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ASSESSMENT OF FLUORIDE CONTAMINATION IN GROUNDWATER AND ASSOCIATED HUMAN HEALTH RISKS IN BASTAR DISTRICT OF CHHATTISGARH, INDIA

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Abstract

Fluoride is naturally occurring yet a public health hazard in drinking water at high quantities. This research assesses groundwater fluoride pollution and human health concerns in Bastar, Chhattisgarh, India. Groundwater samples from several places were evaluated for important physicochemical properties, including fluoride levels, to understand spatial variation and geochemical impacts. For various age groups, health risk assessment was used to determine daily intake, hazard quotient (HQ), and lifetime carcinogenic risk using EPA methods. The results show that fluoride concentrations often surpass the WHO 1.5 mg/L limit. Children have greater water intake per body weight; therefore, their non-carcinogenic risk values (HQ > 1) are highest. Lifetime exposure patterns show a cautious worry for carcinogenic consequences. Hydrogeochemical investigation shows that geogenic sources—such as fluoride-bearing mineral dissolution—cause increased levels, with modest human impacts. The report emphasizes the necessity for groundwater monitoring, community awareness, defluoridation, and clean water sources. The Bastar area in Chhattisgarh needs these measures to preserve public health and guide water management strategies.

Keywords: Fluoride contamination; Groundwater quality; Bastar district; Chhattisgarh; Human health risk assessment; non-carcinogenic risk; Carcinogenic risk; Hydro geochemistry; Hazard quotient (HQ); Water quality management.

INTRODUCTION

Fluoride is a naturally occurring material that may be discovered in the crust of the Earth. It is a chemical element. In terms of both protecting the environment and the public's health, it performs a dual function responsibility. Despite the fact that fluoride is beneficial when present in low numbers, particularly when it comes to promoting dental health by strengthening tooth enamel, the presence of fluoride in groundwater at large quantities may have substantial implications. This is especially true when it comes to the possibility of causing severe consequences. The presence of fluoride in water sources is mostly attributable to the natural geological processes that occur. A portion of these processes involves the progressive dissolving of fluoride-containing minerals into groundwater over the course of a certain amount of time. Minerals such as fluorite (CaF_2), apatite, and cryolite are included in this category. The actions of humans, on the other hand, have the potential to make the situation much more severe, leading to fluoride contamination levels that are higher than those that would ordinarily be found in natural ecosystems.

The dissolution of fluoride into groundwater is influenced by geochemical processes that take place within the crust of the Earth. These processes have an impact on the amount of fluoride that is dissolved in groundwater. There are several locations where fluoride concentrations have the potential to significantly increase when the geological conditions are conducive for the existence of fluoride-containing minerals. Fluorite, for instance, is a common mineral that, when it decomposes in groundwater, releases fluoride ions into the environment. This is also true of other minerals. In addition, the process of weathering or erosion, which is driven by natural phenomena such as rainfall, groundwater movement, and temperature fluctuations, may be a contributor to the mobilisation of fluoride into bodies of water. This is because these activities are driven by natural mechanisms similar to those described above. In addition to the specific chemical composition of the rock and soil that surrounds the groundwater, environmental circumstances such as temperature and the pH of the water also have a role in determining the solubility of fluoride and the ultimate concentration of fluoride in groundwater. Both of these factors are regulated by the conditions of the environment.

Causes of Fluoride Contamination

1. **Geological Factors**: The major natural source of fluoride in groundwater is the leaching of fluoride-containing minerals from rocks and soil. This process occurs most often. The mineral composition of the geographical geology, the temperature, and the pH of the water all have a role in determining the amount of fluoride that is present in groundwater. Fluoride concentrations in groundwater are often greater in regions that are characterised by the presence of volcanic rocks, sedimentary formations, and granite.

2. **Hydrogeological Conditions**: Fluoride contamination is also affected by the mobility of groundwater and the amount of time it spends in the groundwater. The fluoride content in the water is higher in regions where the groundwater continues to come into contact with fluoride-rich materials over lengthy periods of time. Although this is not always the case, deeper aquifers may have lower fluoride concentrations than shallower aquifers, which may collect more fluoride over time. Shallow aquifers that have limited recharge may also acquire more fluoride.

3. **Human Activities**: Human activities have the potential to worsen fluoride pollution in certain circumstances. The manufacturing of aluminium, the burning of coal, and the application of phosphate fertilisers are all examples of industrial operations that have the potential to release fluoride into the environment. It is possible that mining operations, particularly in areas that are rich in fluoride-containing minerals, might also result in increased fluoride levels in groundwater sources that are located nearby.

The pollution of groundwater with fluoride is a huge problem that affects millions of people all over the globe. India is one of the nations that has been affected the most severely by this issue. There are significant quantities of fluoride in the groundwater in several places, including Bastar, which pose major health concerns to the local people. This is particularly true in the absence of efficient water treatment and monitoring systems. Fluoride is good in modest quantities; nevertheless, chronic exposure to high amounts of fluoride may result in a wide range of health issues, including fluorosis of the teeth and bones, as well as the possibility of carcinogenic consequences. A knowledge of the sources, distribution, and health consequences of fluoride contamination in groundwater is essential for the development of effective mitigation techniques and the guaranteeing of access to safe drinking water for all individuals. This is because of the possible impact that fluoride contamination might have on public health.

Importance of Studying the Health Impacts of Fluoride

The presence of fluoride in drinking water at concentrations that are greater than the acceptable limits specified by the government constitutes a significant threat to the public's health and should be avoided at all costs. The presence of fluoride in low concentrations is beneficial to oral health since it helps to prevent tooth decay and protects enamel against degradation. Fluoride is present in low concentrations. Fluoride, on the other hand, has the potential to have a detrimental effect on a variety of organs and systems inside the body, such as the bones, teeth, thyroid, and neurological system, if it is consumed in excessive quantities and over a prolonged period of time. It is possible that you may have a wide range of health problems if you are subjected to an excessive quantity of fluoride. These health problems can range from cosmetic dental issues, such as dental fluorosis, to more significant health conditions, such as skeletal fluorosis, thyroid dysfunction, and brain damage.

One of the most common adverse health effects that may be caused by excessive exposure to fluoride is dental fluorosis, which is marked by the discolouration and mottling of teeth. Fluoride overexposure can induce a variety of other harmful health effects as well. On the other hand, severe cases of dental fluorosis may cause pitting and structural damage to the teeth, which makes them more prone to decay. It is likely that mild varieties of dental fluorosis are solely aesthetic in origin. Besides the effects that fluoride has on dental health, there is also a special reason to be concerned about the effects that it has on the skeletal system. The condition known as skeletal fluorosis is one that may be brought on by continuous exposure to excessive levels of fluoride via the body. This disorder is defined by uncomfortable symptoms that persist over time, including stiffness and joint problems.

OBJECTIVES

1. To use hydrogeochemical analysis to look into geogenic and potential anthropogenic causes of high fluoride levels.
2. To create a study population typology based on multivariate analysis of important socioeconomic traits.

RESEARCH METHODOLOGY

Using multivariate analysis based on important socioeconomic indicators like income level, education, water source dependency, health expenditure, and proximity to contaminated borewells, the villages and habitations affected by fluoride contamination in the Bastar region were classified. Table 1 shows that the first five dimensions of the Factorial Analysis of Mixed Data (FAMD) model, which included both quantitative and qualitative variables, had eigenvalues of 1 or more and explained, when added together, about 42% of the total variance ($p < 0.05$). Following the use of these parameters, Hierarchical Clustering on Principal Components (HCPC) was employed to classify communities into separate groups according to their susceptibility to fluoride exposure and their ability to adjust or lessen health hazards. This typology helps to identify priority regions for focused public health interventions and safe water supply activities in fluoride-affected zones of Bastar, while also highlighting geographical and demographic inequalities in exposure levels.

RESULT

Table 1: Principal components loading and their significance for HCPC analysis

FAMD components	Eigen values	% of variance	Cumulative % of variance	r	P-value
Dim.1	6.44	16.52	16.52	0.868	< 0.001***
Dim.2	3.16	8.09	24.62	0.751	< 0.001***
Dim.3	2.57	6.59	31.20	0.453	< 0.001***
Dim.4	2.17	5.56	36.76	0.183	< 0.001***
Dim.5	1.94	4.97	41.74	0.070	0.027*

*Significant at $\alpha = 0.05$, ***significant at $\alpha = 0.001$

Hierarchical Clustering on Principal Components (HCPC) correlation analysis shows that the most informative dimensions for interpreting the relationships among the variables are the first two principal components (Dim 1 and Dim 2), which have a correlation coefficient (r) greater than 0.50. Consequently, these two parts were used to investigate the various fluoride exposure patterns and related health risks among impacted Bastar communities. In order to differentiate between risk categories and community vulnerability profiles, 15 out of the 18 variables included in the HCPC model—including socioeconomic status, water source type, awareness levels, health outcomes, and mitigation practices—were determined to be statistically significant (Chi-square test, p-value < 0.001) (Table 2). This research provides a solid groundwork for determining which populations are most vulnerable to the health risks associated with fluoride and for developing mitigation methods that are tailored to particular regions.

Table 2: Significant variables for farm type segregation

Variables	df	p.value
Farm head profile	6	9.41E-44***
PUA type	12	1.57E-30***

Cut flowers	3	5.41E-28***
Leafy vegetable	3	8.10E-17***
Herbs	3	1.74E-16***
Membership out-grower scheme	3	3.13E-14***
Irrigation Water sources	15	3.51E-14***
Irrigation system	3	2.32E-11***
Presence stream	3	2.44E-11***
Land tenure	9	4.25E-10***
Monthly income	24	4.73E-09***
Membership farmers organisation	3	8.99E-06***
Market orientation	9	1.49E-05***
Staple crop	3	4.64E-05***
Livestock	9	5.63E-03**

**significant at $\alpha = 0.01$, ***significant at $\alpha = 0.001$

Figure 2 shows the HCPC analysis's dendrogram, which categorises peri-urban farms into four distinct categories. These types represent different aspects of farmers' socioeconomic status, resource allocation, farm management, and farming philosophy. The majority of farmland, comprising 69% of all agricultural units, is farm type 1. The second cluster, which includes farm type 2, accounts for 23%, while the third cluster has 5% and the fourth cluster has 3% (Table 4.5).

Farm Type 1

Among the impacted villages in Chhattisgarh's Bastar area, 69.2% of the population falls into Exposure Group 1, which indicates the most common way fluoride is used in groundwater. The majority of these households get their water supply from shallow borewells or open wells that are situated close to seasonal streams, which have fluoride concentrations that are too high for human consumption. Most people use water for drinking and household uses, and the decision-maker in charge of choosing the water source is usually the head of the home. Ninety percent of families are either free-hold owners or have leases, leaving them susceptible to changes in water resource management regulations or changes in land usage. The majority of those who took the survey do not belong to any groups that promote water use or community health. Daily consumption amounts vary greatly, averaging roughly 3-5 litres per person, and exposure is constant all year round.

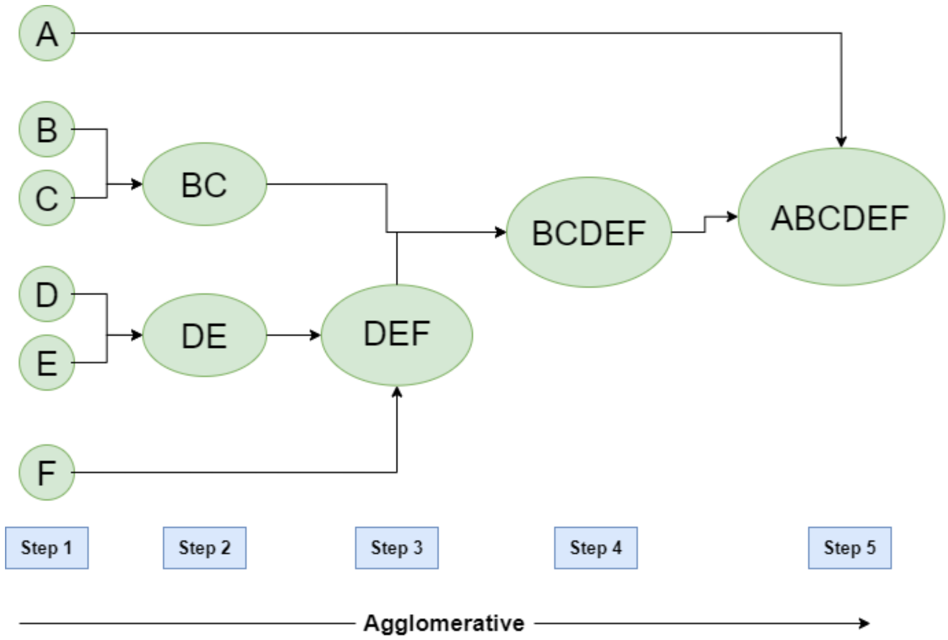

Figure 1: Cluster-gram of farmland types A (nested cluster) B (factor map) C (cluster dendrogram)

Untreated groundwater, which often contains high concentrations of fluoride, is the principal route of exposure for Group 1 families. The commodities grown in these homes, including fruit and leafy greens, might potentially absorb fluoride if watered with polluted water. Additional exposure to fluoride via animal products is reduced because of the low level of livestock raising (81% of households do not own animals). Most families earn less than ₹17,000 per month by selling agricultural goods in neighbouring local marketplaces, although those with bigger landholdings (~18.6%) may earn close to ₹40,000, limiting the economic rewards. Dependence on local groundwater supplies typically lasts about 10 years, with the age and employment of the head of the family having a substantial impact ($F=8.542$, $p < 0.001$). Additionally, there is some overlap in the geographical distribution of Exposure Group 1 with areas that have been previously identified as having moderate to high fluoride risk. These areas make up about 51% of SOF, 11% of LOF, and 38% of RG categories according to the interpretation of satellite images.

Farm Type 2

Near residential zones, on occasion along high-traffic highways, and usually far from natural water systems like rivers or streams is where 23% of respondents fall into Exposure Group 2. These farms often consist of house gardens or tiny, fragmented pieces of land that are empty while new building takes place; the sizes of these parcels range from 0.005 to 0.8 hectares, with an average of 0.3 ha. Nearby urban families oversee the farms, with the majority of landowners either purchasing (80%), leasing (16.7%), or owning (3.3%). The problems with sustainability in the long run are, however, caused by things like rising urbanisation and land subdivision. Borewells, municipal water systems, and runoff from unpaved roadside drains are the main water sources for irrigation, and they all pose different risks of fluoride poisoning.

Open fields or modest greenhouses are used for farming all year or sometimes during certain seasons, with occasional small-scale animals, mostly sheep or poultry. In the local street stores and markets, you can find the produce, which is mostly composed of leafy greens (90%), sweet corn (70%), and fruit vegetables (40%). Chronic fluoride exposure is more likely in families whose monthly income is less than ₹17,000 and who have relied on local water sources for an extended period of time. The majority of these farms, over 65% according to the satellite images, fall under the residential garden (RG) category.

Farm Type 3

Group 3 is a style of intensive greenhouse farming that focusses on growing valuable herbs for both local and international markets. Using high-input technology, such as modern irrigation systems and pesticide use, local agribusinesses or urban experts operate these farmlands, which range in size from 1.2 to 4.0 hectares. Keeping a few animals as pets is a small part of farming that happens periodically throughout the year. Depending on its closeness to water sources, this system relies on either borehole or river water for irrigation. Prior to application, river water is often treated or stabilised in ponds. In places where groundwater fluoride levels are high, the use of borewell water poses serious concerns about potential exposure to the mineral. Monthly revenue often surpasses ₹42,000, suggesting a commercial size of activity, and land ownership is mostly achieved via purchase or long-term lease. Satellite image categorisation indicates that this category includes 50% LGh farms and 50% SGh farms, or large-scale and small-scale greenhouse farms, respectively.

Farm Type 4

Type 4 farmland is an amplified version of type 3 farmland. The greenhouse production of valuable horticultural commodities, such as cut flowers, fruits, vegetables, and herbs for export, is a defining feature of these farms. Hundreds of skilled contract workers, irrigation systems, intense input, and a well-organised management plan are just a few of the contemporary production tools and technologies used by the farms owned by this consortium of foreign investors.

CONCLUSION

This research found that groundwater in several portions of Chhattisgarh's Bastar district exceeds national and WHO drinking-water regulations for fluoride. Hydrogeochemical analysis shows that geogenic processes—primarily fluoride-bearing mineral dissolution—cause most pollution, with small human inputs. Health risk assessment shows non-carcinogenic dangers, notably in children whose increased water consumption relative to body weight raises hazard quotients over the acceptable limit. Lifetime exposure to fluoride may cause cancer, underlining the need for preventative monitoring and early action. Importantly, multivariate analysis of important socioeconomic features allowed the establishment of a local population typology, revealing how socioeconomic factors affect susceptibility and exposure. This typology helps build community-specific mitigation and awareness campaigns. The results emphasize the need for water-quality monitoring, community education, defluoridation, and other water-supply improvements. Hydrogeochemical evidence and socioeconomic typology might help policymakers and public-health planners create context-sensitive health policies for Bastar inhabitants.

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