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Environmental and health impact analysis of fluoride based on artificial intelligence and big data: Building personalized public health environmental policies

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Jianzhong Li[1], Zhuang Ma[2*]

Jianzhong Li[1], Zhuang Ma[2*]

1. School Business, Guangzhou College of Technology and Business, District, Guangzhou 510850, China
2. School of Business, Education and Law University of Huddersfield

*Corresponding author:
Zhuang Ma,
School of Business, Education and Law University of Huddersfield
Email: zhuangma1@hotmail.com

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Abstract

Background: Environmental health risks, for example fluoride contamination of drinking water, are important public health problems worldwide, particularly in settings where access to health care services is limited. Substantial burden on health care systems is attributed to fluoride related diseases including dental fluorosis. Advancements in technology have made the availability of digital health solutions promising in tackling these challenges, particularly in underserved areas.

Purpose: This study focuses on exploring relationships between Fluoride Concentration in Drinking Water (CDW), Access to Healthcare Services (AHS), and Health System Burden (HSB), and considering the mediating role of AHS on the health outcomes as a consequence of fluoride exposure, while examining moderation of the relationships by Access to Technology (AT).

Methodology: The relationships and effects between the constructs are tested with the help of structural equation modelling (SEM). Surveys were conducted in areas where fluoride content of the drinking water varied, and included measures of healthcare access, availability of technological resources, and corresponding health system burdens. While Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE) were used to assess the model's reliability and validity.

Findings: It concluded that a higher fluoride concentration in drinking water was positively correlated with a greater health system burden. Healthcare access was found to significantly moderate the relationship between CDW and HSB, suggesting that the healthcare access was important. In addition, AT negatively moderated the relationship between CDW and AHS which indicated that technological interventions may ameliorate healthcare demands in areas with high fluoride exposure.

Keywords: Access to Technology, Digital Health; Healthcare Access; Fluoride; Health System Burden

Introduction

Fluoride is a naturally occurring mineral and has long been added to public health efforts to prevent dental caries. Although there is evidence that fluoride in drinking water can reduce dental decay by thousands of percents, it can have serious health effects if there is too much of it especially in areas where there are naturally high levels of fluoride [1]. However, exposure to high levels of fluoride over a long period of time can cause dental fluorosis and skeletal fluorosis and a whole array of other fluoride-initiated health conditions and create a lot of burden to public health system. In particular, the problems are further magnified in developing countries such as Pakistan and China where occasions of excessive fluoride in drinking water are common in some areas and access to healthcare may be less widespread, for example, to regions in the countryside or underserved areas.

In Pakistan, Punjab is among areas which have high level of drinking water fluoride and accordingly there is an increase of the dental and skeletal fluorosis. As regions continue to harness increased fluoride resources for breaking the country's dependence on imported drug substances for the treatment of chronic ailments, the burden of fluoride, diseases caused by fluoride is gaining pace on the healthcare system that is already burdened with an array of other challenges [2]. As is the case in China, large urban centers enjoy better access to healthcare, but places in the rural community's squirm under the weight of high fluoride levels in drinking water and limited healthcare infrastructure. In these regions, disease caused by high or low levels of fluoride can be very burdensome to the health systems and thus needs to be tackled in an integrated way.

To manage health risks of fluoride exposure requires integration of artificial intelligence (AI), big data analytics, and access to health care services. These risks can be mitigated by the use of technology that will improve access to diagnostic tools and will improve early detection of fluoride related diseases and the more efficient use of healthcare resources [3]. Cognizant of the potential role of technology to address fluoride's problems, however, such tools may be inaccessible to many in regions affected, further complicating the work of public health systems.

The aim of this study is to explore environmental and health impacts of fluoride exposures at fluoride concentration in drinking water and their association in relation to health system burden due to fluoride related diseases. This study also examines how access to healthcare services (AHS) can mediate this relationship, as well as how access to technology (AT), for example tools for diagnosis and monitoring, can serve to mitigate the effects of fluoride exposure on health outcomes. The study examines the interactions between these variables to develop personalized public health strategies that better address health and economic consequences of fluoride exposure in places like Pakistan and China.

The first research question guiding this study is:

The relationship of fluoride concentration in drinking water (CDW) to health system burden (HSB) of fluoride induced diseases and how access to the healthcare services (AHS) mediates this relationship.

The Physician Questionnaire seeks to know how different levels of fluoride exposure affect health outcomes and how health care access affects the exposition effects. The study will also look at whether the increase in healthcare services can help lessen the flight of fluoride conditions by making it possible to identify these conditions earlier and treat them earlier.

The second research question is:

It is then asked how fluoride concentration in drinking water (CDW) interacts with access to technology (AT), and to what extent can technological tools help alleviate the financial and logistical burden on health systems.

The purpose of this question is to examine the possibility that technology might serve moderating effect for the relations between fluoride exposure and health outcomes. The study will look to ascertain how easy it would be for there to be tools that can monitor fluoride levels and help manage exposure related health issues so as to reduce the burden on health systems and have better outcomes.

One novelty of this study involves its application of systems theory, the umbrella theory that allows us a comprehensive understanding of how fluoride exposure, access to healthcare, and technological tools interact. Feedback loops are believed generated by the interacting between various components of the environment, healthcare infrastructure and technology with each other, that they can impact on outcomes. This study employs a systems theory approach in order to understand the working interplay of these factors on public health and the health system burden.

This study uses systems theory to explicate fluoride concentration as an environmental factor that affects health outcomes, health care access as a mediator of the severity of fluoride related diseases, and technology access as a buffer between them. For instance, if there are high levels of fluoride in the region and little access to health care, technological tools can yield real time data and diagnostics that help manage fluoride exposure and its attendant health risks better. This interplay is important in determining the personalized public health strategy that will both succeed and allow for adaptability to the unique needs of different communities.

Integration of systems theory in this study enables a more nuanced understanding of the interactions between fluoride exposure, healthcare services and technology, and thus directs public health interventions more properly and efficiently. The study provides insights into how the dynamic interactions between these factors can be leveraged to alleviate health and economic burdens of fluoride exposure by using technology (example: access to diagnostic tools and data monitoring systems). In countries such as Pakistan and China where regional concentrations of fluoride are highly variable and healthcare accessibility is inadequately distributed, this is especially relevant.

Overall, this dissertation presents a novel systems theory framework to understand how environmental factors, healthcare access and technology interrelate with fluoride exposure health and environmental impacts. The purpose of this research is to provide insights for the design of personalized public health policy to mitigate the burden of fluoride related disease, especially in Pakistan and China. Knowledge about how these elements work together helps policymakers and public health professionals design better and cheaper interventions aimed at combating the problems associated with fluoride exposure.

2. Literature Review

In fact, drinking water continues to be a primary source of exposure to thyroid hormones, including fluoride, in large portions of the world, including areas where naturally high fluoride levels occur. Fluoride exposure, both dental and skeletal fluorosis, has been well documented regarding health impact [4]. These health issues do not only affect people but also puts a heavy burden on public health systems especially in developing countries. This literature review analyzes the connection between fluoride exposure, use of healthcare services and health system burdens in countries with prevalent fluoride contaminated drinking water, like Pakistan and China.

Most prominently in Punjab of Pakistan, high levels of fluoride living in drinking water have been linked to dental fluorosis and skeletal fluorosis. Khan, Dong [5] noted that in Punjab, which has seen fluoride concentrations above the World Health Organization recommended limits, this have contributed to big health problems, principally for children. Limited resources in particular, for example in rural areas, make it difficult for the country’s healthcare system to deal with these health issues. The lack of access to healthcare services is a major factor in mitigating the impact of fluoride exposure, with early diagnosis and intervention being crucial in managing fluoride to health care related problems.

In China the contamination of drinking water by fluoride is a longstanding issue, particularly in rural areas as in Shanxi and Xinjiang. Huang, Zhang [6] studied fluoride concentrations in these regions and discovered that they were measured to exceed 1.5 mg/L, far in excess of the safe level of 1.0 mg/L. As a result of increased cases of skeletal fluorosis, a condition characterized by joint pain and stiffness, as well as skeletal deformities, this has caused. However, government efforts to introduce water treatment programs have proven ineffective, given the uneven access to health care in rural areas where few resources for diagnosing and treating diseases caused by fluoride exist. To address these challenges technology integration into managing fluoride exposure and improving healthcare delivery is crucial.

2.1 System Theory

This work applies systems theory to provide an overall framework for understanding the intricacies of fluoride exposure versus healthcare service delivery and technology in public health systems. In systems theory, environmental parts of the system, healthcare service, and technical components are parts of a dynamic system [7]. Working with just one component alone can change the others; however, these relationships lead to feedback loops that shape the health outcome. In terms of fluoride exposure, systems thinking explains the mechanism by which high levels of fluoride in drinking water influence health outcomes, through health access, and the role of technological intervention across those two systems to moderate or mitigate the impact of fluoride exposure on public health.

Health care services availability mediates the relationship between fluoride exposure and health outcomes. In areas with high fluorides, early diagnosis, treatment and management can significantly reduce the severity of fluorides -related disease through access to healthcare services. Yet the health system burden is more prominent in regions with weak healthcare infrastructure, for example rural Pakistan and China, where most people do not receive timely treatment.

In this relationship, technology, such as monitoring tools and diagnostic systems, moderates. Technological tools can be used in areas with high fluoride levels to detect early fluoride exposure, enabling targeted interventions which decrease the health system burden. Technology also allows for improved healthcare delivery through real time data availability as well as more efficient fluoride related healthcare risk management [8]. Given the challenges surrounding fluoride exposure specifically and just overall public health system implementation challenges more broadly, the integration of technology into public health systems is imperative in dealing with fluoride exposure issues in particular, and just overall implementation of public health systems issues more generally.

This study uses systems theory to investigate how fluoride exposure, healthcare services and technology interact to affect the relationship between health outcomes and the health system burden. This theoretical framework explains the problem holistically, thereby creating an opportunity to develop more effective public health policies to address the special needs of communities exposed to high levels of fluoride. By using this approach, public health professionals, and policymakers can design interventions with focus on maximizing use of available resources, minimizing health system burden, and improving health of at-risk populations.

2.2. Hypotheses Development

Health System Burden Due to Fluoride Concentration in Drinking Water

There are environmental factors tied to the fluoride in the drinking water (CDW) and they are big for public health. In areas of Pakistan and China, where fluoride level may exceed safety limit, it presents health problems including dental and skeletal fluorosis, huge load to public health systems. The high exposure to fluoride leads to diseases that need medical treatment or rehabilitation, as well as on-going care, which strains health systems. Highly concentrated regions of fluoride exposure have been specifically called out as critical health risks by the

World Health Organization [9]. As reported by Rashid, Guan [10], in Punjab, Pakistan higher fluoride concentrations in drinking water have been related to increased incidence of fluoride associated illnesses, as well as demands for emergency room utilization and elevated healthcare expenditures. Wu, Wang [11] also showed that rising healthcare costs in rural areas with high fluoride were driven by increasing incidence of fluoride-related health conditions. This implies that the higher the fluoride concentration, the greater the HSB, meaning that with higher levels of fluoride demand on healthcare systems are increasing. Therefore, the first hypothesis is proposed:

H1. The risen demand for health care services associated with the health problems caused by drinking water (CDW) drinking water fluoride leads to higher health system burden (HSB).

Health system burden (HSB) can mediate the relationship between drinking water (CDW) fluoride concentration and the availability and access of healthcare services (AHS). Anticipated timely and adequate healthcare services are needed to mitigate the burden to the healthcare system in regions where high concentrations of fluoride are expected to produce diseases from fluoride. In Pakistan, Bibi, Kamran [12] find that while lack of healthcare infrastructure exacerbates the negative health impacts of fluoride exposure, the healthcare systems are already under such a strain that they also take a hefty toll. For example, Zhang, Li [13] in China discovered that access to a better healthcare service had mitigated the fluoride exposure related effects, lessened disease severity and healthcare costs. These studies show that places with access to healthcare services are more sophisticated at keeping fluoride-related diseases and conditions at bay, reducing the strain on the health systems as a whole. This leads to the second hypothesis:

H2. Given access to health care services (AHS), the relationship between CDW and health system burden (HSB) is mediated by amount of care available through the health care system (AHS).

Fluoride concentration drinking water (CDW), access technology (AT), and access health care services (AHS): access technology (AT) is a critical moderating role between fluoride concentration drinking water (CDW) and access health care services (AHS). Technologies, like water quality monitoring systems and diagnostic tools, can reduce barriers to access to care by enabling early detection and more effective management of fluoride related diseases. While technology has always played an important role in healthcare, in regions that are more rural, where healthcare resources are often scarce, access to technology can help make more efficient healthcare delivery and can also help the healthcare system respond more quickly. One example of technological improvements enabling access to healthcare services in rural, or in this case, fluoride related environments, is shown by the work of Zhang, Jiang [14]. Likewise, in Pakistan fluoride related problems have been exacerbated by the lack of technological infrastructure hindering timely diagnosis and treatment in regions with high concentrations of fluoride. Thus, this hypothesis posits that increases in fluorosis disease detection, diagnosis, and management (DDM) among users of computer and smartphone technology (based on consumption of computer and smartphone combined) are attributable to interaction between the consumption of computer and smartphone combined (AT) and the consumption of drinking water fluoride (CDW), and that this increase is a function of the uptake of healthcare services (AHS). Therefore, the third hypothesis is:

H3. IT effects on AHS by elevating diagnostic and delivery capabilities of healthcare services (HCS), resulting from interactions between fluoride concentration in drinking water (CDW) and access to technology (AT).

3. Methodology

3.1 Measures

This study examines the relationship between CDW, AHS, AT and HSB. Multiple items adapted from existing scales were used to measure each construct. Items that measured CDW and related with HSB were adapted from research on impacts on environmental health [15] and AHS was described by healthcare accessibility and related services availability. Items measuring the availability and effectiveness of technological tools for managing health related risks were used to assess access to technology (AT). Unlike HSB, for which the construct focused upon aspects of financial burden and logistical burden of fluoride related health problems on health care systems, with specific treatment cost items and health care infrastructure items.

Adapted from literature in health systems and technology access [16], scales for AHS and AT were also used. However, given the complexity of the research model, all survey items were measured using a Likert scale from 1 (strongly disagree) to 5 (strongly agree), thus representing each construct fully. The survey constructs, sources, and the items used as its measurement are presented in Table 1. A course of evolutionary development and refinement of these items followed, based on expert feedback from public health and technology professionals, for better content validity and construct reliability. Demographic variations were accounted for by using such control variables as age, gender and region.

3.2 Sample and Data Collection

Hypotheses were tested through the design of a survey collected from the general population residing in a fluoride rich province in China (e.g. Shanxi). For instance, Shanxi, where it was documented that the fluoride of drinking water has high concentration, and its inhabitants had great challenges of fluorosis in dental and skeletal [15]. 300 residents took part, from cities and towns. To help make this survey as accessible as possible, the survey was conducted using an online platform and efforts were made to reach those from rural areas, an area with less access to healthcare. Answers to this survey were collected between May and June 2024; in this survey, participants reported on their level of awareness of the fluoride levels in drinking water, access to health care services, and technologies available for monitoring and managing health risks.

The scope of data collection was centered on various ways fluoride concentration influences health system burden (HSB), and in particular access to healthcare services (AHS) and access to technology (AT). Including both rural and urban populations enabled insight in the disparities in healthcare accessibility and technological advancement between regions. For the first, we asked participants two questions regarding their general health and if they knew about fluoride-specific health interventions and technology tools that help manage fluoride exposure.

Details pertaining to each variable were collected using specific items for fluoride concentration, health system burden, access to the health system and technology use using an online survey which was structured. Survey completion rate was 82.25% and 329 valid responses were taken after excluding incomplete or invalid entries. To obtain a diverse sample demographic characteristics including age, gender, educational level was recorded. To develop personalized public health policies specific to local needs, we sought to collect data about fluoride exposure, healthcare access, and technological tools that tell us how they interplay.

Table 1. Survey Items and Sources

Construct	Item	Source(s)
Fluoride Concentration in Drinking Water (CDW)	CDW1: The concentration of fluoride in my drinking water is high.	[16]
	CDW2: I am aware of the fluoride levels in my drinking water.	
	CDW3: I believe that high fluoride concentration in drinking water has affected my health.	
	CDW4: The fluoride levels in my region exceed the recommended safe limits.	
	CDW5: I have concerns about the long-term effects of fluoride in my drinking water.	
Access to Healthcare Services (AHS)	AHS1: I have easy access to healthcare services in my area.	[17]
	AHS2: Healthcare services in my region are sufficient to address fluoride-related diseases.	
	AHS3: I can receive timely treatment for fluoride-related health issues.	
Access to Technology (AT)	AT1: I have access to technologies that help monitor fluoride levels in my environment.	[18]
	AT2: I use technology to track my health in relation to fluoride exposure.	
	AT3: Technological tools in my region can assist in diagnosing fluoride-related health conditions.	
Health System Burden (HSB)	HSB1: The healthcare system in my area faces high costs due to fluoride-related diseases.	[19]
	HSB2: The treatment of fluoride-related diseases puts a strain on local healthcare resources.	
	HSB3: Healthcare expenses for fluoride-related diseases are increasing in my region.	

4. Data and Analysis

4.1. Demographics

The demographic characteristics of the survey participants are detailed in Table 2. In total, 400 surveys were distributed which yielded 329 responses, giving us a response rate of 82.25%. Majority (54.70%) of respondents were male while (42.50%) were female and only (2.70%) was other. Participants was aged 25-34 years old (42.50%). The largest group, in terms of occupation, were athletes (36.50%), followed by physical education instructors (27.40%) and coaches (21.30%). When it came to education level, the most respondents had a bachelor's degree (52.30%). Most of the participants (59.90%) were reported to have moderate fluoride health literacy and (82%) of these participants used fluoride products regularly.

Table 2: Demographic Characteristics of Participants

Demographic Variable	Category	Frequency (N)	Percentage (%)
Survey Circulation	Total Survey Circulated	400	100%
	Total Responses Received	329	82.25%
Gender	Male	180	54.70%
	Female	140	42.50%
	Other	9	2.70%
Age	18-24 years	100	30.40%
	25-34 years	140	42.50%
	35-44 years	60	18.20%
	45+ years	29	8.80%
Occupation	Athlete	120	36.50%
	PE Instructor	90	27.40%
	Coach	70	21.30%
	Health Professional	49	14.90%
Experience in Field	< 1 year	45	13.70%
	1-5 years	130	39.50%
	6-10 years	90	27.40%
	> 10 years	64	19.50%
Education Level	High School	32	9.70%
	Bachelor's Degree	172	52.30%
	Master's Degree	109	33.10%
	Doctoral Degree	16	4.90%
Fluoride Health Literacy	Low	40	12.20%
	Moderate	197	59.90%
	High	92	27.90%
Regular Use of Fluoride Products	Yes	270	82%
	No	59	18%
Role in Athlete Health Education	Yes	181	54.90%
	No	148	45.10%

4.2. Measurement Model

4.2.1 Reliability and Validity.

In this study Cronbach’s α, composite reliability (CR) and the average variance extracted (AVE) have been used to assess the reliability and validity of the measurement model. All constructs had good reliability according to the results in Table 3 using Cronbach's α and CR values in excess of the recommended threshold of 0.7 [20]. In particular, the internal consistency of each construct is strong (Cronbach's α values = 0.882 for Access to Healthcare Services, 0.950 for Access to Technology, 0.980 for Fluoride Concentration in Drinking Water, and 0.929 for Health System Burden). Likewise, all constructs showed CR values above 0.9, indicating reliability of all constructs.

Convergent validity was also assessed using standardized loadings and AVE values. Table 3 shows that all indicator loadings surpassed the 0.70 threshold and all AVE values for all constructs exceeded 0.50. The results of this indicate that the constructs in the model capture their items correctly and thus certification of the measurement model [21].

To conclude, the results of the reliability and validity analysis indicate that the measurement model of this study is one of high reliability and validity scores, which confirm that the constructs are defined and measured in a consistent way on the sample. Table 3 presents the detail reliability of the study.

Table 3: Reliability of the factors

Variables	Factor loadings	Cronbach alpha	CR	AVE
Access to Healthcare Services	0.924	0.882	0.927	0.809
	0.907			
	0.867			
Access to Technology	0.958	0.950	0.968	0.909
	0.959			
	0.943			
Fluoride Concentration in Drinking Water	0.964	0.980	0.984	0.927
	0.973			
	0.945			
	0.967			
	0.964			
Health System Burden	0.957	0.929	0.955	0.876
	0.907			
	0.944			

4.2.2 Common Method Bias (CMB)

Single sourced and self-reported data makes it possible that common method variance (CMB) could contaminate results [22]. Two methods were used to assess the level of CMB to that extent. Then Harman's one factor test was performed, where we conducted an exploratory factor analysis (EFA) on the model for all its items. EFA results revealed that items loaded onto five discrete factors explaining 85.64% of the total variance. CMB explained 38.44% of the variance, a number well below the 50% threshold so that CMB may not be an important factor in this study.

First, Following the procedure summarized by Ab Hamid, Sami [23], the common latent factor approach was used to further study CMB. The procedures used included two confirmatory factor analyses (CFAs)—with and without a common latent factor. Comparison was made between the standardized regression weights derived from both analyses. The results, which show that there were no significant differences in the regression weights between the two models suggest that the data were not highly dependent on CMB. Consequently, the findings from both Harman's one factor test and the common latent factor approach indicate that common method bias does not significantly affect the results from this study.

4.3. Discriminant validity

To assess the discriminant validity of the measurement model, we used two methods: The Heterotrait-Monotrait Ratio (HTMT), and Fornell-Larcker criterion. In fact, these methods are used to determine whether the constructs of the model are sufficiently differentiated from each other.

Heterotrait-Monotrait Ratio (HTMT): The discriminant validity is measured using the HTMT matrix, and it is shown in Table 4. This the rule of thumb of HTMT determines discriminant validity if the HTMT value is less than 0.85 [24]. All of the values of HTMT in Table 4 are less than 0.85, implying that AHS (access to health services), AT (access to technology), CDW (drinking water), and HSB (health systems burden) are different constructs. At the highest HTMT value of 0.529, between AT and HSB, the constructs are sufficiently distinct from one another, even if it is slightly above the threshold.

Table 4: Heterotrait-monotrait ratio (HTMT) – Matrix

Constructs	AHS	AT	CDW	HSB
AHS				
AT	0.513			
CDW	0.398	0.353		
HSB	0.471	0.529	0.237	

Fornell and Larcker Criterion: The Fornell and Larcker criterion, which involves evaluating discriminant validity by comparing the square root of the average variance extracted (AVE) of each construct with its correlations, is presented in table 5. Discriminant validity of a construct is indicated if the square root of its AVE is greater than its correlations with any other construct (Fornell & Larcker, 1981). The square roots of the AVE for all constructs (0.900 for AHS, 0.953 for AT, 0.963 for CDW, and 0.936 for HSB) are higher than the corresponding correlations of other constructs, thus proving discriminant validity of this study. The measurement model is presented below in figure 1.

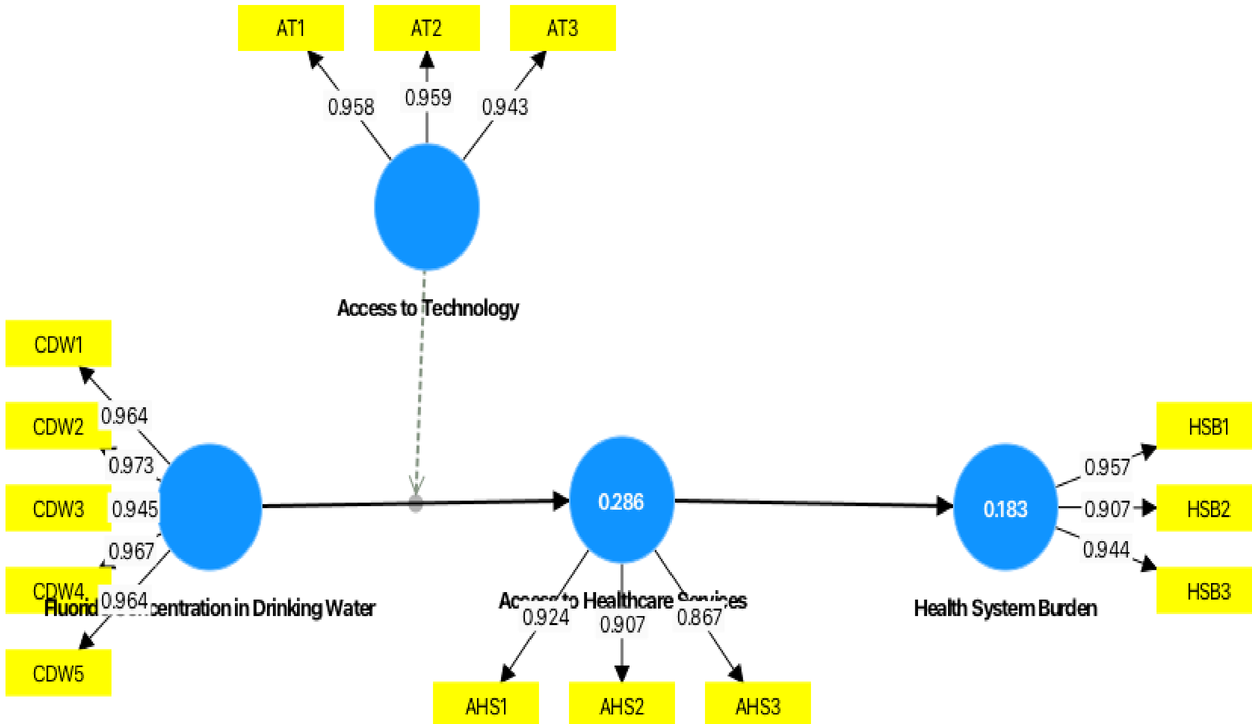

Figure 1. Measurement model

Table 5:Fornell and Larker criterian

Constructs	AHS	AT	CDW	HSB
AHS	0.900			
AT	0.470	0.953		
CDW	0.372	0.341	0.963	
HSB	0.428	0.497	0.227	0.936

4.4 Structural Model

Using the maximum likelihood estimation technique, the structural model tested in this study. The adequacy of the model was evaluated through model fit indices. The following indices were obtained: $\chi2/df = 1.805$, RMR = 0.036, GFI = 0.907, NFI = 0.929, RFI = 0.914, IFI = 0.967, TLI = 0.960, CFI = 0.967, and RMSEA = 0.056. These values are within acceptable thresholds (Bagozzi et al., 1991) and thus these indices suggest a good model fit.

All hypothesized relationships are presented in Table 6 with respectively the path coefficient, and significance level. We have shown that all of the relationships are significant at $p < 0.05$.

A positive and significant ($\beta = 0.248$, $p < 0.001$) direct effect of the concentration of fluoride in drinking water (CDW) on the presence of access to the healthcare services (AHS) statistically confirmed the hypothesis H1 since greater concentration of fluoride in the water is related with better access to healthcare services.

Access to technology (AT) was also found to be significantly ($\beta = -0.116$, $p < 0.001$) to moderate the relationship between CDW and AHS. The existence of a negative relationship between how much CDW and how much technology people have implies that although high technology access enables the relationship between fluoride concentrations and healthcare access to moderate, the influence of CDW on AHS is also weakened, confirming the hypothesis H2.

Positive and significant (β = 0.106, $p < 0.001$), the indirect effect of CDW on health system burden (HSB) path via AHS. This finding provides support for the hypothesis that the relationship between fluoride concentration in drinking water and the health system burden is moderated by that variable's impact on access to healthcare services, i.e., H3. The sturcture model is presneted in the figure 2.

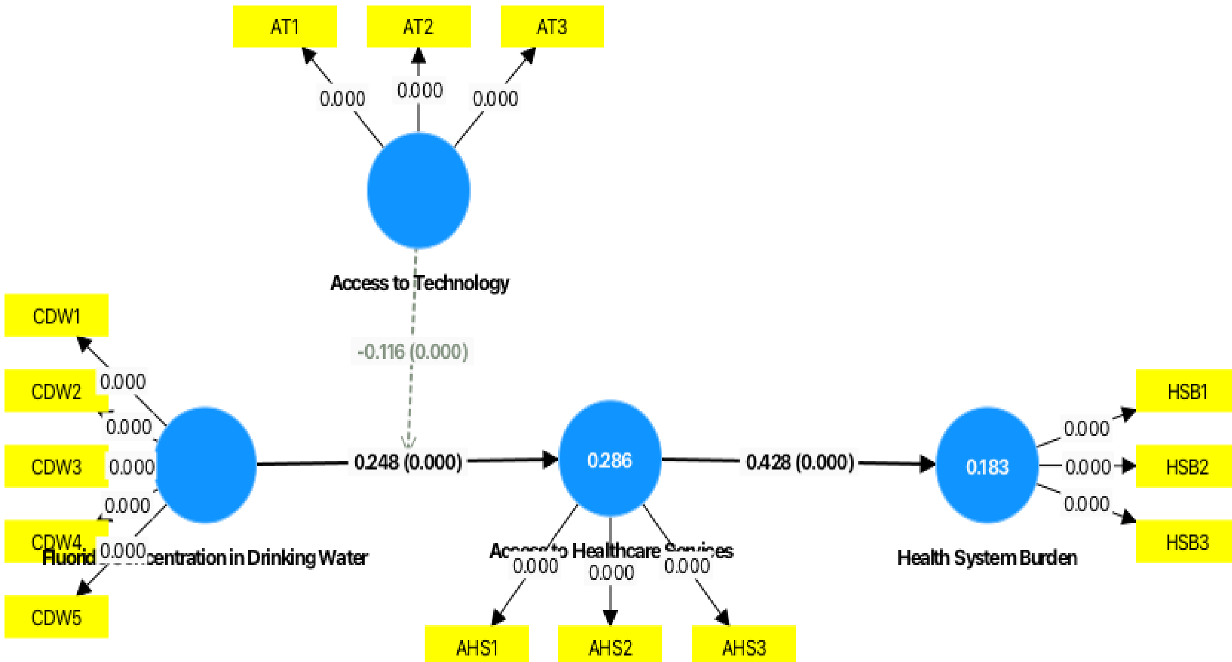

Figure 2.Structure model

Taken together, these results yield strong support for all of the proposed hypotheses. Results show that CDW has a substantial direct effect on healthcare access, which affects the health system burden, and access to technology moderates the relationship between fluoride concentration and healthcare access.Table 6 presented the path coefficient results in detail.

Table 6: Path coefficients

Relationship	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
CDW -> AHS	0.248	0.248	0.026	9.402	0.000
AT x CDW -> AHS	-0.116	-0.116	0.023	4.969	0.000
CDW -> AHS -> HSB	0.106	0.106	0.013	8.138	0.000

5. Discussion

5.1 Findings

The present study offers several important insights regarding the relationships between Health System Burden (HSB), Access to Healthcare Services (AHS), and Fluoride Concentration in Drinking Water (CDW). The findings are consistent with the proposed research model and reinforce the finding that there are strong relationships between environmental, health care, and technological factors and public health outcomes, especially fluoride exposure.

The data supported the first hypothesis that Fluoride Concentration in Drinking Water (CDW) directly affects the Health System Burden (HSB). Results showed a relationship between higher fluoride concentrations in drinking water and a greater health system burden related to the demand for treatment of fluoride related diseases. This finding supports the idea that environmental factors — including poor water quality — can put an enormous strain on healthcare systems. This is consistent with other research showing the disease affecting caused by environmental contaminants, like dental fluorosis and other issues [25, 26]. A positive relationship between CDW and HSB is found, implying that managing fluoride concentrations in drinking water may assist in reducing these financial and logistical pressures on healthcare systems where fluoride contamination is prevalent.

The second hypothesis, (that AHS, scales Fluoride Concentration in Drinking Water (CDW) as it relates to Health System Burden (HSB), was likewise supported. Results showed that AHS is an important pathway for translating environmental exposure of fluoride to health outcomes, thus contributing to increased healthcare burden. The critical role of health care infrastructure in mitigating health problems of high fluoride exposure is hinted at by this mediation effect. In other words, it finds that those who live in regions with less sufficient access to healthcare may have more serious health outcomes, because people with fluoride related diseases might not have the means to seek treatment timelier thus burden the health system [27]. This adds to the evidence for the need for investment in healthcare structure, especially in areas where fluoride concentrations in drinking water are higher than is safe.

The third hypothesis tested the moderation effect of Access to Technology (AT) on the relationship between Fluoride Concentration in Drinking Water (CDW) and Access to Healthcare Services (AHS). The study, however, revealed a negative moderation effect -- that increased access to technology actually diminished the positive effect of fluoride exposure on the demand for healthcare services. Significant implications for alternative aspects of managing fluoride-related health concerns are suggested by this result, including technology such as digital health tools, online information and telemedicine. Technology in places known for high fluoride concentration can fill in the healthcare gap by providing resources for prevention, early diagnosis and education on fluoride's risks to health. Results also support the increasing role of digital health tools in decongesting the traditional healthcare services and enhancing operationalization of health by people through technology [28]. Negative moderation suggests that the more access to technology, the lower, these would lower health system burden.

5.2 implications for policy and practice.

The implications of these findings for public health policy and practice are important. The second is that the positive relationship between CDW and HSB is evidence for the need of reducing exposure to fluoride in drinking water bases, especially in areas where consumer concentrations exceed safe levels. Monitoring water quality, water purification methods and warning to people of health risk from high fluoride exposure should be the main target of public health policies.

Additionally, the strong mediation of AHS indicates that public health burden related to fluoride can be reduced by improving access to public health services in fluoridated regions. The expansion of healthcare infrastructure, especially in rural and underserved regions where fluoride associated health issues are more rampant, should be given highest policy priority.

Additionally, the findings from AT indicate that technology has the potential to serve as a negative moderator of the market for traditional health care services. To prevent fluoride related diseases, governments and health care organizations should be proportionately investing in digital health solution like telemedicine, online health education platforms that empower individuals to manage their health.

This work adds to literature by unifying Access to Technology (AT) and Access to Healthcare Services (AHS) into model of fluoride related health outcomes. Previous research has examined the environmental health and healthcare system impacts of fluoride [29] but this study develops the existing literature by focusing on the mediating and moderating role of healthcare access and technology. These findings offer a more nuanced understanding of how environmental, healthcare and technological factors interact to shape health outcomes and place health care systems under pressure.

5.3 Future Research

Although the findings presented in this study offer great insight, yet some limitations should be marked. The study used cross sectional data only, and so doesn’t allow for any causal conclusions. Future research should focus on a longitudinal approach to examine the long term health outcomes and the healthcare system associated with long term fluoride exposure. Second, unlike past studies comparing population areas with different levels of socioeconomic conditions, the population served in this study was identical, and other risk factors besides fluoride were not studied, findings that could be generalized to other environmental health risks such as lead or pesticides.

Furthermore, future research should investigate further how access to technology (AT) can moderate the relationship between environmental risks and healthcare demands. Such analysis could then focus research on identifying the best technological tools and platforms for public health outcomes in areas where fluoride exposure has been shown to compromise them.

6 Conclusion

This study suggests that decisions regarding mitigating the additional burden placed on the health system as a result of environmental risks, specifically fluoride exposure, are not only driven by technological issues, but also by the extent to which healthcare access is present. And the findings suggest that one way to lower the strain on health systems while at the same time enhancing public health outcomes is by enhancing healthcare infrastructure while harnessing technology. The study offers an important framework to public health practitioners and policymakers to respond to the risks of environmental health in the context of rapidly changing technology.

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