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Review Paper

Smart management of water aiding in efficient resource use in pulses

CS Praharaj*, Narendra Kumar and CP Nath

ICAR-Indian Institute of Pulses Research, Kanpur 208024 (Uttar Pradesh)

**Current address: ICAR-Indian Institute of Groundnut Research, Junagadh (Gujarat) 362 015*

****Corresponding author e-mail:***
cspraharaj@hotmail.com

ABSTRACT

Smart water or input management strategies for any field crops or pulses are highly location-specific with socioeconomic relevance and offer an alternative for a quantum jump in crop production with sustainable resource management and resource-use efficiency (RUE). Pulses are well-known for their rich source of protein content along with higher values of minerals/vitamins, low glycemic index, high dietary fibre, tolerance to abiotic/biotic stresses, and contribute to valuable ecosystem services, such as symbiotic or biological nitrogen fixation (SNF or BNF), improvement of soil quality, low water footprint & negative carbon footprint with higher soil conservation values. It is assessed and predicted that India's agricultural systems will require irrigation networks that are fully data-driven and operate at scale by 2050. Keeping this in view, irrigation scheduling or water management should be smart, especially in pulses, as it has to play a significant role, for the sustainable intensification/ diversification of existing cereal-based or monocropping systems. Pulses are also credited with N supplementation to soil/crop (N-fixation), improvement of soil quality, lower water footprint, negative carbon footprint with higher soil-water conservation values, and thus, are truly candidate crops in promotion of climate-smart Agriculture (CSA). Smart technologies such as GPS, satellite imagery, AI-driven irrigation scheduling, IoT-based soil moisture sensors, and data analytics will be critical for optimizing scarce agricultural resources. Aligned with the mission of Aatmanirbharta in Pulses and the target of achieving 30 million tonnes of pulse production by 2030, the timely adoption of these technologies is essential to address water and input constraints. Farm-level, real-time decision-making based on soil–plant–climate data can significantly enhance water and input-use efficiency. Looking ahead to 2050, agriculture must emphasize integrated, smart, and data-driven approaches for sustainable water management and efficient resource use.

Key words: ICMPs, Pulses, Pulses Productivity, Resource use, SDGs, Smart Water Use

INTRODUCTION

Conservation of precious natural resources such as land, water, air, and biodiversity are prerequisite for the survival of mankind, and in fact, these need to be conserved and utilized optimally and efficiently for long-term sustainability. Over the years, the conventional agricultural practices have exploited natural resources mostly for short-term gain without a vision for sustainable agriculture development. This has exposed our natural resources to various kinds of degradation and loss of soil organic carbon (SOC). As a result, the loss of SOC increases soil erosion, reduces biological activity, soil biota, and biodiversity, and depletes nutrient stock in the soil-water-plant system, ultimately leading to poor vegetative growth and economic yield (Jat et al. 2025) in many arable crops.

Water, known as life, has been the most important critical input for agricultural production since time immemorial. It is becoming more precious by each passing year as the commodity has demands for diverse uses by multiple sectors, limiting its availability in scale and quality under varied agroecologies (involving both rainfed and irrigated conditions). The supply of good quality water is binding further constraints in availability, competing factors for its use, priority allocations, and the season of the year. Therefore, it envisages on demand-driven and need-based sustained use of water resources more judiciously and sensibly. In the context of agriculture, it warrants the amalgamation of smart or precision water use as per crop demands, fortified with improved technologies and higher use-efficiency, especially in the presence of diverse/

multiple constraints. Therefore, one of the doable approaches for effective on-farm management of water really lies in its smart use, signifying higher output production and accelerated resource-use efficiency (RUE). It is obvious from the fact that when a few life-saving/supplementary irrigations are applied at critical crop stages of water stress during the peak demand or monsoon break, their effect is apparent with soil moisture improvement and realization of yield formation.

PULSES AS A CONTENDER CROP

Pulses are also considered as protein capsules (18-30% protein in 100 g seed) with 2-3 times more protein compared to cereals and several times more than tuber crops like potato. They are rich in lysine (1.18-2.9%), which is generally deficient in cereals, but deficient in sulphur-containing amino acids (methionine and cysteine), which are adequate in cereals. Thus, a blend of both cereals and pulses diet supplies balanced amino acids with a high biological value. Pulses are the cheapest source of dietary protein and quite rich in minerals such as calcium, phosphorus, potassium, magnesium, iron, copper, zinc, and selenium (Salukhe and Kadam 1989). Potassium constitutes 25-30% to the total mineral content in pulses, and thus it can be beneficially utilized in the diets of people who are on diuretics to control hypertension. Pulses are also rich in micronutrients, like Fe (50-120 mg/kg), Zn (20-54 mg/kg), and Se (370- 670 mg/kg), and vitamins, especially in thiamin, riboflavin, niacin, pyridoxine, and folic acid (Ali 2025).

Pulses have good-quality carbohydrates in enormous quantities (60-70%), which supply energy. Pulse carbohydrate is complex in nature, including mono-and oligosaccharides, starch, and other polysaccharides. Starch is the most abundant carbohydrate and varies from 31.5 to 53.6% (Srivastava and Ali, 2004). It is said that oligosaccharides improve longevity and reduce colon cancer risk. Moreover, over 70% of the raffinose family of sugars can be removed by simply germinating seeds. Besides these, pulses have a good amount of crude fibres (both soluble and insoluble fibres). Pulse seeds are also free from gluten, sodium, and cholesterol. The low glycemic index coupled with low lipid content (1.0-4.%) of pulses makes them an ideal food against diabetics. These attributes of pulses have made them a really wonderful diet for human beings.

In India, a good number of pulses are cultivated across different seasons under diverse agroclimatic conditions. These are produced to the extent of 25.38 million tons from around 27.5 million hectares during 2024-25. These crops include chickpea (Cicer arietinum L.), pigeonpea [(Cajanus cajan (L) Millspaugh)], mungbean [(Vigna radiate (L) Wilczek)], urdbean [(Vigna mungo (L) Hepper)], lentil (Lens culinaris Medikus), peas (Pisum sativum L.), mothbean [(Vigna aconitifolium (L) Jacq) Marechal], horsegram (Mrotyloma uniflorum (Lam) Verdc.], cowpea (Vigna unguiculata L.), lathyrus (Lathyrus sativus L.) and French bean (Phaseolus vulgaris L.). Their response to life-saving irrigation or supplementary irrigation is immense (Praharaj et al. 2016; Praharaj et al. 2023a,b). In addition, their unique capability to fix atmospheric nitrogen, providing protein through nutritious food/feed, conserving natural resources, and thus, maintaining ecological harmony have made these unique candidate crops for sustainable agricultural production (Praharaj et al. 2023a,b). Further, their ability to thrive well even in more-fragile environments constrained by harsh climate, marginal soils, and poor crop management, and superior performance have enabled these to become a truly viable candidate crop for rainfed/dryland agriculture.

WHY PULSES?

The value of pulses is far more important in Indian agriculture because of the very nature of food habits of people (vegetarianism), chronic protein-energy malnutrition (low availability and poor access to protein-rich food), and low-input agriculture (> 55% rainfed areas, resource-poor farmers). Consequently, pulses remained an integral part of subsistence agriculture since time immemorial. It continues to be cultivated even in many regions by the small and marginal (and some large) farmers to meet the basic needs (of rice-dal). However, with advancement in the agriculture sector, the share of pulses in total food crops area has progressively diminished right from 19.6% in 1950-51 to 7.16% in 2023-24, and the per capita availability has decreased from 64 g to 48 g/capita/day during the same period (Ali 2025). The global per capita arable land availability is also projected to shrink to 0.08 ha by 2050, as estimated by FAO (2021). This has a bearing on sustainable crop production and nutritional security on one hand and widens the shortfall in demand and supply (7.6 million tonnes) on the other (Ali 2025). Yet, to reduce this deficit, Indian Government has promoted the cultivation of pulses through strengthening R & D activities by establishing All India Coordinated Pulse Improvement Project (AICPIP) in 1966; and a premier research institute on pulses in 1993 (ICAR-IIPR, Kanpur); and launching of several development schemes catering to the need of pulses such as NPDP-1970, TMOP-1990, ISOPOM-2004, NFSM-2007, APPP-2010, Seed-hubs-2016. As a result of this, pulse production, area, and productivity during 2023-24 increased by 41%, 17%, and 21%, respectively, compared to those during 2013-14. However, the imports (INR 310 billion in 2024) have increased by about 20% of domestic production due to increased domestic demand and the use of pulses in food supplements and others. However, pulses continue to remain in forefront of production for self-reliance and policy imperatives due to their vital role in food and nutritional security, ensuring the UN's Sustainable Development Goals (SDGs).

Besides its above importance, most often, these pulses are either cultivated as a component crop in a crop rotation or an intercropping system, or even grown alone with a specific purpose meant for food, fodder, vegetables, green/green leaf manuring, or input for agriculture-based industries. Since their requirements for nutrients and other inputs are also low, and that in respect of water is about one-fifth of the requirement of cereals, pulses thus play an important role in soil amelioration, realizing nutritional security, and sustainable crop production. Both biotic and abiotic stresses influence crop production and yield realization in pulses. However, mainly abiotic factors such as agroecological situation, including climatic aberrations resulting in soil moisture/nutrient-related stresses, influence crop performance the most (Praharaj et al. 2017). Both scarcity and excess in water availability may reduce crop growth, resulting in less yield realization. Because of its pertinent role in food and nutritional security, pulses figure prominently in the UN's SDGs, focusing on balance in human nutrition, soil restoration, and climate mitigation. This resulted in the declaration of the year 2016 as "International Year of Pulses", and the role of pulses is immense for mankind.

WATER AS A CRITICAL INPUT

India is regarded as one of the most inefficient users of water in the world, so far as agriculture is concerned. The country has only 4% of the world's freshwater resources yet sustains nearly 18% of the global population, as per FAO estimates. It is estimated that the overall efficiency of surface irrigation is around 35%, with 65% of water aggravating the man-made problems of waterlogging and secondary salinization (Chaudhary et al. 2025). To add further, overexploitation of groundwater has continued unabated and is becoming a serious problem now. It is projected that three-fifths of groundwater blocks will become critical if the current rate of water drought or stress continues to influence production systems. With per capita availability of water below the benchmark figure of 1700 m^3/year, India was labelled as a water-stressed nation way back in 2006 (Jat 2025). Further Forecasts indicated that 40% of the country's population will not have even access to safe drinking water by 2030. Therefore, its strategic and smart management is the key to holistic water conservation, its appropriate distribution, and further efficient utilization by different stakeholders.

Scarcity of water itself is one of the most important and critical constraints to India's agricultural growth. Rapid groundwater extraction and its depletion over time for several decades, coupled with inefficient irrigation practices and increasingly erratic and variable monsoon patterns, steadily eroded the reliability of the water supply for farming (Jat et al. 2025). Groundwater depletion is also a major concern, especially in the Indo-Gangetic Plains (IGP) due to the continuous rice-wheat cropping system, and even the problem is more acute in Trans- and Upper-IGP regions where intense cultivation of cereal monocropping systems (rice, wheat, maize, sugarcane etc.) takes place. Pulses in general do require a lesser amount of water and hence can be used as an alternative to cereal crops in this region. Pulses, on account of their low water requirements (200-250 mm) and high water-use efficiency (WUE), are considered a hope for future agriculture and its sustainability. In fact, WUE of pulses is much higher compared to cereals and the crops yielding similar content of protein. For instance, pulses need 2500 gallons of water for each tonne produced compared to 4500 gallons for chicken, 5500 gallons for mutton, and 13500 gallons for beef (Solh 2016). Global water consumption by cereals is reported to be about 60%, as against 4% in pulses. By consuming one ha-mm of water, chickpea could produce about 12.5 kg of grain as against 7 kg of wheat and 2.5 kg of rice (Ali 2025). It is also reported (Ding et al. 2018) that lower protein yield-based water footprint (an average of 6.58 m^3/kg) was observed for pulse crops compared to higher values (9.25 m^3/kg) for cereal crops although reverse is true in terms of grain yield based water footprint (an average of 1.59 m^3/kg for pulse crops and 1.18 m^3/kg for cereal crops). However, the scenario may change in different agroecological regions and cropping systems (Ali 2025). Further, among different sources of protein food, CO_2 produced per kg of lentil is only 0.9 kg as against 1.9 kg for milk, 2.7 kg for rice, 2.9 kg for potatoes, 6.9 kg for chicken, and 39.2 kg for lamb (Solh 2016). The pulses typically fix 20-90 kg N/ha through symbiotic/biological N fixation (BNF) and thus curtail production of industrial N-fertilizers (Ali 2025). Moreover, the N-use efficiency of industrial nitrogen is low due to gaseous losses contributing to global warming, and leaching and erosion losses, which further cause pollution of water courses and storage (not in the case with N-fixation by pulses).

In the context of Indian agriculture, the value of pulses is far more important due to socio-economic attributes of inherent food habits, protein-energy malnutrition, and low-input agriculture (resource-poor farmers with marginal and small land-holdings). Thus, pulses do justify their worthiness in meeting out ecosystem-compatibility compared to many other crop(s). In the case of water scarcity, some of the innovative techniques could reinforce the ability of pulses to compete and perform advantageously, winning over the constraints at least to some extent. In case of water, it is rewarding by way of technology upscaling and/or providing a sound footing at least for better water delivery and its use efficiency. These include integration of smart systems or techniques involving use of artificial intelligence and machine learning [artificial intelligence (AI) & machine learning (ML)], precision land levelling, no-till or reduced tillage systems, furrow-irrigated raised bed or BBF planting systems, crop diversification and its appropriate residues management systems (Praharaj and Singh 2019; Praharaj et al. 2023a,b). For example, a trial on zero till seed drill highlights the importance of the use of machinery for higher farm income and input-use efficiency (Kumar et al. 2023). In addition, certain methods like application of hydrogel, seaweeds, asphalt or bitumen emulsion, salt (Sodium chloride), organic or inorganic mulches, and hydrophobic materials are effective (Gupta et al. 2020). Similarly, the importance of the no-till system in India is evident in terms of the emission of greenhouse gases (GHGs) and carbon sequestration. It is computed that for each litre of diesel fuel consumed, 2.6 kg of CO_2 is released to the atmosphere. Assuming that 150 litres of fuel per annum per tractor per hectare is used for irrigation purposes in a conventional system, it would amount to nearly 400 kg CO_2 being emitted per annum per hectare (Praharaj et al. 2018). Further, open soil surface or less soil cover, and mechanical soil disturbances (excess tillage) cause soil compaction, reduce infiltration, and increase run-off leading to soil loss, floods, sedimentation of water reservoirs and river basins, and disturbances to wild and marine life (Jat et al. 2025). Therefore, no tillage and no-till sowing (a cost-cutting option) has been proven a significant step in strategic water conservation and its judicious management in agriculture (Nath et al. 2024). It has also been amply demonstrated from many field trials and crops through saving on irrigation water, fuel, labour, production cost, energy, etc., along with its positive effects on soil health and environmental quality benefits (Praharaj et al. 2017; Praharaj et al. 2018). Therefore, conservation agriculture (CA), with its ancestry in universal principles of providing minimum soil disturbance/traffic, permanent soil cover, and appropriate/efficient crop rotations/farming systems, is now regarded as the express way to sustainable agriculture and for realizing SDGs (Praharaj et al. 2017). Therefore, amalgamating CA and precision water management could benefit the soil-water-plant continuum.

Similarly, enabling water surplus as an opportunity could help in water saving and its efficient use. The country, on average, receives about 750 mm of rainfall, of which hardly 30 to 35% is conserved/stored and used for agriculture. There seems to be vast potential for in-situ and ex-situ rainfall conservation. Estimates indicate that by 2047, the availability of water for agriculture is likely to decrease from the present level of 83% to about 65 to 70% (Singh et al. 2025). This happens during the monsoon, where the more relevant constraint is the availability of excess soil moisture or water logging condition, rendering an unfavourable microenvironment for crop growth and development. This could result in reduced soil aeration, hampered root-nodulation, reduced nutrient(s) uptake, and unfavourable microclimate for suppression of fungal pathogenic diseases (blight & rot). This could further result in reduced plant population, crop vigour, and poor yield. In addition, the absence of appropriate rainwater management (resulting in ponding of water during the season, and scarcity of water thereafter) leads to floods, causing huge loss to the property/people. Thus, there is an urgent need to evolve an enduring solution to these problems by conserving and managing available water resources to make a visible impact. It needs a national-level drive giving special emphasis on conservation, recharge, and management of water resources. Besides these, producing per drop more crop (reached 9.683 million hectares now in India during 2025) through micro irrigation particularly surface/subsurface drip-fertigation needs to be amply promoted resulting in saving of 50-60% on water, 20-40% on fertiliser N, 50% on labour expenses, enhancing crop yields by 25-75%, and improving the quality of produce especially under protected environment as compared to conventional systems (Chaudhary 2025). These efficient micro-irrigation (drip and sprinkler), providing a roadmap for widespread adoption of water-efficient technologies, which can serve as a foundation for the advanced irrigation systems necessary in 2050 (Jat et al. 2025).

Therefore, suitable management strategies or technologies to offset the adverse effects of excess soil moisture need to be mitigated by appropriate and sustainable technological interventions, such as suitable land configurations (ridge and raised bed planting or BBFs), proper plant population, and other need-based precision soil/crop management techniques (Praharaj and Singh, 2019; Kumar et al. 2023). On the other hand, water deficit during later stages of crop growth (terminal water stresses) adversely affects the development of reproductive organs that may lead to depressed yields. Thus, management of surplus water during rainy months on one hand, and water supplementation to compensate soil-moisture deficit during post-rainy months on the other hand, are imperative for productivity enhancement and sustainability in pulse crops.

Since the environmental impact of agriculture demands a comprehensive assessment beyond water usage alone, the concept of the environmental footprint offers a framework for quantifying the human impact on the environment (Brahmanand et al. 2025). These key indicators include the water footprint, which measures the volume of freshwater consumed and polluted throughout the production process. Further, the nutrient footprint assesses the impact of nutrient flows on ecosystems, especially in relation to nitrogen and phosphorus, focusing on their potential for eutrophication and other environmental effects. Legume intercropping in cereals grown with wider rows reduces nitrate leaching. Parallel multiple cropping (a system of growing two dissimilar growth habit crops with minimum competition) of sugarcane and urdbean, and that of pigeonpea and maize, resulted in low nitrate nitrogen content in the soil profile as compared to sole cropping (Yadav 1982). And further, the carbon footprint measures the total amount of GHGs generated by food production activities, including inputs such as irrigation, fertilizer, agrochemicals production, energy consumption, and field and related agricultural operations (Sah and Devakumar 2018; Brahmanand et al. 2025).

SMART MANAGEMENT OF WATER

Smart management of water includes a smart way of precision water use in agriculture, utilizing technology to tailor inputs like water, fertilizers, and pesticides precisely to meet the unique needs of each field, minimizing waste and optimizing resource utilization, while automated machinery and robotic systems are used for accurate tasks, like planting, harvesting, monitoring, and maintenance. Site-specific nutrient management (SSNM) and precision agriculture techniques are pivotal in optimizing input/water use in agricultural food systems. And, the key elements include GPS technology, satellite imagery, and sensors for detailed data collection on conditions of soil, weather patterns, and crop health, which is then analyzed through machine learning and data analytics algorithms to produce practical insights. Therefore, precision water use is regarded as the key innovation for sustained production (Praharaj and Singh 2019, Praharaj et al. 2023, Brahmanand 2025).

Thus, technological innovation in water use is the need of the hour, enabling judicious resource use. Undoubtedly, future growth in pulses production will result from improvement in crop productivity, as there is very little scope of bringing more area under its cultivation. Thus, precision water use in field crops, which has gained momentum in India during the last 15 years, will have to progressively expand to other crops, including pulses, to replace currently practiced unsustainable intensive agriculture. Adoption of digital/mobile devices, access to high-speed internet, low-cost and reliable satellite communications, and advanced farm equipment, including drones, will boost precision water-use further. E-extension services could add further impetus to decision-support services (DSS) on mobile apps or such other digital platforms. Using information from multiple & diverse data-sources, viz., weather data, GIS special mapping information, soil sensor data, satellite/drone pictures, e-extension platforms can provide real-time (special and temporal) recommendations to the farmers. Recently, some of the newly developed agriculture apps that provide valuable insights and guidance on Best Management Practices (BMPs) or Good Agricultural Practices (GAPs), including precision water use, besides other handy crop husbandry practices (Singh et al. 2019).

Addressing the challenge of mismanagement in irrigation water requires technological innovations to integrate highly efficient irrigation technologies such as drip systems, subsurface, micro-sprinklers, variable-rate irrigation, sensor-based scheduling, and precision irrigation, supported by real-time monitoring tools. For better ecosystem services, equally important is the mainstreaming and wide deployment of carbon sequestering practices under the gamut of conservation agriculture/organic or natural farming (Mishra et al. 2012a,b; Praharaj et al. 2025), including reduced or zero tillage, residue cover/retention, efficient cropping systems, agroforestry, and biochar applications, besides other need-based technology interventions. It not only builds SOC and enhances water retention but also supports India's international commitments to net-zero and carbon-neutral food systems in the time to come (Jat et al. 2025; Kumar et al. 2023).

India is predicted to face a 40% water deficit by 2030 as per the Government of India (Niti Aayog,2018). Therefore, certain smart technological innovations such as AI-driven irrigation scheduling, internet of things - enabled soil moisture sensors, and water recycling systems will be critical to optimize limited resources. Pilot projects in states with varied agroecologies in the Indian states of Maharashtra and Karnataka clearly demonstrated that innovative irrigation technologies would reduce water consumption by 30–40% while increasing yields by 15–20% as envisaged in the World Bank report 2022 (Jat et al. 2025). Therefore, proven adoptable strategies such as rainwater harvesting, aquifer recharge, and decentralized water storage structures need to be scaled up on a massive scale to buffer against climate variability. Similarly, adoption of integrated watershed management (IWM) approaches and robust policy frameworks, including those promoting crops appropriate to available water resources in different agroecologies, are need of the hour to regulate unsustainable groundwater extraction and ensure equitable water use.

It is also pertinent to visualize the role of climate-smart agriculture (CSA) involving the long-term twin strategies for precision water or input use and mitigation of Climate Change impact on Agriculture. A compiled information indicated that the rise in annual mean temperature during 2022 was around 1.15 ˚C over pre-industrial revolution levels (Jat et al. 2025). It is further predicted that with the current situation continuing as business as usual, climate change will be imperative, resulting in 25% decline in the agricultural productivity in India by 2050 compared to that in 2013-14 (as the baseline). With more than half (51%) of India's agricultural land being rainfed, climate change poses a critical threat to agricultural and food systems. Therefore, shifting to CSA with climate-smart crop varieties, compatible crop(s) and cropping system diversification, and adoption of climate resilient soil-water-crop management practices are crucial (as climate proofing options) to sustaining crop productivity under climate stresses. In addition, the development of multi-enterprise models for diverse use of water in agriculture, including integration of several enterprises (such as crops, fisheries, dairy, horticulture, mushroom, bee keeping, rain water harvesting for groundwater recharge, and efficient use of irrigation water), is a prerequisite and necessary.

In this context, the role of appropriate policy initiatives such as the Integrated Watershed Management program (IWMP), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), or more recently the Viksit Bharat –Guarantee for Rozgar and Ajeevika Mission (Gramin) 2025 (VB-G RAM G) in rainfed areas can not be overlooked, as it imparts stability to the existing agricultural food systems. PMKSY operates through four key components: Accelerated Irrigation Benefit Programme (AIBP), Har Khet Ko Pani, Per Drop More Crop, and Watershed Development. These components collectively aim to modernize irrigation infrastructure, rehabilitate canals, and promote drip and sprinkler systems. In policy terms, PMKSY represents a shift from supply-driven irrigation expansion to demand-driven efficiency and sustainability. In addition, linking water-use practices with productivity goals, it has helped in guiding production towards more efficient resource use. And, the success of these schemes depends on convergence with other programs, including soil health, watershed management, and crop diversification, for ensuring a holistic approach to resource management.

Beyond Per Drop More Crop, the next frontier is Decision Intelligence, wherein the soil moisture sensors, thermal indices, drones, and digital twin models guide water delivery with precision. In the context of Indian agriculture, where groundwater depletion and uneven rainfall threaten farm livelihoods, integrating AI scheduling with automated irrigation frameworks will not only conserve water but also stabilize system productivity and household income. By embedding these smart systems into agricultural landscapes, the country could be empowered to shift from reactive irrigation to predictive, resilient water management, transforming agronomy into a vital and sustainable pillar of climate-proof, nutrition-secure food systems. Therefore, AI-driven irrigation systems are transforming agricultural water management by optimizing usage based on real-time data. These systems collect information from soil moisture sensors, weather patterns, and crop stress indicators to determine irrigation rates, ensuring water is applied efficiently and automatically. And, continuous monitoring of soil moisture, temperature, humidity, and evapotranspiration enables AI to make precise irrigation decisions (Krishnan et al. 2022). For example, the sensor-based automated system developed by Savitha and Uma Maheswari during 2018, using Arduino Technology to deliver water in the right amounts at the correct times, and boosts crop productivity by up to 40% while minimizing water waste, is noteworthy (Jat et al. 2025).

Indian agriculture should meet the food demand of 1.61 billion people by 2050. Therefore, adaptation strategies under CSA are crucial for climate resiliency for our food production systems. Strategies and actions for agricultural adaptation for crops focused at local and regional levels include GAP or BMP such as use of climate (drought, flood, and heat-tolerant) resilient crop varieties, altered planting dates to match changing rainfall and temperature patterns, and crop diversification to spread risk and enhance resilience. Sound soil and water management practices, including conservation agriculture, integrated crop & nutrient management practices, rainwater harvesting, micro-irrigation, and other efficient water-use practices, are useful and necessary (Praharaj et al. 1993, Praharaj 2005; Kumar et al. 2023). Similarly, in farming systems involving the livestock sector too, the adaptive strategies, including improved breeds resistant to heat and diseases (both survival and output production), climate-resilient fodder systems, feed and shelter management, and silvi-pastoral practices etc. are beneficial. Amalgamating the adaptation strategies, the cross-sectoral issues, such as early warning systems, disaster risk management, education/awareness, capacity development, and climate information services, are particularly relevant for agricultural stakeholders.

Therefore, it is established that the primary constraint in maintaining or increasing pulse production in the rainfed regions has been the shortage of water in the time of need. Thus, GAP involving appropriate water conservation and its precision management plays the most important role. Within the technology framework, considerable production/yield increase in pulses would be possible with short-duration varieties that fit well in different cropping/farming systems to augment vertical expansion of pulses in the country. Appropriate intervention of precision technologies in relation to water use has been a boon to profitable pulses cultivation. This must include precision irrigation management amalgamated with drone/sensors/AI technologies (including drip, subsurface, variable-rate irrigation, sensor-based scheduling), land levelling, no-till systems, FIRB planting systems, crop diversification, and its residue management, etc. (Nath et al. 2024). Kushwaha et al. (2024) demonstrated that sensor- and index-based scheduling increases the efficiency of agricultural water use. Similarly, drones, or Unmanned Aerial Vehicles (UAVs), are GPS-guided aircraft capable of autonomous flight (Celen et al. 2020). In agriculture, these are increasingly important tools in precision farming, increasing the efficiency of a range of agronomic activities, including pest detection, weed identification, nutrient deficiency monitoring, yield prediction, spraying, soil analysis and land mapping, water stress detection, and livestock management. Recent studies also demonstrated their efficiency in input application (Chen et al. 2021). The advanced spraying drones, equipped with 10–20 litre tanks, variable-flow nozzles, and automatic control systems, can cover up to 10 hectares per hour while reducing chemical use by 45% compared to conventional methods. Similarly, fertilizer spraying applications were reviewed (Souvanhnakhoomman 2021), which indicated that the use of drones enables more precise application, reducing fertilizer consumption by up to 30% while maintaining or enhancing crop yields. Together, these analyses highlight drones as key enablers of sustainable, resource-efficient, and highly productive agriculture (Jat et al. 2025). Similarly, in a study from Morocco, introducing an innovative real-time irrigation management system that integrates weather data, soil moisture levels, and precipitation forecasts to guide irrigation decisions is a good one (Jat et al. 2025). Their IoT-based algorithm dynamically analyses climate, soil, and crop conditions to regulate water application, enabling flexible and sustainable irrigation planning. The system's effectiveness shows that real-time IoT-driven irrigation substantially reduces water wastage while maintaining stable crop yields. Thus, for optimum water management in pulses, there is a need for synergy for holistic water (and other inputs) management (Kumar et al. 2023). In this endeavour, promotion of grain legumes as a water-efficient enterprise could emerge as a transition towards sustainability in intensive food production systems in India against a possible natural resource degradation and vagaries of climate (Praharaj et al. 2016).

It is predicted that by 2050, India's agriculture will operate under a higher level of climate vagaries, including tighter water budgets, more erratic monsoon seasons, and greater heat stress. This will enable AI-driven irrigation technologies to be handier and more indispensable. Micro-irrigation hardware has already expanded rapidly under the Per-Drop More-Crop scheme. And, the next frontier could be decision intelligence, where soil moisture sensors, thermal indices, drones, and digital twin models guide water delivery with precision. Therefore, AI-driven irrigation systems are transforming agricultural water management by optimizing usage based on real-time information or data. Thus, continuous monitoring of certain physical indicators such as soil moisture, temperature, humidity, and evapotranspiration is crucial for enabling AI to make precise irrigation decisions (Krishnan et al. 2022). Lastly, precision management involving diverse/variable inputs (irrigation, nutrients, and other agrochemicals) needs to be followed using advanced techniques (such as IoT-enabled sensors, variable applicator technologies, efficient irrigation systems, and Decision Support System platforms, etc.) integrated with real-time monitoring network systems for optimum performance and scaling output.

For efficient use of irrigation water, a strong need is felt for extending subsidies for promotion of furrow irrigated raised bed planting (FIRB) in rice-wheat crop rotation areas on the pattern of sprinkler and drip irrigation. In FIRB, wheat, rice, and summer moong are planted on ridges, and irrigation is applied in furrows. This helps in saving irrigation water to the tune of 30 to 35%. The groundwater level is declining at an alarming rate due to over extraction to irrigate water guzzling rice crop using the flood method of irrigation in northwest India. Thus, there is a need to develop short-duration water-efficient crop varieties, replacement of rice areas with low water-demanding crops such as cotton, soybean, maize, millets, oilseeds, and pulses. There is a strong case to prepare an underground water quality map with a focus on salinity and heavy metal contamination. To continuously monitor changes in groundwater quality on a biannual basis, the tube wells in the vulnerable area need to be marked for sampling to incorporate timely corrective measures. Similarly, the use of wastewater in agriculture and developing technology for safe and judicious use of wastewater, including industrial effluents in agriculture, is a need of the hour. Besides these, there is a need for a complete analysis of wastewater at the source point and its current use at the site, to develop a baseline for action. And, planning for the separation of domestic wastewater from industrial effluents loaded with heavy metals and toxins needs to be strategized. Close monitoring of such water annually will be needed to check nitrate leaching in soil, groundwater, and the edible portion of the crops. Similarly, close watch on micro-organisms build up (E. coli) has to be monitored. It may also be useful for the rehabilitation of unused waste land areas in the periphery of big cities, and also along roads, railway tracks, and canals. However, careful monitoring of soil, groundwater, and air pollution will be required to incorporate timely corrections. And, the most effective and practical way to deal with wastewater is to establish permanent wastewater treatment plants in all parts of the country.

CONCLUSION

By 2050, India's agricultural systems will require irrigation networks that are fully data-driven and operate at scale. Thus, smart water management in pulses could play a significant role in their sustainable intensification/diversification of already scarce resource bases in the context of SDGs and meeting out concerns of livelihood security in the future. This highlights the value of integrating soil–plant–climate data with IoT technologies to promote climate-resilient, resource-efficient, and sustainable farming systems. These integrated approaches not only enable farmers to address the pressing challenges of climate change, food security, and land-use optimization, but they also enhance the adaptability of agricultural systems to endemic and evolving environmental variability. This improves agricultural management practices, ensuring efficient resource utilization while minimizing environmental impacts and increasing agricultural sustainability. Ultimately, incorporating soil–plant–climate data into farm-level decision-making enhances both economic growth and ecological sustainability, securing the long-term health of both agricultural production and natural ecosystems.

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