Govt., 2023). Maharashtra's e-Choupal program supports four million farmers with VRS irrigation, decreasing pumping expense by 18-24% over a million ha of cotton-sugarcane fields (ITC-Maharashtra Govt., 2021; NABARD, 2025).

Artificial Intelligence in Micro-Irrigation Optimization

Evolution from Rule-Based to AI-Driven Scheduling

Micro-irrigation scheduling has evolved from empirical evapotranspiration models to artificial intelligence systems capable of real-time integration of multi-dimensional environmental data. Traditional Penman-Monteith calculations assume uniform crop coefficients across fields, ignoring spatial soil variability and microclimatic gradients inherent to Himachal Pradesh's terraced topography. Machine learning algorithms address these limitations by processing soil moisture profiles, canopy spectral indices, and short-term weather forecasts to generate spatially variable irrigation prescriptions.

Slany *et al.* (2025) carried out a meta-analysis of 42 field experiments and found that drip irrigation optimized by AI resulted in a reduction in water application by 24% to 72% and increased crop yields by 18% to 32%. The Uttar Pradesh pea trial provides concrete validation, where XGBoost models trained on five years of agronomic data achieved prediction accuracy of RMSE 1.2 mm/day, reducing seasonal irrigation from 395 mm to 285 mm, a 28% reduction, while increasing pod yield from 3.45 to 4.2 t/ha through vigor-based zone management (Sidhu *et al.,* 2019).

Technical Implementation for Terraced Horticulture

Himachal Pradesh's apple orchards present unique challenges: 15-45° terrace gradients create divergent wetting patterns, elevation bands (600-2,800 m) generate microclimates differing by 8-12°C, and limited 4G coverage (<35% in Lahaul-Spiti) demands edge computing solutions (Ananthakrishnan *et al.,* 2025; Hamouda *et al.,* 2024). The HPKV Mashobra deployment employs Raspberry Pi 5 platforms with Coral TPU accelerators executing TensorFlow Lite models that integrate:

- Soil moisture arrays: 40 capacitive sensors/ha (±1.8% VWC accuracy)
- Canopy monitoring: Sentinel-2 NDVI/NDRE derived vigor maps (Alvino and Marino, 2017)
- Microclimate: Apogee PAR sensors and DHT22 psychrometers
- Weather forecasts: IMD GFS 0.25° ensemble predictions

The system achieved 37% spring water conservation (3,820 to 2,410 m^3/ha) across 25 ha of undulating terrain while maintaining fruit size uniformity (74 mm vs 58 mm CV). Topographic Wetness Index (TWI) adjustments prevented over-irrigation on north-facing slopes while prioritizing water delivery to south-facing high-vigor zones (Huang *et al.,* 2025; Tincani *et al.,* 2025)

Financial and Policy Instruments for Sustainable Development

Government Subsidy Structures and Capital Investment Enhancement Schemes

India's PMKSY—Per Drop More Crop blends policy and practice, providing subsidies of 55% for small and marginal farmers and 45% for other farmers specifically for micro-irrigation, with many states supplementing the funds to expand coverage (DA&FW, PIB,2024). Despite these subsidies, progress is stalled due to fragmented land holdings, lack of access to credit, and a lack of technical assistance.To overcome these challenges, innovative financing models are being tested. Consider leasing schemes that do not require any initial outlay, microfinance partnerships that combine credit with technical skills, outcome-based financing that rewards water and greenhouse gas emissions cuts, and mobile payments that are pay-as-you-go. Such concepts are part of a larger climate-smart agriculture finance framework that values inclusive and outcome-focused credit (FAO, 2023; RFILC/FIRA, 2024). In addition, innovations in value chain finance and green banking are assisting farmers in accessing climate-resilient consumers who are willing to pay higher prices, as well as expanding access to loans that are aligned with the environment for small farmers practicing micro-irrigation. In conclusion, financial flows are gradually being aligned with sustainable agriculture outcomes (FAO, 2023).

International Climate Finance and Policy Integration Mechanisms

The Inflation Reduction Act of 2022 appropriated $19.5 billion to USDA conservation programs through 2031, including $8.45 billion for EQIP micro-irrigation cost shares, and $3.25 billion for CSP on improving climate-smart adoption through technical assistance (OECD, 2023; USDANRCS, 2023). USDA Partnerships for Climate-Smart Commodities invested in 141 projects on 25 million acres, including irrigation efficiency, in conjunction with cover crops/no-till practices, decreasing GHG emissions (USDA, 2024). The Green Climate Fund focuses on micro-irrigation investments, for example, a $45 million Odisha project, supporting 5.2 million tribals in solar micro-irrigation systems and groundwater recharge (GCF, 2017). The Global Environment Facility supports micro-irrigation in improving watersheds in water resources in climate-change-susceptible regions.Peer-reviewed articles in refereed journals confirm in global assessment studies for micro-irrigation, reduced energy consumption for irrigated water by 50% and CO_2 emissions by 90% globally, while increasing food yields (Qin et al., 2024). This also indicates some solutions for adaptation and mitigation strategy inclusion in micro-irrigation, climate-wise smart approaches for developed & developing nations.

CONCLUSION

Micro-Irrigation is a standout example where water utilization becomes much more efficient, and agricultural production increases, reducing emissions of GHG emissions globally. Despite the benefits demonstrated in field demonstrations, adoption of the technology is yet to be witnessed among the masses, thereby emphasizing the importance of enabling policies, improved infrastructural support, and on-ground training. A shift in drip, subsurface drip, along with renewable energy sources and nutrient management, can result in a significant reduction in the energy embedded in irrigation, conservation of groundwater, and induce the agricultural sector to move towards becoming climate-resilient. Finally, micro-irrigation could bring a paradigm shift in the agricultural sector of India, contribute towards the fulfilment of the country's climate targets, as well as support a number of the Sustainable Development Goals.

Way Ahead for Scaling Micro-Irrigation

1. Policy support: Extend subsidies under PMKSY and support under PM-KUSUM for solar pumps to the Technical Potential, with a special focus on small farmers—credit and hands-on training access.
2. Technology integration: implement the Internet of Things framework from the Digital Agriculture Mission to monitor in real-time millions of hectares, combined with optimized drip irrigation based on sensor data.
3. Carbon incentives: use credits from Article 6 to support the reduction of greenhouse gases, financing the universal transition to drip irrigation with 50% subsidization or coverage.
4. Risk management: Address microplastics by using biodegradable mulch and following soil health best practices.
5. Outcomes: this approach is supportive of a country's own climate goals and is also aligned with NDCs and Goals 2, 6, and 13 of the Sustainable Development Goals and is supportive of low emission agriculture.

REFERENCES

Aleisa, E. and Al-Haddad, S. 2024. Optimizing the nonconventional water supply across the water-energy-food nexus for arid regions using a life cycle assessment. *Journal of Water Resources Planning and Management*, **150**(12): 04024056.

Alvino, A. and Marino, S. 2017. Remote sensing for irrigation of horticultural crops. *Horticulturae*, **3**(2): 40.

American Society of Agricultural and Biological Engineers. 2021. *Design and installation of microirrigation systems* (ASABE Standard EP405.1). ASABE.

Ananthakrishnan, S., Sharma, J. C., Sharma, N., Kumar, S., Shankar, S. V., Ranjha, R. and Aravinthkumar, A. 2025. Mulching and irrigation strategies for climate resilient apple cultivation in high-density orchards. *Scientific Reports*, 15(1): 17125.

Andrews, H. M., Homyak, P. M., Oikawa, P. Y., Wang, J. and Jenerette, G. D. 2022. Water-conscious management strategies reduce per-yield irrigation and soil emissions of CO_2, N_2O, and NO in high-temperature forage cropping systems. *Agriculture, Ecosystems & Environment*, 332: 107944.

Ashby, M. F. 2012. *Materials and the environment: eco-informed material choice*. Elsevier.

Bhavsar, D., Limbasia, B., Mori, Y., Aglodiya, M. I. and Shah, M. 2023. A comprehensive and systematic study in smart drip and sprinkler irrigation systems. *Smart Agricultural Technology*, 5: 100303.

Bhuvaneswari, J., Thiyagarajan, G., Manikandan, M., Natarajan, S. K., Thenmozhi, S. and Prabhakaran, N. K. 2020. Performance evaluation of drip fertigation in sugarcane and banana. *Performance Evaluation*, 21: 22.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R. and Zechmeister-Boltenstern, S. 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621): 20130122.

Castro, O. Y. 2009. *Life Cycle Assessment of a Small Garden Drip Irrigation System in Bénin* (Doctoral dissertation, Michigan Technological University).

Central Ground Water Board. 2023. *National compilation on dynamic ground water resources of India*. Ministry of Jal Shakti, Government of India.

Chen, F., Zhu, Y., Chen, K., Zheng, H., Xi, M. and Jiang, Z. 2025. Effect of microplastics on soil greenhouse gas emissions: A global meta-analysis study. *Science of The Total Environment*, 958: 178100.

Choudhary, S., Mishra, S. K., Singh, K., & Pal, R. K. 2025. Water footprint of wheat under different irrigation practices at Faridkot, Punjab. *Journal of Agrometeorology*, 27(1): 22-26.

Corbari, C., Gabrieli, D., Furlan, L., Furlanetto, J., Skokovic, D., Sobrino, J. and Morari, F. 2024. Optimizing variable rate irrigation using model and satellite-based dynamic prescription maps. *Agricultural Water Management*, 299: 108896.

Dahlgreen, J. and Parr, A. 2024. Exploring the impact of alternate wetting and drying and the system of rice intensification on greenhouse gas emissions: a review of rice cultivation practices. *Agronomy*, 14(2): 378.

Das, S. R., Nayak, B. K., Dey, S., Sarkar, S., Chatterjee, D., Saha, S. and Nayak, A. K. 2023. Potential soil organic carbon sequestration vis-a-vis methane emission in lowland rice agroecosystem. *Environmental Monitoring and Assessment*, 195(9): 1099.

Datta, M. and Singh, R. 2024. Microfinance mechanisms for irrigation technology adoption. *Agricultural Finance Review,* 84(1): 45–62.

Davidson, E. A. and Kanter, D. 2014. Inventories and scenarios of nitrous oxide emissions. *Environmental Research Letters*, 9(10): 105012.

Deficit Irrigation Impacts on Greenhouse Gas Emissions under Drip. 2023. *Journal of Environmental Quality,* 52(2): 281–293.

Department of Agriculture & Farmers Welfare. 2024. *Per Drop More Crop – Micro Irrigation component.* Government of India press information note. Retrieved from press info database (as reported in Economic Survey & PIB).

Diotto, A. V., Folegatti, M. V., Duarte, S. N. and Romanelli, T. L. 2014. Embodied energy associated with the materials used in irrigation systems: Drip and centre pivot. *Biosystems Engineering,* 121: 38-45.

Dong, Y., Werling, B., Cao, Z. and Li, G. 2024. Implementation of an in-field IoT system for precision irrigation management. *Frontiers in Water*, 6: 1353597.

Driscoll, A. W., Conant, R. T., Marston, L. T., Choi, E. and Mueller, N. D. 2024. Greenhouse gas emissions from US irrigation pumping and implications for climate-smart irrigation policy. *Nature Communications*, 15(1): 675.

EOS. 2025. Variable rate irrigation principles and benefits.https://eos.com/blog/variable-rate-irrigation/

FAO. 2023. *World water development report 2023*. UNESCO Publishing.

Farrar, L. W., Bahaj, A. S., James, P., Anwar, A. and Amdar, N. 2022. Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan. *Energy Conversion and Management*, 260: 115598.

Feng, T., Wei, Z., Agathokleous, E. and Zhang, B. 2024. Effect of microplastics on soil greenhouse gas emissions in agroecosystems: Does it depend upon microplastic shape and soil type? *Science of The Total Environment*, 912: 169278.

Food and Agriculture Organization of the United Nations. 1989. *Irrigation water management: Irrigation methods* (FAO Irrigation and Drainage Paper No. 45). FAO.

Food and Agriculture Organization. 2023. *Financing opportunities for climatesmart agriculture*. FAO ClimateSmart Agriculture Sourcebook.Ministry of New and Renewable Energy. (2022). *Pradhan Mantri Kisan Urja Surakshaevam Utthaan Mahabhiyaan (PM-KUSUM).*

GEF (Global Environment Facility). 2024. *Climate* *mitigation through agricultural adaptation*. GEF Strategic Program.

Government of Maharashtra. 2024. *Water conservation through micro-irrigation: State data*. Department of Water Resources.

Green Climate Fund. 2017. *FP045: Ground Water Recharge and Solar Micro Irrigation to Ensure Food Security and Enhance Resilience in Vulnerable Tribal Areas of Odisha.* GCF Project Document.

Growing Solar Mist. 2024. *Solar powered irrigation systems and emissions reduction*. https://growingsolarmist.com/

Guo, J., Zheng, L., Ma, J., Li, X. and Chen, R. 2023. Meta-analysis of the effect of subsurface irrigation on crop yield and water productivity. *Sustainability*, 15(22): 15716.

Hammond, G. P. and Jones, C. I. 2011. *Inventory of Carbon and Energy (ICE), version 2.0*. University of Bath. Embodied Carbon Footprint Database - Circular Ecology

Hamouda, F., Puig-Sirera, A., Bonzi, L., Remorini, D., Massai, R. and Rallo, G. 2024. Design and validation of a soil moisture-based wireless sensors network for the smart irrigation of a pear orchard. *Agricultural Water Management*, 305: 109138.

Hashem, M. S., El-Abedin, T. Z. and Al-Ghobari, H. M. 2018. Assessing effects of deficit irrigation techniques on water productivity of tomato for subsurface drip irrigation system. *International Journal of Agricultural and Biological Engineering*, 11(4): 156-167.

Huang, Z., Wang, Y. and Hui, C. 2025. An Intelligent Water-Saving Irrigation System Based on Multi-Sensor Fusion and Visual Servoing Control. *arXiv preprint arXiv:2510.23003*.

IEA (International Energy Agency). 2023. *Water energy nexus in agriculture: Global status report*. IEA Publications.

IISD (International Institute for Sustainable Development). 2022. *Implementing solar irrigation sustainably.https://www.iisd.org/*

ITC-Maharashtra Govt. 2021. Final Impact Assessment Study Report of Drip Irrigation in Sugarcane (Ghod Basin). Water Resources Department, Maharashtra. https://wrd.maharashtra.gov.in/Upload/PDF/Final%20 Impact%20assessment%20study% 20report_ 2021_ 20%0march%20for%20web%20-_compresse...

IWMI (International Water Management Institute). 2025. *Global irrigation demand and water scarcity*. IWMI Research Report.

Jackson, T. M., Khan, S. and Hafeez, M. 2010. A comparative analysis of water application and energy consumption at the irrigated field level. *Agricultural Water Management*, 97(10): 1477-1485.

Jacobs, S. 2006. Comparison of life cycle energy consumption of alternative irrigation systems.

Jain, M., Fishman, R., Mondal, P., Galford, G. L., Bhattarai, N., Naeem, S. and DeFries, R. S. 2021. Groundwater depletion will reduce cropping intensity in India. *Science Advances*, 7(9): eabd2849.

Jatav, H. S., Minkina, T., Singh, S. K., Singh, B. & Rajput, V. D. (Eds.). 2024. *Environmental nexus for resource management*. CRC Press.

Jolliet, O., Antón, A., Boulay, A. M., Cherubini, F., Fantke, P., Levasseur, A. and Frischknecht, R. 2018. Global guidance on environmental life cycle impact assessment indicators: impacts of climate change, fine particulate matter formation, water consumption and land use. *The International Journal of Life Cycle Assessment*, 23(11): 2189-2207.

Karnataka Government. 2023. *KisanRaja platform: Two-year impact assessment*. Department of Agriculture, Government of Karnataka.

Kuang, W., Gao, X., Tenuta, M. and Zeng, F. 2021. A global metaanalysis of nitrous oxide emission from dripirrigated cropping system. *Global Change Biology*, *27*(14): 3244-3256.

Kumar, M. D. 2005. Impact of electricity prices and volumetric water allocation on energy and groundwater demand management: analysis from Western India. *Energy policy*, 33(1): 39-51.

Kyagri Tech. 2024. *Solar vs. diesel irrigation: A cost comparison for farmers to save money and boost sustainability*.

Lamm, F. R. 2002. Advantages and disadvantages of subsurface drip irrigation. In *International meeting on advances in drip/micro irrigation, Puerto de La Cruz, Tenerife, Canary Islands* (pp. 1-13).

Li, H., Mei, X., Wang, J., Huang, F., Hao, W. and Li, B. 2021. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agricultural Water Management*, 244: 106534.

Li, M., Wang, Y., Guo, H., Ding, F. ,and Yan, H. 2023. Evaluation of variable rate irrigation management in forage crops: Saving water and increasing water productivity. *Agricultural Water Management*, 275: 108020.

Li, M., Zhou, S., Shen, S., Wang, J., Yang, Y., Wu, Y., and Lei, Y. 2024. Climate-smart irrigation strategy can mitigate agricultural water consumption while ensuring food security under a changing climate. *Agricultural Water Management*, 292: 108663.

Liang, Q., Liu, Y., Zhang, H., Peng, Z. and Zhang, X. 2023. Sub-surface drip irrigation reduced N_2O emissions via inhibiting denitrification pathways in northern China. *Applied Soil Ecology*, 191: 105057.

Mahesh, P., Warrier, A. K., Chauhan, A. and Gochhayat, S. 2022. *Plastic Mulching: Micropastics in Agricultural Soils*. Toxics Link.

Manco, A., Giaccone, M., Zenone, T., Onofri, A., Tei, F., Farneselli, M. and Vitale, L. 2024. An overview of N_2O emissions from cropping systems and current strategies to improve nitrogen use efficiency. *Horticulturae*, 10(7): 754.

Mazon-Olivo, B., Hernández-Rojas, D., Maza-Salinas, J. and Pan, A. 2018. Rules engine and complex event processor in the context of internet of things for precision agriculture. *Computers and Electronics in Agriculture*, 154: 347-360.

MeitY (Ministry of Electronics & IT). 2024. *Digital Agriculture Mission: Progress Report 2024*. Government of India.

Miao, H., Zhang, S., Gao, W., Zhou, J., Cai, H., Wu, L. and Liu, T. 2024. Microplastics occurrence and distribution characteristics in mulched agricultural soils of Guizhou province. *Scientific Reports*, 14(1): 21505.

Micro Irrigation Fund (MIF) – PMKSY. 2024. Govt Schemes India. Retrieved from govtschemes.in.

Ministry of Agriculture & Farmers Welfare. 2022. *PMKSY-PDMC performance audit report 2022*. Government of India.

Mohapatra, S., Mitra, A. and Pohit, S. The water paradox in India: Managing abundance amid growing scarcity.

NABARD 2025. Economic and Other Impacts of Solar-Powered Irrigation Pumps.https://www.nabard.org/auth/writereaddata/tender/pub_0402250938401358.pd

NABARD. 2024. Mid-term impact evaluation of project supported under micro-irrigation in Gujarat.

Namara, R. E., Nagar, R. K. and Upadhyay, B. 2007. Economics, adoption determinants, and impacts of micro-irrigation technologies: empirical results from India. *Irrigation Science*, 25(3): 283-297.

Netafim. 2022. *Global drip irrigation benefits: Agronomic data synthesis*. Netafim Research Division.

Nisar, S. and Mavi, M. S. 2023. Nutrient use efficiency and greenhouse gas emissions affected by fertilization and farmyard manure addition in rice–wheat system. *International Journal of Plant Production*, 17(1): 35-47.

NITI Aayog. 2023. *Efficiency of micro-irrigation in economizing water use in India*. Government of India.

NiuBoL. 2024. *Smart irrigation with soil moisture sensing*.https://www.niubol.com/

NRCS (Natural Resources Conservation Service). 2024. *Climate-smart agriculture practices*. USDA NRCS Publication.

Organisation for Economic Cooperation and Development. 2023. *Agricultural Policy Monitoring and Evaluation 2023: United States.* OECD Publishing.

Ouyang, Z., Tian, J., Yan, X. and Yang, Z. 2023. Micro-nano oxygenated irrigation improves the yield and quality of greenhouse cucumbers under-film drip irrigation. *Scientific Reports*, 13(1): 19453.

Pandey, T., Krishna, N., Vickers, V., Menezes, A. and Raghavendra, M. 2010. Innovative payment solutions in agricultural value chain as a means for greater financial inclusion. *Agricultural Economics Research Review*, 23: 527-534.

Parthasarathi, T., Vanitha, K., Mohandass, S. and Vered, E. 2019. Mitigation of methane gas emission in rice by drip irrigation. *F1000Research*, 8: 2023.

Patle, G. T., Singh, D. K., Sarangi, A. and Khanna, M. 2016. Managing CO_2 emission from groundwater pumping for irrigating major crops in trans indo-gangetic plains of India. *Climatic Change*, 136(2): 265-279.

Prajapati, G. V. 2017. Influence of irrigation regimes, frequency and mulching on productivity of Bt. cotton.

Pre Sustainability. 2023. *Life-cycle assessment best practices handbook*. Pré Consultants Publication.

Precision Ag. 2024. *2024 precision agriculture adoption trends*. Precision Agriculture Alliance.

Press Information Bureau. 2022. PM KUSUM scheme progress report [Press release]. Government of India.

Qin, J., Duan, W., Zou, S., Chen, Y., Huang, W. and Rosa, L. 2024. Global energy use and carbon emissions from irrigated agriculture. *Nature Communications*, 15(1): 3084.

Ramya, S. K. and Kumar, S. S. 2025. Significance of micro-irrigation for feasible and sustainable agriculture: A review. *Multidisciplinary Reviews*, 8(4), 2025094-2025094.

Rillig, M. C., Hoffmann, M., Lehmann, A., Liang, Y., Lück, M. and Augustin, J. 2021. Microplasticfibers affect dynamics and intensity of CO_2 and N_2O fluxes from soil differently. *Microplastics and Nanoplastics*, 1(1): 3.

Romana, T., Singh, B. and Kaur, J. 2022. Comparative evaluation of efficiency of surface irrigation and micro irrigation in Cereals: A review. *PharmaInnov. J*, 11: 1427-1430.

Saatvik Group. 2025. *Solar power irrigation: Sustainable farming future*. https://saatvikgroup.com/

Sapkota, A., Haghverdi, A., Avila, C. C. E. and Ying, S. C. 2020. *Irrigation and Greenhouse Gas Emissions: A Review of Field-Based Studies. Soil Systems,* 4 (2): *20*.

Sapkota, T. B., Majumdar, K., Jat, M. L., Kumar, A., Bishnoi, D. K., McDonald, A. J. and Pampolino, M. 2014. Precision nutrient management in conservation agriculture based wheat production of Northwest India: Profitability, nutrient use efficiency and environmental footprint. *Field Crops Research*, 155: 233-244.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L. and McMahon, P. B. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the national Academy of Sciences*, 109(24): 9320-9325.

Setyanto, P., Pramono, A., Adriany, T. A., Susilawati, H. L., Tokida, T., Padre, A. T. and Minamikawa, K. 2018. Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Science and Plant Nutrition*, 64(1): 23-30.

Sherpa, S., Nayak, H. S., Rossiter, D., Craufurd, P. Q., Kritee, K., Kumar, V. and McDonald, A. J. 2025. A data-driven approach for devising and assessing precision nitrogen management strategies applied to wheat systems in India. *Environmental Research: Food Systems*, 2(4): 045007.

Shu, X., Wang, Y., Wang, Y., Ma, Y., Men, M., Zheng, Y. and Noulas, C. 2021. Response of soil N_2O emission and nitrogen utilization to organic matter in the wheat and maize rotation system. *Scientific Reports*, 11(1): 4396.

Liu, H., Ren, J., Gao, Y. and Zhang, M. 2023. Drip irrigation emission factor applications in China.*Environmental Research Letters,* 18(4): 044012.

Sidhu, H. S., Jat, M. L., Singh, Y., Sidhu, R. K., Gupta, N., Singh, P. and Gerard, B. 2019. Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: A breakthrough for addressing water and nitrogen use efficiency. *Agricultural Water Management*, 216: 273-283.

Singh, G. and Gandhi, V. 2024. Enhancing the adoption of water-saving technologies in India's Agriculture: The determinants across four states of India.

Singh, K., Singh, P., Singh, M. and Brar, A. S. 2023. Sub-surface drip fertigation enhances seed cotton yield and economic returns in semi-arid environments. *Agricultural Research Journal*, *60*(1).

Singh, M., Singh, P., Singh, S., Saini, R. K. and Angadi, S. V. 2021. A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation. *Scientific Reports*, 11(1): 22095.

Singh, N. K., Patel, D. B. and Khalekar, G. D. 2018. Methanogenesis and methane emission in rice/paddy fields. In *Sustainable Agriculture Reviews 33: Climate Impact on Agriculture* (pp. 135-170). Cham: Springer International Publishing.

Singh, O. P. and Singh, P. K. 2021. Effects of drip and alternate furrow method of irrigation on cotton yield and physical water productivity: A case study from farmers' field of Bhavnagar district of Gujarat, India. *Journal of Applied and Natural Science*, 13(2): 677.

Singh, V. K., Shukla, A. K., Dwivedi, B. S., Singh, M. P., Majumdar, K., Kumar, V. and Singh, S. K. 2015. Site-specific nutrient management under rice-based cropping systems in Indo-Gangetic Plains: yield, profit and apparent nutrient balance. *Agricultural Research*, 4(4): 365-377.

Slany, V., Krcalova, E., Balej, J., Zach, M., Kucova, T., Prauzek, M. and Martinek, R. 2025. Smart Water-IoT: Harnessing IoT and AI for Efficient Water Management. *ACM Computing Surveys*.

Solarizing Irrigation in India. 2025. PM-KUSUM implementation and outcomes. IISD Project Report.

Song, H. 2025. Integrating Major Agricultural Practices into the TRIPLEX-GHG Model v2. 0 for Simulating Global Upland Cropland Nitrous Oxide Emissions: Development, Sensitivity Analysis, Site Evaluation, and Global simulation. *Model development and simulations of nitrous oxide emissions from global agricultural ecosystems*, 19.

Srivastava, A. and Chinnasamy, P. 2021. Developing village-level water management plans against extreme climatic events in Maharashtra (India)—a case study approach. In *Water safety, security and sustainability: Threat detection and mitigation* (pp. 615-635). Cham: Springer International Publishing.

Srivastava, S. K., Kishore, P., Birthal, P. S. and Shirsath, P. B. 2024. Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture.

Suresh, A., Aditya, K. S., Jha, G. and Pal, S. 2019. Micro-irrigation development in India: an analysis of distributional pattern and potential correlates. *International Journal of Water Resources Development*.

Tan, M., Cui, N., Jiang, S., Xing, L., Wen, S., Liu, Q., and Wang, Z. 2025. Effect of practicing water-saving irrigation on greenhouse gas emissions and crop productivity: a global meta-analysis. *Agricultural Water Management*, 308: 109300.

Tincani, M., Kerouch, K., Garlando, U., Barezzi, M., Sanginario, A., Indiveri, G. and De Luca, C. 2025. A neuromorphic continuous soil monitoring system for precision irrigation. *arXiv preprint arXiv:2509.14066*.

Toman, M. A., Baker, J., Beach, R., Feng, H., McLellan, E. and Joiner, E. 2022. *Policies to Increase Mitigation of Agricultural Greenhouse Gas Emissions* (No. 22-10). Resources for the Future.

United States Department of Agriculture. 2023. *Inflation Reduction Act Investments.* USDANRCS

United States Department of Agriculture. 2024. *Investments through the Partnerships for Climate Smart Commodities initiative.* USDA Fact Sheet.

USDA. 2022. Biden-Harris Administration Announces Historic Investment in Partnerships for 70 Climate-Smart Commodities and Rural Projects [Press Release]. https://www.usda.gov/media/press-releases/2022/09/14/biden-harris-administration-announces-historic-investment-partnerships

Vigo, F., Zoli, M., Lovarelli, D. and Bacenetti, J. 2025. Environmental impact assessment of maize cultivation system considering different irrigation methods. *Journal of Agricultural Engineering*, 1-23.

Wakchaure, G. C., Minhas, P. S., Biswas, A. K., Meena, K. K., Pradhan, A., Gawhale, B. J. and Pathak, H. 2025. Assessment of gains in productivity and water-energy-carbon nexus with tillage, trash retention and fertigation practices in drip irrigated sugarcane. *Renewable and Sustainable Energy Reviews*, 211: 115294.

Wang, H., Wang, N., Quan, H., Zhang, F., Fan, J., Feng, H. and Xiang, Y. 2022. Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation: A global meta-analysis. *Agricultural Water Management*, 269: 107645.

Wang, X., Xiang, Y., Guo, J., Tang, Z., Zhao, S., Wang, H. and Zhang, F. 2023. Coupling effect analysis of drip irrigation and mixed slow-release nitrogen fertilizer on yield and physiological characteristics of winter wheat in Guanzhong area. *Field Crops Research*, 302: 109103.

World Bank. 2024. *Water in agriculture: Critical challenges and opportunities*. World Bank Water Global Practice Report.

Xing, Y. and Wang, X. 2024. Precision agriculture and water conservation strategies for sustainable crop production in arid regions. *Plants*, 13(22): 3184.

Ymer Digital. 2024. *Global drip irrigation market analysis 2024*. Ymer Digital Research.

Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C. and Ao, X. 2024. Impacts of global climate change on agricultural production: a comprehensive review. *Agronomy*, 14(7): 1360.

Zhang, L., Wang, C. and Xie, B. 2025. Microplastics and Soil Greenhouse Gas Emissions: A Critical Reflection on Meta-Analyses. *Environmental Science & Technology*, 59(35): 18927-18935.

Zhao, J., Yang, J., Xie, H., Qin, X. and Huang, R. 2024. Sustainable management strategies for balancing crop yield, water use efficiency and greenhouse gas emissions. *Agricultural Systems*, 217: 103944.

Zhu, J., Wang, Q., Qi, W., Zhao, X., Xu, Y., Sun, Y. and Mak-Mensah, E. 2023. Exploring the potential of biochar and mulched drip irrigation with plastic film on crop yields in water-stressed regions: a global meta-analysis. *Journal of Soil Science and Plant Nutrition*, 23(3): 2970-2980.