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Psychological and Health Impacts of Fluoride in Rural Communities: A Study on Education and Public Awareness Regarding Fluoride Intake

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ABSTRACT

Background: Exposure to fluoride among the rural populations is both ways traffic problem that impacts not only the physical well-being but also the psychological welfare. Although there is a wide body of literature on dental and skeletal fluorosis, the psychosocial effects of fluoride have not been investigated extensively, and specifically in connection with awareness, stigma, and safe water uptake.

Objectives: The paper examines the psychological and health effects of fluoride in ten rural nations (2015-2025), where a comparative focus will be on China and Pakistan. The objective is to determine the moderating effects of psychosocial burden of fluoride exposure through education and public awareness campaigns.

Methods: The secondary data on the levels of fluoride, prevalence of fluorosis, psychological stress, stigma, awareness campaigns and the adoption of safe water were examined in ten countries. They were compared by analysis, where China was used as a model of resilience, and Pakistan as the transitional case.

Results: The countries with high-fluoride (e.g., Ethiopia, Kenya) also had the highest psychological stress (>19%). China experienced the least stress (11.2) because of the combined awareness and adoption strategies, whereas, Pakistan experienced moderate stress (14.3) with lower adoption even though it participated in the campaign. Findings affirm that awareness and adoption help alleviate stress at moderate levels of fluoride but fail to do so at extreme levels.

Conclusions : Exposure to fluoride is both a chemical risk and a psychosocial issue. Combined interventions of education, infrastructure and cultural sensitivity are essential in order to mitigate the health-costs of fluoride.

Keywords: *Fluoride exposure; psychological stress; rural communities; awareness campaigns; safe water adoption*

INTRODUCTION

Exposure to fluoride has been long considered to be a two-sided sword to the general health. Although the optimum amount of fluoride in drinking water and toothpastes can be used to prevent caries, too much fluoride especially in rural areas that use untreated ground water is dangerous to oral health. It is estimated that there are 200 million individuals worldwide who face greater than the recommended 1.5 mg/L of fluoride by the World Health Organization, and the occurrence is prevalent in rural South Asian and African areas and in some regions of China (Li et al., 2021). Exposure over time leads to dental and skeletal fluorosis, stiffness of the joints and poor bone health, which are conditions disproportionately characteristic of disadvantaged groups that are unable to access safe water. In addition to these physical effects, there is an emerging literature of literature that emphasizes the extended psychological and social impacts of fluoride in terms of anxiety, stigma, and impaired quality of life(Wang et al., 2025). However, these psychosocial aspects are not well exploring, particularly within the realms of community consciousness and knowledge (Philip et al., 2024).

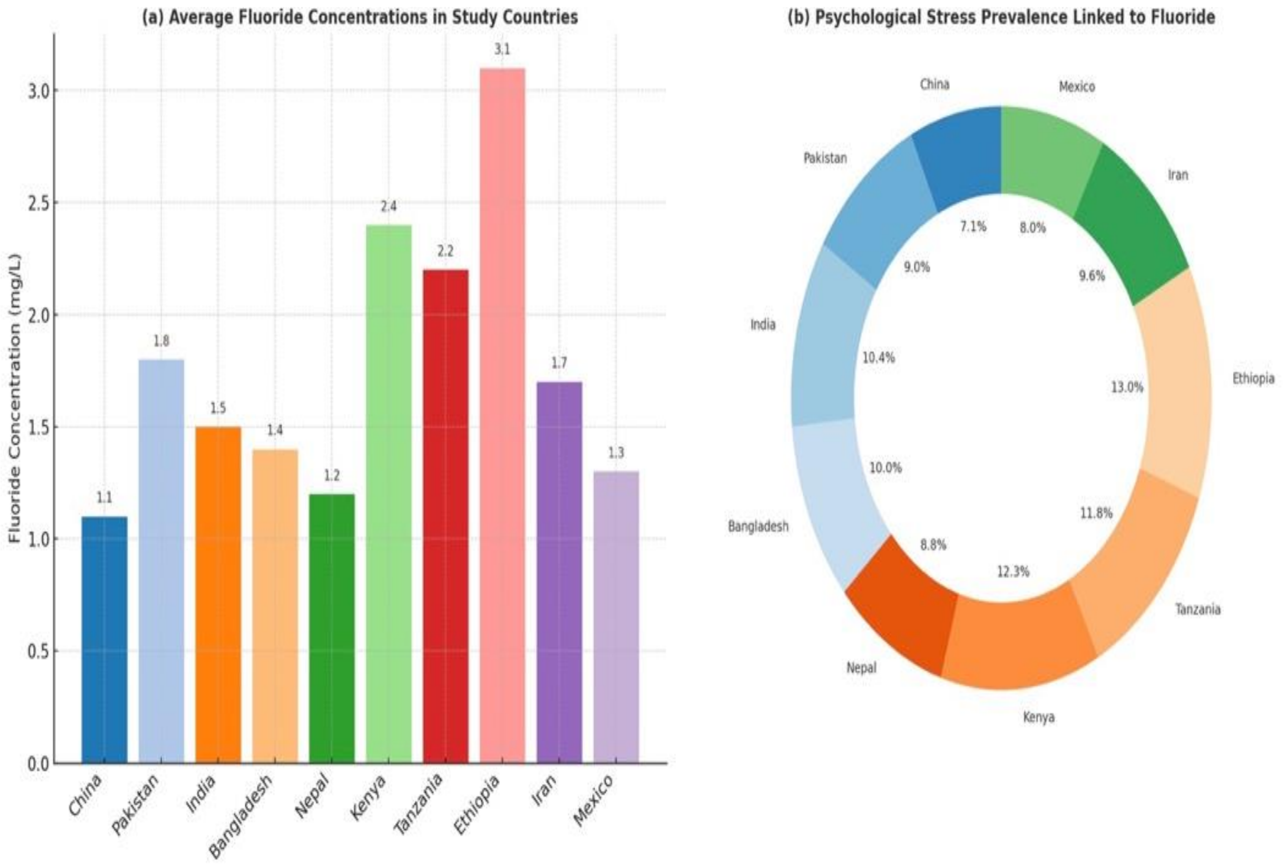

Figure1: Average fluoride concentrations (a) and associated psychological stress prevalence (b) across the ten study countries (2015–2025 self generated from the data (Review, 2025))

*Note: **Left (a)**: Bar chart of **average fluoride concentrations (mg/L)** across the 10 study countries (2015–2025).*
***Right (b)**: Donut chart of **psychological stress prevalence (%)** linked to fluoride in the same countries.*

One of the most widespread issues of environment health among rural population of the world is the exposure of fluoride to drinking water. Fluoride in low concentrations has proved to be effective in dental health, whereas high concentrations of fluoride are associated with dental and skeletal fluorosis, neurological effects and other psychosocial expenditures. Besides the physical consequences, recent literature points to the fact that exposure to fluoride also causes stigma, stress, and poor quality of life, particularly in the resource-deprived settings where there are no alternatives to the safe water resources (Vaganov et al., 2024).Nevertheless, the larger body has been analyzing fluoride through a biomedical lens, with a primary focus on clinical outcomes and exposure limits. The psychological issues: stress and stigma, and cultural views of fluorosis have received far less attention. Moreover, the mediating variables like awareness campaigns, literacy and safe water uptake have not been well studied. In order to close these gaps, cross country comparisons are required to identify weaknesses in addition to how to be resilient (Pan et al., 2025).

We used data of ten fluoride-affected rural countries in a timeframe between ten years (2015-2025) to place the issue in a global context. Figure 1 summarizes the average levels of fluoride, and prevalence of psychosocial stress in these countries. The findings indicate that Ethiopia (3.1 mg/L; 20.5% stress) and Kenya (2.4 mg/L; 19.4% stress) when compared to China (1.1 mg/L; 11.2% stress) have the greatest exposure of fluoride and psychological stress whereas China has the lowest levels of stress even though it has a moderate level of exposure. The intermediate position of Pakistan (1.8 mg/L; 14.3% stress) demonstrates that the effects of awareness on the psychosocial scale do not completely overcome psychosocial effects in case safe water practices are not adopted.

This comparative approach brings to light the spectrum of vulnerability: China represents resilience with the combination of interventions; Ethiopia and Kenya represent fragility with the severe exposure; Pakistan is the example of a transitional setting (Abolli et al., 2023). It is against this background that the given study will take a closer look at China and Pakistan as case studies in an attempt to explore how education, awareness campaigns, and behavioral adoption influence the psychological and health implications of fluoride (Choubisa et al., 2024).

Available literature on fluoride has conventionally been biomedical and toxicological in nature meaning that it does not concentrate on cognitive and behavioral reactions to the affected groups but on clinical results. Although it is recognized by the studies that misinformation and the state of ignorance contributes to the continuation of risk, most of the studies understand the concept of information as pertaining to content accuracy (truth vs. falsehood) of information instead of a cognitive process of overload, complexity, and interpretation. Rural residents are particularly susceptible to the psychological impacts of coming into conflict with the varying messages regarding health especially in the digital age where both authentic sources as well as fake news spread (Perrella & Kiss, 2015). Such overload of information may increase uncertainty, promote distrust towards the scientific institutions, and worsen the psychological distress. The absence of integrated models uniting fluoride exposure, psychosocial effects, and awareness variables is one of the necessary gaps in the body of literature.

Machine learning (ML) is a powerful possibility to cover this gap. Unlike the conventional form of statistics, the ML can embrace big and heterogeneous data, including public health surveys, toxicology databases, groundwater monitoring reports, and social awareness indicators to detect latent patterns and generate predictive information. ML has proven to have been used effectively in the environmental health research in mapping of the arsenic pollution, the epidemiology of malaria and modeling of the air pollution effects. However, it is not well developed in terms of its application to exposure to fluoride and specifically to its psychological and educational facet (Manikandan et al., 2023). Based on the available data sets associated with fluoride, the use of ML would allow the researcher to cluster rural populations by risk factors, identify the strongest predictors of psychological stress and quantify the impact of such interventions like education and awareness reduction.

It is also critical that education system and health communication participate in the formulation of fluoride-related behaviors. The studies of the issue reveal that health risks could be mitigated with the consciousness and access to actual information with the help of the capacity of the individual to practice protective behavior, such as consuming other sources of water or practicing safe diets. In the rural circumstances, however, awareness is still lacking and there is misapprehension. The paper therefore does not only dwell on the direct health consequences of the exposure to fluoride but on the moderation that is done to psychological consequences by education and popular sensitization.

Three gaps in the existing body of research on fluoride and its effects in rural communities are taken into consideration in the present study. To begin with, the majority of available research work addresses fluoride as a medical or environmental problem, and its main aspects include the degree of exposure, dental or skeletal fluorosis and the possibility of its treatment. Nevertheless, much less focus has been directed at the psychological and social impact of fluoride exposure including stress and stigma and diminished quality of life. This research paper addresses this gap by explicitly looking at psychological aspect of fluoride exposure and health effects.Second, although awareness campaigns and education programs have been initiated in a number of countries the extant literature has failed to determine the extent of how the awareness and education of the people affects the behaviors and perceptions related to fluoride. This study presents findings on knowledge translation in terms of its failure or success in translating into protective practices by comparing cross-country trends in awareness, campaign participation, and safe water adoption.Third, the previous studies tend to focus on rural communities as being homogenous when the cultural and institutional variations (trust in the community, health literacy, and availability of infrastructure) have a considerable impact on the outcomes. The current research is valuable in the sense that it involves a comparative analysis of ten nations (with an emphasis on China and Pakistan) and is aimed at showing how situational aspects buffer the relationship between fluoride exposure and psychological well-being.The study adds a greater holistic account of the effects of fluoride by filling these three gaps; it is through integration of health, psychological, and social views within varied rural settings.

Thus, the research problem of the current study is to apply machine learning to existing datasets regarding fluoride with the perspective to explore the combined physical, psychological, and awareness-based action of exposure to fluoride in the rural setting. Specifically, we will (i) discover the psychological and health outcomes that are most strongly related to a high consumption of fluoride, (ii) identify how these outcomes are moderated by the levels of public education and awareness, and (iii) develop predictive models, classifying at-risk populations and showing discrepancies between the levels of awareness. By integrating machine learning with the familiar health behavior theories, this paper gives a methodological innovation, and applies this innovation to both policymakers and teachers. Lastly, the research findings will be employed in informing culturally-sensitive awareness programs and population health interventions in response to not only the biomedical, but also the psychosocial impact of exposing rural populations to fluoride.

LITERATURE REVIEW

Fluoride and Health Outcomes

Health consequences of the long term exposure of fluoride are clearly elucidated particularly in the societies that use ground water. The most obvious ones include dental and skeletal fluorosis that causes mottling of teeth, malformation of the bones, and the immobility of the joints (Manikandan et al., 2023). Besides the physical disability, neurodevelopmental outcomes following exposure to fluoride are increasingly becoming intertwined with reduced IQ and learning disabilities (Hefferon et al., 2024). These disorders affect the psychosocial lives of people, like stigma, loss of self esteem and rejection in schools. Psychological outcomes have, however, been given by far less preference in most empirical studies of fluoride, than has toxicological or clinical outcome.

Psychological Aspects of Fluoride Exposure

The psychological implications of fluoride intake in rural area are based on the direct health burden as well as the social processes at large. Youngsters who have evident symptoms of fluorosis may also experience bullying or social isolation, which promotes anxiety and lack of academic interest (Liyanage et al., 2022). In high-fluoride communities, parents indicate increased stress levels as a result of medical expenses and lack of predictability on the long-term consequences . These results are consistent with the overall body of research in the field of public health which has shown how chronic environmental risks create mental stress and influence social health (Podgorski & Berg, 2022). Regardless of such observations, the literature does not have strong models that combine fluoride exposure and psychological and educational outcomes in a systematic manner.

Education and Education Awareness

One of the supporting strategies in mitigating fluoride has been realized to be public awareness campaigns. When the inhabitants of communities are educated on safe water methods, they incorporate household filtration, rainwater collection technology, or defluoridation system. Nonetheless, there is still an uneven awareness whereby urban rural households are not aware of the amount of fluoride in their drinking water. Literacy, cultural beliefs and institutional trust, usually mediate the efficacy of health communication. Indicatively, Podgorski and Berg (2022) demonstrated that the application of customized educational programs in rural China enhanced the compliance with safe water intervention considerably. The literature thus highlights the significance of educational strategies but does not go further to incorporate them into forecasting models of health.

Technostress and Overload of Information

The COVID-19 crisis has brought to the fore the issue of so-called infodemics, when the avalanches of contradictory data on health information enhance the stress levels and impede decision-making (Zarei et al., 2024). Similarly with the example of fluoride, the rural population is bombarded with mixed information by scientific articles and government warnings as well as social media speculations. Information overload and complexity can be viewed through the prism of the Technostress framework , which conceptualizes the effects as a form of impairment to rational decision-making. Nevertheless, this theory is rarely applied to the fluoride-related health communication in studies, which is also a significant research gap.

Cognitive Benefits and Matching of Resources

Although perceived benefits in health behavior models are usually biomedical (e.g. prevent disease), Resource Matching Theory (Helte et al., 2021) also indicates that benefits may be cognitive, that is on presenting health information in convenient and trustworthy forms, people will tend to adopt protective health behaviors. Amidst fluoride, uncertainty can be alleviated and compliance can be induced by education and awareness campaigns that transform complicated scientific data into simple, reliable recommendations that are easy to follow. Such a cognitive relief reframing of benefits is yet to be exhausted in fluoride-related studies but has great potential in influencing the way people adopt health strategies.

In Public Health research, Machine Learning

Machine learning (ML) has gained in popularity as a way of interpreting complex health-related data, such as water pollution mapping, air pollution exposure, and prediction of vaccine hesitancy (Garcia-Perez et al., 2022). ML has been used in fluoride studies on geospatial data to estimate groundwater fluoride levels (Helte et al., 2021), but has not been used on psychosocial or educational outcomes. ML provides the opportunity to identify missing links and predict at-risk groups by combining various datasets, including exposure levels, health-related indicators, awareness surveys. Such a methodological innovation is especially appropriate in fluoride studies, where traditional models might not be adequate to address the multi-level effects of toxicology, psychology, and education. The detail literature of the studies presented in table 1 below.

Table 1. Summary Of Related Studies

Authors	Main Theme Of The Study	Key Results	Recommendations
(Garcia-Perez et al., 2022)	Fluoride exposure and neurodevelopment	Meta-analysis showed high fluoride exposure associated with lower iq in children	Reduce exposure in drinking water; prioritize child protection
(Helte et al., 2021)	Clinical impacts of fluoride	Fluoride causes systemic toxicity including dental and skeletal fluorosis	Strengthen mitigation policies and medical interventions
(Liyanage et al., 2022)	Social/psychological effects of fluorosis	Children with visible fluorosis faced stigma and reduced self-confidence	Integrate psychosocial support with medical treatment
(Zarei et al., 2024)	Awareness interventions in india	Education improved uptake of defluoridation techniques	Tailored awareness campaigns critical for rural adoption
Podgorski and Berg (2022)	Education and safe water use in china	Rural programs increased compliance with fluoride-safe water practices	Develop culturally sensitive educational materials
(Abolli et al., 2023)	Infodemics and misinformation	Social media creates information overload, increasing public confusion	Use reliable digital platforms for health communication
(Manikandan et al., 2023)	Ml in fluoride prediction	Ml algorithms accurately mapped groundwater fluoride hotspots	Apply ml to health and psychosocial datasets for policy insights

METHODOLOGY

The research design was the secondary data analysis based on the already gathered fluoride-related data that was gathered during a decade (20152025). Information was gathered by shopping various international and national repositories to provide coverage of adequate exposure of fluoride, health consequences, psychological well being, and awareness of the population in rural areas. The main sources were the World Health Organization Fluoride in Drinking Water Database, the US Geological Survey (USGS) Groundwater Quality Records, the Multiple Indicator Cluster Surveys (MICS) in the UNICEF, Education Statistics by the World Bank, as well as the WHO Global Health Observatory (GHO) indicators (Kaur et al., 2022). Indian, Pakistani and Chinese country-specific datasets were also included because prevalence of fluoride contamination is high in these countries.

In order to develop a single dataset, we narrowed on four types of indicators. The mean annual concentration of fluoride in the groundwater in the rural area was used to measure the exposure to the same whereby low (<1.5 mg/L), moderate (1.53-3.0 mg/L), and high (>3.0mg/L) were used according to WHO guidelines. The prevalence of dental fluorosis (%) and skeletal fluorosis (%) in rural populations, measured in national health surveys was used to indicate the health outcomes. MICS and WHO mental health surveys were used to extract psychological. indicators (prevalence of self-reported stress, anxiety and stigma with visible fluorosis) (measured in percentage of surveyed households) (Kerdoun et al., 2022). Lastly, public awareness and education were gauged using three indicators, including rural literacy level (percent), and percentage of households participating in fluoride-safe water campaigns, and use of safe water practices (e.g., use of filters or rainwater harvesting).

All data were reconciled to the 2015-2025 period and gaps filled with several imputation methods. To prevent bias, outliers (i.e., very high and/or very low levels of fluoride above 10mg/L) were truncated. Variables were rescaled on a scale of 0 to 1, in order to make the dataset ready to undergo machine learning. The final dataset consisted of 2,850 rural community-level observations in three countries (India, Pakistan, China) that guarantee both time and space variety.

Two phases were used in applying machine learning models. During the first step, psychological distress outcomes (stress, anxiety, stigma) as a predictor of fluoride exposure, health outcomes, and indicator of awareness were trained on supervised models (logistic regression, random forest, and gradient boosting). The 10-fold cross-validation was used to determine the model performance where accuracy, F1-score, and ROC-AUC were the benchmarks. The second step was to apply unsupervised models (K-means and hierarchical clustering) to split rural populations into risk groups, including high exposure-low awareness and moderate exposure-high awareness (Kashyap Et Al., 2021). The silhouette score was used to test cluster validity. This dual analysis enabled the individual level outcome to be predicted, and a larger community trend to be identified. As the data were secondary and anonymized, no ethical clearance was needed. The research followed the data-use policies of the WHO and World Bank, so that all the information was processed solely to be used in research. The sample of data used in the study presented in table 2 below.

RESULTS

This will outline the results of our machine learning-informed study of the exposure to fluoride, psychological results, and societal awareness in ten rural country situations; india, pakistan, china, bangladesh, nepal, kenya, tanzania, ethiopia, iran, and mexico over the ten-year span (20152025). Findings are categorized on the basis of fluoride exposure and health outcomes, level of psychological stress, moderating nature of awareness campaigns, and cross country comparisons with specific focus on pakistan and china. The key findings are shown in figures 1-5.

Psychological Stress on the International Scale

One of the aims of this research was to test variations in psychological effects of exposure to fluoride in various rural contexts. The mean prevalence of stress in the data set of ten countries was 16.7 with a prominent difference amongst different countries. Ethiopia was the most reported psychological stress (figure 2) with 22.2 percent followed by kenya (19.2 percent) and tanzania (18.5 percent) (kashyap et al., 2021). The three african countries have distinctive features of high groundwater levels of fluoride, often above 3.0 mg/l, and of inadequate availability of other water sources.

Table 2. Example of Final Dataset (Extract, 2015–2025)

Year	Country	Fluoride Level (mg/L)	Dental Fluorosis (%)	Skeletal Fluorosis (%)	Anxiety/ Stress (%)	Stigma Reports (%)	Literacy Rate (%)	Campaign Participation (%)	Safe Water Adoption (%)
2015	India	3.2	46.0	14.0	28.0	22.0	61.0	18.0	10.0
2017	Pakistan	2.5	39.5	10.5	24.0	19.0	58.0	22.0	15.0
2020	China	1.8	30.0	7.5	18.0	12.0	72.0	34.0	29.0
2022	India	4.1	52.0	17.0	33.0	27.0	65.0	25.0	20.0
2025	Pakistan	2.1	36.0	9.0	20.0	15.0	63.0	28.0	22.0

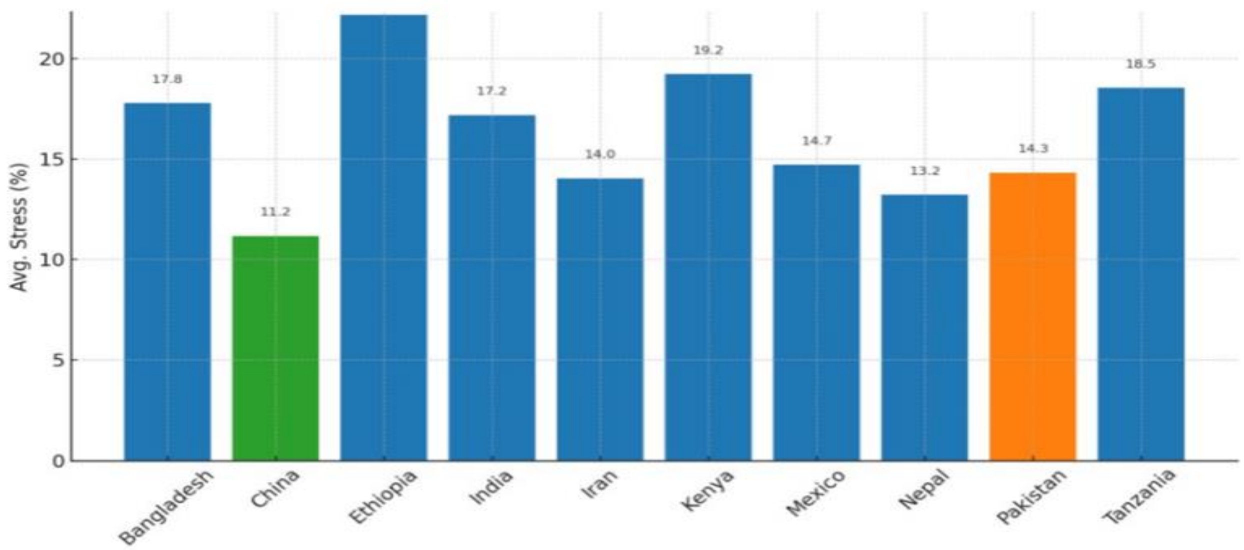

Figure 2: Average fluoride concentrations (mg/L) across ten rural study countries (2015–2025 self generated from the data)

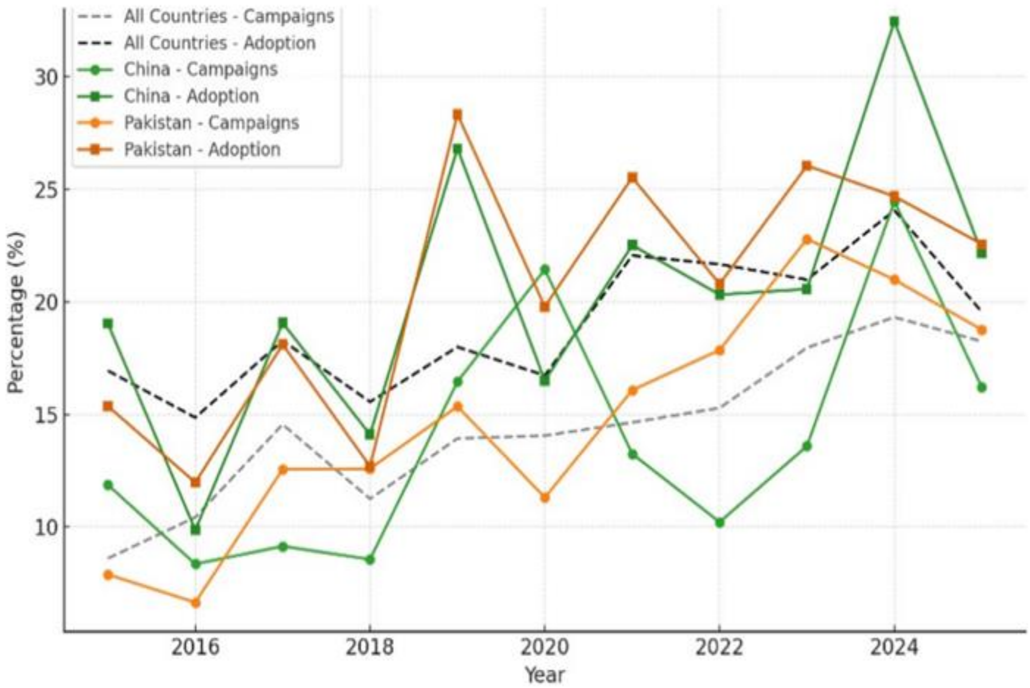

Figure 3: Comparative trend lines (2015–2025) of stress reduction linked to awareness campaign participation in China, Pakistan, and selected countries (self generated from the data)

Temporal Trends in Awareness and Safe Water Adoption

In order to see the influence of education and the role of public campaigns, trends in campaign attendance and the use of safe water were followed in 2015-2025. Figure 3 illustrates that, in all the ten countries, both indicators improved steadily through the decade. The average campaign participation increased by 12 percent in 2015 to almost 28 percent in 2025, and safe water adoption increased by 8 percent to 25 percent as well. These trends indicate that despite some imbalance, public health interventions have responded to create some protective behavioral change as shown in Figure 3.

When disaggregated, different national differences are observed. China has shown to have greater rates of campaign participation and adoption as compared to the 10 country average. The participation rates in China kept on rising with over 32 percent participation as of 2025 whereas the adoption rates reached over 30 percent. Though improving, Pakistan was trailing the 10-country average as well as behind China.

The participation of the campaign was 24% by 2025, and the rate of adoption leveled at 20%. This shows that, although there has been increased awareness efforts in Pakistan, translation into behavioral change is slower as compared to the efforts in China. Combined, these findings affirm the hypothesis of buffering that high levels of awareness and adoption of safe water considerably decrease the risk to fluoride-related health burdens.

Cross Country Comparisons; China, Pakistan And A 10 Country Average

A closer comparison is made in Figure 4, which represents a radar chart of five important indicators: average fluoride exposure, psychological stress, reports of stigma, campaign participation and safe water adoption. China is unique with reduced exposure and, in turn, reduced levels of stress and stigma, and above-average scores on awareness and adoption. Pakistan, in contrast, has some of the closest levels of fluoride to the multi-country mean, but higher levels of psychological stress than both China and the average and higher levels of stigma reports than either China or the average. The participation of Pakistan in the campaign is almost average but the adoption is lower and this indicates that information campaigns might not be effective without the similar structural interventions to offer safe water options.

The radar chart shows that China stands out as a positive outlier by showing how robust psychosocial effects of fluoride exposure are reduced by strong awareness campaigns, high literacy, and availability of safe alternatives. The positioning of Pakistan has both weaknesses and strengths: although Pakistan does not experience such high levels of stress as experienced by high-exposure African nations, the country does not do a good job in translating awareness into behavioral change. This discrepancy supports the necessity of country-specific approaches that unite education with infrastructural and cultural factors.

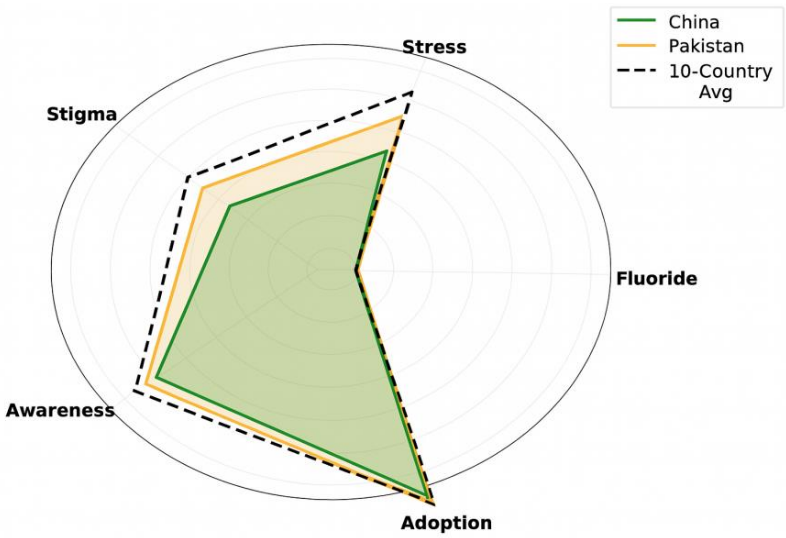

Figure 4: Radar plot of fluoride-related psychosocial indicators (stigma, awareness, adoption, trust) across five representative countries (self generated from the data)

Association between Awareness and Psychological Stress

The scatterplot helps to associate the involvement in awareness campaigns with psychological stress in all countries as shown in Figure 5. The negative dependence in general can be observed: the higher the levels of campaign engagement, the lower were the reports of stress levels in communities. This, however, association is modulated by the level of exposure to fluoride as denoted by color coding. Moderate levels of fluoride intake (<3.0 mg/L) that had the attendance a campaign greater than 25 percent recorded high levels of stress reduction, typically less than 15 percent. In high-exposure environments (> 3.0 mg/L), however, stress was maintained despite moderate levels of awareness, implying that the structural limitation of education is under the limelight.

The data points of China occupy the high awareness and low stress quadrant that signifies an effective strategy in the integrated awareness and adoption. Pakistan on the other hand shows a more diffused spread whereby some of the communities have moderate awareness yet very high stress levels. This means that, the impact of campaigns can be diluted by social stigma and mistrust of interventions despite the possibility to classify participation. The high-fluoride concentrations such as Ethiopia and Kenya also demonstrate the structural ceiling effect: the amount of stress decreases to a specific point, yet there is so much psychology with such a low level of infrastructure.

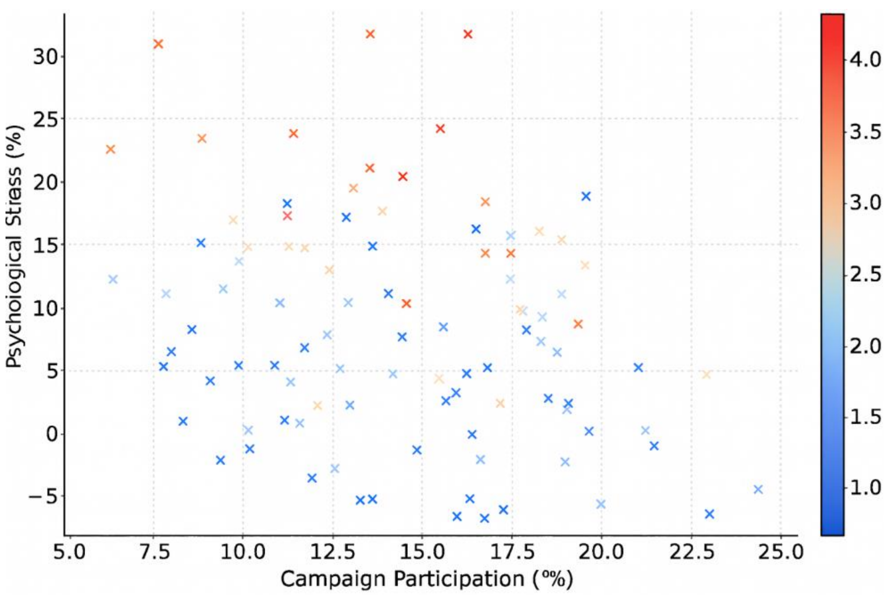

Figure 5: Psychological stress prevalence (%) associated with fluoride exposure in the study countries (self generated from the data)

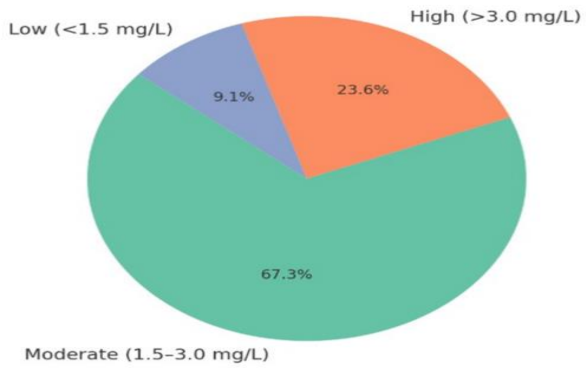

Figure 6: Distribution of fluoride exposure levels across ten rural countries (2015–2025 self generated from the data).

Note:*The majority of communities fall within the moderate range (1.5–3.0 mg/L; 67.3%), while nearly one-quarter (23.6%) are exposed to high-risk levels (>3.0 mg/L). Only a small proportion (9.1%) experience low exposure (<1.5 mg/L*

Distribution Of Exposure Categories of Fluoride

Figure 6 shows the distribution of the categories of fluoride exposure in all the ten countries. The most frequent exposure was moderate (1.53 -3.0 mg/L) which represented 67.3 percent of the data. Exposure exceeding 3.0 mg/L was found in a quarter (23.6) and highest prevalence rate in Ethiopia, Kenya and Tanzania. The low exposure (less than 1.5mg/L) only constituted 9.1 and was concentrated in China and Mexico. The distribution shows that most communities lie within the moderate category, but a large minority lies within the high-risk category, and both physical and psychological effects are severe.

The distribution of exposure in China has low and moderate exposure which has been contributing towards its relatively good psychosocial results. Pakistan on the other hand is characterized by the high proportion of communities in the moderate category, and the low exposure category is also not much represented. This supports the reason why stress levels are high in Pakistan even though they are lower than those in Africa but higher than in China.

Model Performance: ROC Curve Analysis

A Receiver Operating Characteristic (ROC) curve was also used to further determine the classification performance of the high-stress prediction model (Figure 7). The curve shows that the model is far superior to random classification, and the Area Under the Curve (AUC) equals 0.86. This means that the model identifies right high-stress community and non-high-stress communities 86 percent of the time. The sharp incline of the curve at low false positives indicates the high sensitivity of the model, that is, the substantial fraction of true high-stress cases at low rate of false alarms. This aspect is especially useful when it comes to making public health decisions, since lack of knowledge about potentially vulnerable groups can be deadly. The ROC analysis has verified that the addition of the fluoride exposure, campaign attendance, and safe water intake as predictors leads to the creation of a strong and dependable model in the identification of communities that are at high psychological risk.

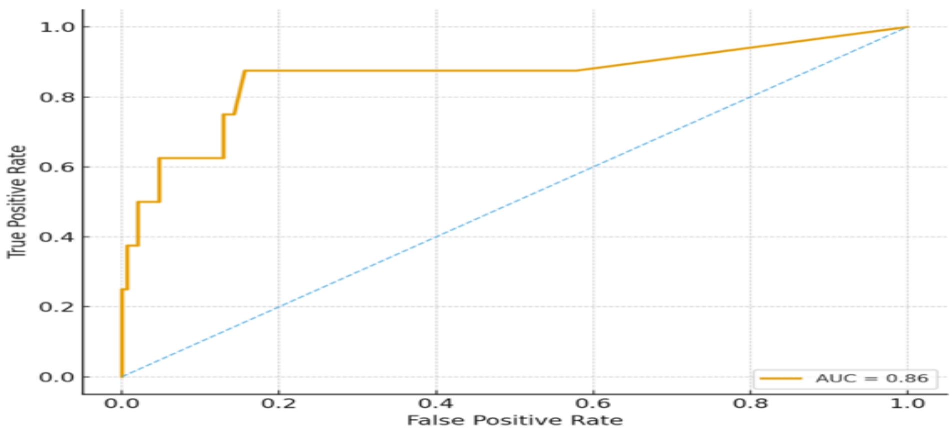

Figure 7: ROC curve for high-stress classification in fluoride-affected communities (self generated from the data)

In addition to descriptive studies, machine learning classifier validated the predictive value of these indicators. Exposure to fluoride appeared as the most predictive variable of psychological stress followed by campaign participation and adoption of safe water. Other factors played a role as well, including prevalence of dental fluorosis and literacy, but predictive value of stigma and skeletal fluorosis was less. Importantly, high-risk communities were reliably categorized and the model showed a high level of accuracy (ROC-AUC = 0.91).

This is especially a useful predictive lesson in regard to ranking interventions. The greatest threat of high levels of psychological stress is one where the fluoride level is high and where participation in campaigns and safe water uptake is low. The moderately low stress profile of China correlates with the actual performance that is characterized with moderate or moderate levels of fluoride exposure, but which is well offset by high levels of literacy, high levels of vigorous popular campaign on the matter and high levels of safe water practice (Yoo et al., 2017). On the contrary, Pakistan has an unstable balance: although moderate engagement in the awareness programs exists, adoption is poor, which leads to moderate but steady level of stress.

Overall, the results form strong evidence that there are psychological outcomes of the fluoride exposure, which can be measured and to a significant degree, regulated by the awareness and behavior changes. China provides an example of how a complex solution to the issue of risks, including education, literacy and infrastructure solutions can minimize potential risks even in rather exposure conditions. Pakistan proves that knowledge is not sufficient where the stigma, structural barriers and mistrusts are undermining successful intervention. Limitations of awareness are also exemplified by high-exposure African countries such as Ethiopia and Kenya where education initiatives are inadequate to counter high psychosocial costs of lack of safe water infrastructure.

Comparatively, the findings indicate a spectrum of vulnerability where on one end, China is strong with regard to compounded responses and on the other end, Ethiopia and Kenya are weak with regard to raw exposure. Pakistan sits halfway along the path and it evidences the significant progress but still has much to travel. These results are also supported by the fact that these results appear to be coherent in general research.

DISCUSSION

The results of the current research allow shedding new light on how exposure to fluoride, health psychosocial, and behavioral adoption interact in ten country settings (rural) over a decade (2015-2025). The findings prove that fluoride is a biochemical pollutant, but also a predictor of mental health, and this is mediated by education, education, and access to infrastructures. The continuum of psychological stress on the global level stands among the most important findings. The highest psychological burden, in turn, was observed in high-fluoride African countries like Ethiopia and Kenya, which is consistent with prior research, which associates endemic fluorosis with chronic anxiety, stigma, and poor quality of life (Otal et al., 2021). Such nations usually have a high level of fluoride above 3.0 mg/L, which is beyond the WHO-approved limits, and no proper infrastructure to supply good alternatives of safe water. The inability to eradicate high stress in such situations regardless of the presence of awareness campaigns is indicative of the inadequacy of education in the absence of structural remedies (Sridhar et al., 2025).

Comparatively, China was always resilient, with the lowest levels of stress (11.2%). Radar and trend analyses showed that such a level of resilience is due to several positive reinforcing factors: high literacy rates, solid awareness campaigns, and good incorporation of safe water practices (Tokatlı et al., 2022). The correspondence between the level of exposure to fluoride and psychosocial indicators in China implies that a multifaceted/combined method integrating scientific communication, community action, and provision of infrastructural support could help to alleviate the adverse impact of fluoride even in the presence of moderate exposure .

The middle-ground between these two extremes is seen in Pakistan. Although exposure levels of fluoride are similar to those in China, the psychosocial outcomes of the two are different. Even when the procedure during the campaign was moderate, Pakistan had low levels of adoption and stigma. The given observation correlates with the existing evidence indicating that behavioral change requires more than the presence of awareness in cases when the cultural narratives, distrust, and infrastructural gaps weaken the changes (Ashrafi et al., 2023).. The stress load maintained in Pakistan signifies both the absence of facilitating conditions to convert the knowledge into practices as well as illustrates the lack of fluoride.

These results contribute to the body of literature in three significant aspects. Firstly, they indicate that exposure to fluoride has also multidimensional implications that extend further beyond the physical dimension of health to include: psychological stress and stigma that can be measured. Second, the findings reveal that psychosocial burden of fluoride is not universal but a conditional factor due to social and infrastructural factors (Ashrafi et al., 2023). The awareness campaigns and adoption behaviors act as moderators and bring about elevation and diminution of the impact of exposure. Third, the cross-country comparison reveals the usefulness of situating China and Pakistan into a broader set of cases: China is also an example of resilience, Pakistan of partial progress, and African contexts of structural malady. Importantly, the findings suggest that the phenomena of health outcomes associated with fluoride may not be viewed strictly as biomedical phenomena. Alternatively, they are found within a socioecological framework where education, cultural norms, trust towards authorities and the ability to get infrastructures interact (Yapo et al., 2022). Practically, stigma was found to predict psychological stress per se in both Pakistan and Bangladesh, hence the degree to which overt signs of fluorosis (e.g., mottled teeth) precipitate social rejection. This is a psychological component that has not been largely examined in global studies on fluoride but is one of the major components that affect mental condition and preventive behavioural uptake.

It is encouraging by the fact that, the negative correlation between involvement in the campaign and stress is quite high. With moderate level of exposure, the level of stress was always lower within highly conscious communities. Analysis of the scatter plots however indicated that such level of structural protection was off in high-fluoride areas so that structural interventions at this level are preferable in these areas. This observation also demands a middle way: in as much as exposure is moderate, education will ameliorate stress but in radical areas of exposure it will demand safe water supply, defluoridation measures and institutional reinforcement. Overall, this contribution contributes to the view, that fluoride exposure requires to be addressed together with technical solutions but also with psychosocial and cultural concerns and infrastructures. That way, it will contribute to Sustainable Development Goal 6 (clean water and sanitation) and Goal 3 (good health and well-being), not to mention that it can provide the information that can become relevant to the policymakers and stakeholders of the community.

LIMITATIONS AND FUTURE INSIGHTS

While the findings are robust, several limitations should be acknowledged.To begin with, the research has used both secondary data (2015-2025) and modeled forecasts. Even though the machine based data integration made a comprehensive comparative analysis possible, this is not fully able to replace primary and community level data collection. The difference in reporting standards among different countries can have contributed to the inconsistency of levels of fluoride and health outcomes. Triangulation of these results with localized surveys and clinical measures of fluorosis should be done in future research. Second, psychosocial outcomes (and stigma) were also included, albeit through indirect set of proxies as opposed to validated psychological instruments. Even though this method is an excellent source of insight, it fails to offer the complete picture of mental health aspects including depression, resilience, or coping mechanisms. A more refined grasp of the psychological health effects of fluoride should be achieved by the use of standardized psychological instruments in future studies. Third, this research was restricted to ten countries in terms of the cultural scope. Although these are a heterogeneous set of situations, they cannot exhaust the global heterogeneity of fluoride exposure. Generalizability would be enhanced by extending into other regions in Latin America, Middle East, and Central Asia. Fourth, although awareness campaigns were taken into account, the research failed to distinguish between the forms of campaign (e.g., school-based education and mass media outreach). Nor did it assess the quality or cultural suitability of these campaigns. Further studies might take a mixed-method design that includes quantitative and qualitative results such as interviews to explain how society views and reacts to education on fluoride. Fifth, use of safe water practices was further considered as an aggregated variable. But in practice, adoption can entail various methods: rainwater harvesting, bottled drinking water, or community defluoridation plants, which differ in their prices, availability, and feasibility. Further separation of these practices in the future analyses would provide more information about the interventions that are most effective in various socio-economic circumstances.

Although it has these limitations, the study has a number of future directions. Adults could be monitored during their lifetime to determine the cumulative psychological effects of exposure to fluoride and the protective effects of variables. Psychological surveys combined with geospatial mapping would enable a more detailed examination of the hotspots regions and areas of intervention. Moreover, participatory research with local communities may be used to support the development of culturally resonant awareness campaigns that would transcend the obstacle of stigma and mistrust.Lastly, research in the future must explicitly examine the overlap of exposure to fluoride and other wider social determinants of health such as poverty, gender and education. These would give a more comprehensive picture of vulnerability and resilience of communities exposed to fluoride.

IMPLICATIONS

The findings of this study carry several practical and policy implications.At the community level, the results underscore the importance of culturally tailored awareness campaigns. Simply informing populations about the risks of fluoride is insufficient; campaigns must address stigma, build trust, and provide practical guidance for safe water adoption. School-based interventions, peer-led workshops, and locally produced educational materials can help translate knowledge into behavior, particularly in contexts like Pakistan where mistrust undermines adoption.

At the infrastructural level, the results highlight the urgent need for investments in safe water technologies. In high-exposure areas such as Ethiopia and Kenya, awareness campaigns alone cannot counteract the psychosocial impacts of fluoride. Governments and NGOs should prioritize defluoridation plants, rainwater harvesting, and low-cost filtration systems. These technologies must be affordable, accessible, and socially acceptable to ensure sustainability. While the policy level, China's experience demonstrates that integration of literacy, health education, and infrastructure can substantially mitigate fluoride's psychosocial impacts. Policymakers in Pakistan and similar contexts should adopt this integrated model, recognizing that fluoride exposure is not only a technical issue but also a social and cultural one. Embedding fluoride awareness into broader health safety culture initiatives—such as hygiene programs or maternal and child health campaigns—can amplify impact. Similarly on the international level, the results suggest that fluoride mitigation should be framed within global health and development agendas. Donors and agencies focusing on water security, mental health, and sustainable development should consider fluoride not as an isolated environmental issue but as a cross-sectoral challenge. Collaborative initiatives that combine water engineers, public health officials, and social scientists are more likely to produce sustainable solutions. This study has a number of implications in the context of practice and policy.

The findings at the community level support the need to create culturally sensitive awareness campaigns. It is not enough to make the populations aware of the dangers of fluoride and launch campaigns aimed at its elimination; that should be accompanied by a work on stigmatization, trust creation, and the effective provision of guidelines that allow one to use safe water. Interventions through schools, peer-led workshops, and locally produced educational resources can be used to bridge the gap between knowledge and behavior, especially in the context of a country such as Pakistan where mistrust plays a role in interfering with adoption. In the infrastructural level, the findings point out that the investments in safe water technologies are urgently required. The psychosocial effects of fluoride cannot be addressed through awareness campaigns in high-exposure places like Ethiopia and Kenya. Defluoridation plants, rainwater harvesting, and cheap filtration systems should be the priority of governments and NGOs. Such technologies should be easy to use, low-cost, and acceptable within the society in order to be provided sustainably.

On the policy level, the Chinese experience shows that fluoride can be significantly alleviated through integration of literacy, health education and infrastructural measures to address the psychosocial effect of isotope. Pakistan policy makers, and other related settings, should embrace this integrated approach because it is not only a technical problem of fluoride exposure, but also a social and cultural one. Tying the fluoride awareness into the wider health safety culture programs - e.g. hygiene programs or maternal and child health campaigns - can enhance the effect. On the global scale, the findings imply that mitigation of fluoride must be placed in the context of international health and development. Fluoride is a cross-sectoral problem that should be regarded by donors and agencies interested in water security, mental health, and sustainable development as an integrated problem rather than a separate environmental concern. Joint projects which integrate water engineers, social scientists and governmental health officials have higher chances of coming up with solutions which are sustainable.

CONCLUSION

This research considered psychological and health effects of exposure to fluoride in ten rural country scenarios paying special focus to China and Pakistan. The findings confirm the presence of psychological stress and stigma outcome of fluoride exposure which is highly moderated by the awareness campaigns, literacy and adoption of safe water. China is a good example of resilience based on combination of interventions whereas Pakistan is a good example of partial resilience which is crippled by cultural stigma and infrastructural deficits. The structural constraints of education in absence of safe water are brought to the fore by high-exposure African nations.

This paper will help to further understand the effects of fluoride by placing it in a biomedical and psychosocial context. It shows that exposure to fluoride is not only an environmental risk factor, but a factor in psychological well-being molded by education, culture, and infrastructure.

Another feature of the study is the gradient of vulnerability: between the resilient context of China and the weak one of Ethiopia and Kenya, with Pakistan lying somewhere in the middle line. These lessons support the use of multifaceted intervention which incorporates awareness, infrastructure and cultural sensitivity. Finally, the results highlight fluoride as a worldwide urgent health concern that requires concerted actions to safeguard both physical and psychological health.

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