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A review of environmental iodine geochemistry in high-rainfall areas: Iodine deficiency disorders and medical geological approaches, focusing on northern Iran

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ABSTRACT

Iodine deficiency disorders (IDD) remain a significant public health challenge globally, with particular severity in regions characterized by specific geochemical and climatic conditions. While national salt iodization programs in Iran have successfully reduced IDD prevalence among school-aged children, emerging evidence indicates persistent iodine insufficiency among pregnant women and the potential vulnerability of high-rainfall regions. This study presents a systematic narrative review integrating medical geology, environmental geochemistry, and public health perspectives to elucidate the mechanisms controlling iodine distribution in high-rainfall environments, with specific application to northern Iran. Following PRISMA 2020 guidelines, we conducted a systematic search of Scopus, PubMed, and Google Scholar for studies published between 2000 and 2023 addressing iodine geochemistry, environmental factors in IDD, and medical geology approaches. The review identifies intense leaching, acidic soil conditions, high organic matter mobility, and rapid weathering as primary geochemical processes governing iodine depletion in soils and water systems of humid regions. Despite proximity to the Caspian Sea, northern Iran's high rainfall (>1800 mm annually), acidic soils, and intensive leaching create conditions analogous to known IDD-endemic areas in South and Southeast Asia. We propose an integrated conceptual framework linking geological, hydrological, and agricultural factors to human iodine nutrition. Findings indicate that reliance solely on salt iodization may be insufficient in geochemically vulnerable regions, necessitating complementary approaches including geochemical hazard mapping, soil-water-food chain monitoring, and agronomic biofortification strategies. This study provides the first systematic integration of medical geology principles with Iran's national IDD surveillance data, offering a methodological foundation for region-specific environmental health interventions.

Keywords:
Iodine deficiency disorders
Medical geology
Iodine geochemistry
High-rainfall regions
Northern Iran

1. Introduction

Iodine is an essential micronutrient required for thyroid hormone synthesis, which regulates numerous physiological processes including neurodevelopment, growth, and reproduction (Zimmermann & Boelaert, 2015). Iodine deficiency disorders (IDD) encompass a spectrum of adverse effects ranging from mild goiter to cretinism, irreversible mental retardation, and increased infant mortality (World Health Organization, 2014). Despite significant progress in salt iodization programs over recent decades, approximately 1.6 billion people remain at risk of iodine deficiency globally, with at least 50 million children suffering from preventable cognitive impairment (Andersson et al., 2012).

The geographical distribution of IDD is not random but follows predictable patterns determined by underlying geological, hydrological, and climatic factors (Selinus et al.,

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2013). Iodine is a highly mobile element in surface environments, and its biogeochemical cycle is strongly influenced by weathering processes, leaching intensity, climatic conditions, and biological activity (Fuge, 2013). Medical geology, as an interdisciplinary field, provides a conceptual framework for understanding these environment-health relationships and has demonstrated that regions with high rainfall, intense leaching, and acidic soils are classically predisposed to iodine deficiency (Dissanayake & Chandrajith, 2009).

Iran has implemented one of the most successful national IDD control programs in the Eastern Mediterranean Region. Comprehensive surveillance over 25 years (1989-2014) has documented dramatic reductions in goiter prevalence from approximately 68% to below 6% and sustained adequate urinary iodine concentrations (UIC) in school-aged children (Delshad & Azizi, 2017). However, the first national survey of pregnant women conducted in 2014 revealed moderate iodine deficiency in this vulnerable group, with median UIC of 87.3 μg/L, well below the WHO recommendation of 150-249 μg/L for pregnancy (Delshad et al., 2016). This finding raises important questions about the sustainability of iodine sufficiency across all population subgroups and geographical regions.

Northern Iran, characterized by humid subtropical climate, annual precipitation exceeding 1800 mm in some areas, dense Hyrcanian forests, and intensive chemical weathering, presents a unique environmental context for iodine nutrition. While proximity to the Caspian Sea might intuitively suggest iodine abundance, the geochemical behavior of iodine in high-rainfall environments often results in net depletion through continuous leaching of soils and mobilization of organic-bound iodine (Shetaya et al., 2012). This paradox—coastal location yet potential iodine deficiency—has been documented in other high-rainfall coastal regions globally, including parts of Southeast Asia and the Pacific Islands (Untoro et al., 2006).

The present study addresses a critical gap in the literature: the absence of systematic integration between Iran's comprehensive IDD surveillance data and medical geology principles. We aim to: (1) synthesize global evidence on iodine geochemistry in high-rainfall environments; (2) evaluate the environmental vulnerability of northern Iran to iodine depletion using a medical geology framework; (3) assess the implications of geochemical factors for current IDD control strategies; and (4) propose an integrated monitoring and intervention framework incorporating environmental determinants.

2. Materials and Methods

2.1. study design

This study was designed as a systematic narrative review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines (Page et al., 2021). This approach was selected to enable comprehensive synthesis of heterogeneous evidence from geochemistry, environmental science, epidemiology, and public health disciplines.

2.2. Search Strategy

We conducted systematic searches of three electronic databases: Scopus, PubMed, and Google Scholar. The search strategy combined terms related to iodine geochemistry, environmental factors, and medical geology using Boolean operators. Key search terms included: "iodine geochemistry," "iodine deficiency disorders," "medical geology," "humid climate," "leaching," "soil iodine," "environmental iodine," "groundwater iodine," and "biofortification." The search period covered publications from January 2000 to December 2023, building upon foundational studies identified through reference harvesting.

2.3. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) peer-reviewed original research or systematic reviews; (2) direct relevance to iodine behavior in environmental matrices (soil, water, atmosphere); (3) focus on high-rainfall, tropical, or subtropical environments; (4) presentation of primary data on iodine concentrations in environmental samples or secondary data synthesis; and (5) publication in English or Persian languages. Exclusion criteria comprised non-peer-reviewed sources, duplicate publications, purely clinical studies without environmental components, and studies lacking methodological transparency.

2.4. Screening and Data Extraction

Following removal of duplicates, titles and abstracts were screened independently against inclusion criteria. Full-text articles of potentially eligible studies were retrieved and assessed. Data were extracted using a standardized form capturing: study location, environmental setting, climatic characteristics, sample types (soil, water, food), analytical methods, iodine concentrations, and key geochemical findings. Quality assessment focused on methodological clarity, analytical validity, and relevance to study objectives.

2.5. Data Synthesis

Given the heterogeneity of study designs and outcome measures, a narrative synthesis approach was employed. Findings were organized thematically around: (1) mechanisms of iodine mobilization and immobilization in high-rainfall environments; (2) environmental factors controlling iodine bioavailability; (3) evidence from analogous regions globally; and (4) implications for northern Iran. The synthesis framework was structured around the soil-water-plant-human continuum central to medical geology.

3. Results and Discussion

3.1. Iodine Geochemistry in High-Rainfall Environments

The systematic review identified consistent patterns in iodine behavior across diverse high-rainfall environments globally. Iodine exists in multiple oxidation states (-1 to +7), with iodide (I^-) and iodate (IO_3^-) being the predominant inorganic forms in environmental systems (Fuge, 2013). In well-oxidized environments, iodate is thermodynamically stable, while iodide predominates under reducing conditions. This redox sensitivity has profound implications for iodine mobility and bioavailability.

Table 1 summarizes key environmental factors controlling iodine distribution in high-rainfall regions based on synthesis of included studies.

Table 1.key environmental factors controlling iodine distribution in high-rainfall regions based on synthesis

Environmental Factor	Effect on Iodine Availability	Mechanism	Reference
High precipitation	Decreased soil iodine	Intense leaching, vertical transport	Fuge, 2013
Acidic soil pH (pH < 6)	Decreased iodine retention	Reduced adsorption, increased solubility	Shetaya et al., 2012
Low clay content	Decreased iodine retention	Reduced surface area for adsorption	Johnson, 2003
High organic matter	Variable (initial accumulation, eventual loss)	Complexation followed by mineralization	Muramatsu et al., 2004
Steep topography	Decreased iodine	Rapid runoff, reduced infiltration	Dissanayake & Chandrajith, 2009
Ancient, weathered soils	Severely decreased iodine	Long-term depletion, nutrient exhaustion	Fuge & Johnson, 1986

The primary mechanism of iodine loss in high-rainfall environments is leaching—the vertical transport of dissolved iodine species through the soil profile by percolating water (Shetaya et al., 2012). Experimental studies have demonstrated that iodide is particularly mobile, with leaching rates exceeding those of iodate under most conditions. In regions with annual precipitation exceeding 1500 mm, the cumulative effect of decades to millennia of leaching results in severe depletion of total soil iodine reserves.

Soil properties mediate susceptibility to leaching. Coarse-textured soils with low clay content and limited organic matter exhibit minimal iodine retention capacity (Johnson, 2003). Conversely, soils rich in iron and aluminum oxides, common in highly weathered tropical environments, may retain some iodine through adsorption, though this fraction may not be readily bioavailable. The net effect in most high-rainfall environments is progressive iodine depletion over pedogenic timescales.

3.2. The Soil-Water-Plant Continuum

Iodine enters the food chain primarily through plant uptake from soil, with additional contributions from drinking water and, in coastal areas, seafood consumption. In high-rainfall regions, each compartment of this continuum exhibits characteristic iodine dynamics.

Soil compartment: Total soil iodine concentrations in high-rainfall regions typically range from <1 to 20 mg/kg, substantially lower than the global average of approximately 5 mg/kg for non-degraded soils (Muramatsu et al., 2004). The available fraction—iodine that can be taken up by plants—is even more limited, often representing <10% of total soil iodine. Factors increasing iodine availability include slightly acidic to neutral pH, adequate moisture (but not waterlogging), and moderate organic matter content.

Water compartment: Groundwater and surface water iodine concentrations in high-rainfall regions are typically low (<5 µg/L) due to dilution and limited contact time with iodine-bearing minerals (Fuge, 2013). Rainwater itself contains negligible iodine except in immediate coastal zones where marine aerosol deposition occurs. However, marine aerosol deposition decreases exponentially with distance from the coast, becoming insignificant beyond 50-100 km even in coastal regions.

Plant compartment: Crop iodine concentrations reflect soil availability, with most staple foods (rice, wheat, vegetables) containing <50 µg/kg fresh weight in iodine-deficient regions (Zimmermann & Boelaert, 2015). This is insufficient to meet human requirements, which range from

90-150 µg/day for non-pregnant adults to 250 µg/day during pregnancy and lactation (WHO, 2007).

3.3. Evidence from Analogous Regions

High-rainfall regions globally have been documented as IDD-endemic areas despite proximity to oceans. Table 2 presents selected examples from the literature.

Table 2. Iodine deficiency in high-rainfall coastal regions: Selected evidence

Region	Annual Rainfall (mm)	Population Affected	Key Findings	Reference
Gorgan Province, Iran	600-1000	School children	26.4% goiter prevalence post-iodization	Bazrafshan et al., 2005
Northern Thailand	>1500	Pregnant women	Inadequate UIC despite child sufficiency	Gowachirapant et al., 2009
Highlands of Papua New Guinea	>2000	General population	Classic IDD endemic, iodine oil required	Untoro et al., 2006
Central Java, Indonesia	>2000	School children	Persistent goiter despite iodization	Untoro et al., 2006
Southeastern Bangladesh	>2000	Rural populations	Low soil iodine, high IDD prevalence	Dissanayake & Chandrajith, 2009

These examples demonstrate that high rainfall, rather than coastal proximity, is the dominant environmental determinant of iodine status in many regions. The Southeast Asian experience is particularly instructive: despite decades of salt iodization programs, pockets of iodine deficiency persist in mountainous and high-rainfall areas, necessitating targeted environmental interventions.

3.4. Application to Northern Iran

Northern Iran, comprising the Caspian Sea littoral provinces (Gilan, Mazandaran, Golestan) and the northern slopes of the Alborz Mountains, exhibits environmental characteristics that align closely with known IDD-vulnerable regions globally.

Climatic characteristics: Mean annual precipitation ranges from 600 mm in eastern Golestan to >1800 mm in western Gilan, with some stations recording >2000 mm annually. Rainfall is distributed throughout the year, maintaining continuous soil moisture and year-round leaching potential. High humidity and moderate temperatures promote rapid organic matter decomposition and mineralization.

Geological and soil characteristics: The region is underlain by Mesozoic and Cenozoic sedimentary rocks, including limestones, marls, and sandstones, with limited iodine-bearing minerals. Soils are predominantly Alisols, Acrisols, and Cambisols—highly weathered, acidic (pH 4.5-6.0), with variable organic matter content and moderate to low clay activity (Delshad & Azizi, 2017). These characteristics favor iodine mobility rather than retention.

Hydrological characteristics: Dense river networks, high groundwater tables, and rapid through-flow characterize the region's hydrology. Continuous water movement through the soil profile maximizes leaching potential and minimizes residence time for iodine accumulation in either soils or aquifers.

Paradox of coastal proximity: The Caspian Sea, while a large water body, differs fundamentally from open oceans in iodine dynamics. As a closed basin with limited exchange, marine aerosol production is restricted compared to oceanic coastlines. Additionally, prevailing wind patterns often transport air masses from land to sea rather than vice versa, limiting marine iodine deposition. Limited available data suggest Caspian seawater iodine concentrations are comparable to or lower than open ocean values, though systematic studies are lacking.

3.5. Implications for IDD Surveillance and Control

The environmental vulnerability of northern Iran to iodine depletion has important implications for the national IDD control program. Current surveillance, based primarily on school children UIC and household salt iodine content, may not adequately capture the nutritional status of populations in geochemically vulnerable regions or the pregnancy-related increases in iodine requirements.

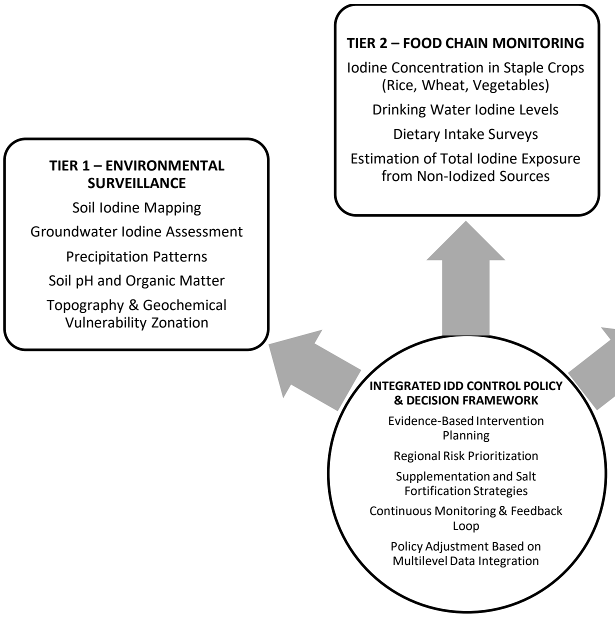

Figure 1. Conceptual integrated framework demonstrating multilevel environmental, food-chain, and biological surveillance pathways for evidence-based IDD prevention and control in high-rainfall regions

The framework proposes three interconnected monitoring levels:

Level 1: Environmental surveillance. Systematic mapping of soil iodine concentrations, groundwater iodine content, and key environmental covariates (precipitation, soil pH, organic matter, topography) to identify geochemical vulnerability zones. This would build upon existing soil and water databases maintained by Iranian environmental and agricultural agencies.

Level 2: Food chain monitoring. Assessment of iodine concentrations in staple crops (rice, wheat, vegetables) and drinking water sources from vulnerable regions, combined with dietary intake surveys to estimate total iodine exposure from non-iodized salt sources.

Level 3: Targeted biological surveillance. In addition to school-based UIC monitoring, periodic assessment of pregnant women and lactating mothers in identified vulnerable regions, with disaggregated analysis by geographical location and environmental characteristics.

The 2014 national survey of pregnant women, which documented moderate iodine deficiency (median UIC 87.3 μg/L) despite national iodine sufficiency in children, provides empirical support for this targeted approach (Delshad et al., 2016). The observed trimester-related decline in UIC (first: 92.1 μg/L; second: 86.0 μg/L; third: 76.8 μg/L) is consistent with the progressive depletion of maternal iodine stores under conditions of marginal intake—a pattern that would be exacerbated in regions with environmental iodine scarcity.

3.6. Potential Intervention Strategies

Recognition of environmental iodine vulnerability necessitates consideration of intervention strategies beyond salt iodization. While salt iodization remains the cornerstone of IDD control and has proven highly effective in Iran, complementary approaches may be required for populations with limited access to iodized salt (e.g., remote rural communities) or those with elevated requirements.

Agronomic biofortification involves increasing iodine content of staple crops through iodine-containing fertilizers. Field trials in China and India have demonstrated that soil or foliar application of iodate or iodide can increase grain iodine concentrations 10-100-fold, providing meaningful contributions to dietary intake (Zimmermann & Boelaert, 2015). Rice, the dominant staple in northern Iran, is particularly amenable to this approach. Implementation would require: (1) identification of optimal application rates and methods for local soil conditions; (2) assessment of iodine stability during storage and cooking; (3) evaluation of efficacy through controlled trials; and (4) development of agricultural extension programs.

Drinking water iodization has been implemented in some regions (e.g., Thailand, Italy) where centralized water systems serve defined populations. This approach ensures consistent iodine delivery independent of dietary patterns and salt intake. Technical feasibility in northern Iran would depend on water system characteristics, acceptance by water utilities and consumers, and cost-effectiveness compared to alternatives.

Supplementation for vulnerable groups remains essential for pregnant and lactating women, as demonstrated by current evidence of insufficiency. The American Thyroid Association recommends 150 µg/day iodine supplementation for all pregnant and lactating women in North America, where salt iodization is less comprehensive than in Iran (Becker et al., 2006). Similar recommendations may be appropriate for Iranian pregnant women, particularly those in geochemically vulnerable regions, until environmental and dietary iodine adequacy can be assured.

Table 3 summarizes intervention options with their advantages, limitations, and applicability to northern Iran.

Table 3. intervention options with their advantages, limitations, and applicability to northern Iran

Intervention	**Advantages**	**Limitations**	**Applicability to Northern Iran**
Salt iodization	Established program, low cost, population-wide	Reaches only those consuming iodized salt; may not meet pregnancy requirements	Currently implemented; requires sustained quality control
Agronomic biofortification	Targets dietary staple, sustainable, reaches entire population	Requires agricultural infrastructure, efficacy testing, regulatory framework	High potential given rice-based agriculture; research needed
Drinking water iodization	Consistent delivery, independent of diet	Requires centralized systems, monitoring infrastructure, capital investment	Limited to areas with piped water; feasibility assessment needed
Targeted supplementation	Assures adequate intake for vulnerable groups	Requires health system delivery, compliance, recurrent cost	Recommended for pregnant women immediately
Dietary diversification	Addresses multiple nutrients, culturally appropriate	Requires behavior change, may not achieve adequate iodine intake alone	Complementary approach; promotes consumption of iodine-rich foods

4. Conclusion

This study provides the first systematic integration of medical geology principles with national IDD surveillance data for Iran, with specific application to the high-rainfall northern regions. The key conclusions are:

4.1 Environmental factors significantly influence iodine nutrition. High rainfall, acidic soils, intensive leaching, and rapid organic matter turnover create conditions predisposing to environmental iodine depletion, independent of proximity to marine sources.

4.2 Northern Iran exhibits geochemical vulnerability. Despite coastal location, the region's environmental characteristics align closely with known IDD-endemic areas globally, warranting targeted investigation and monitoring.

4.3 Current surveillance may underestimate regional vulnerability. Reliance on school-based UIC and household salt iodine content may not capture the nutritional status of pregnant women or populations in geochemically vulnerable regions.

4.4 Integrated environmental-nutritional surveillance is needed. Systematic mapping of soil and water iodine concentrations, combined with targeted biological monitoring in vulnerable populations and regions, would strengthen IDD control programs.

4.5 Complementary interventions warrant consideration. Agronomic biofortification, drinking water iodization, and targeted supplementation should be evaluated as potential complements to salt iodization for geochemically vulnerable populations.

Limitations of this study include the absence of primary environmental data from northern Iran, reliance on published literature from analogous regions, and the conceptual rather than empirical nature of the proposed framework. These limitations highlight priority areas for future research.

Future research directions should include: (1) systematic geochemical mapping of soil and water iodine concentrations across northern Iran; (2) assessment of iodine content in staple foods and drinking water sources; (3) dietary iodine intake surveys in vulnerable regions; (4) controlled trials of agronomic biofortification under local conditions; (5) integration of environmental data with health surveillance systems; and (6) development of predictive spatial models for IDD risk based on environmental covariates.

The success of Iran's national IDD control program over the past three decades represents a major public health achievement. Sustaining this success in the face of environmental vulnerability and changing population characteristics requires continued adaptation and innovation. The medical geology perspective offered here provides a framework for such adaptation, ensuring that no population subgroup or geographical region is left behind in the elimination of iodine deficiency disorders.

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