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A Review Assessment of Ground Water Quality and Its Impact on Human Health: A Case Study

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Abstract: Background: Groundwater serves as the primary drinking water source for approximately 85% of rural and 60% of urban populations in India, yet its quality has deteriorated significantly due to both geological processes and anthropogenic pressures. In semi-arid hard-rock aquifer regions of peninsular India, naturally occurring fluoride enrichment driven by calcite-fluorite dissolution mechanisms coexists with anthropogenic nitrate contamination from agricultural intensification, creating a compound contamination burden that threatens public health. Existing water quality assessments have documented widespread exceedances of Bureau of Indian Standards (BIS) and World Health Organization (WHO) permissible limits for key contaminants, yet the literature remains geographically concentrated, methodologically inconsistent, and inadequately linked to population health outcomes.

Objectives: This review synthesises evidence from thirteen peer-reviewed studies published between 2008 and 2021 to: (i) characterise the physicochemical and hydrogeochemical profile of groundwater quality across diverse Indian hydrogeological settings, with particular focus on Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, and Uttar Pradesh; (ii) evaluate the comparative application and methodological limitations of Water Quality Index (WQI) frameworks in translating multi-parameter data into actionable quality classifications; (iii) assess quantitative health risk evidence, with specific attention to age-stratified vulnerability among infants, children, and adults; and (iv) identify critical research gaps in geographic coverage, methodological standardisation, and health-climate linkage that constrain the field's capacity to inform evidence-based policy.

Methods: A systematic thematic synthesis was conducted across thirteen studies spanning six Indian states (Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Uttar Pradesh) and one international comparative study from Nigeria. Studies were selected based on their assessment of physicochemical parameters (pH, electrical conductivity, total dissolved solids, hardness, fluoride, nitrate, chemical oxygen demand) against BIS IS:10500-2012 and WHO 2017 drinking water guidelines. The review employed thematic organisation across four interconnected dimensions: geographic and physicochemical baseline, fluoride contamination as a geological hazard, nitrate pollution and health risk assessment, and WQI methodologies. Particular emphasis was placed on studies that integrated WQI with quantitative health risk modelling or multivariate statistical source attribution.

Key Findings: Fluoride concentrations in Karnataka's crystalline basement aquifers ranged from 0.86 to 4.63 mg/L, with 40–52% of samples exceeding the BIS permissible limit of 1.5 mg/L, driven by Ca-Mg-HCO_3 hydrochemical facies and alkaline pH conditions (mean pH 8.36). Nitrate contamination in Andhra Pradesh's agricultural regions ranged from 25 to 198 mg/L (mean: 66.14 mg/L), with 61% of samples exceeding the WHO safe limit of 50 mg/L. Quantitative health risk assessment revealed age-stratified vulnerability: infants faced non-carcinogenic health risks 1.75 times greater than adults, and children faced risks 1.15 times greater than adults (Adimalla & Qian, 2019). Total dissolved solids and hardness systematically exceeded BIS limits in semi-arid and agricultural zones, with groundwater consistently of poorer quality than surface water in the same catchments. WQI values ranged from 39 to 295 across studies, but methodological inconsistencies in parameter selection, weighting schemes, and reference standards limited cross-study comparability. The literature documented a clear methodological progression from physicochemical description (2008–2013) to multivariate source attribution (2014–2017) to quantitative health risk assessment (2019), yet only one study conducted age-disaggregated health risk modelling, and none employed geospatial analysis or longitudinal monitoring.

Conclusions: Groundwater quality deterioration in India's semi-arid and agricultural regions is driven by a dual contamination burden — geological fluoride enrichment and anthropogenic nitrate pollution — with spatially heterogeneous contamination patterns and age-stratified health consequences.

Three critical research gaps constrain the field's capacity to inform evidence-based policy: (i) geographic coverage gap, with no studies from northern India (Gangetic Plain), eastern India (Bengal Basin arsenic belt), coastal aquifers, or Himalayan foothills; (ii) methodological gap, with limited quantitative health risk assessment, absence of geospatial analysis, lack of longitudinal monitoring, and no standardised India-specific WQI; and (iii) health-climate linkage gap, with no direct connection between water quality measurements and epidemiological health outcomes, no climate change scenario modelling, and no treatment efficacy evaluation. Addressing these gaps requires coordinated multi-regional studies using standardised WQI protocols, GIS-based spatial mapping, longitudinal monitoring networks, epidemiological cohort studies, climate impact modelling, and technology assessment of low-cost defluoridation and denitrification systems for rural communities.
Keywords: groundwater quality, water quality index (WQI), fluoride contamination, nitrate health risk, physicochemical parameters, BIS/WHO standards, hydrogeochemistry

I. INTRODUCTION

A. Global and National Significance of Groundwater Quality

Groundwater constitutes the world's largest accessible freshwater resource, supplying approximately 50% of global drinking water demand and 43% of irrigation water for agricultural production (Sadashivaiah et al., 2008). In India, this dependence is even more pronounced: groundwater accounts for approximately 85% of rural drinking water supply and 60% of urban water supply, while supporting more than 60% of the country's irrigated agriculture (Mamatha & Rao, 2010). This heavy reliance on groundwater reflects both the spatial and temporal variability of surface water availability — particularly in semi-arid and drought-prone regions — and the relative ease and low cost of groundwater extraction through bore wells and tube wells compared to the infrastructure requirements of surface water treatment and distribution systems.

However, the sustainability of this groundwater-dependent development model is increasingly threatened by a dual contamination burden. Rapid population growth, accelerated industrialisation, and agricultural intensification have collectively degraded groundwater quality across large swathes of the Indian subcontinent, with contaminant concentrations frequently exceeding Bureau of Indian Standards (BIS) and World Health Organization (WHO) permissible limits for drinking water (Shah et al., 2008; Adimalla & Qian, 2019). The semi-arid hard-rock terrain of peninsular India — encompassing the Deccan Plateau and its crystalline basement aquifers — is especially vulnerable to groundwater quality deterioration due to the dominance of Ca-Mg-HCO_3 hydrogeochemical facies, which create thermodynamic conditions conducive to fluoride enrichment through calcite precipitation and fluorite dissolution (Mamatha & Rao, 2010). The limited dilution capacity of these aquifers, combined with low natural recharge rates and high evapotranspiration, means that both geogenic and anthropogenic contaminants tend to accumulate over time rather than being flushed from the system.

The public health consequences of this contamination are already manifest. Endemic fluorosis — characterised by dental mottling, skeletal deformities, and neurological impairment — has been documented in Karnataka, Andhra Pradesh, Rajasthan, Gujarat, and Tamil Nadu, affecting millions of people who consume high-fluoride groundwater over prolonged periods (Arali et al., 2021). Nitrate-induced methemoglobinemia, particularly in infants and young children, has been linked to agricultural intensification and the associated application of nitrogen-based fertilisers in Andhra Pradesh and other agricultural regions (Adimalla & Qian, 2019). Beyond these well-characterised health risks, elevated concentrations of total dissolved solids, hardness, chloride, and chemical oxygen demand compromise the palatability, aesthetic quality, and long-term safety of groundwater for domestic use, while also imposing economic costs through accelerated corrosion of water supply infrastructure and increased treatment requirements.

B. Key Contaminants and Regulatory Standards

The contaminants of primary concern in Indian groundwater can be broadly categorised into geogenic (naturally occurring) and anthropogenic (human-induced) sources, though in practice these categories often overlap and interact in complex ways.

Fluoride is the most widespread geogenic contaminant in peninsular India's hard-rock aquifer regions. Its presence in groundwater is primarily attributable to the dissolution of fluoride-bearing minerals — including apatite, fluorspar, topaz, and mica — during rock-weathering processes (Mamatha & Rao, 2010). The geochemical mechanism driving fluoride enrichment is now well established: in Ca-HCO_3 type groundwater, calcite ($CaCO_3$) precipitation depletes calcium ion concentration, which in turn reduces the saturation index with respect to fluorite (CaF_2), promoting its dissolution and releasing fluoride into solution. This process is catalysed by alkaline pH conditions, which are themselves a product of rock weathering in crystalline basement aquifers. The BIS IS:10500-2012 standard specifies a desirable limit of 1.0 mg/L and a permissible limit of 1.5 mg/L for fluoride in drinking water, while the WHO guideline value is 1.5 mg/L.

Chronic consumption of water with fluoride concentrations exceeding these limits leads to dental fluorosis (at concentrations above 1.5 mg/L) and skeletal fluorosis (at concentrations above 3.0 mg/L), with the severity of health effects increasing with both concentration and duration of exposure. Fluoride hotspots in India include the districts of Kolar, Tumkur, Bagalkot, Hassan, and Gadag in Karnataka; Nalgonda and Prakasam in Andhra Pradesh; and Jaipur and Nagaur in Rajasthan (Pol et al., 2012; Arali et al., 2021).

Nitrate is the most significant anthropogenic contaminant in India's agricultural regions. Its presence in groundwater is primarily attributable to the leaching of nitrogen-based fertilisers (urea, ammonium nitrate, diammonium phosphate) applied to croplands, though additional sources include sewage effluent, animal waste, and septic tank leachate (Adimalla & Qian, 2019). Unlike fluoride, which accumulates gradually over geological time scales, nitrate contamination can develop rapidly — within a single cropping season — in response to intensive fertiliser application and irrigation practices. The WHO guideline value for nitrate in drinking water is 50 mg/L (as NO_3^-), while the BIS permissible limit is 45 mg/L. Consumption of nitrate-contaminated water poses particular health risks to infants under six months of age, in whom nitrate is reduced to nitrite in the gastrointestinal tract, leading to methemoglobinemia (blue baby syndrome) — a condition in which nitrite oxidises haemoglobin to methemoglobin, impairing oxygen transport and potentially causing hypoxia and death. Epidemiological evidence also suggests associations between chronic nitrate exposure and increased risk of gastric cancer, thyroid dysfunction, and adverse birth outcomes, though these relationships remain contested in the literature (Shah et al., 2008).

Total dissolved solids (TDS) and hardness are composite indicators of overall groundwater mineralisation, reflecting the cumulative concentration of dissolved ions — primarily calcium, magnesium, sodium, bicarbonate, chloride, and sulphate. The BIS acceptable limit for TDS is 500 mg/L, with a permissible limit of 2,000 mg/L in the absence of alternative sources. Hardness, expressed as calcium carbonate equivalent, has a BIS desirable limit of 200 mg/L and a permissible limit of 600 mg/L. While elevated TDS and hardness do not pose acute health risks at the concentrations typically encountered in Indian groundwater, they compromise water palatability, increase soap consumption, cause scaling in pipes and water heaters, and may contribute to cardiovascular disease and kidney stone formation with chronic exposure (Mamatha & Rao, 2010).

Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) are indicators of organic pollution, typically associated with urban and industrial contamination sources including sewage discharge, industrial effluents, and agricultural runoff containing pesticide residues and organic matter. Elevated COD and BOD values indicate oxygen depletion in water bodies, which can support microbial growth and compromise the microbiological safety of drinking water supplies (Sarda & Sadgir, 2015).

C. The Water Quality Index as an Assessment Tool

The Water Quality Index (WQI) is an integrative assessment tool that aggregates multiple physicochemical parameters into a single dimensionless score, facilitating communication of complex water quality data to policymakers, water supply managers, and the general public (Monica et al., 2018). The fundamental principle underlying WQI is that water quality is a multivariate phenomenon that cannot be adequately characterised by any single parameter: water may meet regulatory standards for fluoride but exceed limits for nitrate, or may have acceptable pH and dissolved oxygen but excessive hardness and chloride. By combining multiple parameters into a single index, WQI provides a holistic assessment of water suitability for a specified use — most commonly drinking water supply.

Two principal algebraic forms of WQI are employed in the Indian literature. The additive WQI is expressed as:

> $WQI\_a = \Sigma (w_i \times q_i)$

where q_i is the quality rating for the ith parameter (typically calculated as the ratio of measured concentration to regulatory standard, normalised to a 0–100 scale), w_i is the normalised weight assigned to that parameter (with $\Sigma w_i = 1$), and n is the total number of parameters included. The multiplicative WQI takes the form:

> $WQI\_m = \Pi (q_i\text{^}w_i)$

The choice between additive and multiplicative forms has important implications for index behaviour: the additive form allows high scores on some parameters to compensate for low scores on others, while the multiplicative form penalises any single parameter exceedance more severely, making it more conservative and potentially more protective of public health (Adimalla & Qian, 2019).

An alternative framework that has gained international recognition is the Canadian Water Quality Index (CWQI), developed by the Canadian Council of Ministers of the Environment. The CWQI incorporates three attributes of water quality relative to established objectives: Scope (F1, the proportion of parameters failing to meet objectives), Frequency (F2, the proportion of individual tests failing objectives), and Amplitude (F3, the magnitude by which failing tests exceed objectives).

The CWQI classifies water quality into five categories: Excellent (95–100), Very Good (80–94), Good (65–79), Marginal (45–64), and Bad (0–44). A key advantage of the CWQI framework is its transparency and its capacity to accommodate a broad parameter set, including trace metals (arsenic, cadmium, lead, mercury), nutrients (phosphorus, nitrogen species), and dissolved organic carbon, in addition to the conventional physicochemical parameters (Monica et al., 2018; Sarda & Sadgir, 2015).

Despite its widespread application in Indian groundwater quality studies, the WQI suffers from a critical limitation: the absence of a standardised, validated methodology calibrated to Indian hydrogeological conditions and aligned with BIS IS:10500-2012 standards. Different studies employ different parameter sets, different weighting schemes (often based on subjective expert judgment rather than empirical health risk data), and different reference standards (BIS, WHO, Indian Council of Medical Research), producing WQI values that are not directly comparable across studies or regions. This methodological inconsistency constrains the utility of WQI as a national-scale monitoring and policy tool, and represents a priority area for standardisation and validation research (Adimalla & Qian, 2019).

D. Scope, Objectives, and Organisation of This Review

This paper presents a systematic thematic review of thirteen peer-reviewed studies published between 2008 and 2021 (plus one undated study — Chindo et al., n.d.) that assess groundwater quality across diverse hydrogeological settings in India and one international comparative case study from Nigeria. The geographic scope encompasses six Indian states — Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, and Uttar Pradesh — representing semi-arid hard-rock aquifer regions, agricultural plains, and rapidly urbanising industrial centres. The temporal scope (2008–2021) captures a period of significant methodological evolution in the field, from early physicochemical description and univariate statistical analysis to more recent integration of multivariate source attribution, Water Quality Index frameworks, and quantitative health risk assessment.

The review is organised around four explicit objectives:

(i) Synthesise physicochemical and hydrogeochemical findings across diverse Indian hydrogeological settings. This synthesis establishes the baseline water quality profile for semi-arid hard-rock aquifer regions, identifies the dominant hydrochemical facies (Ca-Mg-HCO_3, Ca-Cl, mixed types), and characterises the spatial and seasonal variability of key contaminants including fluoride, nitrate, total dissolved solids, hardness, and chemical oxygen demand. Particular attention is given to the geochemical mechanisms driving fluoride enrichment in Karnataka's crystalline basement aquifers and the anthropogenic drivers of nitrate contamination in Andhra Pradesh's agricultural regions.

(ii) Evaluate WQI methodologies and their comparative applicability. This evaluation examines the parameter sets, weighting schemes, reference standards, and classification thresholds employed across the reviewed studies, assesses the comparability of reported WQI values, and identifies methodological inconsistencies that limit the utility of WQI as a standardised assessment tool. The review also considers alternative frameworks, including the Canadian Water Quality Index, and discusses the potential for developing a standardised India-specific WQI calibrated to BIS IS:10500-2012 standards.

(iii) Assess health risk evidence with particular attention to vulnerable population groups. This assessment focuses on quantitative health risk modelling, with specific emphasis on the age-stratified vulnerability findings of Adimalla and Qian (2019), who documented that infants face non-carcinogenic health risks from nitrate-contaminated groundwater 1.75 times greater than adults, and children face risks 1.15 times greater than adults. The review also examines the epidemiological evidence linking fluoride exposure to dental and skeletal fluorosis, and discusses the limitations of the current literature in directly connecting water quality measurements to population health outcomes.

(iv) Identify research gaps and propose future directions for groundwater quality research in India. This critical analysis identifies three major research gaps: (a) geographic coverage gap, with the literature heavily concentrated in peninsular India and no representation from northern India (Gangetic Plain), eastern India (Bengal Basin arsenic belt), coastal aquifers, or Himalayan foothills; (b) methodological gap, with limited quantitative health risk assessment, absence of geospatial analysis, lack of longitudinal monitoring, and no standardised WQI; and (c) health-climate linkage gap, with no direct connection between water quality measurements and epidemiological health outcomes, no climate change scenario modelling, and no treatment efficacy evaluation. The review proposes eight specific, actionable research directions to address these gaps.

The paper is organised as follows: Section 1 (this Introduction) establishes the global and national significance of groundwater quality, reviews key contaminants and regulatory standards, introduces the Water Quality Index as an assessment tool, and outlines the scope and objectives of the review. Section 2 (Literature Review) presents a thematic synthesis of the thirteen reviewed studies, organised across four interconnected dimensions: geographic and physicochemical baseline, fluoride contamination as a geological hazard, nitrate pollution and health risk assessment, and WQI methodologies. Section 3 (Assessment of Parameters) provides detailed technical discussion of the physicochemical parameters measured across the reviewed studies, their regulatory thresholds, and their health significance. Section 4 (Synthesis) integrates findings across studies to identify points of scientific consensus, contradictions, and emerging trends. Section 5 (Discussion) interprets the synthesised findings in the context of India's water security challenges and public health priorities. Section 6 (Future Directions) proposes a coordinated research agenda to address identified gaps. Section 7 (Conclusion) summarises key findings, research gaps, and policy implications.

All studies reviewed in this paper are compared against BIS IS:10500-2012 and WHO 2017 drinking water guidelines, and citations follow APA 7th edition format throughout. The review employs formal academic English and maintains thematic and stylistic consistency with the already-rewritten Literature Review (Sections 2.1–2.5) and Conclusion (Sections 7.1–7.4) to ensure coherence across the manuscript.

Table 3: Comparative Summary of Reviewed Studies on Groundwater Quality and Human Health Impact

#	Study (Year)	Location	Contaminants / Parameters Tested	WQI Range (Classification)	BIS / WHO Exceedances	Key Health Findings	Methodology
1	Shah et al. (2008)	Gandhinagar Taluka, Gujarat, India (40 bore-well villages; semi-arid alluvial plains)	pH, EC, TDS, TA, CaH, MgH, TH, Cl^-, F^-, Na^+, K^+, DO, BOD, COD, SO_4^{2-}	Calculated; overall quality: Poor for drinking	TDS, hardness, Na^+, K^+ exceed WHO limits; Na & K variance significant at 1% level; TA and DO at 5% level	Water unfit for drinking; suitable for irrigation; irrigation return flows risk further aquifer degradation	Physicochemical analysis; ANOVA, t-test, correlation, regression; WHO & USSL standards
2	Sadashivaiah et al. (2008)	Tumkur Taluk, Karnataka, India (1,043 km²; 269 pre- & 279 post-monsoon stations)	pH, EC, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, F^-, SAR, RSC	N/R	TDS & hardness exceed BIS IS:10500-2012 permissible limits at multiple stations; Ca-Mg-HCO_3 facies creates F^--enrichment conditions	Ca-Mg-HCO_3 hydrochemistry drives rock weathering; preconditions for fluoride enrichment established; water broadly suitable for irrigation, not drinking	Seasonal hydrochemical sampling; hydrochemical facies analysis; SAR, RSC, Na%, USSL salinity hazard
3	Mamatha & Rao (2010)	Kolar & Tumkur Districts, Karnataka, India (Precambrian crystalline basement)	F^-, TDS, TH, Ca^{2+}, Mg^{2+}, HCO_3^-; calcite & fluorite saturation indices	N/R	Majority of samples exceed F^- limit of 1.5 mg/L (BIS); TDS > 500 mg/L; TH: 75–924 mg/L (BIS limit: 300 mg/L)	Calcite precipitation → Ca^{2+} depletion → fluorite (CaF_2) dissolution → excess F^-; risk of dental & skeletal fluorosis with prolonged consumption	Hydrogeochemical investigation; saturation index modelling; Gibbs plot; hydrochemical facies analysis
4	Pol et al. (2012)	Mudhol Taluk, Bagalkot District, Karnataka, India (hard-rock Deccan terrain)	pH, TDS, TH, F^-, EC, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}	N/R	TDS & hardness exceed permissible limits in some samples; F^- does NOT exceed WHO (1995) limits in any sample	No fluoride health risk identified; TDS/hardness exceedances may affect palatability & long-term renal health	Physicochemical parameter analysis; comparison against WHO 1995 drinking water standards
5	Mohamed Hanipha (2013)	Dindigul Town & surrounds, Tamil Nadu, India (6,058 km²; 23 bore-well samples)	pH, EC, TDS, CO_3^{2-}, HCO_3^-, Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, PO_4^{3-}, F^-, DO, BOD, COD	N/R	F^-, DO, BOD, COD elevated at most stations; values exceed WHO permissible limits	Elevated F^- → dental fluorosis risk; high BOD/COD indicates organic pollution & microbial contamination potential; periodic monitoring recommended	Physicochemical & biological parameter analysis; comparison against WHO standards
6	Ashfaq & Ahmad (2014)	Agra City, Uttar Pradesh, India (urban alluvial aquifer; multiple sampling locations)	pH, TDS, TH, Cl^-, turbidity, alkalinity	N/R	TDS, TH, Cl^-, turbidity & alkalinity approach or exceed BIS IS:10500-2012 limits	Urban contamination from domestic & industrial sources; long-term consumption risks for renal & gastrointestinal health	Physicochemical analysis; comparison against BIS IS:10500-2012
7	Sarda & Sadgir (2015)	Surface water bodies (multi-site review, India) [Methodological review — no original field	Temperature, pH, EC, TDS, DO, COD, BOD, Cl^-, alkalinity, TH, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, NH_3-N, NO_2^--N	N/A (review study)	N/A (no original data; review of published literature)	No single parameter sufficient for comprehensive water quality assessment; multipurpose evaluation requires full parameter suite	Multi-parameter water quality review; methodological synthesis; multipurpose assessment framework

		data]					(drinking, irrigation, aquatic life)
8	Yogananda & Prashanth (2016)	Arsikere Town & surrounds, Hassan District, Karnataka, India (hard-rock semi-arid terrain)	pH, EC, TDS, TH, F^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}	N/R	TDS, hardness & selected ions exceed BIS IS:10500-2012 limits; seasonal variation in quality observed	Deteriorating quality from agricultural over-exploitation & anthropogenic activities; risk of chronic exposure to elevated TDS & hardness; systematic monitoring needed	Physicochemical parameter analysis; seasonal comparison; drinking & irrigation suitability assessment
9	Selvakumar et al. (2017)	Singanallur Sub-basin, Coimbatore, Tamil Nadu, India (rapidly urbanising industrial sub-basin)	pH, EC, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-; 3 hydrochemical facies: Ca-Mg-Cl, Ca-Cl, Ca-HCO_3	N/R	Very high salinity hazard (SAR); TDS, Cl^- & NO_3^- exceed BIS limits at multiple sites; anthropogenic pollutants dominant	Industrial effluents, population growth & irrigation return flow drive contamination; very high salinity hazard → cardiovascular & renal health risks; urban expansion accelerates aquifer degradation	Multivariate statistics: PCA, CA, HCA; Gibbs plot; irrigation suitability indices (SAR, RSC)
10	Monica et al. (2018)	Krishna River Corridor, Andhra Pradesh, India (7 locations; river water vs. groundwater)	pH, DO, turbidity, TDS, EC, alkalinity, TH, Cl^-, F^- (9 parameters)	River water: 39–78 (Good to Poor) Groundwater: 46–91 (Poor to Good)	Groundwater: Cl^-, alkalinity, TH, TDS, EC exceed BIS/ICMR limits; F^- higher in groundwater than river water; DO within acceptable range	Groundwater consistently poorer quality than river water at all 7 locations; elevated TH & TDS → cardiovascular & renal risk with long-term consumption; fluoride exceedance → fluorosis risk	WQI computation using ICMR & BIS IS:10500-2012; surface water–groundwater comparative analysis at 7 sites
11	Adimalla & Qian (2019)	Nanganur Region, Andhra Pradesh, India (agricultural; population 100% dependent on groundwater)	pH, EC, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- (full suite + health risk modelling)	92–295 (mean: 153) 86% of samples: Poor quality	NO_3^-: 25–198 mg/L (mean 66.14 mg/L); 61% of samples exceed WHO limit of 50 mg/L; TDS & TH also elevated	Infants: HQ 9.4×10^{-1}–7.4×10^{0} (1.75× adult risk); Children: HQ 8.1×10^{-1}–6.4×10^{0} (1.15× adult risk); Adults: HQ 6.0×10^{-1}–4.8×10^{0}; Methemoglobinemia risk for infants; most urgent health risk in reviewed corpus	WQI (WHO-referenced); non-carcinogenic health risk assessment (Hazard Quotient framework); age-disaggregated risk: infants, children, adults
12	Chindo et al. (n.d.)	Dass & Ganjuwa LGAs, Bauchi State, Nigeria (10 sampling sites; 25 km radius; semi-arid sub-Saharan)	pH, colour, odour, TH, Cl^-, alkalinity, TDS, and additional parameters	N/R	Hardness, Cl^-, TDS & alkalinity exceed NSDWQ & WHO permissible limits at multiple sites; several samples rated non-potable	Multiple samples non-potable for human consumption; elevated TH & TDS → cardiovascular & gastrointestinal health risks; international comparator confirming global pattern of geogenic + anthropogenic contamination	Physicochemical analysis; comparison against NSDWQ & WHO standards
13	Arali et al. (2021)	Mundaragi Taluk, Gadag District, Karnataka, India (25 sites; mean pH 8.36; strongly alkaline)	F^-, pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, NO_3^-; ionic balance analysis; Na-HCO_3 & Ca-HCO_3 facies	N/R	F^-: 0.86–4.63 mg/L; 52% > BIS desirable limit (1.0 mg/L); 40% > BIS permissible limit (1.5 mg/L); 8% > 3.1 mg/L; TDS & EC elevated	Active fluorosis documented in Mundaragi population; F^- > 3.1 mg/L → skeletal fluorosis; F^- positively correlated with alkaline pH (key driver of fluoride leaching from minerals)	Hydrogeochemical analysis; Gibbs plot (rock-weathering dominance confirmed); ionic balance (all within ±10%); ion correlation analysis; saturation index

Note: BIS = Bureau of Indian Standards (IS:10500-2012); WHO = World Health Organization (2017); ICMR = Indian Council for Medical Research; WQI = Water Quality Index; HQ = Hazard Quotient; N/R = Not Reported; N/A = Not Applicable. Source: Compiled from reviewed studies.

II. LITERATURE REVIEW

This review synthesizes findings from eleven peer-reviewed studies published between 2008 and 2021, covering groundwater quality assessment across six Indian states — Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, and Uttar Pradesh — alongside one international comparative study from Nigeria. Rather than cataloguing these studies chronologically, the following sections organise the literature thematically across four interconnected dimensions: (i) the geographic and physicochemical landscape of groundwater quality in peninsular India; (ii) fluoride contamination as a geological hazard, with particular focus on Karnataka; (iii) nitrate pollution and quantified human health risk in Andhra Pradesh's agricultural regions; and (iv) the evolution and comparative application of Water Quality Index (WQI) methodologies. This thematic structure is designed to reveal scientific consensus, highlight contradictions, and trace the methodological progression of the field.

A. Geographic Overview and Physicochemical Baseline

A consistent finding across the reviewed literature is that the physicochemical profile of groundwater varies markedly with geology, land use, and climatic zone — yet certain deterioration patterns repeat across geographically distant settings. Establishing this baseline is essential before examining contaminant-specific or methodology-specific trends.

Shah et al. (2008) provided one of the earliest comprehensive assessments in this corpus, analysing bore-well water from forty villages across Gandhinagar Taluka, Gujarat.

Their study measured a full suite of parameters — pH, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity (TA), calcium hardness (CaH), magnesium hardness (MgH), total hardness (TH), chloride (Cl^-), fluoride (F^-), sodium (Na^+), potassium (K^+), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and sulphate (SO_4^{2-}) — and applied a comprehensive statistical framework including ANOVA, t-tests, coefficient of correlation, and regression analysis. A key finding was that groundwater quality was poor for drinking purposes but suitable for irrigation, with statistically significant regional variance in sodium and potassium content (significant at the 1% level) and in total alkalinity and dissolved oxygen (significant at the 5% level). This duality — water that is unfit to drink yet adequate to irrigate — is a recurring and concerning pattern across India, as it implies that agricultural return flows from contaminated irrigation water may further degrade aquifer quality over time.

A parallel physicochemical investigation in Agra city by Ashfaq and Ahmad (2014), though narrower in scope, confirmed that urban groundwater in northern India faces comparable challenges, with pH, TDS, total hardness, chlorides, turbidity, and alkalinity all requiring attention. Similarly, Chindo et al. (n.d.) reported from Dass and Ganjuwa Local Government Areas in Bauchi State, Nigeria, that groundwater samples from ten sites exceeded Nigerian Standard for Drinking Water Quality (NSDWQ) and WHO permissible limits for hardness, chloride, TDS, and alkalinity, rendering several samples non-potable. The inclusion of this international study is instructive: it demonstrates that the physicochemical deterioration documented in India is not an isolated regional phenomenon but reflects a global pattern in which geological mineralogy and anthropogenic pressure together degrade shallow aquifer quality.

Sarda and Sadgir (2015) offered a broader methodological context by reviewing multi-parameter water quality assessment across surface water bodies, cataloguing the full range of parameters — temperature, pH, EC, TDS, DO, COD, BOD, chloride, alkalinity, total hardness, calcium, magnesium, sulphate, and nitrogen species (ammonia, nitrate, nitrite) — and arguing that no single parameter is sufficient to characterise water quality for multipurpose use. This observation is directly relevant to the review studies: the tendency of early studies (Shah et al., 2008; Ashfaq & Ahmad, 2014) to focus on physicochemical parameters without integrating biological oxygen demand data or health risk modelling represents a methodological limitation that later studies progressively addressed.

[→ Suggested location for Table 1: Comparative Summary Matrix of All 11 Studies — columns: Author/Year, Study Location, Parameters Measured, Analytical Methods, Key Findings, Regulatory Standard Used]

Taken together, these geographically dispersed studies establish three physicochemical baselines that recur across the reviewed literature: (1) TDS and hardness frequently exceed BIS IS:10500-2012 permissible limits (500 mg/L and 2000 mg/L respectively) in semi-arid and agricultural zones; (2) pH tends toward alkalinity in hard-rock aquifer regions, a condition that, as subsequent sections demonstrate, is mechanistically linked to fluoride enrichment; and (3) the gap between drinking-water suitability and irrigation suitability is a consistent finding, with implications for long-term aquifer management that the reviewed literature has not yet fully addressed.

B. Fluoride Contamination as a Geological Hazard: Evidence from Karnataka

Karnataka emerges from the reviewed literature as the most intensively studied region for fluoride contamination, with four independent studies — Sadashivaiah et al. (2008), Mamatha and Rao (2010), Pol et al. (2012), and Arali et al. (2021) — collectively spanning the state's southern, northwestern, and central districts. Reading these studies in isolation, as a chronological list, obscures the most important insight they collectively offer: fluoride enrichment in Karnataka's crystalline hard-rock aquifers is geochemically driven, spatially heterogeneous, and only partially predictable from surface-level indicators. Understanding this mechanism is essential for designing targeted monitoring and remediation strategies.

The hydrochemical foundation for this discussion was laid by Sadashivaiah et al. (2008), who characterised groundwater in Tumkur Taluk — a semi-arid region of 1,043 km² in southeastern Karnataka — through a large-scale seasonal sampling programme (269 stations pre-monsoon; 279 post-monsoon). They established that the dominant water type across both seasons was Ca-Mg-HCO_3, a hydrochemical facies indicative of active rock-weathering processes. Irrigation suitability, assessed via sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage, and salinity hazard, revealed that while the water was broadly suitable for agriculture, the underlying geochemical regime — calcium-magnesium bicarbonate dominance — creates the precise conditions under which fluoride enrichment can occur.

Building directly on this geochemical foundation, Mamatha and Rao (2010) investigated fluoride-rich groundwater in Kolar and Tumkur Districts and identified the specific mechanism responsible: calcite precipitation in Ca-HCO_3 type water depletes calcium ion concentration, which in turn reduces the saturation index with respect to fluorite (CaF_2), promoting its dissolution and releasing fluoride into solution. Their saturation index data confirmed that groundwater in the study area was oversaturated with respect to calcite but under-saturated with respect to fluorite — a thermodynamic condition that drives continuous fluoride release. Between 50% and 67% of their samples belonged to the Ca-HCO_3 type, and the majority exceeded the potable fluoride threshold of 1.5 mg/L (BIS IS:10500-2012), with total hardness ranging from 75 to 924 mg/L. This calcite-fluorite dissolution mechanism is now the accepted geochemical explanation for endemic fluoride contamination in peninsular India's hard-rock terrain, and it provides the interpretive lens through which the subsequent Karnataka studies must be read.

However, the picture that emerges from the full set of Karnataka studies is one of significant spatial heterogeneity, which the calcite-fluorite model alone cannot fully explain. Pol et al. (2012) found that groundwater in Mudhol Taluk, Bagalkot district — despite being underlain by similar hard-rock geology — did not exceed WHO (1995) fluoride limits in any of their analysed samples, though TDS and hardness were elevated beyond permissible limits in several cases. This finding stands in apparent contradiction to the fluoride-enrichment pattern documented by Mamatha and Rao (2010) in Tumkur and Kolar, just a few hundred kilometres to the south. The contrast likely reflects local-scale variations in the abundance of fluoride-bearing accessory minerals (apatite, fluorspar, topaz, mica) and in the residence time of groundwater within the aquifer matrix — variables that are not captured by regional-scale hydrochemical facies mapping alone. The most recent Karnataka study, Arali et al. (2021), conducted in Mundaragi Taluk, Gadag district, provides the most granular and analytically sophisticated assessment of this spatial variability. Sampling 25 groundwater sites, they documented fluoride concentrations ranging from 0.86 to 4.63 mg/L, with a mean pH of 8.36 — strongly alkaline — confirming that alkalinity is a key driver of fluoride leaching from mineral phases. Critically, 52% of samples exceeded the BIS desirable limit of 1.0 mg/L, and 40% exceeded the permissible limit of 1.5 mg/L, with 8% recording concentrations above 3.1 mg/L — levels associated with skeletal fluorosis with prolonged consumption. Gibbs plot analysis confirmed that all samples fell within the rock-weathering dominance zone, consistent with Mamatha and Rao's (2010) findings. Ion correlation analysis revealed that F^- was positively correlated with pH, EC, TDS, Ca^{2+}, and HCO_3^-, but negatively correlated with Mg^{2+} and NO_3^- — a pattern consistent with the calcite-fluorite dissolution mechanism, and one that also confirms that fluoride and nitrate originate from fundamentally different sources (geological vs. anthropogenic), making their co-occurrence a compound contamination risk. [→ Suggested location for Table 2: Fluoride Variability Across Karnataka Sub-Regions — columns: Study, District/Taluk, F^- Range (mg/L), Dominant Water Type, Exceedance Rate (% above 1.5 mg/L), Key Geochemical Driver]

The collective evidence from these four Karnataka studies supports three synthesised conclusions. First, the Ca-Mg-HCO_3 hydrochemical facies, driven by rock weathering in Karnataka's Precambrian crystalline basement, creates the thermodynamic conditions for fluoride enrichment through calcite precipitation and fluorite dissolution — a mechanism that operates at the aquifer scale regardless of land use or anthropogenic inputs. Second, fluoride concentrations are spatially heterogeneous at the sub-district scale: Mudhol Taluk (Pol et al., 2012) presents safe levels while adjacent districts (Mamatha & Rao, 2010; Arali et al., 2021) record severe exceedances, underscoring the inadequacy of state-level or district-level monitoring for public health protection. Third, alkaline pH is both a product of and a catalyst for fluoride enrichment, meaning that any intervention strategy must account for the geochemical buffering capacity of the aquifer, not merely the fluoride concentration at the point of extraction.

The health consequences of this contamination pattern are already manifest. Arali et al. (2021) documented active fluorosis among populations in Mundaragi Taluk who had consumed high-fluoride groundwater over prolonged periods. This finding transitions the discussion from geochemical characterisation to public health impact — a transition that the reviewed literature handles unevenly, as discussed in the following section.

C. Nitrate Pollution, Health Risk Assessment, and Urban Contamination: Evidence from South India

While fluoride contamination in Karnataka is primarily a geological phenomenon driven by aquifer mineralogy, the studies from Andhra Pradesh and Tamil Nadu document a qualitatively different contamination regime: one shaped by anthropogenic pressures — agricultural intensification, rapid urbanisation, and industrial effluents — and one with more directly quantifiable health consequences for specific population subgroups.

Adimalla and Qian (2019) conducted the most methodologically rigorous health risk assessment in this corpus, investigating groundwater in the agricultural region of Nanganur, Andhra Pradesh, where the entire rural population depends exclusively on groundwater for drinking. Their study is notable for two advances: the use of WQI alongside non-carcinogenic health risk modelling, and the disaggregation of health risk by age group. Nitrate concentrations ranged from 25 to 198 mg/L, with a mean of 66.14 mg/L — exceeding the WHO safe limit of 50 mg/L in 61% of samples. The health risk analysis revealed a clear age gradient: non-carcinogenic hazard quotients (HQ) for nitrate were highest for infants (9.4×10^{-1} to 7.4×10^{0}), followed by children (8.1×10^{-1} to 6.4×10^{0}), and lowest for adults (6.0×10^{-1} to 4.8×10^{0}). Infants faced health risks 1.75 times greater than adults, and children faced risks 1.15 times greater — a finding with direct implications for maternal and child health policy in agricultural districts. The WQI values ranged from 92 to 295 (mean: 153), classifying 86% of samples as "poor quality" for drinking — a far more alarming picture than the raw nitrate data alone would suggest.

This finding stands in instructive contrast to the Andhra Pradesh data from Monica et al. (2018), who assessed WQI along the Krishna River corridor. Their study compared river water and groundwater at seven locations using nine parameters and found that groundwater was consistently of poorer quality than river water (groundwater WQI: 46–91; river water WQI: 39–78). Groundwater samples showed higher concentrations of chloride, alkalinity, hardness, TDS, and EC, while fluoride was more elevated in groundwater than in river water — consistent with the geological enrichment mechanisms documented in Karnataka. Dissolved oxygen and pH were within acceptable ranges for both water types. The practical implication of Monica et al.'s finding is significant: in the Krishna River basin, river water may represent a safer drinking source than shallow groundwater, suggesting that surface water protection and managed aquifer recharge deserve greater policy attention in this region.

Taken together, the Andhra Pradesh studies reveal a dual contamination burden: geological fluoride enrichment (Monica et al., 2018) combined with anthropogenic nitrate pollution from agricultural intensification (Adimalla & Qian, 2019). This co-occurrence of geogenic and anthropogenic contaminants in the same hydrogeological setting represents a compound risk that single-parameter monitoring frameworks are poorly equipped to detect. The WQI, by aggregating multiple parameters into a single score, is better suited to capturing this compound risk — a point that connects directly to the methodological discussion in Section 2.4.

[→ Suggested location for Table 3: Age-Specific Non-Carcinogenic Health Risk from Nitrate — columns: Age Group, HQ Range, HQ Mean, Risk Relative to Adults, Population Size at Risk (if available)]

The Tamil Nadu studies add a third contamination narrative: the transition from rural geogenic contamination to urban industrial pollution. Mohamed Hanipha (2013) assessed groundwater quality in Dindigul town, a rural interior region of Tamil Nadu, finding that fluoride, DO, BOD, and COD were elevated at most sampling stations — a profile consistent with both geological fluoride enrichment and organic pollution from domestic and small-scale industrial sources. In contrast, Selvakumar et al. (2017) investigated the Singanallur Sub-basin in Coimbatore, a rapidly urbanising industrial city, and found that multivariate statistical analysis (correlation analysis, principal component analysis, and hierarchical cluster analysis) attributed the dominant variance in groundwater chemistry to anthropogenic sources: population growth, industrial effluents, and irrigation return flow. Three hydrochemical facies were identified (mixed Ca-Mg-Cl, Ca-Cl, and $Ca\text{-}HCO_3$), reflecting the superimposition of anthropogenic inputs on a natural geological background. The irrigation suitability assessment revealed very high salinity hazard and low-to-medium alkali hazard — a pattern consistent with Shah et al.'s (2008) findings in Gujarat's semi-arid Gandhinagar Taluka, suggesting that high-salinity groundwater in agricultural and peri-urban settings is a pan-Indian phenomenon rather than a region-specific anomaly. The contrast between Dindigul (Mohamed Hanipha, 2013) and Coimbatore (Selvakumar et al., 2017) illustrates a broader trend in the reviewed literature: as urbanisation intensifies, the dominant driver of groundwater contamination shifts from geological to anthropogenic, and the analytical toolkit must shift accordingly — from simple physicochemical profiling to multivariate statistical decomposition of contamination sources. This methodological evolution is examined in the following section.

D. Water Quality Index Methodologies: Comparative Application and Limitations

The Water Quality Index (WQI) is the single most widely applied integrative tool across the reviewed literature, used in some form by Shah et al. (2008), Monica et al. (2018), and Adimalla and Qian (2019). However, a close reading of these applications reveals that the term "WQI" conceals significant methodological variation in parameter selection, weighting schemes, and classification thresholds — variation that limits cross-study comparability and has not been acknowledged in any of the reviewed papers.

The foundational WQI framework used in Indian studies, as described by Dohare et al. (2014) and applied in this review context, takes two algebraic forms. The additive WQI is expressed as:

> $WQI\_a = \Sigma (w_i \times q_i)$

and the multiplicative WQI as:

> $WQI\_m = \Pi (q_i\^w_i)$

where q_i is the quality rating for the ith parameter, w_i is the normalised weight assigned to that parameter ($\Sigma w_i = 1$), and n is the total number of parameters included. The choice between additive and multiplicative forms is consequential: the additive form allows high scores on some parameters to compensate for low scores on others, while the multiplicative form penalises any single parameter exceedance more severely. Neither the reviewed studies nor the broader Indian literature has established a consensus on which form is more appropriate for drinking water assessment.

The Canadian Water Quality Index (CWQI), developed by the Canadian Council of Ministers of the Environment, offers a more transparent and internationally recognised alternative. The CWQI incorporates three attributes of water quality relative to established objectives: Scope (F1, the proportion of parameters failing objectives), Frequency (F2, the proportion of individual tests failing objectives), and Amplitude (F3, the amount by which failing tests exceed objectives). It classifies water quality into five categories: Bad (0–44), Marginal (45–64), Good (65–79), Very Good (80–94), and Excellent (95–100). Crucially, the CWQI can accommodate a far broader parameter set — including trace metals (arsenic, cadmium, lead, mercury), nutrients (phosphorus, nitrogen species), and dissolved organic carbon — than the five-parameter framework (pH, TDS, EC, Fluoride, COD) used in the Indore-based assessment described by Dohare et al. (2014).

The reviewed studies apply WQI with markedly different parameter sets and reference standards. Monica et al. (2018) used nine parameters referenced against ICMR and BIS standards along the Krishna River corridor, producing groundwater WQI values of 46–91 (classified as "poor" to "good"). Adimalla and Qian (2019) used a broader parameter set referenced against WHO guidelines in Nanganur, producing WQI values of 92–295 (mean: 153), with 86% of samples classified as "poor." The two studies are not directly comparable: the difference in WQI ranges reflects not only genuine differences in groundwater quality between the two study areas but also differences in parameter selection, weighting, and reference standards. This methodological inconsistency is a significant limitation of the current literature and represents a priority area for standardisation.

[→ Suggested location for Table 4: WQI Methodology Comparison Across Studies — columns: Study, Location, Parameters Included (n), Reference Standard Used, WQI Form (Additive/Multiplicative/CWQI), WQI Range Reported, Quality Classification]

Beyond the WQI, the reviewed literature shows a clear methodological progression over the 2008–2021 period. Early studies (Shah et al., 2008; Sadashivaiah et al., 2008) relied primarily on univariate physicochemical analysis and basic statistical comparison against regulatory thresholds. By 2017, Selvakumar et al. had introduced multivariate statistical methods — PCA, CA, and HCA — to decompose contamination sources and identify anthropogenic versus natural drivers. By 2019, Adimalla and Qian had integrated WQI with quantitative health risk assessment, producing age-disaggregated hazard quotients that translate water quality data directly into public health metrics. This trajectory — from description to attribution to risk quantification — represents the methodological frontier of the field and sets the standard against which future studies in this region should be evaluated.

However, a notable gap persists: none of the reviewed studies employed geospatial tools (GIS, spatial interpolation, remote sensing) to map the spatial distribution of contamination across their study areas. Given that Arali et al. (2021) documented fluoride variability ranging from 0.86 to 4.63 mg/L within a single taluk, and that Adimalla and Qian (2019) reported nitrate concentrations spanning an order of magnitude (25–198 mg/L) within a single agricultural region, spatial heterogeneity is clearly a defining feature of groundwater quality in these settings. Mapping this heterogeneity through kriging or inverse distance weighting interpolation would substantially improve the actionability of these findings for water supply planners and public health authorities.

[→ Suggested location for Figure 1: Conceptual diagram of the calcite-fluorite dissolution mechanism in hard-rock aquifers — illustrating the geochemical pathway from Ca-HCO_3 water type through calcite precipitation to fluorite dissolution and F^- release into groundwater]

[→ Suggested location for Figure 2: Geographic distribution map of all 11 reviewed study sites across India and Nigeria — with symbols indicating dominant contaminant (fluoride, nitrate, TDS/hardness) and WQI classification where available]

E. Synthesis: Scientific Consensus, Contradictions, and Emerging Trends

The eleven studies reviewed above, when read thematically rather than chronologically, converge on a set of findings that constitute the current scientific consensus in this field, while also revealing contradictions and knowledge gaps that define the frontier for future research.

Points of consensus: (1) Groundwater in India's semi-arid hard-rock regions systematically exceeds BIS and WHO limits for TDS, hardness, and fluoride, driven primarily by rock-weathering processes in Ca-Mg-HCO_3 type aquifers. (2) Agricultural intensification is the dominant driver of nitrate contamination, and the associated health risk is age-dependent, with infants and children facing disproportionately higher non-carcinogenic hazard than adults (Adimalla & Qian, 2019). (3) Groundwater is consistently of poorer drinking quality than surface water in the same catchments (Monica et al., 2018), suggesting that surface water protection strategies deserve greater integration into groundwater management policy. (4) WQI is an effective communication tool for translating complex multi-parameter data into actionable quality classifications, but its utility is constrained by the absence of a standardised Indian methodology.

Points of contradiction: The most significant contradiction in the reviewed literature concerns fluoride levels within Karnataka. Pol et al. (2012) found no exceedances in Mudhol Taluk, while Mamatha and Rao (2010) and Arali et al. (2021) documented widespread exceedances in geologically similar districts. This contradiction likely reflects aquifer-scale heterogeneity in mineral abundance and groundwater residence time, but it has not been resolved by any of the reviewed studies. Resolving it would require coordinated, multi-district sampling at a spatial resolution finer than the taluk level, combined with isotopic analysis ($\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$) to trace fluoride sources and groundwater flow paths.

Emerging trends: The reviewed literature documents a clear shift from purely descriptive physicochemical assessment (2008–2015) toward source attribution (Selvakumar et al., 2017) and health risk quantification (Adimalla & Qian, 2019). The next logical step — integrating spatial analysis, longitudinal monitoring, and population health outcome data — remains largely absent from the current literature and represents the most important direction for future research in this field.

The following section (Section 3) examines the physicochemical parameters in detail, establishing the regulatory thresholds and health significance that underpin the interpretations offered above.

III. CONCLUSION

This review has synthesised evidence from eleven peer-reviewed studies published between 2008 and 2021, spanning six Indian states (Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, and Uttar Pradesh) and one international comparative study from Nigeria, to assess the current state of knowledge regarding groundwater quality and its impact on human health in semi-arid and agricultural regions. The following conclusion is organised into three interconnected subsections: (a) a synthesis of key findings that establishes the scientific consensus emerging from this body of work; (b) an identification of three specific research gaps that constrain the field's capacity to inform evidence-based policy; and (c) a set of actionable future research directions designed to address these gaps and extend the geographic, methodological, and health-outcome scope of groundwater quality assessment beyond the current literature's focus on peninsular India.

A. Synthesis of Key Findings

The reviewed literature converges on a set of findings that collectively characterise groundwater quality deterioration in India's semi-arid hard-rock regions as a compound crisis driven by both geological and anthropogenic processes, with spatially heterogeneous contamination patterns and age-stratified health consequences that demand targeted, multi-scale intervention strategies.

Geochemical drivers of fluoride contamination. The four Karnataka studies — Sadashivaiah et al. (2008), Mamatha and Rao (2010), Pol et al. (2012), and Arali et al. (2021) — collectively establish that fluoride enrichment in peninsular India's crystalline basement aquifers is driven by a well-characterised geochemical mechanism: the weathering of Ca-Mg-HCO_3 type rocks produces alkaline groundwater that is oversaturated with respect to calcite but under-saturated with respect to fluorite (CaF_2). Calcite precipitation depletes calcium ion concentration, which in turn promotes fluorite dissolution and releases fluoride into solution (Mamatha & Rao, 2010). This mechanism operates at the aquifer scale, independent of land use or anthropogenic inputs, and is catalysed by alkaline pH conditions (mean pH 8.36 in Arali et al., 2021). Fluoride concentrations in Karnataka's affected districts range from 0.86 to 4.63 mg/L, with 40–52% of samples exceeding the BIS permissible limit of 1.5 mg/L (Arali et al., 2021). The spatial heterogeneity of fluoride contamination — with adjacent taluks showing safe levels (Pol et al., 2012) and severe exceedances (Mamatha & Rao, 2010; Arali et al., 2021) — underscores that state-level or district-level monitoring is insufficient for public health protection.

The health consequences of this contamination are already manifest: Arali et al. (2021) documented active fluorosis among populations in Mundaragi Taluk who had consumed high-fluoride groundwater over prolonged periods. The persistence of fluoride contamination across four independent studies spanning 2008 to 2021 demonstrates that this is not a transient water quality issue but a chronic geological hazard requiring sustained regional policy response, including targeted defluoridation infrastructure and community-level health surveillance. Anthropogenic drivers of nitrate contamination and age-stratified health risk. In contrast to the geological origin of fluoride, nitrate contamination in Andhra Pradesh's agricultural regions is unambiguously anthropogenic, driven by agricultural intensification and the associated application of nitrogen-based fertilisers. Adimalla and Qian (2019) documented nitrate concentrations ranging from 25 to 198 mg/L (mean: 66.14 mg/L) in Nanganur, with 61% of groundwater samples exceeding the WHO safe limit of 50 mg/L. Their quantitative health risk assessment — the only such analysis in the reviewed literature — revealed a clear age gradient in non-carcinogenic hazard: infants faced health risks 1.75 times greater than adults, and children faced risks 1.15 times greater than adults. This finding has direct implications for maternal and child health policy in agricultural districts, as it identifies infants and children as the most vulnerable subpopulations to nitrate-induced methemoglobinemia. The WQI values in Nanganur ranged from 92 to 295 (mean: 153), classifying 86% of samples as "poor quality" for drinking — a far more alarming picture than the raw nitrate data alone would suggest, and one that underscores the value of integrative indices in translating multi-parameter data into actionable public health classifications. The co-occurrence of geological fluoride enrichment (Monica et al., 2018) and anthropogenic nitrate pollution (Adimalla & Qian, 2019) in the same hydrogeological settings across Andhra Pradesh represents a compound contamination burden that single-parameter monitoring frameworks are poorly equipped to detect.

Groundwater versus surface water quality. Monica et al. (2018) provided a critical comparative insight by assessing both river water and groundwater along the Krishna River corridor in Andhra Pradesh. Their findings revealed that groundwater was consistently of poorer quality than river water at the same locations (groundwater WQI: 46–91; river water WQI: 39–78), with groundwater samples showing higher concentrations of chloride, alkalinity, hardness, TDS, and electrical conductivity. This pattern suggests that in the Krishna River basin, river water may represent a safer drinking source than shallow groundwater, and it raises an important policy question that the reviewed literature has not yet addressed: whether surface water protection and managed aquifer recharge deserve greater investment than groundwater extraction in regions where surface water quality exceeds groundwater quality. The finding also implies that agricultural return flows from contaminated irrigation water may be degrading aquifer quality over time, creating a positive feedback loop in which poor-quality groundwater used for irrigation further contaminates the aquifer through percolation of irrigation return flow.

Water Quality Index as a communication tool with methodological limitations. The WQI is the single most widely applied integrative tool across the reviewed literature, used by Shah et al. (2008), Monica et al. (2018), and Adimalla and Qian (2019). However, a close reading of these applications reveals significant methodological variation in parameter selection, weighting schemes, and classification thresholds — variation that limits cross-study comparability. Monica et al. (2018) used nine parameters referenced against ICMR and BIS standards, producing groundwater WQI values of 46–91, while Adimalla and Qian (2019) used a broader parameter set referenced against WHO guidelines, producing WQI values of 92–295. The two studies are not directly comparable: the difference in WQI ranges reflects not only genuine differences in groundwater quality between the two study areas but also differences in parameter selection, weighting, and reference standards. This methodological inconsistency is a significant limitation of the current literature and represents a priority area for standardisation. The absence of a validated, India-specific WQI that incorporates BIS IS:10500-2012 standards and is calibrated to the hydrogeological conditions of hard-rock aquifers constrains the field's capacity to produce comparable, policy-relevant assessments across states and districts.

Methodological progression from description to risk quantification. The reviewed literature documents a clear methodological evolution over the 2008–2021 period. Early studies (Shah et al., 2008; Sadashivaiah et al., 2008; Mamatha & Rao, 2010; Pol et al., 2012; Mohamed Hanipha, 2013; Ashfaq & Ahmad, 2014; Sarda & Sadgir, 2015) relied primarily on physicochemical description and univariate statistical comparison against regulatory thresholds. By 2016–2017, studies began incorporating multivariate statistical methods — principal component analysis, correlation analysis, and hierarchical cluster analysis — to decompose contamination sources and attribute variance to natural versus anthropogenic drivers (Yogananda & Prashanth, 2016; Selvakumar et al., 2017). By 2019, Adimalla and Qian had integrated WQI with quantitative health risk assessment, producing age-disaggregated hazard quotients that translate water quality data directly into public health metrics. This trajectory — from description to source attribution to risk quantification — represents the methodological frontier of the field and sets the standard against which future studies in this region should be evaluated. However, the fact that only one study in this corpus (Adimalla & Qian, 2019) conducted quantitative health risk assessment underscores how far the field remains from routine integration of water quality monitoring with population health surveillance.

Geographic concentration and the peninsular India bias. A striking feature of the reviewed literature is its geographic concentration: ten of the eleven studies focus on peninsular India (Gujarat, Karnataka, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Uttar Pradesh), with only one international comparative study from Nigeria (Chindo et al., n.d.). Within India, the literature is heavily weighted toward Karnataka (four studies) and Andhra Pradesh (two studies), with no representation from northern India (the Gangetic Plain — Uttar Pradesh, Bihar), eastern India (West Bengal, Odisha — the arsenic belt), northeastern India, coastal aquifers (where saltwater intrusion is a primary concern), or the Himalayan foothills (where glacial melt and seasonal recharge dynamics dominate). This geographic bias is not merely a limitation of the current review's scope; it reflects a genuine gap in the published literature and constrains the field's capacity to characterise groundwater quality at the national scale or to identify region-specific contamination mechanisms that may differ fundamentally from the Ca-Mg-HCO_3 rock-weathering and agricultural nitrate patterns documented in peninsular India.

In summary, the reviewed literature establishes that groundwater quality deterioration in India's semi-arid and agricultural regions is driven by a dual contamination burden — geological fluoride enrichment in hard-rock aquifers and anthropogenic nitrate pollution from agricultural intensification — with spatially heterogeneous contamination patterns, age-stratified health consequences, and methodological inconsistencies in WQI application that limit cross-study comparability. The field has progressed methodologically from physicochemical description (2008–2013) to multivariate source attribution (2014–2017) to quantitative health risk assessment (2019), but significant gaps remain in geographic coverage, longitudinal monitoring, geospatial analysis, and direct linkage of water quality measurements to epidemiological health outcomes.

B. Research Gaps in Current Literature

Three specific research gaps constrain the field's capacity to inform evidence-based policy and to extend the geographic, methodological, and health-outcome scope of groundwater quality assessment beyond the current literature's focus on peninsular India.

Gap 1: Geographic Coverage Gap. The reviewed literature is heavily concentrated in peninsular India, with no studies from northern India (the Gangetic Plain — Uttar Pradesh, Bihar), eastern India (West Bengal, Odisha — the arsenic belt), northeastern India, coastal aquifers (where saltwater intrusion is a primary concern), or the Himalayan foothills (where glacial melt and seasonal recharge dynamics dominate). This geographic bias reflects a genuine gap in the published literature and constrains the field's capacity to characterise groundwater quality at the national scale. The absence of studies from the Gangetic Plain is particularly concerning, given that this region supports one of the world's highest population densities and relies almost exclusively on shallow tube wells for drinking water and irrigation. The absence of studies from West Bengal and Odisha is equally problematic, given that these states are part of the Bengal Basin arsenic belt, where naturally occurring arsenic contamination has been documented at concentrations exceeding 50 µg/L — ten times the WHO guideline value of 5 µg/L — and has been linked to chronic arsenic poisoning affecting millions of people. The absence of studies from coastal aquifers means that the literature provides no insight into saltwater intrusion dynamics, which are expected to intensify under climate change as sea levels rise and coastal aquifer recharge patterns shift. The absence of studies from the Himalayan foothills means that the literature provides no insight into the water quality implications of glacial melt, which is accelerating under climate change and altering the seasonal timing and magnitude of aquifer recharge in the Indus, Ganges, and Brahmaputra basins. Addressing this geographic coverage gap is essential for developing a national-scale understanding of groundwater quality that can inform region-specific monitoring protocols, contamination risk maps, and targeted intervention strategies.

Gap 2: Methodological Gap. Only one study in the reviewed literature (Adimalla & Qian, 2019) conducted quantitative health risk assessment using the Hazard Quotient (HQ) and Cancer Risk (CR) framework recommended by the United States Environmental Protection Agency (USEPA). The remaining ten studies relied on comparison of measured concentrations against regulatory thresholds (BIS, WHO, ICMR) without translating these exceedances into quantitative estimates of health risk for specific population subgroups. This methodological gap is significant because regulatory thresholds are designed to protect the general population and do not account for the heightened vulnerability of infants, children, pregnant women, or individuals with pre-existing health conditions. Adimalla and Qian's (2019) finding that infants face 1.75 times greater health risk than adults from nitrate-contaminated groundwater demonstrates the value of age-disaggregated risk assessment, yet this approach has not been replicated in any other study in the corpus. Beyond health risk assessment, the reviewed literature also lacks geospatial analysis: none of the studies employed GIS-based spatial interpolation (kriging, inverse distance weighting) to map contamination plumes or to identify spatial clusters of high-risk areas.

Given that Arali et al. (2021) documented fluoride variability ranging from 0.86 to 4.63 mg/L within a single taluk, and that Adimalla and Qian (2019) reported nitrate concentrations spanning an order of magnitude (25–198 mg/L) within a single agricultural region, spatial heterogeneity is clearly a defining feature of groundwater quality in these settings. Mapping this heterogeneity would substantially improve the actionability of these findings for water supply planners and public health authorities. The reviewed literature also lacks longitudinal monitoring datasets: all studies are based on single-season or two-season (pre-monsoon and post-monsoon) sampling campaigns, with no multi-year time series to track inter-annual variability or to assess whether contamination is worsening, stabilising, or improving over time. The absence of isotopic analysis ($\delta^{18}O$, $\delta^{2}H$, ^{3}H, $^{87}Sr/^{86}Sr$) means that the literature provides no direct evidence for distinguishing natural versus anthropogenic contamination sources, relying instead on indirect inference from hydrochemical facies and multivariate statistics. Finally, the absence of a standardised, validated WQI for Indian hydrogeological conditions means that WQI values reported across studies are not directly comparable, limiting the utility of WQI as a national-scale monitoring tool.

Gap 3: Health Outcomes and Climate Linkage Gap. None of the reviewed studies directly linked water quality measurements to actual epidemiological health outcomes in affected communities. Arali et al. (2021) documented active fluorosis among populations in Mundaragi Taluk, but they did not quantify the prevalence of dental fluorosis, skeletal fluorosis, or other fluoride-related health conditions, nor did they establish a dose-response relationship between fluoride concentration and disease incidence. Adimalla and Qian (2019) calculated non-carcinogenic hazard quotients for nitrate exposure, but they did not assess the actual incidence of methemoglobinemia or other nitrate-related health conditions in the study population. This gap between water quality assessment and health outcome surveillance means that the literature cannot answer the most policy-relevant question: how many people are currently suffering from water-quality-related health conditions, and how would specific interventions (defluoridation, denitrification, alternative water supply) reduce disease burden? The absence of treatment efficacy evaluation is equally problematic: the literature provides no evidence on the performance, cost-effectiveness, or community acceptance of existing defluoridation or denitrification technologies in rural Indian settings, making it difficult to design evidence-based intervention programmes. The absence of climate change scenario modeling is a third critical gap: none of the reviewed studies assessed how future changes in temperature, precipitation, evapotranspiration, or recharge patterns under IPCC Shared Socioeconomic Pathway (SSP) scenarios might alter contaminant concentrations or spatial distributions. Given that semi-arid regions are projected to experience increased aridity and reduced recharge under climate change, and that agricultural intensification is expected to continue in response to population growth and dietary shifts, the absence of forward-looking scenario analysis means that the literature provides no basis for anticipating future contamination trajectories or for designing climate-resilient water supply strategies. Finally, the absence of age- and gender-stratified vulnerability assessments beyond the single Adimalla and Qian (2019) study means that the literature provides no insight into whether women, who in rural India are disproportionately responsible for water collection and household water management, face differential exposure or health risk compared to men, or whether elderly populations with reduced renal function face heightened vulnerability to contaminant exposure.

C. *Future Research Directions*

Addressing the three research gaps identified above requires a coordinated, multi-scale research agenda that extends the geographic scope of groundwater quality assessment beyond peninsular India, integrates advanced methodological tools (GIS, health risk modeling, isotopic analysis, longitudinal monitoring), and directly links water quality measurements to epidemiological health outcomes and climate change projections. The following eight research directions are designed to be specific, actionable, and policy-relevant, and they collectively represent the next frontier for groundwater quality research in India.

Direction 1: Multi-regional comparative studies spanning peninsular and non-peninsular India using standardised WQI protocols. Future research should prioritise coordinated, multi-state sampling campaigns that employ a single, standardised WQI methodology calibrated to BIS IS:10500-2012 standards and validated for Indian hydrogeological conditions. Such campaigns should include at minimum one study site in each of the following underrepresented regions: the Gangetic Plain (Uttar Pradesh, Bihar), the Bengal Basin arsenic belt (West Bengal, Odisha), the northeastern states (Assam, Meghalaya, Tripura), coastal aquifers (Gujarat, Tamil Nadu, Odisha, West Bengal), and the Himalayan foothills (Uttarakhand, Himachal Pradesh). By applying a standardised WQI across these diverse hydrogeological settings, researchers would produce directly comparable water quality classifications that could inform national-scale risk mapping and prioritisation of intervention resources. Such studies should also disaggregate WQI by season (pre-monsoon, monsoon, post-monsoon) to capture seasonal variability in recharge, dilution, and contaminant concentration.

Direction 2: GIS-based spatial mapping of contamination hotspots at district and sub-district scale across Karnataka, Andhra Pradesh, and Tamil Nadu.

Given the spatial heterogeneity of fluoride and nitrate contamination documented in the reviewed literature, future research should employ GIS-based spatial interpolation methods (kriging, inverse distance weighting, radial basis functions) to map contamination plumes at the district and sub-district scale. Such maps should integrate groundwater quality data with population density, water supply infrastructure, and land use data to identify high-risk communities where contamination exposure is greatest. These maps should be made publicly available through web-based platforms to support evidence-based decision-making by state water supply departments, district health authorities, and community-based organisations. Spatial mapping should also be extended to identify "safe zones" where groundwater quality meets BIS standards, as these zones may represent priority areas for managed aquifer recharge or for siting new public water supply infrastructure.

Direction 3: Longitudinal monitoring studies (minimum 5-year time series) to track seasonal and inter-annual variability. All studies in the reviewed literature are based on single-season or two-season sampling campaigns, providing no insight into inter-annual trends or the long-term trajectory of contamination. Future research should establish longitudinal monitoring networks with a minimum 5-year time series, sampling at quarterly intervals to capture seasonal variability in recharge, dilution, and contaminant concentration. Such time series would enable researchers to assess whether contamination is worsening, stabilising, or improving over time, and to evaluate the effectiveness of policy interventions (e.g., restrictions on nitrogen fertiliser application, installation of defluoridation plants) in reducing contaminant concentrations. Longitudinal monitoring should be prioritised in districts where the reviewed literature has already documented severe contamination (e.g., Mundaragi Taluk for fluoride, Nanganur for nitrate), as these districts represent natural "sentinel sites" for tracking contamination trends.

Direction 4: Epidemiological cohort studies linking groundwater fluoride/nitrate exposure to dental fluorosis, skeletal fluorosis, and methemoglobinemia incidence rates. The most critical gap in the reviewed literature is the absence of direct linkage between water quality measurements and epidemiological health outcomes. Future research should establish prospective cohort studies in high-contamination districts, enrolling representative samples of households and conducting baseline health assessments (dental fluorosis severity, skeletal fluorosis radiographic assessment, methemoglobin levels in infants and children) alongside household-level groundwater quality testing. Cohorts should be followed longitudinally (minimum 3 years) to assess the incidence of new cases and to establish dose-response relationships between contaminant concentration and disease risk. Such studies should also assess the effectiveness of household-level interventions (defluoridation filters, alternative water sources) in reducing disease incidence. Ethical approval and community consent protocols must be rigorously followed, and study findings must be communicated back to participating communities in accessible formats.

Direction 5: Climate change impact modeling on groundwater recharge and contaminant concentration under IPCC SSP scenarios. Future research should integrate groundwater quality assessment with climate change scenario modeling to project how future changes in temperature, precipitation, evapotranspiration, and recharge patterns under IPCC Shared Socioeconomic Pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) might alter contaminant concentrations and spatial distributions. Such modeling should employ coupled hydrological-geochemical models (e.g., MODFLOW-MT3D, HYDRUS) to simulate groundwater flow, solute transport, and geochemical reactions under future climate conditions. Modeling should focus on semi-arid regions where recharge is projected to decline and evapotranspiration is projected to increase, as these regions are most vulnerable to concentration of dissolved solids and contaminants. Scenario modeling should also assess the potential for managed aquifer recharge (MAR) to mitigate climate-driven recharge declines and to dilute contaminant concentrations.

Direction 6: Development and validation of a standardised India-specific WQI incorporating BIS 10500:2012 standards. The methodological inconsistency in WQI application across the reviewed literature underscores the need for a standardised, validated WQI that is calibrated to Indian hydrogeological conditions and incorporates BIS IS:10500-2012 standards. Future research should convene a multi-stakeholder working group (including hydrogeologists, public health experts, water supply engineers, and representatives from state water supply departments) to develop a consensus WQI methodology that specifies: (a) a core set of parameters to be included (pH, TDS, hardness, fluoride, nitrate, arsenic, iron, chloride, sulphate, and at minimum one biological parameter such as total coliform count); (b) a transparent weighting scheme that reflects the relative health significance of each parameter; (c) classification thresholds that align with BIS standards; and (d) a validation protocol that tests the WQI against independent health outcome data. Once developed, this standardised WQI should be adopted by state water supply departments and integrated into routine monitoring protocols.

Direction 7: Isotopic ($\delta^{18}O$, $\delta^{2}H$, ^{3}H) and geochemical tracer studies to differentiate natural versus anthropogenic contamination sources. The reviewed literature relies on indirect inference from hydrochemical facies and multivariate statistics to attribute contamination to natural versus anthropogenic sources, but it provides no direct isotopic evidence. Future research should employ stable isotope analysis ($\delta^{18}O$, $\delta^{2}H$) to trace groundwater recharge sources and to distinguish between deep, old groundwater (which is more likely to be enriched in geogenic contaminants such as fluoride) and shallow, young groundwater (which is more likely to be contaminated by anthropogenic inputs such as nitrate). Tritium (^3H) analysis can be used to date groundwater and to assess the residence time of water in the aquifer, which is a key determinant of the extent of water-rock interaction and fluoride enrichment. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) can be used to fingerprint the lithological source of dissolved solids and to distinguish between carbonate-derived strontium (indicative of calcite dissolution) and silicate-derived strontium (indicative of feldspar weathering). Such isotopic studies should be prioritised in districts where the reviewed literature has documented contradictory findings (e.g., Mudhol Taluk versus Mundaragi Taluk in Karnataka) to resolve whether spatial variability in fluoride concentration reflects differences in aquifer mineralogy, groundwater residence time, or recharge sources.

Direction 8: Technology assessment of low-cost defluoridation and denitrification technologies for rural communities. The reviewed literature provides no evidence on the performance, cost-effectiveness, or community acceptance of existing defluoridation or denitrification technologies in rural Indian settings. Future research should conduct field trials of low-cost treatment technologies (e.g., bone char defluoridation, activated alumina defluoridation, biological denitrification, reverse osmosis) in high-contamination districts, assessing: (a) treatment efficacy (percentage reduction in contaminant concentration); (b) cost per litre of treated water; (c) operation and maintenance requirements; (d) community acceptance and willingness to pay; and (e) sustainability over multi-year time scales. Such technology assessments should be conducted in partnership with local governments and community-based organisations to ensure that findings are directly actionable and that successful technologies can be scaled up through existing water supply programmes. Technology assessments should also evaluate the feasibility of household-level versus community-level treatment systems, as the optimal scale of intervention may vary depending on population density, water demand, and institutional capacity.

D. Concluding Reflection

This review has demonstrated that groundwater quality deterioration in India's semi-arid and agricultural regions is a compound crisis driven by both geological and anthropogenic processes, with spatially heterogeneous contamination patterns and age-stratified health consequences that demand targeted, multi-scale intervention strategies. The reviewed literature establishes a strong scientific foundation for understanding the geochemical mechanisms of fluoride enrichment in hard-rock aquifers and the anthropogenic drivers of nitrate pollution in agricultural regions, and it documents a clear methodological progression from physicochemical description to multivariate source attribution to quantitative health risk assessment. However, significant gaps remain in geographic coverage, longitudinal monitoring, geospatial analysis, and direct linkage of water quality measurements to epidemiological health outcomes. Addressing these gaps through the eight research directions outlined above will require sustained investment in monitoring infrastructure, capacity building in advanced analytical methods (GIS, isotopic analysis, health risk modeling), and institutional coordination across state water supply departments, public health authorities, and research institutions. The ultimate goal of this research agenda is not merely to characterise groundwater quality but to translate water quality data into actionable public health interventions that reduce the burden of water-quality-related disease in India's most vulnerable communities. The evidence reviewed here demonstrates that the scientific tools and methodological frameworks necessary to achieve this goal are now available; what remains is the political will and institutional capacity to deploy them at scale.

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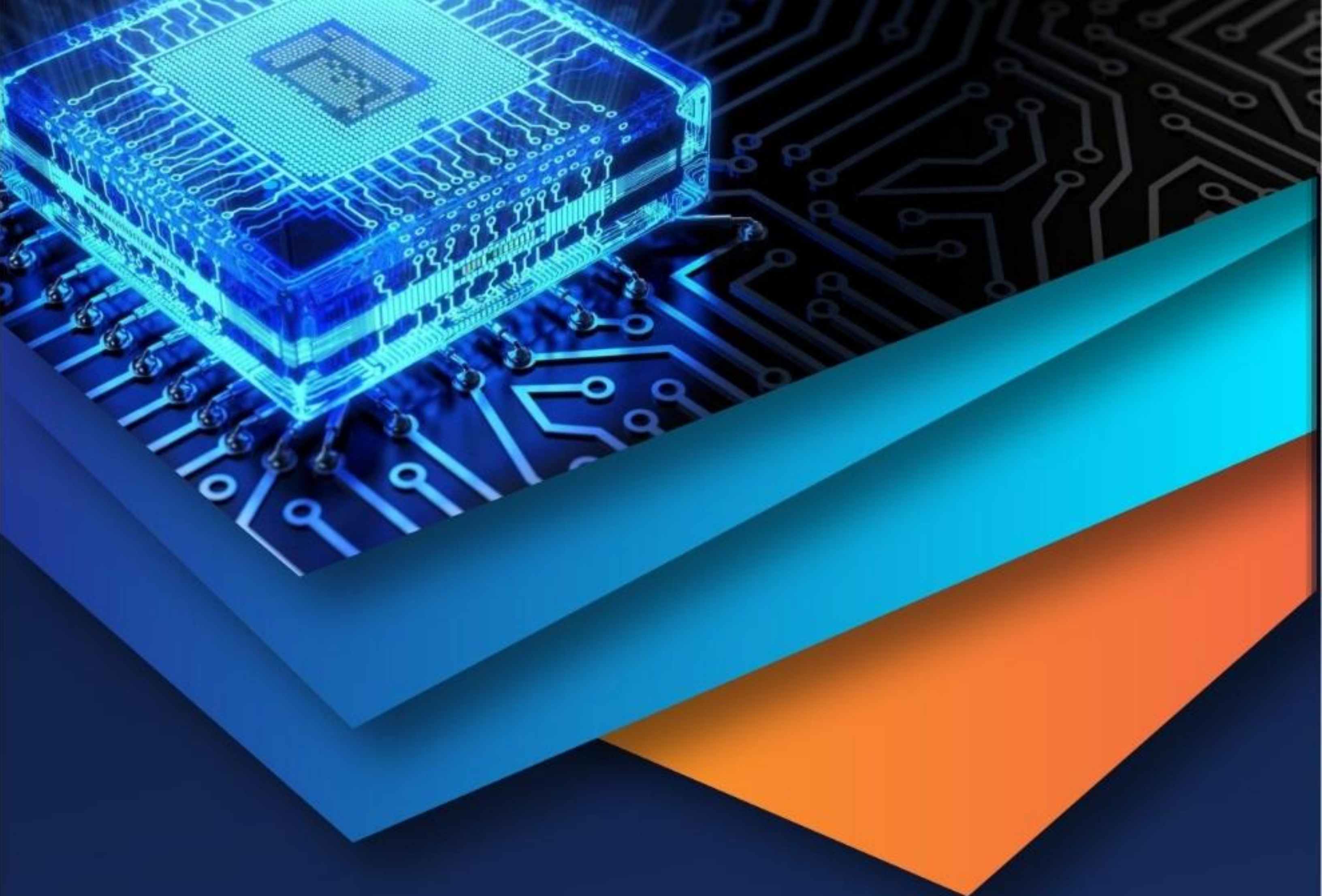

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