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Irrigation water quality assessment for sustainable soil health and crop production in Kerala

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Abstract

Water quality is a critical determinant of sustainable agriculture, influencing soil health, nutrient dynamics, crop productivity and environmental quality. This review examines the status, assessment, and management of irrigation water quality, with particular emphasis on Kerala, where agriculture depends on diverse water sources and highly variable monsoonal rainfall. The review discusses major irrigation water sources, key physicochemical and biological quality parameters, standardized assessment methods, and internationally accepted quality guidelines, including electrical conductivity, sodium adsorption ratio, residual sodium carbonate, pH, and specific ion toxicity. It highlights the impacts of poor-quality irrigation water on soil salinity, sodicity, nutrient availability, microbial activity, crop growth, and yield. Recent advances in water quality monitoring, including IoT-based real-time sensing, are also evaluated alongside sustainable management approaches such as source protection, water treatment, phytoremediation, bioremediation, precision irrigation, and integrated nutrient management. Strengthening irrigation water quality assessment and adopting science-based management strategies are essential to enhance agricultural productivity, protect soil resources, and ensure long-term food and water security.

Keywords: Irrigation water quality, water quality assessment, water quality index (WQI), precision irrigation, sustainable crop production

Introduction

Water is essential for life on Earth, playing an irreplaceable role in sustaining both ecosystems and human societies. People use it for drinking, municipal services, and various economic activities, with agriculture being the largest consumer accounting for over 85% of global water use. The economic contribution of water to irrigated agriculture is still not well measured on a global scale. Understanding this value is crucial for agribusiness investors acquiring land and water rights, as well as for farmers and rural communities engaged in such negotiations. Informed decisions about selling or securing water rights or investing in irrigation infrastructure, require reliable methods based on globally available data to assess the value that irrigation water generates in agriculture (APHA, 2012) ^[5].

Apparently, variations in water quantity and quality are occurring mainly as consequences of increase in human population and changing environmental factors. These changes may lead to instability in water availability to different sectors like domestic consumption, agriculture, industry, and hydropower generation. Although several measures have been implemented to strengthen rainfed agriculture, their effectiveness is increasingly constrained by changing rainfall patterns and climate change. Rising mean annual temperatures, prolonged hydrometeorological droughts, and declining crop productivity are projected under future climate scenarios. Furthermore, shifts in cropping patterns and the increasing occurrence of extreme weather events are likely to aggravate water shortages and food insecurity in semi-arid regions (Todmal, 2023) ^[57]. To tackle the issue, we need a detailed understanding of the receipt of monsoon showers in different states of our country, population trend, water use and water conservation.

Agriculture relies on a consistent supply of water of acceptable quality. In the past, concerns about water quality were often minimal because high-quality sources were abundant and easily accessible. However, this situation is changing in many regions. Intensive use of the best water sources has forced both new and existing irrigation projects to depend on lower-quality, and less desirable supplies.

To avoid problems associated with using such undesirable water, careful planning is needed to ensure that it is managed for maximum benefit (Ayers and Westcot, 1985) [4].

The average annual water availability of any region or country is largely dependent upon hydro-meteorological and geological factors. However, water availability per person is dependent on the population of the country. In our country, there is a drastic reduction in per capita water availability of water due to drastic rise in population. Based on the study entitled “*Reassessment of Water Availability in India using Space Inputs, 2019*” conducted by Central Water Commission, the average annual per capita water availability for 2021 and 2031 has been assessed as 1486 m³ and 1367 m³, respectively. Annual per-capita water availability less than 1700 m³ is considered as water stressed condition while that below 1000 m³ is considered as water scarcity condition (MOJS, 2024).

Irrigation Water Sources and Challenges in Kerala

Irrigation system in Kerala is supported by a combination of natural and man-made water sources, adapted to its unique topography and climatic conditions (Tripathi and Davis, 2020) [58]. The state is characterized by diverse terrain from highlands to coastal plains which necessitates region-specific irrigation practices. Groundwater, accessed through wells and boreholes, plays a vital role due to its year-round

water availability, especially in areas where surface water is limited. Surface water sources such as rivers, canals, tanks, and ponds contribute seasonally, depending on monsoonal inflows and local water storage infrastructure (Varma, 2017) [59]. In the hilly regions, traditional methods like borrowing horizontal tunnels deep into laterite formations are still used to tap groundwater for small-scale irrigation. The integration of these varied sources reflects the adaptive nature of Kerala’s farming systems (Joji *et al.*, 2021) [33]. However, the increasing variability in rainfall patterns, along with rising demand and localized water stress, has underscored the need for sustainable irrigation practices, improved storage systems, and efficient water use technologies to maintain agricultural resilience in the face of environmental change.

Kerala receives approximately 3000 mm of rainfall annually, more than three times the national average. However, spatial and temporal variability is significant (Simon and MohanKumar, 2004; Krishnakumar *et al.*, 2009; Nair *et al.*, 2014) [50, 35, 44]. Based on Cropping Systems Research Institute data, 69% of the rainfall occurs during the Southwest monsoon, 16% during the Northeast monsoon, and the rest in summer. Due to the region's physiography, much of this water quickly drains into the sea, and the reduction in rainy days combined with erratic rainfall patterns adversely impacts agriculture and food security.

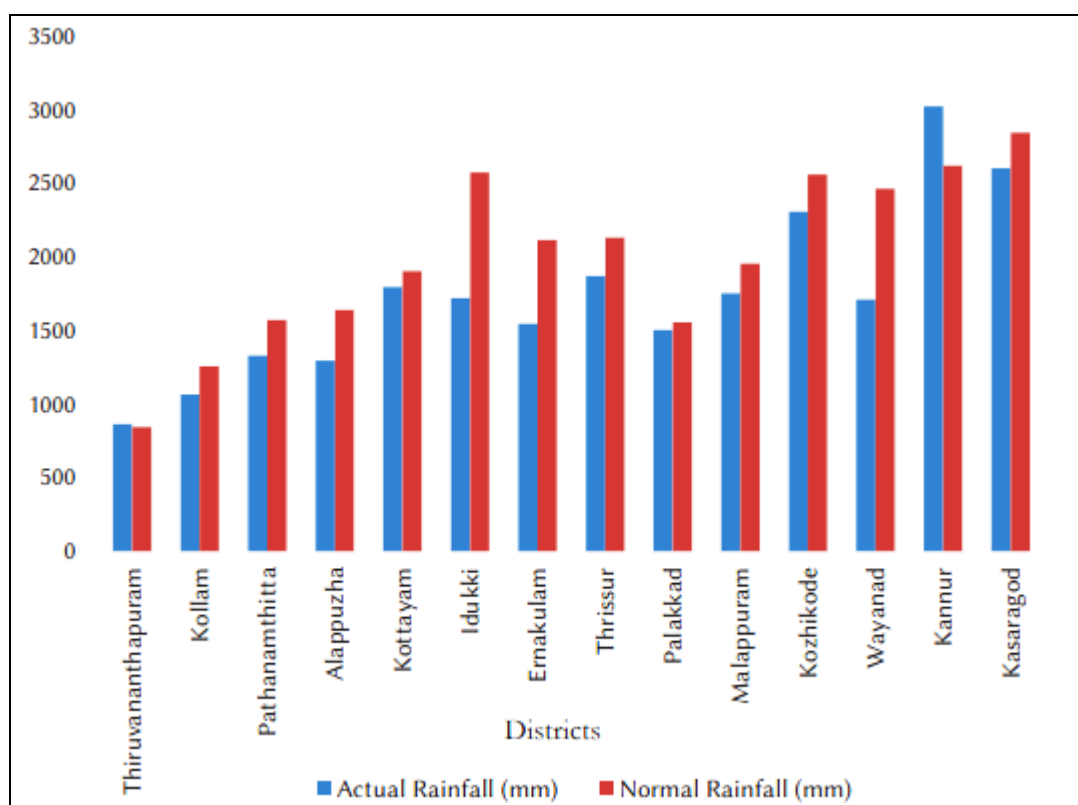


Fig 1: Monsoon rainfall received from June, 1 to September 30, 2024 (Source: India Meteorological Department, 2024)

The district-wise deviations in actual versus normal rainfall across Kerala (Fig 1.), reveals that southern districts like Thiruvananthapuram, Kollam, and Pathanamthitta received higher-than-normal rainfall, while central and northern districts such as Idukki, Ernakulam, and Thrissur experienced deficits. This uneven distribution underscores significant spatial variability in monsoon performance,

which may impact agricultural planning, water resource management, and climate adaptation strategies in the region. Groundwater is another major source, accessed via open and bore wells. Its use has increased due to urbanization and population growth. According to the new Groundwater Estimation Committee (GEC) methodology (2015), the criteria of categorization of assessment unit are as follows

According to the Government of Kerala (GOK, 2024), groundwater assessment units are categorized based on the stage of groundwater extraction. Assessment units with groundwater extraction of 70% or less are classified as safe. Units with extraction levels greater than 70% and up to 90% are categorized as semi-critical. Those with extraction levels greater than 90% and up to 100% are classified as critical, while units with groundwater extraction exceeding 100% are considered over-exploited.

In addition to rivers and wells, traditional sources like tanks, ponds, springs and surangas contribute to irrigation and drinking water supply. Surangas are horizontal tunnels dug into laterite hills, mainly found in Kasaragod (around 510). The state has over 1000 tanks and ponds with a combined storage capacity of 15000 Mm³ during summer, and around 240 natural springs support highland communities.

Furthermore, Kerala hosts around 33 dams and reservoirs, essential for hydroelectric power, irrigation, and water supply. Major dams include Idukki, Mullaperiyar, Malampuzha, and Banasura Sagar. While beneficial, dams disrupt river flow, sediment transport, and ecosystems, and contribute to deforestation and land submergence. Altered flow regimes also affect downstream water availability, particularly during dry periods.

Private wells remained the dominant source of irrigation in Kerala during 2018-19 to 2020-21, although the irrigated area declined from 124,020 ha to 114,121.37 ha over the period. Government canals constituted the second major source, with only a marginal reduction from 85,358 ha in 2019-20 to 81,801.33 ha in 2020-21. In contrast, private canals contributed a negligible share but exhibited a gradual increase from 513 ha to 694.53 ha. Tank irrigation showed a steady decline, decreasing from 49,376 ha in 2018-19 to 43,434.58 ha in 2020-21, while irrigation from other sources remained substantial at nearly 150,000 ha annually. The total net irrigated area remained around 404,000 ha during

2018-19 and 2019-20 before declining to 389,793.68 ha in 2020-21, possibly due to rainfall variability, groundwater stress, and changing agricultural practices. However, the gross irrigated area increased steadily to 521,478 ha in 2020-21, indicating greater irrigation intensity through multiple cropping. The proportion of net irrigated area to net area sown remained nearly constant at about 20%, while paddy continued to occupy approximately 30% of the total irrigated area, highlighting its sustained importance in Kerala's irrigated agriculture.

Depending on the intensity of rainfall, the following aquifer recharge, and the methods used to collect and use groundwater, the quality of irrigation waters varies across different areas, nations, and places. The range of crops for cultivation is restricted and groundwater salinity is increased when groundwater is used for agriculture in hot, desert nations with little rainfall. Determining the quality of the irrigation water is therefore crucial (CGWA, 2023). The amount and make-up of soluble salts in water define its suitability for irrigation. There are five fundamental criteria for assessing water quality for irrigation: ion toxicity, residual sodium carbonates (RSC), sodium hazard (sodium adsorption ratio or SAR), pH, water salinity (EC). Plant toxicity from boron and chlorides is described (Zaman *et al.*, 2018) [66].

Assessment of Irrigation Water Quality: Concepts, Indicators, Methods and Water Quality Indices

Water quality for agriculture is an important factor to be considered for sustainable use and ecosystem conservation. The concentration and composition of soluble salts in water will determine its quality for various purposes like human and livestock drinking, irrigation of crops, etc. (Zaman *et al.*, 2018) [66]. Guidelines given by FAO (Table 1) delineates the expected quality parameters for a quality irrigation water

Table 1: FAO Guidelines for irrigation water quality (FAO, 2025) [18]

Potential Irrigation Problem	Units	Degree of Restriction on Use	Slight to Moderate	Severe
Salinity (affects crop water availability)				
EC _w	dS/m	< 0.7	0.7-3.0	> 3.0
TDS	mg/l	< 450	450-2000	> 2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using EC _w and SAR together)				
SAR = 0-3	EC _w =	> 0.7	0.7-0.2	< 0.2
SAR = 3-6	EC _w =	> 1.2	1.2-0.3	< 0.3
SAR = 6-12	EC _w =	> 1.9	1.9-0.5	< 0.5
SAR = 12-20	EC _w =	> 2.9	2.9-1.3	< 1.3
SAR = 20-40	EC _w =	> 5.0	5.0-2.9	< 2.9
Specific Ion Toxicity (affects sensitive crops)				
Sodium (Na)-surface irrigation	SAR	< 3	3-9	> 9
Sodium (Na)-sprinkler irrigation	me/l	< 3	-	> 3
Chloride (Cl)-surface irrigation	me/l	< 4	4-10	> 10
Chloride (Cl)-sprinkler irrigation	me/l	< 3	-	> 3
Boron (B)	mg/l	< 0.7	0.7-3.0	> 3.0
Miscellaneous Effects (affects susceptible crops)				
Nitrogen (NO ₃ -N)	mg/l	< 5	5-30	> 30
Bicarbonate (HCO ₃)-overhead sprinkling only	me/l	< 1.5	1.5-8.5	> 8.5
pH	-	Normal Range 6.5-8.4	-	-

Parameters for assessing irrigation water quality

Irrigation water quality is a critical determinant of soil health, crop productivity, and long-term sustainability of agricultural systems. The suitability of water for irrigation

depends not only on its availability but also on its physicochemical and biological characteristics, which directly influence soil properties, plant growth, and nutrient dynamics.

Table 2: Water quality parameters

Parameter	Method	Reference
Physical Properties		
Color (hazen units)	Florel-Ule colour scale method	Gupta (1999) ^[25]
Turbidity	Nephelometry based on scattering of light (Turbidity Meter)	Gupta (1999) ^[25]
Suspended solids	Filtration method	Gupta (1999) ^[25]
Chemical Properties		
pH	pH meter	Jackson (1973) ^[32]
EC	Conductivity meter	Jackson (1973) ^[32]
BOD	Modified Winkler's method (Incubation followed by titration) (BOD incubator)	APHA (2012) ^[5]
COD	Refluxing and titration (COD reflux unit)	APHA (2012) ^[5]
NH ₄ -N and NO ₃ -N	Macro-Kjeldahl distillation and titrimetry	Bremner and Keeney (1965) ^[10]
Phosphates	Spectrophotometry	Watanabe and Olsen (1965) ^[62]
Potassium, Sodium	Flame photometry	Jackson (1973) ^[32]
Calcium, Magnesium	Versenate titration	Hesse (1971) ^[27]
Sulphates	Turbidimetry	Chesnin and Yien (1951) ^[14]
Carbonates and bicarbonates	Titration	Tandon (1995) ^[55]
Fe, Mn, Cu, Zn, Cd, Pb, Al	Emission spectroscopy	Wei and Yang (2010) ^[63]
Pesticide residue	GC-MS and LC-MS/MS (modified QuEChERS method)	Asensio-Ramos <i>et al.</i> (2010) ^[6]
Biological Properties		
Bacterial counts	Serial dilution and plate count method	Wacksman (1992) ^[61]
Coliforms	Standard fermentation/membrane filter technique	APHA (2012) ^[5]
Algae	Haemocytometer method	Singleton and Sainsbury (2006) ^[51]

The assessment of irrigation water quality requires the evaluation of key physical, chemical, and biological parameters using standardized analytical methods. Physical properties, including colour, turbidity, and suspended solids, provide information on the aesthetic quality and particulate load of water. Chemical parameters such as pH, electrical conductivity (EC), biological oxygen demand (BOD), chemical oxygen demand (COD), nutrients (NH₄-N, NO₃-N, phosphates), major cations (K, Na, Ca, and Mg), sulphates, carbonates, bicarbonates, trace metals, and pesticide residues are essential for assessing water suitability for irrigation, identifying potential salinity and toxicity hazards, and evaluating environmental contamination. Biological indicators, including bacterial counts, coliforms, and algal populations, reflect the microbiological quality and potential health risks associated with water use. Standard protocols recommended by APHA and other internationally recognized analytical methods ensure accuracy, reproducibility and comparability of water quality data, thereby supporting sustainable irrigation management, environmental monitoring, and informed decision-making in agricultural production systems.

Suitability of irrigation water (SI)

According to BIS (2019), irrigation water suitability can be determined using the following equation

$$SI \propto QSPCD$$

Q = quality of irrigation water, that is, total salt concentration, relative proportion of cations/anions, etc;

S = soil type, texture, structure, permeability, fertility, calcium carbonate content, type of clay minerals and initial level of salinity and alkalinity before irrigation;

P = salt tolerance characteristics of the crop and its varieties to be grown, and growth stage usually categorized as tolerant, semi-tolerant and sensitive;

C = climate, that is the total rainfall, its distribution and evaporation characteristics; and

D = drainage conditions, depth of water table, nature of soil profile, presence of hard pan or lime concentration and management practices.

Water Quality Indices

It is used to assess the suitability of water for irrigation by evaluating various water quality parameters like Electrical Conductivity, Sodium Adsorption Ratio, Sodium, Chloride, and Bicarbonate. Other parameters like pH, Total Dissolved Solids, Total Hardness, and various ions. Results can guide irrigation management practices, such as choosing appropriate crops, adjusting irrigation techniques, or implementing water treatment strategies.

A comprehensive assessment of river water quality in Kerala by Jyothi *et al.* (2021) ^[34] evaluated rivers across the northern, central, and southern regions using 11 physicochemical water quality parameters. Water quality was classified according to the Indian Water Quality Index (WQI) as Excellent (0-25), Good (26-50), Poor (51-75), Very Poor (76-100), and Unsuitable for Drinking (>100). The results indicated that rivers in central Kerala, including the Periyar and Muvattupuzha, predominantly exhibited poor water quality. In contrast, most rivers in southern Kerala were classified as having good water quality. The northern region showed variable water quality, with the Kada Lundi River categorized as good, whereas the Chaliyar River was classified as poor, reflecting regional differences in anthropogenic pressure and pollution levels.

Effects of Water Quality on Soil Health and Crop Productivity

The quality and management of irrigation water are pivotal in sustaining soil fertility, enhancing its physical, chemical, and biological properties, and in turn improving crop performance (Suvendran *et al.*, 2024). Water quality critically shapes soil structure, nutrient dynamics, and microbial activity, and thereby directly affects crop performance. Salinity, sodicity, and toxic ions from poor-quality irrigation water can impair infiltration, disrupt

nutrient balance, and degrade soil health, ultimately reducing yield potential. Sustainable agriculture demands vigilant monitoring and management of water quality to preserve both soil and crop health.

Influence on Soil Health

Irrigation sustains soil water content close to field capacity (the amount of water a soil can hold after excess water has drained away), which is the optimal state for plant roots and soil biota (Luo *et al.*, 2023) ^[37]. Adequate moisture enables capillary movement of water, ensuring nutrients are available in the rhizosphere (Holz *et al.*, 2024) ^[29]. In arid and semi-arid regions, this prevents prolonged desiccation, which can cause the breakdown of soil aggregates and collapse of pore spaces, reducing infiltration and aeration.

However, moisture helps in the formation and stabilization of soil aggregates through microbial polysaccharide secretion and organic matter decomposition (Zhang *et al.*, 2024) ^[67]. Well-structured soils have higher macro- and microporosity, which improves infiltration rates and reduces surface crusting. Quality irrigation prevents dispersive clay behavior often seen in sodium-rich water, which would otherwise destroy aggregate stability (Xie *et al.*, 2024) ^[64].

Water acts as the primary solvent for nutrient ions, allowing them to move toward roots via mass flow and diffusion (Holz *et al.*, 2024) ^[29]. Good-quality irrigation water, with balanced pH and low electrical conductivity (EC), prevents the precipitation of key nutrients such as phosphorus and micronutrients and minimizes nutrient antagonism (Boyer *et al.*, 2024) ^[9]. In contrast, saline or sodic irrigation water can lead to ionic imbalances, reducing nutrient uptake efficiency (Atta *et al.*, 2023) ^[7].

Soil microorganisms, including nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*), phosphate-solubilizing bacteria, and mycorrhizal fungi, require moist conditions for metabolic activity (Aasfar *et al.*, 2021) ^[3]. Proper irrigation sustains an active microbial biomass that drives nutrient mineralization, humus formation, and pathogen suppression. Moisture fluctuations within a safe range (not extreme wetting/drying) enhance microbial resilience (Chen *et al.*, 2024) ^[13].

Repeated application of high-quality water prevents secondary salinization and sodification processes that impair soil permeability and crop tolerance (Hailu *et al.*, 2025) ^[26]. Excess sodium can replace calcium and magnesium on soil exchange sites, leading to clay dispersion, while excess salts can create osmotic stress for plants. Controlled irrigation with low-salt water, combined with leaching fractions, maintains soil chemical balance.

Effect on Crop Yield

Adequate irrigation ensures that plants maintain cell turgor pressure, which is essential for stomatal opening. Open stomata facilitate the diffusion of CO₂ into leaves, sustaining

light-dependent and light-independent reactions in photosynthesis. Water stress disrupts chlorophyll stability, reduces Rubisco activity and diminishes carbohydrate production (Flexas and Medrano, 2002) ^[20].

Water availability mitigates both osmotic stress (due to low soil moisture) and oxidative stress (from reactive oxygen species accumulation under drought) (Rim *et al.*, 2021) ^[48]. Adequately watered plants maintain cell elongation and division rates, ensuring normal leaf expansion, flowering, and fruit set. Irrigation also helps regulate plant hormone levels such as abscisic acid (ABA), which controls stress responses (Priya *et al.*, 2024) ^[46].

Well-timed irrigation maintains adequate soil moisture, ensuring that soluble nutrients remain available within the root zone in synchrony with crop demand. Appropriate irrigation scheduling improves nutrient uptake efficiency while minimizing nitrogen losses through nitrate leaching and ammonia volatilization. Enhanced nutrient use efficiency (NUE) promotes greater biomass production and crop yield per unit of fertilizer applied, thereby reducing production costs and mitigating adverse environmental impacts (Fixen *et al.*, 2015) ^[19].

In rainfed agriculture, crops often face mid-season dry spells that shorten their growth period and reduce yield potential. Supplemental irrigation bridges these gaps, enabling crops to reach full physiological maturity. In some regions, irrigation allows for double or triple cropping, increasing annual productivity without expanding land use (Molla *et al.*, 2021) ^[43].

For many horticultural and cash crops, irrigation influences quality attributes such as fruit size, colour, sugar-acid balance, and firmness by maintaining optimal water supply during critical growth stages. In cereals, adequate water during grain filling improves kernel weight and protein content. For fibre crops like cotton, irrigation affects fibre length and strength (Gell *et al.*, 2022) ^[21].

Contaminants and Emerging Irrigation Water Quality Concerns

Poor quality of water is one of the main factors turning good soil into saline or sodic since it is a universal solvent. Irrigation with saline water adversely affects crop growth and productivity. A high subsoil water table, aridity, seepage from canals, poor drainage, back water flow and intrusion of seawater also lead to salinity and sodicity. Around 1.5 mha area is affected by poor quality water in India. The most affected state is Rajasthan. In the world, over 50 million ha are affected by salinity spread over 24 countries.

According to Malakar *et al.* (2019) ^[38], the growing concern over diverse contaminants present in major irrigation water sources such as surface water, groundwater, and wastewater (Fig. 2) includes trace elements, pathogens, nanoparticles, pharmaceuticals, steroids, mycotoxins, and agrochemicals.

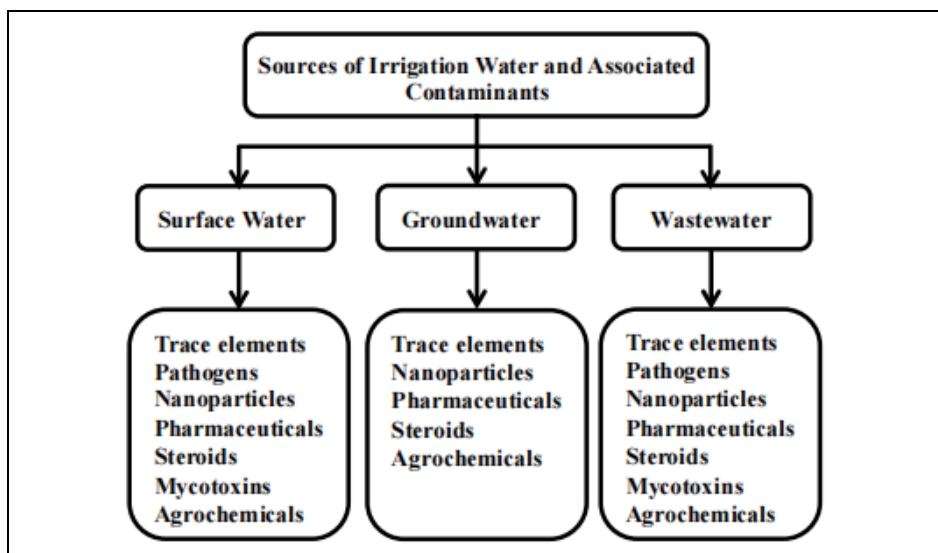


Fig 2: Main sources of irrigation water and different types of contaminants present in those sources

All of these pose significant risks to soil health, crop safety, and human health. While surface water and wastewater often share similar contamination profiles due to anthropogenic discharges and runoff, groundwater is increasingly impacted by geogenic contaminants like arsenic and uranium. Emerging pollutants such as engineered nanoparticles and pharmaceutical residues can accumulate in crops, with potential toxicological implications. This underscores the urgent need for comprehensive, source-specific monitoring and regulation of irrigation water quality to ensure sustainable agriculture and food safety in an era of water scarcity and intensified reuse. There are several soil and plant related problems that arise due to use of poor-quality water for irrigation.

If excess soluble salts of irrigation water accumulate in the crop root zone, crop has difficulty in extracting enough water (Malakar *et al.*, 2019) [38]. Root growth is also suppressed, increasing the difficulty of water uptake. Salinity stress in plants is often called physiological drought. Due to reduced uptake of water and other effects, yields are reduced. The reduction in yield due to salinity is more in warm climates than in cool climates. Salinity reduces cell division, cell enlargement and protein synthesis (El-Banna *et al.*, 2022) [16]. It affects the structure and integrity of plant membranes and causes mitochondria and chloroplasts to swell. Sodium and chloride at toxic levels disrupt the structure of the protein molecules (Alkharabsheh *et al.*, 2021) [2]. High chloride content hinders the development of xylem tissue.

Soil permeability is reduced due to the deflocculation effect of sodium (Tas *et al.*, 2022) [56]. If permeability is reduced, infiltration of water into and through the soil is reduced. Adequate root penetration is inhibited due to the presence of impermeable soil layer caused by CaCO_3 and high exchangeable sodium percentage, crusting of the seedbed, waterlogging, reduced oxygen and nutrient supply to the crops are the problems due to high sodium content relative to Ca and Mg.

Higher levels of certain ions affect the absorption of other nutrient elements (Chhabra, 2022) [15]. A high concentration of sulphate reduces the uptake of calcium and enhances the uptake of sodium. This process causes high levels of sodium in plants, thus causing sodium toxicity. High concentration

of Ca reduces the uptake of K. High concentration of Mg induces Ca deficiency. Recent studies indicate that, more uptake of B, Cl, Na, sulphate and bicarbonate by plants creates toxicity problems (Chhabra, 2022) [15].

Consequently, vegetative growth decreases as osmotic pressure of the soil solution increases. Reduction in growth takes place even without any external toxic symptoms. An increase in salinity, salt injury appears. Thick cuticle, waxy bloom and deep blue-green colour of leaves. At high salt levels, leaf burn appears in barley, sorghum and field beans. Bacteria producing NO_2 and NO_3 are more sensitive to high salt concentration than NH_4 producing bacteria (Ilgrande *et al.*, 2018; Lin *et al.*, 2023) [31, 36]. Azotobacter is resistant to salt concentration. Excessive vegetative growth, lodging and delayed crop maturity result due to excessive nitrogen in water. White and black deposits on soil due to high salt content and sodium and leaf burn due to using poor quality irrigation water in sprinkler irrigation are some of the problems.

Tilth of the soil will be poor due to the high exchangeable sodium percentage. Exchangeable Na tends to make moist soil impermeable to air and water and on drying, soil becomes hard and difficult to work. The dense crusts formed interfere with germination and emergence of seedlings. Soluble carbonates are in water applied to soil in the absence of Ca and Mg in soil, soil becomes alkaline & unfavourable. Na_2CO_3 in irrigation water is toxic to plants.

Sustainable Management Strategies

It is very important to follow proper strategies or approaches to manage the quality of water used in agriculture. Sustainable soil health and crop production relies on good quality water

Source Management

Selecting an irrigation source with low electrical conductivity (EC) (< 0.7 dS/m for most crops), low sodium adsorption ratio, and minimal toxic ions is critical. Shallow groundwater in arid regions often has high salinity due to evaporation, whereas deeper aquifers may offer better quality. Periodic testing ensures the water remains within permissible limits (Minhas and Qadir, 2024) [41].

Water quality can deteriorate rapidly if the source is exposed to agricultural runoff, industrial discharges, or sewage inflows. Establishing buffer strips along canals or reservoirs traps sediments and absorbs excess nutrients. Regulating upstream pollutant loads, fencing off water intakes from livestock, and preventing open dumping are essential to maintain source integrity (Malerba *et al.*, 2022; Park *et al.*, 2023) ^[39, 45].

Recycling irrigation water involves capturing, storing, and reusing runoff or drainage water from fields to improve water-use efficiency and reduce nutrient and sediment loss. This practice lessens pressure on freshwater resources while sustaining crop productivity. Treatment methods include sedimentation, filtration, constructed wetlands, and chemical or biological processes to remove solids, pathogens, and excess nutrients. Regular monitoring of salinity, nutrients, and microbes is essential to prevent build-up and contamination. Combined with good nutrient management, recycled water lowers nitrate and phosphorus pollution and protects groundwater. Effectiveness depends on local conditions, crop types, and water quality needs, requiring site-specific designs and adaptive management (Xu *et al.*, 2016) ^[65].

Using high-quality water during critical growth stages (flowering, fruit filling) and marginal water in vegetative stages reduces yield losses from salinity stress. This approach also stretches the availability of good water over longer periods.

Physical and Chemical Treatment

Settling tanks or sedimentation basins remove coarse suspended solids that could clog irrigation emitters. Sand and screen filters further eliminate fine particles, preventing drip irrigation blockages and ensuring uniform water distribution (Ramachandrudu and Kasa, 2022) ^[47].

Desalination is the process of removing dissolved salts and other minerals from seawater or brackish water to produce freshwater suitable for drinking, irrigation, and industrial applications (Elimelech and Phillip, 2011) ^[17].

Sodium-rich water can be improved by ion exchange resins that replace sodium with calcium or magnesium. This reduces the SAR and mitigates clay dispersion, enhancing infiltration rates and soil structure stability (Hill *et al.*, 2020) ^[28].

Blending poor-quality water (e.g., EC 3.0 dS/m) with high-quality water (e.g., EC 0.3 dS/m) in calculated ratios can bring the final EC to crop-safe levels. This is particularly valuable where only part of the water supply meets standards.

Biological Approaches

Heavy metal pollution in water bodies is a serious environmental problem, threatening not only the aquatic ecosystems, but also human health. Over the years, the main sources of metal pollution have shifted from mining and manufacturing to rock weathering and waste discharge. There are several reports on the deleterious effects of

biomagnification of heavy metals within aquatic organisms and its impact on human nervous, reproductive and cardiovascular systems (Zhou *et al.*, 2020) ^[68]. A new method of decontamination employing green plants is fast emerging, referred as phytoremediation, which is specifically suited for wetland restoration. The plants growing in the contaminated areas will absorb the elements from the sediment/soil/water by roots. The absorbed elements travel from root through cell sap and finally get precipitated in vacuole or cell membrane, thereby reduces the level of contaminants in sediment/soil/water (Meera *et al.*, 2021) ^[40].

Bioremediation is an inventive and optimistic technology which is applicable for the retrieval and reduction of heavy metals in water and polluted lands. Microorganism plays an essential part in bioremediation of heavy metals. By using genetic engineering, genetically modified organisms can be generated which can likely reduce different types of polycyclic hydrocarbons (PAHs). *Flavobacterium*, *Pseudomonas*, *Bacillus*, *Arthrobacter*, *Corynebacterium*, *Methosinus*, *Rhodococcus*, *Mycobacterium*, *Stereum hirsutum*, *Nocardia*, *Methanogens*, *Aspergillus niger*, *Pleurotus ostreatus*, *Rhizopus arrhizus*, *Azotobacter*, *Alcaligenes*, *Phormidium valderium*, *Ganoderma applanatus* are some microbial species that help in bioremediation of heavy metals (Verma and Kuila 2019) ^[60].

Irrigation Scheduling and Methods

According to the investigation of Toumi *et al.* (2024) ^[54], Applying controlled water deficits during less sensitive phenological stages such as post-harvest or mid-season can reduce total water use while maintaining acceptable yields. In saline conditions, Regulated Deficit Irrigation can help minimize salt accumulation in the root zone by strategically timing higher water applications during salt-sensitive growth stages.

Drip and micro-sprinkler irrigation deliver water directly to the wetted root area, reducing evaporation losses and preventing salt deposition on the soil surface. These systems also minimize leaf wetting, which is particularly important in saline environments to avoid foliar injury and improve crop quality.

Nutrient and Soil Management

Effective nutrient and soil management practices are essential for maintaining irrigation water quality while ensuring sustainable agricultural production. Inappropriate fertilizer application, poor soil management, and inefficient irrigation practices can increase the transport of nutrients, sediments, and other contaminants into surface and groundwater, leading to water quality degradation and reduced irrigation suitability. Adopting integrated nutrient and soil management strategies helps improve nutrient use efficiency, minimize nutrient losses through runoff and leaching, and protect surrounding water resources. Table 6 summarises key nutrient and soil management practices and their significance in safeguarding irrigation water quality, based on the recommendations of Sharpley *et al.* (2019) ^[49].

Table 3: Strategies for Nutrient and Soil Management to Protect Irrigation Water Quality

Strategy	Description/Approach	Relevance to Irrigation Water Quality
Nutrient Management Planning	Developing nutrient management plans that match nutrient application rates, timing, and placement to crop needs.	Minimizes nutrient losses to irrigation water, reducing contamination by nitrogen and phosphorus.
Split Nutrient Applications	Applying fertilizers in multiple smaller doses rather than a single large application.	Reduces leaching and runoff of nutrients into irrigation water.
Cover Crops	Growing cover crops during fallow periods to capture residual soil nutrients.	Reduces nutrient leaching into water by holding nutrients in biomass.
Buffer Strips and Riparian Zones	Planting vegetation strips near water bodies or irrigation channels.	Filters sediment and nutrients before they enter irrigation systems.
Manure and Organic Amendment Management	Proper storage, timing, and application of manure and compost.	Prevents nutrient-rich runoff and leaching into irrigation water.
Irrigation Scheduling	Matching irrigation amount and timing to crop evapotranspiration needs.	Prevents excessive water that can transport nutrients to groundwater or drainage systems.
Improved Drainage Management	Controlled drainage or subirrigation systems to regulate water tables.	Reduces nutrient losses via leaching and drainage water.
Soil Testing and Monitoring	Regular soil nutrient analysis to guide application decisions.	Ensures nutrient application aligns with soil capacity, reducing surplus losses to water.
Conservation Tillage	Minimizing soil disturbance to reduce erosion.	Limits nutrient-rich sediment movement into irrigation water.

Monitoring and Regulation

According to the insights of Syu *et al.* (2020) ^[53], there are several strategies for monitoring and regulation of water quality. Testing parameters like EC, SAR, pH, boron, chloride, and bicarbonate before each irrigation season helps in anticipating and mitigating problems. Seasonal changes in water chemistry are common, especially in reservoirs and shallow aquifers.

IoT-based sensors can continuously monitor EC and pH, alerting farmers to quality deterioration. This enables rapid interventions such as blending, treatment, or altering irrigation schedules. A study by Abu Bakar *et al.* (2025) ^[1] employs an IoT-based real-time monitoring and sensor approach. It integrates pH, temperature, and turbidity sensors with an Arduino R3 microcontroller and NodeMCU for Wi-Fi connectivity, linked to the Blynk platform for remote data visualisation and alert generation. The methodology focuses on real-time cloud-based data logging and comparative validation against laboratory measurements.

Water quality fluctuates across regions and seasons, especially in monsoon-dependent areas like Kerala, making consistent assessment difficult. Most water testing is periodic and manual, leading to delays in detecting contamination or changes in quality. Industrial effluents, agricultural runoff, and domestic waste introduce heavy metals, pathogens and salts into irrigation water. Farmers often lack access to knowledge or tools to assess water quality and its impact on soil and crops. Rural areas may lack laboratories, sensors or digital platforms for water testing and data sharing. Absence of region-specific water quality standards for agriculture hampers effective regulation and enforcement.

Emerging Technologies and Future Research Needs

Recent developments in sensor technology, data analytics, and geospatial tools have improved the efficiency and reliability of irrigation water quality assessment. Real-time monitoring systems integrating Internet of Things (IoT) sensors with cloud-based platforms enable continuous measurement of key water quality parameters, including electrical conductivity, pH, turbidity, temperature, and dissolved oxygen. Such systems facilitate rapid

identification of changes in water quality and support timely management decisions, particularly in regions where seasonal fluctuations are pronounced. The integration of remote sensing, Geographic Information Systems (GIS), and machine learning algorithms further enables spatial analysis of water quality, prediction of contamination trends, and identification of areas vulnerable to salinity and pollution. Future investigations should focus on developing integrated monitoring frameworks that combine water quality, soil characteristics, crop response, and climatic variables to improve irrigation planning under changing environmental conditions. Greater emphasis on low-cost sensor technologies and decision-support tools suitable for field-level applications will enhance the practical adoption of precision irrigation strategies.

Although substantial progress has been made in irrigation water quality assessment, important research gaps remain. Long-term datasets describing seasonal and spatial variability of irrigation water quality are limited, particularly under humid tropical conditions such as those prevailing in Kerala. Existing irrigation water quality guidelines are largely based on generalized threshold values and often do not account for interactions among soil properties, cropping systems, climate, and irrigation practices. Information on the occurrence, transport, and agricultural implications of emerging contaminants, including pharmaceuticals, microplastics, nanoparticles, and antibiotic-resistant microorganisms, is also insufficient. Future research should prioritize region-specific irrigation water quality indices, integrated water-soil-crop evaluation models, and long-term validation of reclaimed wastewater for agricultural use. Strengthening interdisciplinary research that combines soil science, hydrology, environmental engineering, and digital agriculture will improve the scientific basis for irrigation water management and support the development of location-specific management strategies under future climatic conditions.

Conclusion

Assessment of water quality in Kerala underscores its pivotal role in sustaining soil health and agricultural productivity. With agriculture consuming over 85% of water resources, the need for reliable, high-quality irrigation water

is more urgent than ever. The study reveals significant spatial and seasonal variability in water availability and quality, driven by monsoonal patterns, population growth, and anthropogenic pressures. Kerala's diverse irrigation sources from rivers and reservoirs to surangas and bore wells reflect both traditional wisdom and modern adaptation, yet many face challenges from salinity, toxic ions, and microbial contamination. Water quality parameters such as EC, SAR, RSC, pH, and specific ion toxicity directly influence soil structure, nutrient dynamics, and microbial activity. Several studies consistently demonstrate that irrigation with saline water accelerates soil salinization and sodicity; however, the severity depends on soil texture, drainage conditions, climate, and crop salt tolerance. Recent studies further indicate that integrated management practices, including gypsum application and precision irrigation, can substantially reduce these adverse effects. Poor-quality water contributes to salinization, sodicity, and heavy metal accumulation, impairing crop yield and posing health risks. Case studies highlight alarming levels of contaminants like lead, arsenic, and cadmium in crops irrigated with polluted water, emphasizing the need for stringent monitoring and remediation.

Real-time water quality monitoring using Internet of Things (IoT) devices can revolutionize irrigation management. Machine learning can forecast water quality trends and guide farmers on safe irrigation practices. Holistic models that link water quality with soil health and crop response will enable precision agriculture. Empowering local communities with training and tools can democratize water governance. Government support for water testing, subsidies for treatment technologies, and stricter pollution controls will drive sustainable practices. Techniques like phytoremediation and biofilters offer low-cost, sustainable solutions to purify irrigation water.

To safeguard agricultural sustainability, integrated strategies are essential, ranging from source protection and water treatment to precision irrigation and phytoremediation. Technological innovations like IoT-based real-time monitoring offer scalable solutions for proactive water management. Ultimately, the synergy between water quality, soil health, and crop performance demands a holistic approach rooted in science, policy, and community engagement. Ensuring clean, reliable irrigation water is not just an agronomic necessity; it is a cornerstone of food security, environmental resilience, and rural livelihoods in Kerala and beyond.

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