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ORIGINAL ARTICLE

A Comprehensive Review on Groundwater Quality of Rajasthan

Kuldeep Karguwal and Yogesh Kumar
Department of Chemistry, Govt Science College, Sikar, Rajasthan
Department of Chemistry, SK Govt Girls College, Sikar, Rajasthan
Email: kuldeep1karguwal@gmail.com

ABSTRACT

In Rajasthan, groundwater forms the primary source of potable and irrigation water, but it is exposed to high rates of stress because of overexploitation and widespread contamination. This review is a synthesis of the current studies on the chemical makeup, sources of pollution, modification of treatment, and management of groundwater resources in the region. High levels of fluoride, nitrate, salinity, and uranium are common and they can be attributed to the processed of geogenic nature, agrifluorisation as well as to industry releases. These wastes have significant health and soil quality consequences on the people. The paper evaluates both the traditional and low-cost remediation solutions such as reverse osmosis, ion exchange, and adsorption-based filters, as well as the policy frameworks and community-based management solutions. Underlying research gaps including lack of long-term follow-up, diversity of interest in new contaminants are also seen. On the whole, the research highlights the fact that sustainable groundwater management in Rajasthan will require the combination of integrated monitoring, scalable technology, and engaged governance to maintain the water systems of the state safe and resilient for the future generations.

Keywords: *Groundwater pollution, Hydrochemistry, Fluoride, Nitrate, Rajasthan, Remediation, Sustainable water management*

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INTRODUCTION

The biggest state of India in terms of area is known as Rajasthan, which is characterized by semi-arid and dry climate conditions. Nearly sixty per cent of the state is arid, and the rest is semi-arid (Everard, 2015). Rajasthan is not only the state that covers approximately 10 per cent of the total land area in the country, but it also has approximately one per cent of surface water supplies in India, and it is also extremely difficult to access water (Everard, 2015). Rainfall is also low and very variable, with a large portion of rainfall received in the short period of the southwest monsoon, which lasts almost all year round. Such limited and unforeseeable precipitation constrains natural storage of surface water, it is a cause of recurrent droughts, and an accentuation of susceptibility to climate change (Narisetty *et al.*, 2023; Everard, 2015; Monir and Sarker, 2024).

As a result of this natural deficit of the surface water, groundwater has become the primary water source for drinking, agriculture, and industry in the state (Singh and Bhakar, 2020; Narisetty *et al.*, 2023; Everard, 2015; Monir and Sarker, 2024). Over 85 per cent of domestic demands in rural areas are satisfied by groundwater, which is also significant in supplying irrigation and urban sectors (Everard, 2015). Nonetheless, continuing reliance on groundwater, which has been caused by growing agriculture, population, and the lack of surface water sources, has led to over-pumping. The numerous aquifers of Rajasthan have recently been designated as overexploited or dark zones, which means unsustainable exploitation and decreasing water tables (Singh and Bhakar, 2020; Everard, 2015; Monir and Sarker, 2024; Barman *et al*., 2023). Water-table drops are already becoming pronounced in several districts, and there are serious concerns regarding the future of the water security in the long term (Barman *et al*., 2023).

Degradation of groundwater through chemicals is also a matter of concern. The water quality degradation is fuelled by natural (geogenic) and human-independent (anthropogenic) processes. The elevated levels of fluoride are very common in most areas, and it is formed because of the dissolution of fluoride-containing minerals found in the underground rocks (Singh and Bhakar, 2020; Narisetty *et al*., 2023; Pandey *et al*., 2023). Most of the districts also have a high level of nitrate, mainly due to the runoff of agricultural fertilisers, poor sanitation, and uncontrolled waste disposal (Singh and Bhakar, 2020; Narisetty *et al*., 2023; Pandey *et al*., 2023). The other significant challenge is salinity, particularly in the west of Rajasthan, where salt dissolved deep gravity seeps encircle the irrigation run-offs, desert conditions, and evaporation (Narisetty *et al*., 2023; Pandey *et al*., 2023). These pollutants make groundwater less suitable for drinking and growing crops and are associated with the largest public-health issues, such as dental and skeletal fluorosis and nitrate-associated disorders, and ecological risks in general (Singh and Bhakar, 2020; Pandey *et al*., 2023).

In this way, Rajasthan has two interconnected problems, namely, depleting groundwater resource and a slow worsening of water quality. All these pressures are a threat to socio-economic development, agricultural productivity, and environmental sustainability of the regions. To achieve long-term water security, the chemical properties of water, their sources and routes of contaminants and the efficacy of the current treatment methods and management tools and techniques must be comprehended.

Aims and Design of the Review.

This review aims to:

- study the chemical property of water in the arid and semi-arid environments in Rajasthan; not only name the key contaminants, but also know where they come from, and review the key health impacts of pollution.
- Review available technologies for treatment and water management to increase the quality of water.
- Indicate gaps in the research and suggest future scientific research and policy development.

HYDROGEOLOGICAL AND CLIMATIC BACKGROUND OF RAJASTHAN

The dry climate, diversified geology, and heavy reliance on groundwater largely influence the water situation of Rajasthan. All these elements combine to dictate the quantity of water that can be found, its movement inside the soil and the way its quality varies with time.

Geographical and Climatic Features Influencing Water Resources

Rajasthan occupies a good chunk of northwestern India and encompasses the Thar Desert on the west and semi-arid plains on the east. Low and immensely uneven rainfall, extremely hot summers and recurrent droughts characterise the climate. In western regions, the average precipitation is usually lower than 500 mm annually, which exposes most of the state to water stress (Singh and Kumar, 2015; Monir and Sarker, 2024; Barman *et al*., 2023). Although in parts of the world, there has been a slight positive increase in rainfall over the past decades, the overall water density is high since most of the rainfall falls during a seasonal monsoon season and evaporates readily due to extreme heating (Yadav *et al*., 2022; Monir and Sarker, 2024; Barman *et al*., 2023).

The surface water is also scarce, as most of the rivers in the state of Rajasthan are seasonal and nearly all the rivers rely solely on the rain during the monsoon to flow

(Gupta *et al*., 2016). During the seasonal non-monsoon weather, most channels dry up, and in other cases, reservoirs have been reduced to only a small percentage of their size. Another thing that depletes surface water is the high evapotranspiration. Consequently, surface water is not enough to depend on one to sustain the domestic or agricultural requirements, thereby making water the lifeline of the state.

Aquifer Types and Groundwater Reliance

There are many geological formations in Rajasthan, and they form various kinds of aquifers.

Three key aquifer systems are identified:

Hard-rock aquifers

These aquifers, which occur in the Aravalli region and the southeastern districts, are composed of granite, gneiss, schist and quartzite. They are also relatively small in storage capacity and highly impermeable, that is, they can hold and transfer very small volumes of groundwater (Coyte *et al*., 2019; Chatterjee *et al*., 2018).

Alluvial aquifers

These aquifers are found in the plains and river basins, and they are made up of loose sand, silt, and gravel. They store more water and yield better than hard-rock aquifers but are at greater risk of contamination and over-extraction (Coyte *et al*., 2019; Chatterjee *et al*., 2018).

Palaeochannel aquifers

These buried channels, mostly under the Thar Desert, were once part of ancient river systems. They often contain good-quality groundwater and benefit from recharge through canal networks such as the Indira Gandhi Canal (Bhadra *et al*., 2022).

Groundwater fulfils about 80–90% of Rajasthan's drinking-water demand and supports a major share of irrigation (Chaudhary & Satheeshkumar, 2018; Gupta *et al*., 2016; Barman *et al*., 2023). Because of this dependence, groundwater extraction has increased sharply in recent decades. Many aquifers have now become "over-exploited," meaning more water is being pumped out than replenished naturally (Chatterjee *et al*., 2018; Barman *et al*., 2023). Falling groundwater levels are now common in many districts, threatening long-term water availability.

Rainfall, Evaporation, and Recharge Patterns

Rainfall in Rajasthan shows strong seasonal and spatial fluctuations, with most precipitation occurring during the monsoon (June–September) (Yadav *et al*., 2022; Monir & Sarker, 2024; Barman *et al*., 2023). The state ranges from less than 200 mm per year in the far west to over 700 mm in southeastern districts (Chaudhary & Satheeshkumar, 2018).

Because evaporation rates are often greater than rainfall, only a small fraction of precipitation infiltrates the soil and reaches aquifers (Singh & Kumar, 2015; Yadav *et al*., 2022). Sparse natural vegetation, thin soils, and widespread hard-rock surfaces make natural recharge even more difficult.

Groundwater recharge mainly occurs through rainfall and stream seepage, and locally through ancient tanks, stepwells, and modern artificial recharge systems, particularly near villages and valleys (Frommen *et al*., 2021; Gupta *et al*., 2016). In some western areas, palaeochannel zones benefit from canal-induced recharge (Bhadra *et al*., 2022). Despite these contributions, recharge is generally low, and groundwater abstraction rates often exceed recharge, causing sustained water-table declines across many regions (Monir & Sarker, 2024; Barman *et al*., 2023).

CHEMICAL CHARACTERISTICS AND SUITABILITY OF GROUNDWATER IN RAJASTHAN

Groundwater in Rajasthan displays a distinctive chemical signature influenced by both natural factors and human activities. Because Rajasthan lies in an arid to semi-arid climatic zone, evaporation is high and natural recharge of aquifers is limited. Consequently, salts are deposited over a long period of time, thus making the groundwater of most of the region's saline than that of various Indian states. Usually, sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) are the dominant cations in Rajasthan waters. This trend shows that the close relations of rock-water interaction and mineral dissolution have a significant impact on the chemistry of groundwater (Chaudhary and Satheeshkumar, 2018; Gantait *et al*., 2022; Pandey *et al*., 2023; Choudhary *et al*., 2024; Kumar *et al*., 2024; Coyte *et al*., 2019). The release of sodium to the water through long-term interactions between the percolating water and the silicate minerals and ion-exchange reactions, which evident off sodium in favours calcium and magnesium, can cause a high concentration of sodium.

The most frequently encountered anions are the chloride (Cl^-) and bicarbonate (HCO_3) anions, though sulfate (SO_4^{2-}) and nitrate (NO_3) are also prevalent. Chloride is usually formed by natural dissolution of the sedimentary formations and concentration by evaporation, whereas bicarbonate is primarily created by the weathering of carbonate minerals, including calcite and dolomite. Gypsum dissolution and fertilisers are often cited as the cause of sulfate contamination, and a high concentration of nitrates is mainly caused by agricultural effluents, septic tanks, and sewage effluent. The level of nitrates is a significant problem in human health since they are associated with such disorders as methemoglobinemia among infants and other chronic health conditions (Choudhary *et al*., 2024; Jandu *et al*., 2021; Rena *et al*., 2022).

The evaporation, mineral weathering, and anthropogenic factors play a prominent role in hydrochemical facies in the state of Rajasthan. Most of the groundwater samples are sodiumchloride (Na -Cl) or sodiumbicarbonate (Na -HCO_3) types, which are evidence of late geochemical development, where long-term evaporation and salt deposition are dominant (Pandey *et al*., 2023; Choudhary *et al*., 2024; Tiwari *et al*., 2020; Kumar *et al*., 2024; Coyte *et al*., 2019; Ram *et al*., 202 But there are also calcium-magnesium-bicarbonate (Ca-Mg-HCO_3) types of water and especially in places where recharge is likely to be more active including fresh carbonate dissolution of water. These facies not only show the main water-rock reactions in the aquifers but also the other secondary processes like cation exchange that add sodium to the content and make the groundwater salty.

In Rajasthan, the significant cause of groundwater chemistry is evaporation. The surface water loss is high due to the low rainfall and high temperature regime, which leaves behind dissolved ions becoming increasingly concentrated. This causes high levels of total dissolved solids (TDS) and electrical conductivity (EC), whereby groundwater is either brackish or salty in most places. Na^+ + and Cl^- are significantly increased by evaporation over prolonged durations, which is an issue regarding their suitability as a source of drinking and agriculture (Ahada *et al*., 2017; Rahman *et al*., 2020; Pandey *et al*., 2023). Moreover, ion-exchange reactions when calcium and magnesium are exchanged by the sodium ions of aquifer sediments are other processes that lead to the further shift of groundwater to more sodium-based compositions (Pandey *et al*., 2023; Tiwari *et al*., 2020; Kumar *et al*., 2024).

These are processes that are aggravated by human activities. Huge application of nitrogen-based fertilisers elevates the nitrate and sulfate concentrations, incorrect sewage dumping and industrial effluents inject chloride, nitrate and others into the shallow aquifers. All these pollutants deteriorate the quality of the water and increase health risks associated (Choudhary *et al*., 2024; Jandu *et al*., 2021; Rahman *et al*., 2020; Rena *et al*., 2022).

The suitability of groundwater is evaluated based on indices like the Water Quality Index (WQI) and the Entropy Water Quality Index (EWQI). These indicators are based on a combination of various chemical parameters to demonstrate the general water quality conditions. Numerous research notes that in Rajasthan, groundwater is often classified as being in a poor condition for drinking because of the high salinity, fluoride, sulfate, and nitrate content (Chaudhary and Satheeshkumar, 2018; Pandey *et al.*, 2023; Rena *et al.*, 2022). The Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Permeability Index (PI) are the parameters that can be utilised in agricultural settings and assess the suitability of irrigation. Important proportions of sodium and carbonates may have negative impacts on soil structure, which makes it less permeable and less crop-producing. This has rendered the groundwater irrigation inappropriate in most regions of Rajasthan despite the sandy soils showing when and, in some cases, able to absorb increased salinity and have adverse effects that are not as serious (Ahada and Suthar, 2017; Jandu *et al.*, 2021; Rahman *et al.*, 2020).

Table 1: Major Ions, Hydrochemical Facies, and Groundwater Suitability in Rajasthan

Parameter / Aspect	Typical Findings in Rajasthan	Implications for Use	Key Citations
Dominant Cations	$Na^+ > Ca^{2+} > Mg^{2+} > K^+$	High sodium contributes to salinity and may affect drinking and irrigation suitability.	Chaudhary & Satheeshkumar (2018); Gantait *et al.* (2022); Pandey *et al.* (2023); Kumar *et al.* (2024); Coyte *et al.* (2019)
Dominant Anions	$Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$	High chloride gives rise to salty water; nitrate is associated with farming dangers and terminal illness.	Chaudhary & Satheeshkumar (2018); Pandey *et al.* (2023); Rahman *et al.* (2020); Jandu *et al.* (2021)
Major Hydrochemical Facies	Na–Cl, Na–HCO_3 most common; Ca–Mg–HCO_3 also present	Indicates influence of evaporation, weathering, and anthropogenic inputs	Pandey *et al.* (2023); Choudhary *et al.* (2024); Tiwari *et al.* (2020); Kumar *et al.* (2024); Coyte *et al.* (2019); Ram *et al.* (2021)
Primary Geochemical Processes	Weathering (silicate & carbonate), evaporation, ion exchange, agricultural inputs	Controls major ion chemistry; increases dissolved solids and salinity	Ahada & Suthar (2017); Pandey *et al.* (2023); Rahman *et al.* (2020); Tiwari *et al.* (2020)
Water Quality Index (WQI/EWQI)	Many samples were categorised as poor or unsuitable for drinking due to high TDS, Na^+, Cl^-, SO_4^{2-}, NO_3^-, and F^-	Unsafe for direct consumption; requires treatment	Chaudhary & Satheeshkumar (2018); Pandey *et al.* (2023); Rena *et al.* (2022)
Irrigation Suitability	Often unsuitable due to high SAR, RSC, PI; some sandy soils are more tolerant	Soil structural damage, reduced permeability, and crop yield loss	Ahada & Suthar (2017); Jandu *et al.* (2021); Rahman *et al.* (2020)

MAJOR CONTAMINANTS IN RAJASTHAN'S WATER RESOURCES

Groundwater in Rajasthan contains a wide range of chemical contaminants from both natural geological sources and human activities. The most significant among these are fluoride, nitrate, uranium, heavy metals, salinity, and related inorganic constituents, along with emerging organic pollutants. Numerous of them are of greater concentration than the recommended drinking-water standards, posing a significant public health issue and restricting access to safe water both in rural areas and urban ones (Coyte *et al.*, 2019; Choudhary *et al.*, 2024).

Fluoride

The most prevalent contamination in groundwater in Rajasthan is fluoride. The concentrations are often beyond the allowable limit recommended in the Indian and WHO guidelines, and unusually high values are observed in central and western districts (Coyte *et al.*, 2019; Tanwer *et al.*, 2023; Choubisa *et al.*, 2022).

Most of the fluoride naturally occurs when groundwater is extracted from the fluoride-bearing minerals such as fluorite, apatite, micas, and it exists in the granite, gneisses and alluvial sediments. Those are rocks that decay gradually and release fluoride into the aquifers (Choubisa *et al*., 2022; Thakur *et al*., 2023).

In certain agricultural areas, phosphate fertilisers and industrial effluents also influence the creation of an extra input that increases concentrations further (Choubisa *et al*., 2022; Pandit *et al*., 2022).

Repeated exposure to fluoride may lead to dental and skeletal fluorosis, which is characterised by discolouration of the tooth, acute pain of the bones, stiffness of the joints, and, in severe cases, malformation that limits movement. It also affects livestock and the livelihoods of rural farmers. In India, the state of Rajasthan has one of the highest fluorosis rates, and some researchers report the prevalence of the disease among the population in the region exceeding 80 per cent and almost 90 per cent of all animals (Choubisa *et al*., 2022; Rani *et al*., 2023).

Nitrate

The problem of nitrate contamination is also prevalent, and more so in areas where there is heavy farming. Its key contributions are:

Unreasonable amounts of nitrogenous fertilisers.

Domestic wastewater

Sewage infiltration

Several studies reveal the deposition of animal waste (Narisetty *et al*., 2023; Jandu *et al*., 2021).

Because of the sandy soils that are highly permeable and prevalent in the whole of Rajasthan, a significant number of nitrates penetrates the groundwater. The concentrations are often higher than required by drinking-water standards and have great seasonal variation. After the rainfall or irrigation cycles that increase the leaching of agricultural fields, concentrations usually increase after the monsoon or sporadic rainfall (Tanwer *et al*., 2023; Pareta, 2024).

Excessive consumption may lead to methemoglobinemia, or blue-baby syndrome, especially in infants, and cannot help but cause gastrointestinal discomfort and lasting health problems in the long run (Tiwari *et al*., 2020; Jandu *et al*., 2021).

Uranium and Other Heavy Metals

Uranium became a contaminant of interest, and many samples surpass the WHO levels, especially in western and central Rajasthan (Keesari *et al*., 2021; Saha *et al*., 2024). It is mainly geogenic, which means it is formed because of the weathering of minerals that contain uranium, i.e. carnotite in the aquifer rocks (Keesari *et al*., 2021). There are also situations whereby phosphate fertilisers can also be a contributing factor (Saha *et al*., 2024).

High uranium presents a risk of kidney toxicity and possible carcinogenicity, with children being particularly sensitive to it because of increased water consumption compared to body weight (Pandit *et al*., 2022; Saha *et al*., 2024).

There are other heavy metals found iron, manganese, lead and cadmium, as well, that are found mostly around industrial or mining areas. They are due to the minerals generated naturally, industrial disposal, as well as the general practice of waste disposal (Balaram *et al*., 2022; Rahman *et al*., 2020). Lead and cadmium are characterised by toxicity to the nervous system and the kidneys.

It has been found that in certain areas (Jaipur, Dausa, and Kota), the amount of uranium in the blood ranged between 100 mg/L and higher (Keesari *et al*., 2021; Saha *et al*., 2024).

Salinity and Total Dissolved Solids (TDS)

TDS The salinity and the TDS in the groundwater are a continuing problem in Rajasthan, and it is especially severe in the arid western areas. Major causes include:

Intense evaporation

Breaking up minerals in the aquifers.

Irrigation return flow

Wastewater discharge

The resultant conditions are high sodium, chloride, sulfate, and bicarbonate concentration (Rahman *et al*., 2020; Choudhary *et al*., 2024).

Salinity impacts water palatability, leading to high corrosion of household systems, and makes the soil less viable to irrigation as it causes the soil to salinise, decreases soil permeability, and declines crop yield (Choudhary *et al*., 2024; Pareta, 2024).

Other Contaminants

Other inorganic pollutants, which include chloride, sulfate, iron, manganese, lead and cadmium, are present in various districts, particularly around industrial congregations, as well as in desert regions where evaporation condenses the ions. The long-term may lead to digestive disorders, developmental anomalies, and destruction of the ecology (Rahman *et al*., 2020; Balaram *et al*., 2022).

New pollutants have also been identified, including dissolved organic carbon and halides. Such compounds may react in chlorination to produce deleterious disinfection by-products, as the distribution and effects are unstudied (Coyte *et al*., 2018; Tanwer *et al*., 2023).

Table 2: Major Contaminants in Rajasthan Groundwater: Sources and Key Impacts

Contaminant	**Major Sources**	**Key Impacts / Risks**	**Key Citations**
Fluoride	Weathering of fluoride-rich rocks, fertilisers, and industrial effluent	Dental and skeletal fluorosis; livestock toxicity	Choubisa *et al.* (2022); Tanwer *et al.* (2023); Pandit *et al.* (2022)
Nitrate	Fertilizers; sewage; animal waste	Methemoglobinemia; gastrointestinal disorders	Tiwari *et al.* (2020); Jandu *et al.* (2021); Pareta (2024)
Uranium	Geogenic mineral dissolution; fertilisers	Kidney toxicity; cancer risk	Keesari *et al.* (2021); Saha *et al.* (2024); Pandit *et al.* (2022)
Heavy metals (Pb, Cd, Fe, Mn)	Mining; industrial discharge; natural minerals	Neurological damage, kidney disease, and water discolouration	Rahman *et al.* (2020); Balaram *et al.* (2022)
Salinity / TDS	Evaporation; mineral dissolution; irrigation return flow	Poor taste; soil salinisation; crop loss	Rahman *et al.* (2020); Choudhary *et al.* (2024)
Organic & emerging contaminants	Wastewater; industrial sources	Disinfection by-product formation: understudied risks	Coyte *et al.* (2018); Tanwer *et al.* (2023)

SOURCES AND MECHANISMS OF CONTAMINATION IN RAJASTHAN'S WATER RESOURCES

Contamination of groundwater in the state of Rajasthan is motivated by a complex of both geogenic (natural) and anthropogenic (human-made) processes. These natural and human pressures are intensified by the state having extreme climate and limited surface water supply, increasing population, and spreading agricultural intensities, and thus, the groundwater is prone to chemical degradation.

Geogenic Processes: Mineral Weathering and Soil–Water Interaction

Natural dissolution of minerals found in the geological formations of the area is also a significant source of groundwater contamination in the state of Rajasthan. A major part of the subsurface geology of Rajasthan is granites, gneisses, schist and alluvial depositions, which consist of minerals that contain fluoride, uranium, sodium and some other trace metals. As the groundwater passes through these rocks, it undergoes weathering and dissolution to release ions into the water over time (Coyte *et al*., 2019; Pandit and Kateja, 2023; Choubisa *et al*., 2022).

One of the most common problems in the state, to the extent that it is a source of fluoride contamination, is primarily caused by this type of geogenic dissolution. The breakdown of the mineral is optimised by the presence of Rajasthan in its alkaline pH, elevated temperature, and long groundwater dwelling (Choudhary *et al*., 2024; Li *et al*., 2021). These conditions lead to a high level of fluoride in drinking water in most of the districts.

On the same note, high levels of uranium in western and central Rajasthan possess a high geogenic element, which is attributed to natural occurrences and weathering of uranium-based minerals, including carnotite and gneissic formations (Tiwari *et al*., 2020). The salinity of the water, as well as the total dissolved solids (TDS), are mostly geogenic and are a product of evaporation and interaction between the rocks and water. The dry climatic conditions of Rajasthan enhance the rate of evaporation and leave behind the dissolved salt deposits, increasing their concentration in groundwater (Subba Rao *et al*., 2022).

Exchange of ions between water and soil minerals is also another important mechanism that can lead to an elevation of sodium and a decrease in calcium and magnesium. This process has an impact on the hardness of water and changes its drinking and irrigation suitability (Pandey *et al*., 2023). A mixture of evaporation and sparse recharge makes these natural processes create a level of contamination, which is further worsened by human activity.

Anthropogenic Activities: Agriculture, Industry, and Waste Disposal

Intensive pollution by humans has increased at an alarming rate because of agricultural expansion, growth in industries and urbanisation.

Nitrate, as a product of fertilisers, animal waste, and sewage infiltration, is the leading anthropogenic pollutant. Overuse of fertilisers in farmlands means that nitrates will percolate into the ground water using soil, particularly during monsoon and irrigation seasons (Choudhary *et al*., 2024; Ahirvar *et al*., 2025). The number of nitrates is especially high in peri-urban and well-cultivated areas.

Industrial sources are also a great contributor. The release of heavy metals and uranium-bearing particles in the soil and water is caused by mining and marble processing plants, which are frequent in southern and central Rajasthan (Frommen *et al*., 2021). The inappropriate management of industrial effluents goes even further to add contaminants like cadmium, lead and manganese.

The disposal of waste and urban sewage spillage contributes to the chloride and nitrate, organic, and heavy metals in shallow aquifers (Rahman *et al*., 2021; Pandey *et al*., 2023). Landfill leachate, open dumping and poor sanitation facilities localise the contaminants.

The quick urbanisation and excessive groundwater extraction aggravate the quality as well as quantity problems. Over-pumping upsets the circulation of water, increasing the geogenic contaminants upwards to concentrate the dissolved minerals (Thakur *et al*., 2023). Therefore, human activities can harness and magnify natural contaminants and expose them.

Case Studies Highlighting Combined Impacts

Far too much of Rajasthan's evidence is inter-sected sources of either natural or human contamination.

The mineral weathering, nitrates through sewage and agricultural processes, co-exist with fluoride and salinity in peri-urban areas in Jaipur. Nonetheless, the water quality can be partially improved with the assistance of the artificial recharge using the classical water storage facilities (Coyte *et al*., 2019).

The level of fluoride contamination of the groundwater in Dausa district is geogenic, but it is aggravated by agricultural activities and excessive use of groundwater. Evaporation and ion-exchange also increase the fluoride movement further (Choubisa *et al*., 2022).
The Ayad River Basin in Udaipur had an increase of TDS, nitrate, and fluoride in the east direction because of waste disposal, agricultural runoffs, and geological forces (Thakur *et al*., 2023).
These examples show that contamination is hardly executed by a single factor. Rather, the groundwater is contaminated with human activism that only increases the contamination levels that are originally natural (Pareta, 2024).

HEALTH AND ECOLOGICAL IMPACTS OF GROUNDWATER CONTAMINATION IN RAJASTHAN

There are extended and significant dangers of groundwater pollution in the state of Rajasthan that affect human health, livestock, agriculture, and the environment at large. It is primarily caused by the high levels of fluoride and nitrate, uranium, heavy metals, and salinity that decrease the usability of this water and result in the lack of sustainable development in the area.

Human Health Risks

Pollutants in drinking water have direct impacts on the health of millions of the population of the state. The worst and widely reported health impacts are related to the exposure to fluoride, nitrate and uranium.
Fluorosis
The greatest water-quality problem in Rajasthan is the pollution of fluoride. Due to the geological environment in the area, levels in the groundwater often exceed both WHO and Indian drinking-water limits (Choubisa *et al*., 2022; Coyte *et al*., 2019). Permanent use of high-fluoride water causes dental and skeletal fluorosis that is prevalent in all rural communities. Even in certain districts, up to 84% of villagers and 88% of livestock have clear signs of fluorosis and more than four million individuals are estimated to have it- the highest burden of the condition was ever reported in India (Choubisa *et al*., 2022; Rani *et al*., 2023).
Mottling, discolouration or pitting of teeth are the first manifestations of dental fluorosis. With time, skeletal fluorosis will impact bones and joints, leading to stiffness, persistent pain, and difficulty in movement (Tiwari *et al*., 2020; Tanwer *et al*., 2023). On the one hand, it is worth noting that nerve-related harm, thyroid impairment, and developmental problems have been suggested as the consequences of fluoride toxicity at larger dosages (Rahman *et al*., 2021).

Nitrate Toxicity

The major diets of nitrate contamination include excessive use of fertilisers, poor sewage disposal and animal waste infiltration (Pandey *et al*., 2023; Choudhary *et al*., 2024). In most agricultural states, the concentration of nitrate in soil water is above the recommended national drinking-water standards, particularly after each monsoon season, when the nitrogen has been washed away.
Nitrates may be changed into nitrite when ingested into the body, reducing the oxygen transfer capacity of blood. This causes methemoglobinemia, also known as blue baby syndrome, which predominantly happens in infants and young children (Pandit *et al*., 2022; Bhattarai *et al*., 2021). Other medical issues are hypertension, thyroid disorders, and gastrointestinal issues (Jain *et al*., 2021).
Several studies have reported hazard indices with the exposure to nitrates that are higher than permissible levels, particularly in populations at risk, like children (Rani *et al*., 2023; Garg *et al*., 2025). Since in most cases, nitrate pollution is combined with fluoride and other elements, this combination can significantly harm the health of people (Thakur *et al*., 2023).

Uranium and Heavy Metals

The pollution of groundwater with uranium and other heavy metals is a topic that has been gaining popularity over the past few years. The levels of Uranium have exceeded the WHO-specific threshold in several districts, with the West and south-eastern regions of Rajasthan recording the highest incidence (Tiwari *et al.*, 2020; Rahman *et al.*, 2021). Prolonged exposure to uranium may cause harm to the kidneys, mineral metabolism and a high risk of cancer. The children are more susceptible since they have a low body mass and immature organ systems (Pandit *et al.*, 2022).

The heavy metals lead, cadmium, iron, and manganese, which are brought in by natural minerals, mining activities, and discharge by different industries, also have the possibility of potential toxicity with prolonged usage (Coyte *et al.*, 2019; Thakur *et al.*, 2023). Such effects involve bone marrow toxicity, reproductive problems and neurological impairment.

Multiple Contaminants

Groundwater is found in most areas with two or more pollutants concurrently. Coupled routes of exposure increase the amount of health burden. As an example, fluoride combined with nitrates may deteriorate outcomes in terms of metabolism and development (Choudhary *et al.*, 2024). This con-toxicity recognises the necessity of considering water-quality management as a whole procedure and not targeting particular parameters.

Impacts on Livestock and Agriculture

Livestock Health

Water contamination equally affects livestock, which depend heavily on the groundwater sources as drinking water. Just like in humans, in the case of long-term exposure to fluorides, dental and skeletal fluorosis occurs, which results in bone defects, swollen joints, difficulty walking, slowed weight gain, and decreased milk production (Choubisa *et al.*, 2022). These health impacts lower the productivity of animals, posing a risk to the rural economies, which rely on dairy and agriculture.

Agricultural Productivity

The economy of Rajasthan relies mainly on agriculture, particularly in rural regions. The watering of crops with contaminated groundwater, however, has a negative influence on crop health, as well as soil quality. Salty, fluoride, and high nitrate ions harm the tissue of crops, slow down their growth, and negatively affect the absorption of nutrients (Tanwer *et al.*, 2023). In the long run, these chemicals destroy the soil structure, elevate the pH level, and decrease the level of organic matter (Pandey *et al.*, 2023).

These chemical transformations reduce the crop yield and quality, especially for crops which are sensitive to salt. Regions with intense salinity are characterised by high losses in intensive production and the level of agricultural revenue (Garg *et al.*, 2025). This situation leads to a production shortage since farmers tend to switch to less lucrative produce or give up farming, which leads to food insecurity.

Ecological Consequences

Besides causing direct human and livestock effects, groundwater pollution has negative ecological consequences.

Salinity, nitrate, and fluoride affect the health of soil, decrease the microbial diversity and decrease the natural processes of the nutrient cycles (Thakur *et al.*, 2023). Salty soil becomes inorganic and lacks structure and water-holding properties, which enhances run-offs and erosion. It leads to land degradation and desertification - one of the primary concerns in Rajasthan (Pandey *et al.*, 2023).

Lack of agricultural productivity ultimately impacts biodiversity since the pressures on the farmed lands trigger habitat destruction and ecological disturbance. Vegetation losses contribute to the further destabilisation of the ecosystems and endanger long-term sustainability (Pareta, 2024).

ASSESSMENT AND MONITORING APPROACHES FOR GROUNDWATER IN RAJASTHAN

The key to successful groundwater management in Rajasthan is also dictated by the efficient monitoring and evaluation measures that would allow identifying the contamination, comprehending its origins, and how to mitigate it. Since groundwater conditions are changing with season and place, the use of field surveying, lab analyses, geospatial analysis, and predictive modelling is gradually becoming involved in recording the fluctuation in the quantity as well as quality of water.

Sampling Strategies and Analytical Methods

Systematic sampling of wells, tube wells and hand pumps over multiple seasons kicks off the monitoring of groundwater to capture the variability in groundwater chemistry. The appropriate collection, handling, storage, and transportation of the samples are ensured using standard procedures, including those suggested by APHA (2012) (Bhakar and Singh, 2018; Narisetty *et al*., 2023).

Spectrophotometric methods are frequently used to measure substantial ions like fluoride, nitrate and sulfate in the laboratory. The quantification of chloride is commonly assessed by applying the Mohr precipitation test, whereas the quantification of the total hardness and major cations is measured by the titration or flame photometry (Rajput *et al*., 2020). The portable field instruments that are used in studying basic parameters are pH, electrical conductivity (EC) and total dissolved solids (TDS).

Quality-control measures are used to guarantee the accuracy of the dataset; this is achieved by determining a balance between cations and anions and ensuring that the responses of ion concentrations measure the composition of the groundwater on the ground and not due to analytical problems (Bhakar & Singh, 2018). These are necessary validation steps, which are important in comparing water-quality outcomes on an inter-regional or seasonal basis.

Use of GIS, Remote Sensing, and Statistical Tools

The use of Geographic Information Systems (GIS) and remote sensing has taken centre stage in the monitoring of groundwater in Rajasthan. The tools are used to visualise the spatial distribution of parameters forming the water quality, introduce the hotspots of contamination by the products in the regions, and assess the change in water conditions with the passing time (Choudhary *et al*., 2024; Gautam *et al*., 2024).

Further use of advanced statistical techniques like Principal Component Analysis (PCA) and Cluster Analysis is also used to explain groundwater data in expansive datasets. PCA aids in determining the key natural and human-controlling factors affecting groundwater chemistry, whereas clustering includes the sampling sites with clear similarities, indicating the common patterns of contamination (Patel *et al*., 2023; Gautam *et al*., 2024). The techniques come in particularly handy in separating or differentiating between geogenic contamination, or a natural source, such as mineral weathering, and anthropogenic contamination, related to agriculture or industry.

Groundwater Vulnerability Mapping (DRASTIC, SINTACS)

Regional planning involves a significant portion of groundwater vulnerability mapping. The DRASTIC tool and the SINTACS tool are based on the principle that the geology of the land determines how vulnerable the land is through the use of factors like the depth to water level, recharge rate, soil type, the aquifer media, topography, the vadose zone characteristics, and hydrolytic conductability (Rajput *et al*., 2020; Gautam *et al*., 2024).

These models tend to be combined with GIS to come up with spatial vulnerability maps that assist authorities in prioritising what to monitor and treat in the areas viewed to be the riskiest. The variants of these models have land-use as well as climate information, which enhances their ability to become more accurate. By comparing the modelled scores of vulnerabilities with the measured levels of contaminants, e.g., fluoride, nitrate, TDS, etc., vulnerable maps are proven (Patel *et al*., 2023). The sensitivity analyses mostly indicate that the recharge conditions and the land-use patterns have significant impacts on the vulnerability measurement (Narisetty *et al*., 2023).

TREATMENT AND REMEDIATION TECHNOLOGIES FOR GROUNDWATER CONTAMINATION: KEY APPROACHES AND EFFECTIVENESS

Fluoride, nitrate, uranium and heavy metal contamination of ground waters in Rajasthan has left a gap in the efficient and sustainable treatment and remediation methods. The methods differ in efficiency, cost, service and applicability to rural or urban environments. They need a combination of traditional, low-cost, and integrated management approaches to have safe and sustainable groundwater utilisation throughout the state.

Conventional Treatment Methods

The most popular and common technologies that are currently applied to eliminate the dissolved and contaminated water encompass reverse osmosis (RO), ion exchange, and activated alumina adsorption, among others, in the removal of fluoride, arsenic, and other ionic components.

Reverse osmosis (RO) is based on the principle of filtration through pressure, that is, the molecules of contaminated water are taken through a semi-porous membrane that selectively permeates the molecules of water and excludes the dissolved salts and contaminants. The RO systems are very high, reaching up to 95-99% in removing the fluoride, nitrate, and heavy metals (Kurniawan *et al*., 2023). Nevertheless, the technology is capital-intensive; not only that it requires experienced operation and maintenance, but it also produces a brine rejection that is inconvenient to dispose of. Therefore, RO systems are usually not available in rural populations with a small technical capability, whereas they are appropriate in urban and industrial settings.

Exchange and activated alumina methods are commonly applied in the selective removal of certain types of ions, including fluoride, nitrate and arsenic. Within ion exchange, the contaminant ions are substituted with harmless ions on the surface of a resin, whereas fluoride is adsorbed on activated alumina by means of surface chemical reactions. Both systems are effective and the resulting water is drinkable, though they necessitate regular regeneration with the use of chemical reagents and leave behind resulting waste, which must be disposed of (Kurniawan *et al*., 2023). They can hence be used more in semi-urban or small-scale settings where there is access to technical support.

Low-Cost and Innovative Approaches

Since most of the population in Rajasthan is rural and most of the communities cannot afford expensive technologies, low-cost and decentralised technologies play a critical role in providing clean water access. According to recent research, adsorption with locally available materials, bio-treatment and rainwater harvesting are promising options (Da'ana *et al*., 2021; Richards *et al*., 2022).

Low-cost adsorption methods involve the utilisation of natural or modified substances like bone char, red soil, laterite or agricultural wastes to eliminate fluoride and nitrate and heavy metals. Such materials are cheap, locally sourced and sustainable, but depend on the concentration of contaminants and water chemistry to be efficient. Another form of emerging approach is called permeable reactive barriers (PRBs), which entail the installation of reactive material underground that is to trap and treat contaminated groundwater, as it passes through. PRBs perform well, especially in the removal of nitrate and metal around the actual areas of pollution, like agricultural or industrial areas.

Biological treatment technologies, such as biofiltration and bioremediation, utilise the use of microorganisms, with the help of which contaminants can be metabolised or

restructured. These processes are non-toxic and can be incorporated at the system's community level in removing nitrate or organic pollution (Da'ana *et al*., 2021).
The problem of rainwater harvesting, which is an old yet useful practice, would enormously decrease the reliance on the fact of contaminated aquifers. When collected rightly with sedimentation and disinfection filters, rainwater may be used as a source of safe drinking water in rural communities. It also contributes to dilution and natural rehabilitation of groundwater quality with time, alongside the application of artificial recharge structures.

Policy and Integrated Management Strategies
Strong policy support, regulatory supervision and community engagement are not possible without technological intervention. The groundwater remediation should be done through a coordinated approach integrating scientific monitoring, local water management and public awareness. It is important to set tough water-quality standards, real-time monitoring networks, and increase water conservation to reduce risks of contamination in the long term (Richards *et al*., 2022).
This is equally important in the form of community engagement and education. Sustainability and ownership can be contributed by encouraging local involvement in the provision of water quality, maintenance of small-scale treatment units and rain harvesting programs. Moreover, incorporating groundwater clean-up into larger Integrated Water Resources Management (IWRM) systems enables halting water supply, land use, and environmental conservation policies towards each other (Kurniawan *et al*., 2023).
In the end, a hybrid solution, which is a recognising approach towards centralised systems and low-cost, locally based responses to the issues of rural hinterland, will provide the most sensible and justified means of enhancing the groundwater quality in Rajasthan.

CASE STUDIES OF GROUNDWATER CONTAMINATION AND REMEDIATION IN RAJASTHAN: SUMMARIES, LESSONS LEARNED, AND BEST PRACTICES

Groundwater in Rajasthan has very serious challenges that occur due to both natural (geogenic) and human-made (anthropogenic) factors. The case studies that follow different districts depict the level of contamination, interventions that may be effective and important lessons in the process of managing groundwater sustainably.
Key Studies
An assessment of 243 wells within the state showed extensive contamination of the wells in terms of fluoride, nitrate, and uranium, with almost 76 per cent of samples falling beyond the World Health Organisation (WHO) recommendations. The analysis discovered the contribution of geogenic sources, including earth-water interactions and evapotranspiration, and anthropogenic sources of agriculture and sewage infiltration. High levels of dissolved organic carbon also posed fears of possible development of disinfection byproducts, which meant that an integrated water-quality monitoring and management system is required (Coyte *et al*., 2019).
At the RIICO industrial area of Dholpur District, groundwater contained a high level of heavy metals (Fe, Cd, Pb), fluoride, nitrate, and total dissolved solids (TDS) in groundwater. Later sampling in post-monsoon had to do with increased contamination by leaching industrial effluence. Whereas water was barely fit to be used as irrigation, it was not safe to be drunk by humans. The research highlighted the necessity to increase the enforcement of effluent treatment standards and enhance the wastewater management (Deshmukh *et al*., 2025).
The numerical groundwater modelling of the Ayad River Basin in Udaipur showed that there were TDS, nitrate, and fluoride progressive concentration towards waste disposal and industrial location. A large percentage of the groundwater could still be used in irrigation, but it would need to be treated and used for drinking. The authors put forward

real-time monitoring networks, mobile-based alerts to the entire congregation, and integrations that utilise sensors to enhance management efficiency (Pareta, 2024).

The level of fluoride was found to be above the acceptable natural weathering of fluorite-bearing rocks in more than 80 per cent of sampled wells in Dausa District, in combination with anthropogenic sources. The water was considered not safe to drink or farm, thus emphasising the need to conduct periodic testing and special fluoride-removal systems (Tiwari *et al*., 2020).

An encouraging opposition to this can be traced in the community-based projects in North Rajasthan. The Arvari, Sarsa, and Baghani catchments' local programs employed the forms of traditional structures like johads and check dams in addition to the socially controlled governance to rehabilitate the drained aquifers. These initiatives have led to better groundwater supply, agricultural performance, and rural living standards and prove that socio-ecological integration can promote long-term sustainability (Everard, 2015).

RESEARCH GAPS & FUTURE DIRECTIONS IN GROUNDWATER MANAGEMENT

Although there are decades of work about groundwater contamination in Rajasthan, there are still several important missing links preventing the successful long-term management and preservation of human health. These consist of the lack of continuous surveillance, the lack of comprehensive knowledge on the emerging contaminants, and the inability to expand treatment technologies to suit the local circumstances.

The gaps are the most urgent: long-term and spatially broad groundwater monitoring is absent. Most of the studies use short-term or seasonal data, which do not give much information on the temporal patterns or the effects of mitigation. The networks of monitoring can be disproportionately represented, especially in rural and peri-urban areas, so that detecting the occurrence of contamination hotspots or tracking the quality of groundwater variations with time becomes challenging (Pareta, 2024; Narisetty *et al*., 2023). This gap can be resolved through the development of adaptive and real-time monitoring systems based on chemical sensors, mobile-based reporting, and citizen involvement to enhance the reliability of the data.

The other significant divide is the fact that there is little emphasis on new contaminants. The traditional pollutants, i.e., fluoride, nitrate, and total dissolved solids, have been studied as the focus, while the modern pollutants, i.e. pharmaceuticals, pesticides, microplastics and disinfection byproducts, are the understudied interactions between various co-occurring contaminants in terms of their effects on ecological and human health are poorly studied as well (Coyte *et al*., 2019; Garg *et al*., 2025). The scope of monitoring in the future should be extended to cover such pollutants and determine their compound health effects.

A third gap attentive of the remediation and treatment technologies relates to scalability and sustainability. Although many low-cost and advanced solutions were tested on the pilot scales, not many have been successfully implemented on the community or regional level. To take advantage of such technologies in such a state as Rajasthan, further studies are required to adjust them to diverse hydrogeological and socio-economic conditions, which can be long-term sustainable and acceptable to communities (Gautam *et al*., 2023).

CONCLUSION

The general evaluation of the situation with groundwater in Rajasthan singles out an area that is undergoing a severe emergency in terms of the environment and human health. There is a high level of fluoride, nitrate, uranium and total dissolved solids (TDS), with most of the districts surpassing national and international safety standards of both drinking and irrigation water. The rationale behind these problems is a multi-factoral interaction of natural processes, e.g. the weakening of rock and evaporation, on one hand, and the actions of people, e.g. the intensive farming, industrial effluence, and non-sustainable use of groundwater, on the other hand. Additional factors that have contributed to water scarcity and degradation are over-exploitation, reduction in the recharge rate, and the impact of climate variability.

These challenges can only be countered by a move to an integrated groundwater management that incorporates scientific, technological, and community-based solutions to the challenges. Hydrogeological, environmental, and socio-economic data may be used to identify vulnerable areas by means of multi-model and data-driven techniques to address resource distribution. Adaptive management techniques, including artificial recharge, reinstatement of traditional water harvesting, and conjunctive use of surface and groundwater, play a very relevant part in enhancing quantity and quality.

Local engagement is also a part of sustainability as well as policy coherence. The experience in taking on board community membership and decentralising water governance has shown potential in the discharge of aquifers and high resilience among several transactions within the Rajasthan district. The policies ought to encourage water-efficient crops, control industrial effluents, and enhance interaction between the water, energy and agricultural industry. In the meantime, technological features like a network of real-time monitoring, mobile-based alerts, and predictive modelling could be used to improve the early identification and sound judgment.

Finally, the sustainability of groundwater in Rajasthan would need a holistic, participative, and adaptive model. Science, technology and community wisdom should be incorporated to protect this important resource, both the well-being of humans and ecological balance, to protect future generations.

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