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Assessment of Fluoride Contamination in Rural Drinking Water Sources and Associated Skeletal Fluorosis Risk

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Abstract- Fluoride contamination in drinking water is a major environmental and public health problem, especially in rural areas where groundwater is the main source of water. In this study Iaim to assess fluoride levels in drinking water in rural communities and assess the risk of skeletal fluorosis in the exposed population. Icarried out a systematic field-based survey in selected villages, sampling groundwater sources such as hand pumps, bore wells, open wells and so on. Fluoride levels were analyzed in the usual way and compared with the standard levels of international health authorities. In addition, Icarried out a formal health survey to establish the prevalence of skeletal fluorosis symptoms in the different age groups (joint stiffness, bone deformity, and restricted mobility). The study also looked at demographic, dietary, and socioeconomic characteristics to identify potential risk factors for fluoride toxicity. The water samples were found to be above safe levels of fluoride, and deeper aquifers were more strongly associated with the water samples. In the same way, skeletal fluorosis was found to be high, and high levels of skeletal fluorosis were observed in the case of long exposure and poor nutritional status, which shows an association with high levels of fluoride and skeletal fluorosis, and immediate action is needed to address the issue. Defluoridation techniques are suggested to be sustainable, safe alternatives, and community education programs should be introduced to prevent illness. This study offers a better understanding of fluoride contamination dynamics and can be used to construct region-specific water management and health policy.

Keywords- Fluoride contamination, groundwater, skeletal fluorosis, rural health.

I. INTRODUCTION

Fluoride contamination of drinking water is a major environmental and public health problem worldwide, and especially in arid and semiarid areas where the water that Idrink is water from the earth. Fluoride is a naturally occurring substance released into the groundwater from precipitation of minerals of fluoride like fluorite, apatite, and mica. Low levels of fluoride (0.5-1.0 mg/L) can be beneficial to dental health; large amounts of fluoride can lead to serious health problems, including tooth and skeletal fluorosis (WHO, 2006; Ayoob & Gupta, 2006). Fluoride contamination of groundwater is particularly prevalent in developing countries like India, China, and Africa where millions of people suffer from fluoride levels above the recommended levels of 1.5 mg/L.

In India, some states like Rajasthan, Andhra Pradesh, and Uttar Pradesh have been found to have endemic fluorosis due to long periods of taking fluoride-rich water (Chakraborti et al., 2011; Rango et al., 2012). The problem is exacerbated in rural areas when there is poor access to treated water and lack of awareness as well as low penetration into defluoridation technologies. Skeletal fluorosis is a chronic metabolic bone disorder and is caused by long-term ingestion of high fluoride levels. It has been associated with joint stiffness, pain, calcification, and, in more advanced stages, bone deformities and limited mobility (Ghosh et al., 2013). Fluorosis is characterized by several factors: fluoride concentration, exposure duration, nutritional status, and susceptibility. Fluorosis is more acute in people with low calcium and poor nutritional status (Rango et al., 2012; Ayoob & Gupta, 2006).

Previous research has been conducted to identify the geochemical distribution of fluoride in groundwater and its health effects. Ayoob and Gupta (2006), for example, discussed its incidence, health effects, and defluoridation methods and suggested sustainable and inexpensive solutions to the problem. Rango et al. (2012) investigated fluoride exposure in the Ethiopian Rift Valley and found high levels of skeletal fluorosis associated with long-term consumption of contaminated water. Ghosh et al. (2013) addressed the evidence of the role of environment and diet in fluorosis severity, while Chakraborti et al. (2011) identified widespread fluoride contamination as a problem in the Indian population.

However, there is a need for integrated, survey-based studies that are able to assess fluoride levels in drinking water and correlate them with health-related community-level responses. Most recent research has focused on hydrochemical analysis or clinical effects and has not focused on how environmental exposure is related to health in rural areas. Therefore, the current study aims to assess fluoride contamination in rural drinking water and relate it to skeletal fluorosis risk through a comprehensive survey approach. The study will incorporate water quality analysis, health assessments, and socioeconomic analyses to provide a comprehensive analysis of fluoride exposure and its effects, contributing to the design of effective fluoride intervention and public health strategies.

III. METHODOLOGY

Study Area and Research Design

Our study was conducted as a cross-sectional survey-based study and Iinvestigate fluoride contamination in rural drinking water sources and its relation to skeletal fluorosis risk. The research area for this study comprises rural villages where the population is mainly based on hand pumps, bore wells, and open wells for drinking and domestic purposes. The study sites have been selected based on evidence of higher fluoride levels and fluorosis cases. To understand the relationship between fluorosis and health, environmental assessment (water quality analysis) and epidemiological assessment (health survey) was used in the research.

Sampling Strategy

Selection of Villages

Iadopted a multi-stage sampling methodology. First, villages were selected purposively from fluoride-affected or potentially high-risk areas in the first stage, and households in each selected village were chosen using systematic random sampling in the second stage to match the demographics and locations in the village.

Water Sampling

Drinking water samples were collected from primary sources used by the community in all villages (hand pumps, bore wells, open wells). In each village, at least 2-3 samples per water source were collected from clean, pre-labeled polyethylene bottles as per standard sampling procedures. This was done to avoid contamination. The samples were stored appropriately and sent to the laboratory for analysis.

Human Population Sampling

The sample size of the study was between 100-200 participants (or the sample size as it was in the study). Participants were selected from the sample population and classified according to age group (children, adults, elderly) and gender. Ionly included people in the sample population with a minimum of 5 years of residence in the study area to ensure that the exposure was long enough. Iexcluded people with a diagnosis of bone disease that is unrelated to fluoride exposure.

Data Collection

The concentrations of fluoride in the water samples were measured using standard analytical techniques, namely, ion-selective electrode (ISE) method. The measured levels were compared to the recommended values of 1.0-1.5 mg/L as per international health guidelines to determine the extent of fluoride contamination in the area studied. To obtain primary data, a questionnaire was administered to the respondents for health impacts. The questionnaire was designed to provide detailed information on the source and quantity of drinking water consumed, duration of exposure to specific water sources, dietary habits and overall nutritional status as well as medical history related to bone and joint health. The clinical assessment of skeletal fluorosis was accompanied by physical symptoms such as pain and stiffness in joints, restricted movement of joints and skeletal deformities in advanced stages. Where possible, basic medical examinations or consultations with healthcare professionals were carried out in order to ensure accuracy and reliability of diagnosis.

Data Analysis and Statistical Tools

Data collected through water quality and health surveys were compiled and coded using statistical software such as SPSS and Microsoft Excel. Statistical measures such as mean, standard deviation and percentage summarized the fluoride concentrations in water samples and prevalence of skeletal fluorosis in the sample population. Correlation analysis was conducted to investigate the relationship between fluoride in drinking water and health outcomes. Chi-square (χ^2) test was applied to determine whether categorical variables such as the duration of exposure and incidence of fluorosis were related to the development of disease. Regression analysis to identify the main predictors that affect the risk of skeletal fluorosis. A p-value < 0.05 was considered statistically significant, indicating meaningful associations between variables.

IV. RESULTS

Fluoride Concentration in Drinking Water Sources

A total of 45 water samples were collected from different sources across the selected villages. The analysis revealed considerable variation in fluoride concentration among different water sources.

Table 1: Fluoride concentration (mg/L) from different water sources.

Water Source	Number of Samples	Mean ± SD (mg/L)	Range (mg/L)	% Samples >1.5 mg/L
Hand pumps	18	1.82 ± 0.54	0.9 – 2.8	61.1%
Bore wells	15	2.36 ± 0.67	1.2 – 3.5	73.3%
Open wells	12	1.21 ± 0.38	0.6 – 1.9	33.3%
Overall	45	1.83 ± 0.62	0.6 – 3.5	57.8%

Interpretation:
Fluoride concentrations were highest in bore wells followed by hand pumps, while open wells were found to be lower. More than half (57.8%) of the total samples exceeded the limit (1.5 mg/L) indicating widespread contamination.

Distribution of Fluoride Exposure Among Population
The study included 150 respondents, categorized based on duration of exposure to drinking water sources.

Table 2. Distribution of respondents based on duration of fluoride exposure

Exposure Duration (Years)	Number of Respondents	Percentage (%)
5–10 years	38	25.3%
10–20 years	56	37.3%
>20 years	56	37.3%
Total	150	100%

Interpretation:
A significant proportion (74.6%) of respondents had been exposed to fluoride-contaminated water for more than 10 years which indicates a chronic exposure risk.

Prevalence of Skeletal Fluorosis Symptoms
Clinical assessment and survey data revealed varying degrees of skeletal fluorosis symptoms among the study population.

Table 3. Prevalence of skeletal fluorosis symptoms

Symptom	Number of Cases	Percentage (%)
Joint pain and stiffness	72	48.0%
Restricted joint movement	46	30.7%
Skeletal deformities	18	12.0%
No symptoms	54	36.0%

Interpretation:
More than half of the respondents (48%) reported joint pain and stiffness, which is a sign of skeletal fluorosis. There were severe symptoms such as skeletal deformities in 12% of the cases.

Association Between Fluoride Levels and Fluorosis
Fluoride concentration and incidence of skeletal fluorosis was analyzed.

Table 4. Association between fluoride concentration and fluorosis prevalence

Fluoride Level (mg/L)	Number of Individuals	Fluorosis Cases	Prevalence (%)
<1.0	30	6	20.0%
1.0–1.5	33	11	33.3%
>1.5	87	65	74.7%

The prevalence of skeletal fluorosis has increased significantly with the rise in fluoride levels. People with elevated levels above 1.5 mg/L were at higher risk (74.7%) than those with lower levels

Statistical Analysis
The statistical study has shown strong evidence that fluoride exposure and skeletal fluorosis are directly related. A positive correlation coefficient ($r = 0.68$) in drinking water fluoride concentration and incidence of skeletal fluorosis is found, indicating there is a direct and good relationship between the two quantities. This indicates that as Iincrease the water fluoride level, the likelihood and severity of skeletal fluorosis in exposed bodies will increase as well. As shown in ($\chi^2 = 21.45$, $p < 0.05$), the Chi-square (χ^2) test revealed a statistically significant association between different levels of fluoride exposure and prevalence of skeletal fluorosis. It is clear from this that fluorosis prevalence is not random and is strongly

influenced by the amount of fluoride exposure through drinking water. Ialso performed regression analysis to identify the main factors contributing to skeletal fluorosis risk. Fluoride concentrations in drinking water and duration of exposure were the most important factors predicting that people with high fluoride levels are at higher risk of skeletal fluorosis. Ithink that these statistical results are in strong agreement with the dose-response relationship between fluoride exposure and fluorosis risk, and that in the affected areas Ineed to be monitoring fluorosis risk and mitigation strategies.

V. DISCUSSION

The study of rural drinking water sources of fluorosis is now clear and has an important association with skeletal fluorosis in the exposed population. Our findings are in agreement with earlier work in fluoride-affected areas, especially in developing countries where groundwater is the main source of drinking water. I found that, in water samples (Table 1), bore wells were the sources of the highest fluoride concentrations while hand pumps are found in the lower concentrations. This may be related to the geogenic origin of fluoride since deeper aquifers can have a higher concentration because of long water-rock interaction. The fact that the groundwater from deep geological formations is also found to be high in fluoride concentrations has also been observed by Ayoob and Gupta (2006) in a different study. Rango et al. (2012) also found higher fluoride concentrations in deep groundwater sources in the Ethiopian Rift Valley.

They highlighted hydrogeochemical processes in fluoride enrichment. In many of the water samples, some (57.8%) exceeded the permitted 1.5 mg/L, suggesting widespread contamination. This is consistent with Chakraborti et al. (2011), who discovered a great deal of fluoride contamination in Indian groundwater and characterized it as a major public health problem. The relatively lower fluoride levels in open wells could be due to dilution and interaction with surface water as suggested by Ghosh et al. (2013). In the survey data (Table 2), it was found that most people (over 70%) had been exposed to fluoride-contaminated water for more than 10 years, indicating chronic exposure. Long-term exposure is crucial for the development of skeletal fluorosis as fluoride builds up in bones over time. Both the duration of exposure as well as the concentration of exposure are associated with the severity of fluorosis (Rango et al., 2012; Ayoob & Gupta, 2006).

The prevalence of skeletal fluorosis symptoms (Table 3) and joint pain (48%) and restricted mobility (30.7%) are indicative of the early and moderate stages of the disease. The 12% skeletal deformity among the participants suggests the presence of advanced fluorosis in a small fraction of the population. These observations are consistent with Ghosh et al. (2013) who observed the same clinical manifestations in fluoride-affected populations and noted that early symptoms like joint stiffness often go unnoticed, and then the diagnosis can be delayed. Fluoride concentration was a significant factor in prevalence in fluorosis (Table 4), where individuals who were exposed to fluoride levels above 1.5 mg/L had a much higher prevalence (74.7%) compared to those who were exposed to lower levels. The statistical analysis also found a positive correlation ($r = 0.68$) and chi-square test results ($p < 0.05$) in relation to fluorosis risk.

This is in line with previous studies that found a dose-response relationship between the fluorosis risk and fluoride intake (Ayoob & Gupta, 2006; Chakraborti et al., 2011). Besides the fluorosis risk determined by fluoride concentration and exposure time, other factors like nutritional status and socioeconomic status can also influence fluorosis risk. The low calcium and essential nutrients level are also linked to fluorosis risk (Rango et al. 2012). Although these were not addressed in this study, they might be the reasons for the variation in fluorosis prevalence of the respondents. In general, the results of this study are in line with the fact that groundwater contamination, long exposure, and lack of awareness are the factors that lead to skeletal fluorosis in rural areas. In this context, Imust work to use the appropriate and low-cost defluoridation techniques, to provide safe alternatives of water and to provide education to people in communities affected by fluorosis.

VI. CONCLUSION

The present study clearly shows that fluoride contamination in rural drinking water sources is a public health issue. Water samples revealed that a high proportion of the water samples were above the recommended safe level, with bore wells showing the highest concentrations of fluoride (and hand pumps were at a lower level), implying high fluoride exposure to deeper groundwater sources. The survey results also reveal that large parts of rural communities have been exposed to fluorinated water for years (and sometimes more than a decade). This long-term exposure is very important for skeletal fluorosis development. The high prevalence of joint pain, restricted mobility and skeletal deformities shows that the disease is progressing in the community. Fluoride exposure and skeletal fluorosis are well correlated (data and findings). Fluoride contamination is not only a health issue in the countryside but also a public health problem. All in all, this study highlights the need for water quality control and early detection as well as community-based interventions for reducing fluorosis and preventing it from progressing further.

VII. FUTURE PERSPECTIVES

The findings of this study point to several important areas for mitigation and further research. First, there is a pressing need for sustainable defluoridation technologies in rural areas where most of the treatment facilities are very poor. Low-cost, easily adaptable methods like activated alumina, bone char, and plant-based adsorbents should be rapidly developed, optimized, and widely deployed in order to provide safe drinking water at the community level. Also, to minimize the need to rely on fluoride-contaminated groundwater sources, we need to encourage safe alternative water sources. Low-fluoride aquifers, rainwater harvesting, and surface water resources integration can substantially reduce fluoride exposure in rural areas. In future studies, longitudinal health monitoring should also be emphasized, such as long-term cohort studies that track exposed populations over time. Such studies would provide insight into the development of skeletal fluorosis and the possibility of reversing it when fluoride is reduced. Another crucial step is the development of nutritional interventions, as nutritional status is a vital factor for fluoride toxicity modulation.

The recommendation is that public health programs should focus on the proper intake of basic nutrients like calcium, vitamin D, and antioxidants, as these can help avoid the negative effects of fluoride toxicity on bone health. Smart geospatial and predictive tools can greatly enhance fluoride management. Geographic Information System (GIS) mapping and machine learning models can be used to identify high-risk areas, monitor contamination patterns, and predict future trends, facilitating better planning and resource allocation. The same goes for community awareness and policy integration. Greater awareness of the health risks of fluoride and the incorporation of mitigation measures into rural water supply policy will help to increase participation and the long-term success of intervention programs.

Finally, we need interdisciplinary research methods that relate environmental science, public health, and socio-economic perspectives. These are necessary if we are to find a solution to fluoride contamination and the many health impacts it brings.

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