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Aluminum electrocoagulation: defluoridation technology for Andhra Pradesh, India

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This paper begins with an overview of the origin, magnitude, geographical distribution, and health consequences of the geogenic fluoride contamination problem around the world and particularly in Nalgonda District, Andhra Pradesh, India. Various current defluoridation technologies are discussed and electrolytic defluoridation (EDF), developed by the Indian National Environmental Engineering Research Institute, is proposed as a potential sustainable solution for groundwater treatment in South India. The paper concludes with a discussion of future research plans to test if EDF meets the requirements to make it an effective solution for Nalgonda: it is culturally acceptable, technically feasible and robust in a rural setting, and operation and maintenance require minimal capital expenditure and skilled labor.

Background

Worldwide, about 200 million people drink water with toxic levels of naturally occurring fluoride that substantially exceed the WHO's guideline value of 1.5 mg/L (WHO 2004). Although effluent from local anthropogenic industries like aluminum smelters or phosphatic fertilizers can introduce fluoride into the environment, its concentration in groundwater is primarily determined by the dissolution of fluoride-rich granitic rocks and is controlled by chemical parameters including pH, alkalinity, and concentration of calcium in the water (Saxena 2003). Exposure to fluoride levels in drinking water exceeding 1.5 ppm can cause mottling of tooth enamel (dental fluorosis), anemia due to poor nutrient absorption, and severe bone deformities in children (skeletal fluorosis) (Brindha et. al 2011). Globally, high levels of geogenic fluoride in groundwater have been reported in many countries including the arid regions of China, India, Sri Lanka, the East African Rift Valley, northern Mexico, and central Argentina (Edmunds and Smedley 2013). In India it is estimated that over 66 million people are at risk of developing fluorosis and face large and adverse social, economic, and health repercussions (UNICEF 1999).

Fluoride contamination of groundwater in Nalgonda district, AP, India

Nalgonda District is a semi-arid region with a population of 3.48 million people, 81% of which live in rural areas as agricultural laborers and farmers (2011 Census). The groundwater aquifers in Nalgonda contain fluoride-rich granitic rocks with an average fluoride content of 1440 mg/kg, which is much higher than the world average concentration (Brindha 2011), resulting in groundwater concentrations reaching up to 20 mg/L (Rao et. al 1993). It is estimated that 10% of the population in the Nalgonda district is affected by the fluoride contamination and that about 10,000 people are completely crippled due to skeletal fluorosis (Nag 2011).

Despite awareness of the problem for over 60 years, fluoride contamination in Nalgonda continues to persist due to lack of groundwater treatment technologies or alternative surface water sources for the rural populations.

Visits to affected villages in the Fall 2013 by the first author (AKC) confirmed the gravity of the situation and the pressing need for a solution. Interviews with officials from the Rural Water Supply Department of Andhra Pradesh, the National Institute of Nutrition, the National Institute of Chemical Technology, the Geologic Survey of India, and the Central Groundwater Board shed light on the state's approach to the fluoride problem and its caveats. The alleviation efforts are currently focused on the construction of pipelines from the Krishna River to villages throughout Nalgonda District. Although plans have been set in place and some funding may have been found, this pipeline project has purportedly been ongoing for years and fluoride-free water has yet to reach the majority of the villages in the district. Many incomplete and unconnected pipes can be found along the highway from Hyderabad to Nalgonda, indicating that the villages further away from the highway still lack access to the surface water. Providing piped water to all the remote affected villages is a very long-term approach that requires significant capital costs and a lot of time. Therefore these projects cannot be expected to solve the fluoride problem in the short term, leaving defluoridation technologies as the only realistic solution, especially for remote villages.

In order for a groundwater treatment technology to be sustainable in Nalgonda, it must be highly effective, socially acceptable, technically feasible and robust in a rural setting, and require minimal capital expenditure and manpower to operate and maintain the system. In addition, we propose that groundwater treatment should be operated at the community level, not at the household level. In 2013, the National Environmental Engineering Research Institute in Nagpur, India distributed household sand filters housed in aluminum containers and chemical sachets (containing an adsorbent like activated alumina) to enable people to defluoridate 30L of groundwater daily. Field visits to over 30 households in 2 villages in Maharashtra using these units (Fall 2013) revealed the following difficulties associated with expecting end users to maintain their own drinking water treatment systems: a) families complained that the aluminum containers holding the filtration unit were leaking, b) many used the tanks as storage space for grains rather than as filters, c) people went against NEERI's proper cleaning instructions and emptied the sand out completely rather than scrape the top layer, and d) some people were not receiving chemical sachets containing the adsorbent due to personal issues with the community distributor. Combined, these shortcomings observed in Maharashtra provide motivation for community-scale defluoridation in Nalgonda.

Photograph 1: Fluorosis patients in Nalgonda District (Nov2013)

An appropriate technology for Nalgonda: electrolytic defluoridation (EDF)

Although many treatment technologies have been developed and proven to be effective in lab, only a few have been distributed in the field and even fewer appear to be sustainable in the long-term. Table 1 lists the multiple existing defluoridation technologies and their main disadvantages. In general, a technology may not be appropriate for rural areas such as Nalgonda if it is: labor intensive, difficult to scale up at the community level (a commonly cited problem of the Nalgonda technique), cost-prohibitive, difficult to source locally (e.g., reverse osmosis and membrane filtration), and/or culturally inappropriate (e.g., bone char) (Table 1).

Table 1. Limitations of Defluoridation Technologies

Process Category	Technology or Method	Main Disadvantages
Chemical Precipitation	Magnesium Oxide	• Requires high pH for operation • Requires frequent addition of adsorbent
	Nalgonda Technique (alum + lime)	• Raises pH to 11-12 • Large Alum dosage (700-1200 mg/L) • Lot of sludge containing Al & sulphate • Labor intensive process
Membrane Process	Reverse Osmosis	• Requires pre-treatment • Wastes water (50% efficiency) & generates salty brine • High Capital and O&M costs • Skilled labor required
Adsorption	Bone Char	• Culturally inappropriate for India
	Activated alumina	• Difficult to source locally, adsorbent requires regeneration • Filters are expensive, must be maintained
	Clays, Biosorbents	• Difficult to scale up and source
Electrochemical	Aluminum Electrocoagulation (EDF)	• High capital cost for plant construction
Non-technical	Piped Water Supply	• Very high capital cost, construction takes a long time • Inaccessible infrastructure in rural areas
	Dilution via Recharge	• Unreliable, intermittent rainfall

References: Mohapatra et. al (2009), Jagpat et. al (2012) , Rao et. al (2010)

The electrolytic defluoridation (EDF) technology developed a decade ago by the National Environmental Engineering Research Institute (NEERI) in Nagpur, Maharashtra, appears to be a promising option for Nalgonda. The treatment process relies on the dissolution of an aluminum anode to produce aluminum hydroxide precipitates that serve as efficient fluoride sorbents and are removed by settling. This technology has been implemented in multiple villages and schools in Maharashtra through the efforts of UNICEF, private tenders, the Ministry of Drinking Water & Sanitation, and local Public Health Engineers Departments. Overall (to NEERI's knowledge), 20 plants of varying capacity (250L- 4000L per day) are operating in communities and many dozens more are being constructed by private tenders. Field visits to existing EDF plants in Maharashtra and discussions with scientists shed light on the operation, maintenance, and efficiency of the technology. . The overall management plan of EDF can be described using the following stages: I) Technology Development: NEERI's Water Technologies Management Division develops the EDF technology, II) Funding/Proposals: NEERI receives proposals to fund and build EDF plants from various state or local entities, such as the Ministry of Drinking Water and Sanitation, Municipal Corporations (in cities), Public Health Engineering Departments (in rural areas), or NGOs (e.g., UNICEF), III) Knowledge transfer: private firms are hired to manufacture electrodes and construct EDF plants based on blueprints developed by NEERI, and IV) Operation/Maintenance: the plants are controlled by municipal corporations or private firms are contracted to maintain them for a set number of years.

Based on the afore-mentioned criteria for an "appropriate" technology for Nalgonda, it seems that EDF could be a potential solution because it can reliably and effectively treat raw water with typical initial fluoride concentrations (5-10ppm) found in Nalgonda, requires minimal maintenance (operator cleans cathode weekly), produces minimal sludge, has a low estimated treatment cost (Rs20/1000L), is based on a modular system that is easy to fabricate/scale up, and the main material (Al) can be found ubiquitously in India (Andey et. al 2013).

Despite these advantages, there are many lessons to be learned before the technology is transferred to Nalgonda. Through NEERI's long-term experience with EDF, it appears that current challenges in rural Maharashtra include:

- Lack of proper maintenance of plants not operated by private vendors in rural areas
- Difficulty changing user behavior and encouraging users to purchase treated groundwater
- Limited technological reach to other fluoride-affected states, except in cases where local governments took initiative
- Potentially prohibitive capital cost for plant construction and costs for electrode replacement/maintenance

Overall, the current efforts to mitigate the endemic fluorosis problem in some North Indian states (Maharashtra, Madhya Pradesh, Chhattisgrah) are well demonstrated by the work done by NEERI scientists. To spread the EDF technology to other Indian states and globally, , certain innovation (technological, entrepreneurial, and social) gaps must be filled, as shown by the severe, long standing, and still largely unresolved problem in Nalgonda District.

Concluding thoughts and future research

Through this explorative study, the first author (AKC) was able to a) understand the potential for scaling up NEERI's electrolytic defluoridation treatment process, b) create a network of connections with schools, educational institutions with labs, and government officials in Andhra Pradesh for future field pilot studies, and c) collect quantitative and qualitative data on water quality and the local levels of endemic fluorosis in the Nalgonda district. The ultimate goal of our research is to find a suitable defluoridation technology for the Naglonda District that meets the requirements of long-term sustainability (i.e., it is locally affordable, easy to maintain, robust, culturally appropriate, and can be scaled up).

To test if EDF is an appropriate technology that can be successfully implemented in Nalgonda, we will conduct some proof of concept experiments to show whether or not aluminum hydroxides help reduce fluoride concentrations to below 1ppm, for varying initial concentrations (5-10ppm). Once it is known how much aluminum is required per weight of fluoride removal, we will compare EDF to other sources of aluminum oxides (e.g., Al salts) to see which option is the most effective. Ideally, the process could be optimized given the local groundwater chemistry in Nalgonda, which can be synthesized based on the chemical reports collected at the Nalgonda District Collector's Chief Planning Office and the Superintendent Engineers of Water Supply.

Along the way, we hope to gain a better understanding of how factors including pH and competing anions affect the defluoridation and current efficiencies of the EDF process by enhancing or inhibiting the corrosion process. Lastly, we believe there may be potential improvements leading to energy and cost savings such as changing the material of the cathode to reduce power consumption and using bipolar electrodes and alternating current to reduce passivation. Furthermore, reversing the polarity to clean the electrode might make the operation easier and lengthen the overall lifetime of the system. It is possible that such improvements in the EDF technology could make it cheaper and more energy efficient compared to its current design, which has not changed since its inception. The EDF technology appears to be a promising potential solution to the fluoride contamination problem in South India because it is easily deployable, has been shown to work in field conditions in North India for over a decade, produces minimal amounts of nontoxic sludge, is easy to operate and maintain by unskilled people, and has the potential to remove other contaminants in water.

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