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Community Participatory Governance in Fluoride Control: Mobilizing Strategies to Foster Environmental Health Awareness and Strengthen Grassroots Management

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ABSTRACT

Purpose: The optimum fluoride intake in humans and the environment would lead to challenges in drinking water areas where groundwater is only the source of drinking water. Although technological means to mitigate fluoride are available, sustained success relies mainly on community participation and governance.

Methods: This article present the fluoride control under Community Participatory Governance (CPG) and underlines mobilization strategies that illustrate the genuine promotive public health and community-based action in reality.

Results: By combining global case studies, policy principles, and participatory strategies, the paper highlights key factors contributing to successful fluoride mitigation, including decentralized planning, inclusive decision-making, social mobilization, and the integration of local knowledge.

Conclusions: The review discusses how the participatory action approach in governance can be combined with health education and environmental stewardship to build community resilience, successful compliance with fluoride mitigation strategies, and long-term sustainability. Future research should explore scalability and the role of digital applications in enhancing participation.

Keywords: *Community empowerment; Community Participatory Governance; Participatory action research; Environmental health awareness; Regional governance; Fluoride control; Social mobilization*

INTRODUCTION

Fluoride (F) occurs naturally in different concentrations in soil, rocks, groundwater, air, plants and animals, and anthropogenically in soil and water. Low concentrations of F have a beneficial effect on dental health by preventing tooth decay. However, prolonged exposure to enhanced F levels in drinking water can severely threaten human health and development.¹ World Health Organization (WHO) recommends that F concentrations in drinking water not exceed 1.5 ppm, while China sets a stricter limit of 1.0 ppm.² The effects are not only clinical, long-term presence together with socioeconomic impact, cascades into decreased productivity, enhanced healthcare costs, and social stigmatization, especially in children and women. Despite continuing efforts to

address F contamination through technical means, such as defluorination units and alternative water systems, one key barrier to progress is the absence of active and sustained community involvement in identifying, managing, and preventing F-induced health issues.³⁻⁵

Eco-health problems, like F contamination, are inherently multidimensional, as infrastructure, governance, and human behaviour. Solving these intertwined concerns requires more technological or policy interventions from the top down. It needs to change participatory and community-based governance models where the community is empowered to drive and deploy solutions.^{6,7} In this respect, a promising model is Community Participatory Governance (CPG). CPG works with village councils,

water user associations, women's self-help groups, NGOs, school-based clubs, and other local agents to enable end-users to co-create culturally appropriate, locally relevant, and environmentally sustainable solutions. The model fosters local ownership of environmental health initiatives and ensures that interventions are rooted in people's lived realities and indigenous knowledge systems. Moreover, citizen involvement increases transparency, promotes confidence in the administration among citizens, and develops resilience to natural environmental threats.^{8,9} When communities have helped plan, benchmark, and monitor water quality, they look out for their water quality and take actions themselves, which often achieve more sustainable and cost-effective results than externally imposed solutions. Progressive control over fluorosis depends on the scientific and technical competence of the ability to mobilize, educate, and associate communities affected by the conditions in significant ways.¹⁰

This review investigates the interactive role between community-level participatory governance and water F control policies, focusing on mobilization strategies to enhance environmental health awareness and local management aspects. It systematically assesses community engagement's role in mitigating F contamination and associated health risks. It proposes a framework for effective participatory governance synthesized from cross-national case studies, empirical data, and theoretical analyses. Key elements, i.e., health education, local leadership, behaviour change communication, and institutional collaboration to

sustain mitigation efforts. Challenges, such as social barriers, policy fragmentation, resource limitations, and power asymmetries, are critically assessed.^{11,12} While technical aspects of F control are well-documented, this study highlights a gap in socio-political analyses, particularly the conditions enabling communities to mobilize as primary aspects in environmental health governance. The findings underscore the need for interdisciplinary approaches integrating ecological, social, and institutional dynamics to empower grassroots action.

FLUORIDE CONTAMINATION AND PUBLIC HEALTH

Fluoride is a naturally occurring mineral, which is required in trace amounts in the diet to maintain good health of bones and teeth. However, its overconsumption causes severe health disorders, mainly dental and skeletal fluorosis.¹ The high prevalence of F in the natural environment, coupled with anthropogenic intervention and climate-mediated changes in the groundwater supply, has led to a growing burden of F-associated toxicity in different developing and developed countries.^{13,14} Knowledge about sources of F contamination, the epidemiological profile of fluorosis, and its large spectrum of environmental and socioeconomic impacts are essential for identifying towards implementing control measures within a community-controlled perspectives (Figure 1).

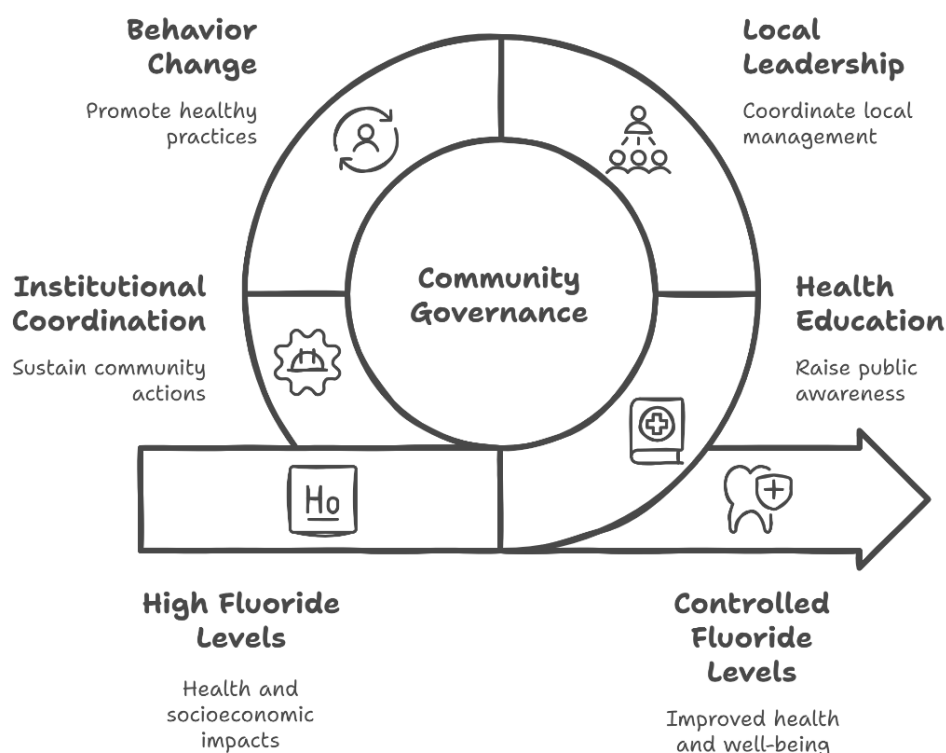


Figure 1. Empowering communities for fluoride mitigation strategies

Sources of Fluoride

Fluoride is ubiquitous in rocks, especially in fluorite (CaF_2), fluorapatite, and cryolite. Fluoride leached from F-bearing geologic formations by percolating water often reaches harmful levels, especially in slow-recharge arid and semi-arid regions. Excess F aquifers are commonly associated to granitic, volcanic, or sedimentary formations.¹⁵ In India, optimum F groundwater is common in the Deccan plateau, parts of the state of Rajasthan, and the Indo-Gangetic plain, and in Africa and different countries, such as Kenya, Tanzania, and Ethiopia because of the Rift Valley geology.¹⁶ Fluoride also gets into the environment through human activities. Industrial discharge from aluminium smelting, phosphate fertilizer production, brick kilns, and coal burning can emit F into the air, where it deposits into soil and water. Moreover, inappropriate application of phosphate fertilizers and F-containing pesticides in agriculture may enhance the F content of soil and runoff water.¹⁵ Industrial wastewater and inappropriate dumping of fluoridated consumer products also degrade surface and groundwater quality. Moreover, industrial F emissions often remain unregulated in low- to middle-income countries, exacerbating the problem.^{17,18} One more recent issue is the influence of climate change on F mobilization. As groundwater levels drop and climates warm, the geochemistry of aquifers will shift, altering the leachability of F into water supplies.

Epidemiology of Fluorosis

The epidemiology of fluorosis can be determined by environmental F level, duration, age, nutritional status, and general health of the individuals exposed to the F. Clinical evidence reveals that lower concentrations of F can induce fluorosis in susceptible groups if intake persists over long periods.^{19,20} The disease is slow-moving and typically diagnosed through dental fluorosis, which has a similar incidence as dental caries and predominantly affects children under the age of eight. The effects of this are discolouration (swirls), mottling, and pitting of the tooth's enamel, as the ameloblasts, cells that produce the enamel, are thus affected in development. It varies from mild white lines to severe brown discolourations and enamel loss. Skeletal fluorosis, the more severe disorder, develops after longer exposure to highest concentration of F, generally over 10-20 years. It causes over-calcification of bones, joint stiffness, pain, and ultimately cripplingly deforming immobility. Skeletal fluorosis is irreversible and debilitating, with significant effects on quality of life, productivity, and mental health. The estimated number of people in India affected by F, called fluorosis, is 62 million, including 6 million children.²¹

China, Pakistan, Sri Lanka, Kenya, Tanzania, Nigeria, Mexico, and some other countries of the Middle East are also endemic. In the US and some areas in Europe, F is applied to prevent dental caries through water

fluoridation. At the same time, enamel fluorosis is the most common and well-studied form of fluorosis and the least severe. Sub-clinical effects of F poisoning are also being regularly identified.^{7,22} These complications involve gastrointestinal disturbances, anaemia, reproductive disorders, and neurological deficits. Recent findings have raised concerns regarding neurodevelopment, showing that higher prenatal F exposure is associated with lower IQ in children. Epidemiological findings demonstrate between long-term F exposure and endocrine disarray, most notably with the onset of thyroid dysfunction.^{14,23}

Adverse Effects of Fluoride on Environment and Population

Fluoride contamination and its health effects are not restricted to physiology alone. It has broader impacts on the environment, socio-economics, community development, living, and intra- and inter-generational well-being. Environmentally, excess F levels in irrigation water can be deposited in agricultural soil, subsequently influencing crop yield and quality. Some crops, including tea, rice, and leafy vegetables, accumulate more F.¹⁵ Soil fertility can be reduced due to chemical imbalances induced by long-term F exposure, impacting food security in susceptible areas.²² Endemic F-related chronic diseases are imposing tough challenges on families, as people do not have access to health facilities.²¹

On a social level, fluorosis can cause discrimination, particularly in young people who have visible dental anomalies. They are often denied marriage, socialization, or psychological health, and this further alienates them. The women and children who suffer the heaviest share of this burden are made more vulnerable by malnutrition and gender-based inequalities in access to care and education. The ongoing costs of monitoring, programs to raise awareness, medical treatment, and defluoridation facilities can be unnecessary burden on resources that can be better used elsewhere. However, these costs can be unuseful, most F remediation projects do not succeed because of poor governance, inadequate community ownership, and fragmented bureaucratic actions. More broadly, F contamination undermines efforts to reach multiple Sustainable Development Goals, such as SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action). The problem highlights the intersectionality of environmental justice, public health, and socioeconomic resilience and demands of multi-sectoral response based on the local situation.^{17,24}

The Community Participatory Governance (CPG) model stands as a delicate step towards narrowing the brittle barrier between technology options and their societal implementation. Local participation, capacity development, and behavioural change by CPG may

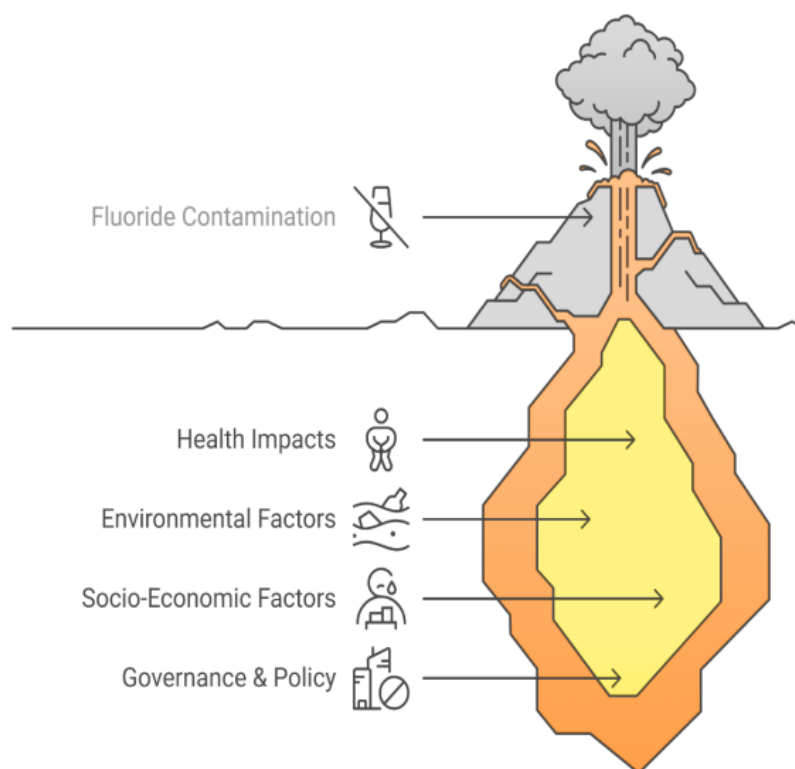


Figure 2. Fluoride contamination

convert passive recipients of soil and water F mitigation strategies into stakeholders, co-managing F mitigation. When the community is aware of the origins and risks of F and tools to monitor and decide on their water, interventions tend to work and persist.^{25,26} A public health response to the problem of F contamination is needed that combines collaborative insights from science with social mobilization, environmental stewardship, and altered governance. The urgency of these challenges and the epidemiological and socioeconomic context in this section offer a robust case for transitioning from reactive, vertical approaches to proactive, community-driven strategies focusing on health equity and environmental sustainability (Figure 2).

TRADITIONAL AND MODERN FLUORIDE CONTROL STRATEGIES

The remediation of F in drinking water has attracted much attention globally in terms of technique and policy dimensions, especially in those regions with severe public health issues due to endemic fluorosis. These interventions comprise household and community-level, traditional and modern control measures of F. Despite being technically feasible and their relative success in controlled situations, a number of the technologies and approaches that have previously been piloted have failed to achieve sustainability in the long term when applied in practice, mostly because weaknesses in delivery models and

sustainability have not integrated community participation to the required level. This part assesses the range of defluorination technologies, the constraints of top-down approaches, comeback issues, and sustained gaps in compliance and efficacy.

The defluorination methods are generally classified into household and community-based technologies. These technologies are based primarily on physical, chemical, or biological mechanisms, which aim to reduce F levels in drinking water according to WHO guideline. Among the several techniques investigated and practised for F treatment at the household level is activated alumina (AA), which adsorbs F.^{11,12} Water is filtered through a porous aluminium oxide intermediate, which filters only F ions. This method is also quite energetic and reduces F levels from the range of >10 ppm to those below the WHO recommendation. However, the filter must be frequently regenerated with chemicals, such as alum or caustic soda, which many rural families do not easily obtain or safely use.^{14,21}

Bone char (BC) is obtained by calcinating animal bones and consists of hydroxyapatite and carbon with excellent F adsorptive capacity. Although it is an inexpensive and locally fabricated method, it develops apprehension in vegetarians and religions that prohibit animal products. The Indian Nalgonda technique applies the principle of chemical precipitation, whereby aluminium sulfate (alum), lime, and bleaching powder are used to precipitate fluorides. It works at home and community levels and is one of the most feasible

methods in rural F-endemic areas.²⁷ The reverse osmosis systems are in high demand because of filter systems for removing F and other contaminants. However, these installations are expensive, require constant operation, generate significant water losses (up to 70%), and are not affordable in low-income and water-limited areas.²⁸

The community RO plant is a centralized system where water is treated at one location and supplied to the whole village or cluster through piped distribution or collection kiosks. These systems work based on capacity. It depends on the electricity, skilled maintenance staff, and strong infrastructure. The concentrated waste of F-containing wafers poses a problem of disposal. Preliminary studies with some biosorption techniques of plant materials, such as tamarind seed, moringa, or neem bark, have shown an efficient alternative. These biosorbents are cost-effective and environmentally friendly, but large-scale application and standardization are still in their infancy.²⁹

Electrocoagulation and nanotechnology-based filters, such as iron oxide nanoparticles (Fe NPs), achieved remarkable removal efficiencies in laboratory conditions. However, their cost, technology quotient, and requirement of continued electricity supply are barriers to community-scale deployment in remote areas. Although several F removal technologies are available and employed, such programs have often not achieved a sustained community network of users hampered by top-down governance arrangements.³⁰ In these projects, interventions are designed and implemented by the government or some outside agency with little input from the local people, who are the owners and maintainers of the system, leading to premature non-functioning of the technologies because of poor ownership. Top-down approaches lack consideration of the sociocultural, economic, and environmental context of the community they serve. The dissemination of bone char filters to vegetarian communities or the widespread fluoridation control programs developed expensively imported technologies in remote areas do not consider the local situation.^{21,31}

Most community-level technology needs perpetual continued help and the contribution of external technical support, power, and spare parts. Systems often break down in rural areas with unreliable electricity and insufficiently trained staff. Moreover, without monitoring or feedback loops between those making decisions and what is happening on the ground, there is no mechanism to quickly address technology failures, and the governance and trust are eroded. There is a significant need for public awareness and capacity building leading to the establishment and sustainability of F control programs. Most interventions do not integrate communities at the design or in-

operation stages. The failure to engage the community in these processes results in gap between community requirements and the impact of intervention, as well as a lack of knowledge transfer and refinement of skills.

In most F-affected areas, people are below the poverty line and cannot pay for filters, chemicals, and maintenance costs. Furthermore, spare parts or reagents cannot be easily found, and local supplies may be exhausted, causing the system to be abandoned. Removal of F usually changes water's organoleptic properties (e.g., taste, odour, colour), which may discourage its use. There is a considerable between the awareness of F effects on health and the importance of mitigation technologies. Fluorosis progress slowly and has been accepted in many regions.³² Behavioural change is improbable without clear communication and noticeable health gains. In rural areas, women are often the primary water gatherers and the managers responsible for household health but are rarely part of technology choices. Not including women in technology design planning and training stages leads to design-implementation mismatches. Furthermore, within the community, inequities may result in uneven access to water without F, and marginalized populations continue to be underserved.³³

Defluorination systems are unreliable due to infrequent water testing and quality control. Local communities have no mechanism to test whether a system operates correctly or F levels have dropped to dangerous levels.³⁰ Overcoming these limitations requires moving away from top-down, technical fixes and towards a more local, communal government. Innovations should be developed collaboratively with communities, considering local knowledge, considerations, gender roles, and economic capabilities. The F mitigation program must include capacity building, local entrepreneurship, and participatory water quality surveillance.^{29,31}

In addition, interdisciplinary work among scientists, engineers, social workers, public health experts, and others are urgently needed to develop technically functional, socially embedded, and culturally sensitive solutions. The policy also must facilitate technological innovation and community engagement designs, enabling efforts toward locally owned and operated systems. Despite the availability of a wide range of F control technologies, the key to successful control in operation lies in the appropriateness, community acceptance, and continued sustainability and maintenance of the project. It is not enough to sustain funding for hardware; bridging the gap from innovation to adoption requires not only the involvement of communities in system design but also sharing responsibility for practical use, with local oversight (governance), and the provision that systems and activities are managed and maintained over time in a way that ensures sustained health outcomes (Figure 3).

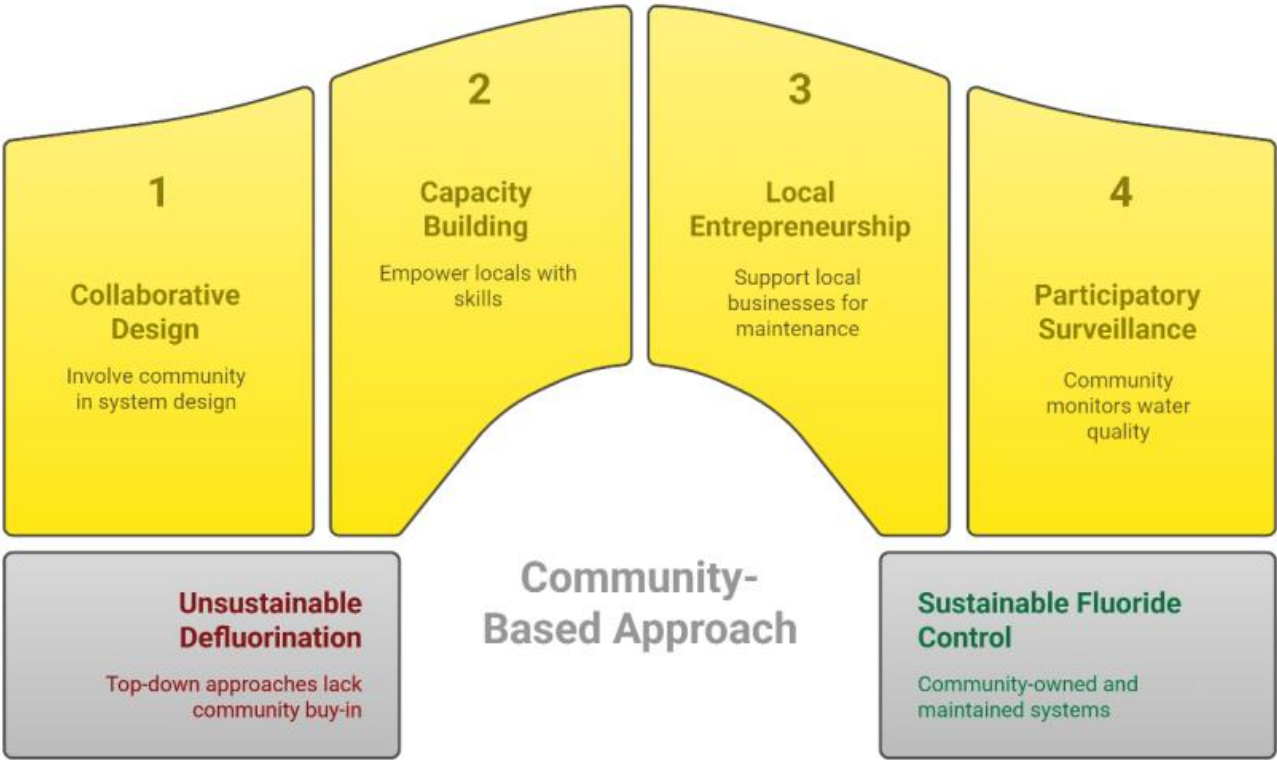


Figure 3. Sustainable fluoride remediation strategies

CONCEPTUAL FRAMEWORK OF COMMUNITY PARTICIPATORY GOVERNANCE (CPG)

Community Participatory Governance (CPG) is a vibrant and equitable governance alternative. It is a local communities to directly engage in shaping, executing, observing, and assessing programs and policies that directly affects. Based on democracy, accountability, transparency, and equity, CPG represents a shift from top-down governance toward a more flat, participatory paradigm where communities can co-create their solutions rather than being recipients. In public health and environmental management, which includes intervention for F mitigation, CPG is a fundamental prerequisite for ensuring that interventions are culturally, socially, economically, and environmentally acceptable. CPG stresses that sustainable solutions, community ownership, and informed decision-making can only be achieved when local voices, practices, and knowledge are incorporated into governance processes, noting that community ownership also raises the legitimacy of decisions and guarantees long-term sustainability.³⁴

Inclusivity, shared responsibility, empowerment, waste local knowledge embedding, and iterative learning characterize the underpinning values of CPG. Inclusion ensures that governance represents the strata of society, particularly the poor and marginalized people, women, children, and the elderly and ethnic groups. Focusing on collective responsibility, such as communities, governments, non-governmental organizations (NGOs), and professionals achieving

outcomes together. Empowerment means providing people and groups with the tools, information, and the ability to affect resources and decisions. Integrating local knowledge ensures that the interventions can be situation-specific (contextual) and align with cultural practices by respecting indigenous and experiential knowledge systems. Iteration learning is supported by rapid feedback loops, adaptive planning, and monitoring systems that consider the changing needs of communities and environmental conditions.³⁵

The successful realization of CPG requires the orchestrated participation of many stakeholders in divergent complementary roles. The community is the principal stakeholder and critical to expressing needs, identifying local problems, co-developing solutions, and maintaining interventions. Community members can provide support through their experience, traditional knowledge, local innovations, and social networks that can assist with trust and sharing information. Their participation enhances group efficacy, stimulates relevance, and promotes compliance.³⁶

Local government authorities are also critical in facilitating CPG and providing the structure and regulations necessary for participatory processes. These roles include, among others, the provision of budget lines, an assurance of the legal and policy-enabling environment for community interventions, hosting inclusive meetings for dialoguing among stakeholders and incorporating community feedback into local development plans. Local governments

mediate between national policy and grassroots activity by translating the objectives and means of policies into locally compatible strategies.³⁷ They also ensure a balanced representation of all community segments in decision-making and strengthen the institutional capacity of community-based organizations (CBOs). Additionally, local authorities can help to decentralize efforts by turning over resources and authority to the lowest administrative levels and creating an enabling environment for community participation.

As enablers or capacity builders, knowledge brokers, and champions, non-governmental organizations or civil society organizations (NGOs/CSOs) have a fundamental role to play in CPG. They can fill the rift between communities and the mechanisms of government through their technical expertise, dedication to external funds, and deep familiarity with grassroots frailty, often mirroring their own. They are responsible for planning community meetings, participating in participatory rural assessments, assisting with mapping stakeholders, and promoting rights-based development theories. Finally, as well as catalysts for social mobilization, NGOs stimulate participation in governance initiatives by generating interest.^{19,22,26} They are also often involved in designing participative, transparent, accountable monitoring and evaluation mechanisms. They also promote the scaling and replication of proven community-driven models by advocating for policy change and expanding awareness nationally and internationally.

The operationalization of CPG in the public health sector is primarily based on health providers, particularly those at the community level, which includes the ASHAs, community health volunteers, and primary healthcare workers; these include responsibilities in health education, risk communication, surveillance, data collection, and service delivery. In the case of F remediation, healthcare workers might educate communities about fluorosis signs and prevention, test for F exposure, and promote household-based methods for treating water with F-safe technologies through surveys.²¹ Their close connection to the community also uniquely positions them to identify emerging health problems, build trust among residents, and serve as intermediaries between formal health care and informal community organizations. In addition, health workers can facilitate healthcare-seeking behaviour and participatory health planning meetings to strengthen the community's capacity to cope with environmental health risks.³³

The synergistic collaboration of these players determines the successful functioning of CPG. This involves clear communication, roles and responsibilities, and institutional mechanisms pooling various partners, like VHSNCs, WUAs, and MSPs. These spaces should operate on principles of conflict resolution, consensus, and mutual respect. Joint monitoring visits, participatory planning workshops, and regular meetings enhance inter-stakeholder relations and the co-production of knowledge and solutions.³⁴

Capacity building is a major component of the CPG model. Programs targeted toward different stakeholders can enhance technical skills, attitudes toward leading, participation, and governance literacy. This can be training for community members in budgeting, grievance redressal systems, water-testing methods, and F mitigation measures. Capacity building for local government leaders could focus on gender-responsive governance, participatory planning, social accountability tools, such as community scorecards and public hearings, policy advocacy programming, and programme design to benefit NGOs. Technical knowledge may need to focus on the skills of teamwork across disciplines, effective communication, and community involvement for health professionals.³⁶

Incorporating CPG in mainstream governance primarily hinges on legally recognizing community-based structures and delegating planning and financial power to local levels. It also needs to safeguard regional bodies, promote the welfare of the underprivileged, and encourage inclusive participation through affirmative action.^{14,22}

The Community Participatory Governance Conceptual Model provides a practical approach to democratizing environmental health interventions, including mineralization and provision. CPG makes interventions more legitimate, effective, and sustainable by placing communities at the centre of decision-making and facilitating collaboration involving various factors, i.e., communities, local governments, NGOs, and health professionals. It emphasizes the need for jointly designed, implemented, and evaluated solutions to complex health and environmental issues to be more effective. CPG proposes a revolutionary process and governance model that accumulates social capital, enhances democratic conduct, and empowers communities to manage their progression paths (Figure 4).

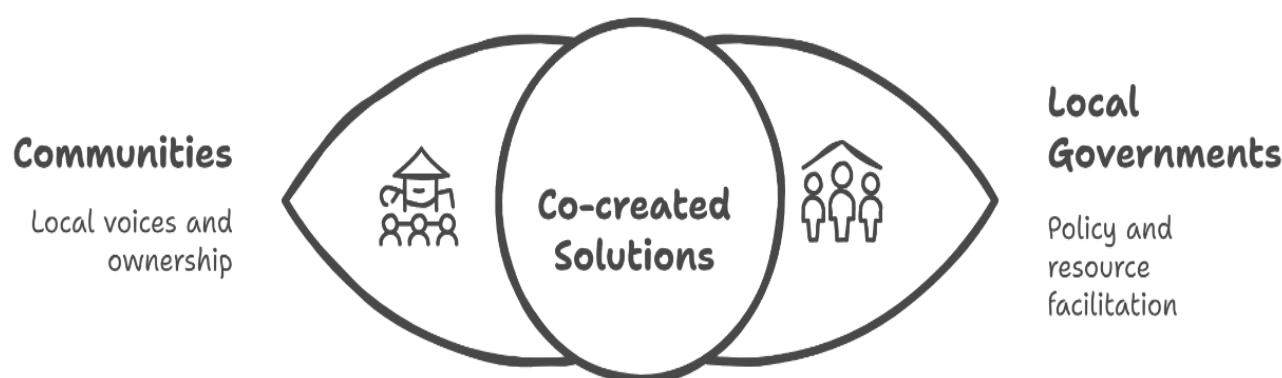


Figure 4. Power of synergy in community governance

MOBILIZATION STRATEGIES FOR PUBLIC HEALTH ENVIRONMENTAL AWARENESS

Public environmental health awareness mobilization campaigns are essential for addressing F contamination within a community participatory governance model. It is vital to develop effective communication strategies that support long-term behaviour change and empower communities to take control over their health and environment. In this regard, the primary methods are Behavior Change Communication (BCC) and Knowledge, Education, and Communication (IEC). BCC employs participatory techniques to stimulate and socially influence individual and group decision-making regarding specific health-positive behaviour.³⁸ It is a tri-phasic concept that encourages stakeholders simultaneously, awareness and mobilization, motivation, and an enabling environment (including technology) to implement preventive (and evasive) measures, such as defluoridation technologies, accessing safe drinking water, and conducting periodic health check-ups. Conversely, IEC facilitates the organized dissemination of accurate information designed to educate individuals and entire communities, empowering to make informed decisions. IEC materials, including posters, leaflets, flipbooks, videos, and audio scripts in local languages and dialects are essential for addressing varying education levels and reaching vulnerable populations.

Schools, self-help groups (SHGs), NGOs, and local community leaders play a significant role in implementing environmental health responses. Schools are fundamental for developing ecological awareness in children, affecting household practice. Fluoride education incorporated into school curricula by providing science clubs, community science clubs, and participatory water testing can help to develop early awareness and a sense of responsibility and provide various benefits that can aid in sustainable change.^{13,14} Equally, self-help groups, especially women's groups, have been effective change agents in rural areas. SHGs can also be trained to identify symptoms of fluorosis, educate others on how to

prevent exposure and manage community water systems. That they are a part of the social fabric offers peer-to-peer influence and trust-based communication. Community leaders, such as Panchayat members, religious heads, and traditional healers, play a vital role in the community. They can be encouraged to act as ambassadors for creating awareness regarding safe water practices and the risk of F.³⁹

With the coming of the digital age, social media and digital platforms provide an opportunity for unprecedented scale and low-cost access to information dissemination. Such platforms as WhatsApp, Facebook, YouTube, and community radio apps can transmit multilingual educational content, videos of safe water practices, infographics on symptoms of fluorosis, or alerts on local water quality. mHealth apps might incorporate alerts, community forums, and reporting functions to monitor fluorosis signs/or broken defluorination units, increasing awareness and transparency. In addition, influencers or homegrown digital celebrities can co-promote information and make it more relevant to different population segments. However, digital inclusion is still a challenge, and hybrid approaches that integrate digital communication are required with traditional outreach.⁴⁰

Context-specific and nuanced communication strategies are fundamental for the successful mobilization of communities. Campaigns must navigate local beliefs, taboos, and norms to prevent backlash and resistance. For instance, messaging needs to recognize these values for F-endemic areas where the customary water sources are culturally respected and should teach safe water practices. Telling stories, performing street theatre, singing folk songs, using puppets, and painting community murals can creatively transfer scientific information in an emotionally appealing and culturally relevant way.³⁹ Involving local artists and community historians may be one way of customizing content to reflect lived experiences and existing knowledge systems. Models of participatory communication, in which communities contribute to

the generation of messaging content (i.e., participatory video), improve the potency of the messages by making them more relevant and acceptable.³⁶

Public education campaigns that mobilize environmental awareness strategy on health problems in F-affected areas will need an integrated, multi-stakeholder communication approach that links science and society. Success relies on adapting approaches to local circumstances, exploiting sociocultural structures, and incorporating communication in daily life to promote sustained evolution toward informed, self-organized community action.

GRASSROOTS MANAGEMENT AND FLUORIDE MITIGATION

Better practice at the grassroots level is fundamental to successfully controlling F contamination, particularly in rural and semi-urban areas where centralized infrastructure may be unavailable or non-operational. Furthermore, strengthening local communities through a decentralized governance approach makes interventions more responsive and sustainable. At its core is establishing and operating local water user committees (WUCs). These committees typically comprise youth, women, marginalized groups, and local health or education workers. Their main tasks are identifying responsible and safe drinking water sources, monitoring the installation and maintenance of defluorination units, collecting water samples, and facilitating educational campaigns. By engaging local stakeholders in planning and decision-making, WUCs can ensure that mitigation approaches are culturally appropriate, locally applicable, and socially acceptable.^{33,40}

Community-level capacity building and training are significant for stakeholders, such as WUCs and others, to perform their roles effectively. This will include capacity-building related to F detection (e.g., field testing kits), operation and maintenance of water treatment equipment, and interpretation of water quality reports. It is also essential that training curricula include soft skills in participation, conflict resolution, finance, and communication. These initiatives foster local ownership and resilience while reducing dependency on external organizations. Training should be comprehensive and ongoing, utilizing a cascade approach where trained personnel educate other community members. Gender-sensitive training systems must ensure that women who fetch water (i.e., the primary community water collectors) can actively participate in F mitigation procedures.^{30,39}

Community surveillance, reporting, and accountability practices also strengthen the network of grassroots management. Responsibility for monitoring

water F levels by trained villagers enables early contamination detection and timely action. There are apps or community logbooks for reporting cases of fluorosis, malfunctioning defluorination units, or drying wells. This information can be shared with local governance and district health authorities to drive coordinated action. Making water quality data available at a community centre or school helps demonstrate transparency and empowers choice. Accountability tools, like public hearings, social audits, and citizen report cards, assist communities in monitoring the implementation and effectiveness of mitigation efforts, channelling complaints, and signalling reform. These mechanisms foster trust and contribute to developing a participatory government culture and shared responsibility. Meanwhile, rural development programs can facilitate the development of F-safe infrastructure, including piped water supply systems, rainwater harvesting tanks, and groundwater recharge structures.^{36,37} Finally, participatory approaches based on nourishment techniques, reinforced by capacity building and supported by robust monitoring, could provide a sustainable solution for F mitigation. This approach also promotes community resilience, cultivates local leadership, and ensures the sustainability of public health interventions in F-affected areas.^{31,33}

CHALLENGES AND LIMITATIONS

While community-participatory governance and decentralized environmental health interventions are increasingly being accepted, the barriers and limitations in promoting efficient F mitigation at the grassroots level are yet to be counteracted. The most notable obstacles include resistance on a sociocultural level, misinformation and myths, and disinterest in our communities. In most F-affected regions, the clinical signs of dental fluorosis, particularly discolouration, are misdiagnosed or attributed to genetic or innocuous causes. These misconceptions reduce the need for clean water sources and involvement in mitigation. For instance, some communities may not accept defluorination procedures because they are unfamiliar with them and are afraid of adverse effects, convenience, and proximity of the available contaminated sources. These challenges require sustained attention, rooted in a long-term commitment to culturally adapted communication and not just one-off "awareness" campaigns, using existing, trusted, local influencers, school programmes, and repeated engagement for familiarity and attitude change.

There are also institutional clogs and policy incoherence that make translating grassroots initiatives into operational terms more difficult. While national and state-level water safety plans could be there, their integration with village-specific plans are usually sporadic, partly due to capacity deficit, bureaucratic

delay, and accountability. While the policies may have mandates for community involvement or the formation of WUCs, they are unlikely to be effectively implemented without legal mandates, technical assistance, and operational funding. In addition, very few defluorination technologies can be standardized and sanctioned, leading to a range of cheap but unacceptable options that erode public confidence.

Fluoride mitigation interventions are initiated with government/donor support but fail after they are disbanded due to poor O&M provisions. The costs that are easy to overlook are the replacement of filter media, the maintenance of pumps, the testing of water, and the cost of the local water manager; if unpaid, this can lead to Machine failure and the programming stops. The ability and willingness of the community to pay are also generally inconsistent, and unless the service is well-known and regularly delivered, it is low in poor neighbourhoods. Long-term, financially sustainable planning must look to other ways of funding to spread the cost of mitigation through larger water tariffs, CSR contributions, and the piloting of microfinancing models that put communities in control of their water systems.

Gender and equity are neglected in F mitigation plans, precluding their practical use and implementation. Women, as the primary collectors of water, managers of indoor health, and caregivers are rarely included in the development process or the leadership of mitigation projects despite being primary shareholders. Dealing with these complex challenges over time will require flexible policy instruments, coalition-building between sectors, grassroots innovation, and political courage.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The multidimensional assessment also suggested that community empowerment (enabled by inclusive decision-making, local monitoring capacity-building and culturally appropriate mobilization strategies) is feasible and essential for sustainable F mitigation. Engagement of multiple factors, such as water user committees, local government, NGOs, health workers, schools, and digital platforms, indicates the extent to which decentralized, community-based approaches are more likely to lead to stronger accountability, better management of resources, and greater attention to prevention, behaviour, and technologies.

The sustainability of this approach depends on establishing the appropriate environment supported by holistic public health and rural development policies, the availability of financing instruments, cross-sectoral coordination, and monitoring and learning systems. Social opposition, vested interest, constraint, and unequal power relationships must be confronted by strategic planning, embedded representation, and

active policy feedback. In the future, importance should be placed on integrating participatory platforms through community co-management, formalizing community involvement in water governance, and sustaining the momentum gained concerning realizing the public health program among the most disadvantage.

Future Research Directions

Analyze the effectiveness of participatory approaches for F monitoring across diverse cultural and socioeconomic contexts to identify best practices, and develop low-cost tools, such as mobile apps, sensor kits and leverage social media for awareness campaigns. Investigate integrating environmental health into school curricula to foster early awareness and intergenerational impact. Incorporate successful grassroots initiatives into national policies, ensuring regulatory backing and sustainable funding. Adopt an interdisciplinary approach combining public health and environmental sciences to holistically address technical and behavioral challenges for better future.

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CONFLICT OF INTERESTS

None

REFERENCES

- [1] Tiwari KK, Raghav R, Pandey R. Recent advancements in fluoride impact on human health: A critical review. *Environ Sustain Indic* 2023;20:100305. [Doi: 10.1016/j.indic.2023.100305](https://doi.org/10.1016/j.indic.2023.100305)
- [2] Mu R, Cui K, Chen Y, Tang Y, Wang K, Sun S. Distribution characteristics and risk assessment of fluoride in surface water of urban typical rivers. *Sci Total Environ* 2024;951:175548. [Doi: 10.1016/j.scitotenv.2024.175548](https://doi.org/10.1016/j.scitotenv.2024.175548)
- [3] Mahmood M, Azevedo LB, Maguire A, Buzalaf M, Zohoori FV. Pharmacokinetics of fluoride in human adults: The effect of exercise. *Chemosphere* 2021;262:127796. [Doi: 10.1016/j.chemosphere.2020.127796](https://doi.org/10.1016/j.chemosphere.2020.127796)
- [4] Sano H, Omine K, Prabhakaran M, Darchen A, Sivasankar V. Groundwater fluoride removal using modified mesoporous dung carbon and the impact of hydrogen-carbonate in borehole samples. *Ecotoxicol Environ Safety* 2018;165:232–42. [Doi: 10.1016/j.ecoenv.2018.09.001](https://doi.org/10.1016/j.ecoenv.2018.09.001)

- [5] Zhang H, Deng S, Zhang J, Wang D, Fan H, Xu Y, et al. Design, characterization, and structure-function relationships of modified polyvinylidene fluoride membranes for water treatment. *J Membrane Sci* 2025;728:124120. [Doi: 10.1016/j.memsci.2025.124120](https://doi.org/10.1016/j.memsci.2025.124120)
- [6] Sah O, Maguire A, Zohoori FV. Fractional urinary fluoride excretion and nail fluoride concentrations in normal, wasted and stunted 4–5 year-old children in Nepal. *J Trace Elements Med Biol* 2022;69:126876. [Doi: 10.1016/j.jtemb.2021.126876](https://doi.org/10.1016/j.jtemb.2021.126876)
- [7] Liang Y, Chen F, Zhang M, Chen L, Xia Y, Zhou Z, et al. Innovative calcium-doped layered yttrium hydroxides for rapid and efficient removal of fluoride from aqueous solutions: Insight into adsorption mechanism. *J Environ Chem Engg* 2023;11(1):109156. [Doi: 10.1016/j.jece.2022.109156](https://doi.org/10.1016/j.jece.2022.109156)
- [8] Zheng J, Wang Q, Xu K, Ma M, Wang Z, Sun Z, et al. Fluoride induces immune-inflammatory disorder in the kidneys via histone lysine crotonylation in vivo. *Ecotoxicol Environ Safety* 2024;288:117385. [Doi: 10.1016/j.ecoenv.2024.117385](https://doi.org/10.1016/j.ecoenv.2024.117385)
- [9] Huang X, Wang S, Wang S, Xiao Z, Zhang M, Zhang H, et al. Fluoride in geothermal water: Occurrence, origin, migration and environmental impact. *J Geochem Explor* 2025;270:107640. [Doi: 10.1016/j.gexplo.2024.107640](https://doi.org/10.1016/j.gexplo.2024.107640)
- [10] Aoun A, Darwiche F, Al Hayek S, Doumit J. The fluoride debate: The pros and cons of fluoridation. *Prev Nutr Food Sci* 2018;23(3):171-80. [Doi: 10.3746/pnf.2018.23.3.171](https://doi.org/10.3746/pnf.2018.23.3.171)
- [11] Rajkumar S, Muruges S, Sivasankar V, Darchen A, Msagati TAM, Chaabane T. Low-cost fluoride adsorbents prepared from a renewable biowaste: Syntheses, characterization and modeling studies. *Arab J Chem* 2019;12(8):3004–17. [Doi: 10.1016/j.arabjc.2015.06.028](https://doi.org/10.1016/j.arabjc.2015.06.028)
- [12] Roshan A, Polya DA, Kumar A, Ghosh A, Glennly AM, Sedighi M, et al. Comparison of the distribution of groundwater remediation units and contaminant (arsenic, iron, fluoride) distribution in Bihar, India for improved water security and management. *J Environ Manag* 2024;372:123157. [Doi: 10.1016/j.jenvman.2024.123157](https://doi.org/10.1016/j.jenvman.2024.123157)
- [13] Bretzler A, Johnson CA. The geogenic contamination handbook: Addressing arsenic and fluoride in drinking water. *Appl Geochem* 2015;63:642–6. [Doi: 10.1016/j.apgeochem.2015.08.016](https://doi.org/10.1016/j.apgeochem.2015.08.016)
- [14] Yan L, Zhang B, Zong Z, Zhou W, Shuang S, Shi L. Artificial intelligence-integrated smartphone-based handheld detection of fluoride ion by Al³⁺-triggered aggregation-induced red-emission enhanced carbon dots. *J Colloid Interface Sci* 2023;651:59–67. [Doi: 10.1016/j.jcis.2023.07.125](https://doi.org/10.1016/j.jcis.2023.07.125)
- [15] Jha SK, Mishra VK, Sharma DK, Damodaran T. Fluoride in the environment and its metabolism in humans. *Rev Environ Contam Toxicol* 2011;211:121-42. [Doi: 10.1007/978-1-4419-8011-3_4](https://doi.org/10.1007/978-1-4419-8011-3_4)
- [16] Demelash H, Beyene A, Abebe Z, Melese A. Fluoride concentration in ground water and prevalence of dental fluorosis in Ethiopian Rift Valley: systematic review and meta-analysis. *BMC Public Health* 2019;19:1298. [Doi: 10.1186/s12889-019-7646-8](https://doi.org/10.1186/s12889-019-7646-8)
- [17] Benson PE. Fluoride-containing materials and the prevention of demineralization during orthodontic treatment—which research method should we now use? *Seminars Orthodontics* 2010;16(4):293–301. [Doi: 10.1053/j.sodo.2010.06.008](https://doi.org/10.1053/j.sodo.2010.06.008)
- [18] Kusam Kumari D, Pandit S, Sharma P, Kuila A. Advancing groundwater sustainability: Strategy combining hydro-chemical analysis, pollution mitigation, and community-based water resource governance. *Groundw Sustain Dev* 2025;29:101433. [Doi: 10.1016/j.gsd.2025.101433](https://doi.org/10.1016/j.gsd.2025.101433)
- [19] Lacson CFZ, Lu MC, Huang YH. Fluoride network and circular economy as a potential model for sustainable development—A review. *Chemosphere* 2020;239:124662. [Doi: 10.1016/j.chemosphere.2019.124662](https://doi.org/10.1016/j.chemosphere.2019.124662)
- [20] Li YJ, Chen GE, Xie HY, Chen Z, Xu ZL, Mao HF. Increasing the hydrophilicity and antifouling properties of polyvinylidene fluoride membranes by doping novel nano-hybrid ZnO@ZIF-8 nanoparticles for 4-nitrophenol degradation. *Polym Test* 2022;113:107613. [Doi: 10.1016/j.polymertesting.2022.107613](https://doi.org/10.1016/j.polymertesting.2022.107613)
- [21] Guth S, Hüser S, Roth A, Degen G, Diel P, Edlund K, et al. Toxicity of fluoride: critical evaluation of evidence for human developmental neurotoxicity in epidemiological studies, animal experiments and in vitro analyses. *Arch Toxicol* 2020;94(5):1375-1415. [Doi: 10.1007/s00204-020-02725-2](https://doi.org/10.1007/s00204-020-02725-2)
- [22] Oulebsir A, Chaabane T, Zaidi S, Omine K, Alonzo V, Darchen A, et al. Preparation of mesoporous alumina electro-generated by electrocoagulation in NaCl electrolyte and application in fluoride removal with consistent regenerations. *Arab J Chem* 2020;13(1):271–89. [Doi: 10.1016/j.arabjc.2017.04.007](https://doi.org/10.1016/j.arabjc.2017.04.007)
- [23] Ren Y, Tong J, Qu G, Ning P, Ren N, Zhang C, et al. Preparation of fluoride adsorbent by resource utilization of carbide slag from industrial waste. *J Environ Chem Engg* 2022;10(6):108632. [Doi: 10.1016/j.jece.2022.108632](https://doi.org/10.1016/j.jece.2022.108632)
- [24] German MS, SenGupta AK. Transforming the global arsenic and fluoride crisis into an economic enterprise: Role of hybrid anion exchange nanotechnology (HAIX-Nano) in Ballia, Uttar Pradesh and Nalhati, West Bengal. Ahuja S, editor. *Advances in Water Purification Techniques*. Elsevier; 2019; 327-54. [Doi: 10.1016/B978-0-12-814790-0.00013-2](https://doi.org/10.1016/B978-0-12-814790-0.00013-2)
- [25] Ross A, Sherriff A, Kidd J, Gnich W, Anderson J, Deas L, et al. A systems approach using the functional resonance analysis method to support fluoride varnish application for children attending general dental practice. *Appl Ergonomics* 2018;68:294–303. [Doi: 10.1016/j.apergo.2017.12.005](https://doi.org/10.1016/j.apergo.2017.12.005)
- [26] Xiao Y, Hao Q, Zhang Y, Zhu Y, Yin S, Qin L, et al. Investigating sources, driving forces and potential health risks of nitrate and fluoride in groundwater of a typical alluvial fan plain. *Sci Total Environ* 2022;802:149909. [Doi: 10.1016/j.scitotenv.2021.149909](https://doi.org/10.1016/j.scitotenv.2021.149909)
- [27] Swarnakar AK, Choubey S, Sar SK. Defluoridation of water by various technique- A review. *Int J Innov Res Sci Eng Technol* 2016;13174-78. [Doi: 10.15680/IJIRSET.2016.0507192](https://doi.org/10.15680/IJIRSET.2016.0507192)
- [28] Wu J, Cao M, Tong D, Finkelstein Z, Hoek EMV. A critical review of point-of-use drinking water treatment in the United States. *npj Clean Water* 2021;4:40. [Doi: 10.1038/s41545-021-00128-z](https://doi.org/10.1038/s41545-021-00128-z)
- [29] Maddela NR, Abiodun AS, Zhang S, Prasad R. Biofouling in membrane bioreactors—Mitigation and current status: a review. *Appl Biochem Biotechnol* 2023;195:5643–68. [Doi: 10.1007/s12010-022-04262-3](https://doi.org/10.1007/s12010-022-04262-3)
- [30] NdéTchoupé AI, Crane RA, Mwakabona HT, Noubactep C, Njau KN. Technologies for decentralized fluoride removal: Testing metallic iron-based filters. *Water* 2015;7(12):6750-74. [Doi: 10.3390/w7126657](https://doi.org/10.3390/w7126657)
- [31] Mariappan Santhi V, Periasamy D, Perumal M, Sekar PM, Varatharajan V, Aravind D, et al. The global challenge of fluoride contamination: A comprehensive review of removal processes and implications for human health and ecosystems. *Sustainability* 2024;16:11056. [Doi: 10.3390/su162411056](https://doi.org/10.3390/su162411056)

- [32] Umer MF. A systematic review on water fluoride levels causing dental fluorosis. *Sustainability* 2023;15(16):12227. [Doi: 10.3390/su151612227](https://doi.org/10.3390/su151612227)
- [33] Duffin S, Duffin M, Grootveld M. Revisiting fluoride in the twenty-first century: Safety and efficacy considerations. *Front Oral Health* 2022;3:873157. [Doi: 10.3389/froh.2022.873157](https://doi.org/10.3389/froh.2022.873157)
- [34] Ugoani J. Participatory governance and community-driven development: the Klugman examples. 2024 Feb 22. RUN/SPGSU/24/04. Available at SSRN: <https://ssrn.com/abstract=4735267> or <http://dx.doi.org/10.2139/ssrn.4735267>
- [35] Della Spina L. Community branding and participatory governance: A glocal strategy for heritage enhancement. *Heritage* 2025;8(6):188. [Doi: 10.3390/heritage8060188](https://doi.org/10.3390/heritage8060188)
- [36] Zamiri M, Esmaeili A. Methods and technologies for supporting knowledge sharing within learning communities: A systematic literature review. *Adm Sci* 2024;14(1):17. [Doi: 10.3390/admsci14010017](https://doi.org/10.3390/admsci14010017)
- [37] Oksanen A, Celuch M, Oksa R, Savolainen L. Online communities come with real-world consequences for individuals and societies. *Commun Psychol* 2024;2:71. [Doi: 10.1038/s44271-024-00112-6](https://doi.org/10.1038/s44271-024-00112-6)
- [38] Madad A, Meitong W, Ma J. Balancing public health and governance: Exploring the role of social governance and health policies in shaping community well-being through fluoride consumption. *Fluoride* 2024;e298. Available from: <https://www.fluorideresearch.online/epub/files/298.pdf>
- [39] Bose D, Bhattacharya R, Kaur T, Banerjee R, Bhatia T, Ray A, et al. Overcoming water, sanitation, and hygiene challenges in critical regions of the global community. *Water-Energy Nexus* 2024;7:277-96. [Doi: 10.1016/j.wen.2024.11.003](https://doi.org/10.1016/j.wen.2024.11.003)
- [40] Deniz-Garcia A, Fabelo H, Rodriguez-Almeida AJ, Zamora-Zamorano G, Castro-Fernandez M, Alberiche Ruano MDP, et al. WARIFA Consortium. Quality, usability, and effectiveness of mHealth apps and the role of artificial intelligence: Current scenario and challenges. *J Med Internet Res* 2023;25:e44030. [Doi: 10.2196/44030](https://doi.org/10.2196/44030)