

*Full Length Research Paper*

# **Performance enhancement of Nalgonda technique and pilot testing electrolytic defluoridation system for removing fluoride from drinking water in East Africa**

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High fluoride concentrations in groundwater pose a health risk to people living in the Rift valley of Ethiopia and beyond. The Nalgonda and electrolytic defluoridation (EDF) fluoride treatment systems were developed and adapted in India for fluoride removal. A recent study evaluated twenty Nalgonda techniques that were implemented in the Rift valley of Ethiopia. A number of these systems were found to be non-functional or had never been utilized. The purpose of this study is to evaluate the performance of the Nalgonda technique and seek ways to enhance the fluoride uptake capacities. Further, pilot testing of the EDF system was conducted in the Rift Valley of Ethiopia to evaluate its effectiveness at fluoride removal using natural groundwater in this setting. This study has shown that the performance of the Nalgonda system was significantly enhanced by adding aluminum hydro(oxide) (AO) and cow bone char powder into the existing Nalgonda systems; the initial fluoride concentration of 9.3 mg/L was lowered to 2.5 mg/L on average. In addition to the increased effectiveness at fluoride removal, the addition of AO and cow bone char powder produced significantly less sludge compared to the existing Nalgonda system. The EDF system proved to be effective at removing the excess fluoride concentration in drinking water in the Rift Valley of Ethiopia; the initial fluoride concentration of 7.9 mg/L was lowered to 2.8 mg/L meeting the USEPA standard fluoride level of 4 mg/L. The pilot study showed Aluminum leaching into the treated water. Thus, further optimization of the electrode size, electrolysis time, and voltage/current used during the electrolysis process is needed to meet the WHO target treatment goal of 1.5 mg/L fluoride level and eliminate aluminum leaching as well.

**Key words:** Electrolytic defluoridation, fluoride, Nalgonda, pilot-testing, sustainability.

## **INTRODUCTION**

More than 748 million people lack access to improved drinking -water supplies globally; it is mainly the low-income and marginalized segment of the population that still lack access to an improved drinking water sources

(WHO 2014). Reasons given for the slow expansion of water supply services to the poor include funding constraints, a community's inadequate operation and maintenance skills (Calow et al., 2013). Furthermore, the

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sustainability of safe water supply schemes is constrained by social, technical, financial, institutional and environmental issues (Brikké and Bredero, 2003). For example, some of the common problems faced by safe water supply systems in Ethiopia include the availability of spare parts, chemicals, capacity for scheme operation and management, tariff collection, and water quality issues (Israel and Habtamu, 2007). The non-functionality rates of the developed safe water supply systems in Ethiopia are also high (up to 33%) due to technical, financial and social problems (Abebe and Deneke, 2008).

Groundwater constitutes 30.1% of total global freshwater (Gleick, 1996) as the single largest available supply of drinking water, especially in rural settings (WHO, 2004). However, groundwater can contain geogenic (dissolution of fluoride and arsenic-containing minerals) and/or anthropogenic sources (e.g., application of pesticides), such as fluoride and arsenic which are known to affect human health (Apambire et al., 1997; Roy and Dass, 2013). A volcano's plume is often the principal source of high concentrations of fluoride in groundwater and the environment (Notcutt and Davies, 1989). For example, drinking water fluoride concentrations in the Ethiopian Rift Valley range from 1-33 mg/L with an average value of 5 mg/L (Haimanot et al., 1987).

Various defluoridation technologies, such as the Nalgonda, bone char and activated alumina have been implemented in Ethiopia (Osterwalder et al., 2014; Frank et al., 2011). Most of these defluoridation systems failed to meet the intended purpose of the provision of fluoride-safe drinking water to the communities. For example, defluoridation systems in Wonji-Shoa irrigation scheme used activated alumina which was expensive and had logistical constraints of operation and maintenances (Teklehaimanot et al., 2006). Supply of equipment and chemicals for fluoride removal is lacking and there is no consistent monitoring mechanism put in place to ensure the quality of treated water. There is a limited engagement of private sectors in the defluoridation processes. As a result, the fluoride removal technologies utilized thus far have not proven sustainable for providing access to safe water supply services in the Rift Valley of Ethiopia.

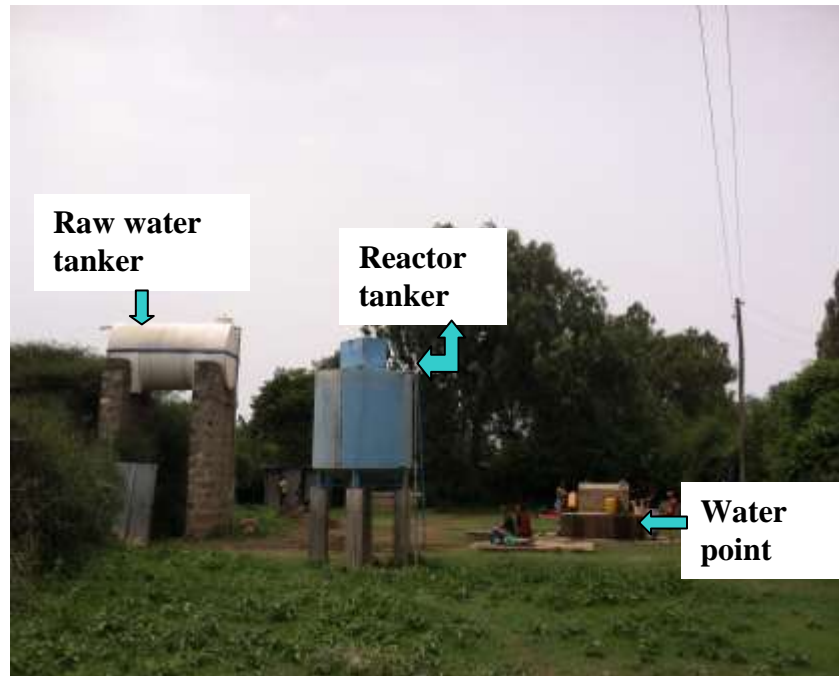
High fluoride levels in drinking water cause damage to human dental and skeletal systems as well as the structure and functions of the non-skeletal systems, such as brain, liver, kidney, and spinal cord (Guan et al., 1998; Wang et al., 2004). Additionally, excess fluoride concentration in drinking water causes various histological structure changes of the kidney, including extensive induction of cell apoptosis and thereby resulting in impairment of renal function and metabolism (Zhan et al., 2006). The kidney is sensitive to fluoride intoxication; where 50-80% of fluoride adsorbed is eliminated (Guan et al., 2000). Liver, as an active site of metabolism, is also susceptible to fluoride toxicity

(Shivashankara et al., 2000; Wang et al., 2000). Fluoride level in drinking water exceeding 2.0 mg/L can cause damage to liver and kidney functions in children (Xiong et al., 2007).

Beyond dental, skeletal and other impacts on the structural functions of human organs, fluorosis has significant socio-economic impacts stemming from the fact that persons who develop skeletal fluorosis suffer considerable hardship and have reduced productivity (Apambire et al. 1997; Frank et al. 2011). It has been estimated that more than 200 million people from more than 25 nations around the world consume water with fluoride concentrations above the World Health Organization (WHO) recommended threshold of 1.5 mg/L (Amini et al., 2008) and are thus at risk of fluorosis. It is therefore critical to either treat fluoride impacted groundwater or find alternative water sources for communities living in fluoride affected areas of the world in order to mitigate the suffering of those people impacted by fluoride-induced health concerns.

Various fluoride removal technologies, such as Nalgonda, electrolytic defluoridation, reverse osmosis, Donnan dialysis, ion-exchange, adsorption and contact precipitation, have been implemented in the field (Ayoob et al., 2008; Brunson and Sabatini, 2009). Adsorption is currently considered as the method of choice for fluoride removal from drinking water because of its high efficiency, potential use of locally available materials, low operation and maintenance cost, high-quality water, and potential for regeneration and reuse (Choy et al., 2004; Jagtap et al., 2012). For example, bone char, activated alumina, red mud, quartz, fly ash, hydroxyapatite, zeolites and modified zeolites, ion exchange resins, layered double hydroxides and chemically activated cow bone (CAB) are among the adsorbents studied for fluoride removal from drinking water (Mohapatra et al., 2009; Du et al., 2014).

However, fluoride removal technologies implemented in the field often fail to be sustainable due to poor community management capacity as well as lack of supply chain for chemicals and equipment (Brunson and Sabatini, 2009). For example, out of more than 20 Nalgonda-based defluoridation systems implemented in the Rift Valley of Ethiopia over the past decade, some were never fully used after installation and more than half of those that were implemented were found to be no longer functional (Osterwalder et al., 2014; Datturia et al., 2015). Of those still functioning and recently tested, treated water fluoride concentration levels were found to be significantly higher than the WHO guideline value of 1.5 mg/L (University of Oklahoma's Water Center survey data, July 2014). Therefore, since excess fluoride concentrations in drinking water cause dental and skeletal fluorosis along with other severe socio-economic problems (Dissanayaka 1991), addressing the technical efficiency, sustainability and scalability challenges is of paramount importance. Yami et al. (2017) suggested that



**Figure 1.** Layout of the small community scale Nalgonda technique, Dodo Wadera defluoridation site in the Rift Valley of Ethiopia (photo by Teshome L. Yami)

sustainability of fluoride treatment systems can be ensured using business model logic in achieving financial and operational sustainability of the systems.

## REVIEW OF EXISTING TECHNOLOGIES IMPLEMENTED IN THE RIFT VALLEY OF ETHIOPIA

### Nalgonda

The Nalgonda technique was developed and adapted in India by the National Environmental Engineering Research Institute (NEERI). It utilizes aluminum sulfate to enhance coagulation-flocculation-sedimentation, the dosage of which is designed to ensure fluoride removal from the water. The use of alum and lime has been extensively studied for defluoridation of drinking water, and it is popularly known as the Nalgonda technique (Nawlakhe et al., 1975). The layout of the Nalgonda system is shown in Figure 1. In Ethiopia, under the fluorosis mitigation project promoted by UNICEF and the Federal Water, Irrigation and Electricity Ministry, the Nalgonda technique has been pilot tested in several rural communities. Furthermore, Catholic Relief Service (CRS) in collaboration with Meki- Catholic Secretariat office implemented this technique in the Ethiopian Rift Valley communities since 2005 (Datturia et al., 2015).

However, the Nalgonda system has been shown to require a high dose of alum, generates inadequate

removal efficiency and has problems associated with large sludge disposal (Shrivastava and Vani, 2009). There were studies conducted to increase the fluoride removal capacity of the Nalgonda systems. For example, Zewge (2016) added aluminum hydro(oxide) (AO) to the Nalgonda system to enhance the fluoride removal capacity. A common concern amongst researchers is that the Nalgonda technique requires a great deal of monitoring and that the daily operators require appropriate training and reliable operation (Ayoob et al., 2008). The experience in WaSH sector demonstrates that community water supply systems fail because the hardware (infrastructure) has been installed but the means to sustain the intervention beyond construction (software) is lacking. The software component requires integration of the social, institutional, technical, economical, operation and management, and environmental aspects. Thus, the hardware and software component of the fluoride treatment systems need to go hand in hand to ensure sustainability. A study conducted on the Nalgonda technique revealed that maintenance costs are high, the process is not automatic, and users do not like the treated water taste (Maheshwari, 2006). Therefore, to enhance the sustainability of the Nalgonda systems requires establishing a strong monitoring system, improving the fluoride removal capacity, and building the management capacity of the community is of paramount importance. The fluoride removal mechanism of the Nalgonda system has been explained as a co-



**Figure 2.** Electro-defluoridation system installed at Berta-Sembi communities in the Rift Valley of Ethiopia (Photo by Teshome L. Yami).

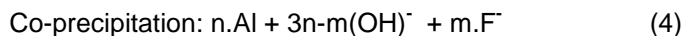
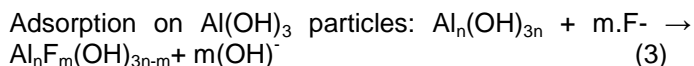
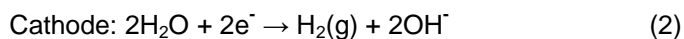
precipitation where the main constituent (fluoride) is removed as flocs via settling due to combination of sorption and ion exchange with the hydroxide groups produced.

### Electro-defluoridation (EDF)

EDF was also developed by NEERI, India, to treat excess fluoride concentration in drinking water. EDF involves the use of aluminum electrodes that release  $\text{Al}^{3+}$  ions by an anodic reaction and hydrogen gas released at the cathode, and the ions then react with fluoride ions that are found in excess near the anode. Figure 2 shows the arrangement of the aluminum electrodes in the reactor tanker. The aluminum cations are transformed into polymeric species and form  $\text{Al}(\text{OH})_{3(\text{s})}$ . The reactive intermediate hydroxyl species formed during the reaction further interact to form a hydroxide of disordered structure which intensifies the fluoride removal (Andey et al., 2013). Compared with traditional chemical coagulation, EDF process requires less space and does not require chemical storage, dilution and pH adjustment. In addition, the EDF system does not require substantial investment and has lower volume of sludge generation compared to the Nalgonda (Mollah et al., 2001; Essadki et al., 2009). It has proven to be effective drinking water supply for small or medium sized community in India (Andey et al., 2013).

### Fluoride removal mechanism EDF

The EDF system's fluoride removal mechanism is through adsorption and co-precipitation with the aluminum-based colloidal precipitates generated by the electrodes (Zhu et al., 2007). The electromechanical reactions promoted by the electrodes (anode and cathode) and the adsorption/co-precipitation reactions are shown in Equations 1 to 4.



### Goal of the study

To date, several fluoride adsorbents have been developed and implemented in the field to remove excess fluoride concentrations from drinking water. However, field level observation shows inefficiency and ineffectiveness of these technologies. The overall goal of this work is therefore to evaluate the performance of the Nalgonda technique implemented in the Rift Valley of

**Table 1.** Quantities of chemicals required for Nalgonda system and dimensions of EDF system.

Fluoride treatment technology		Quantity of media required per treatment batch (kg) <sup>a</sup>		
		Alum	Lime	BC or AO
Nalgonda	Nalgonda alone	5.85	2.93	
	Nalgonda + cow bone char (BC)	4.5	1.6	0.3
	Nalgonda + AO	4.5	0.75	0.25
Dimensions (cm) <sup>b</sup>		Length (cm)	Width (cm)	Depth/ Thickness (cm)
EDF	Reactor tanker	105	100	110
	Aluminum electrode	90	80	0.2

Note: <sup>a</sup>The media quantity was determined based on the quantity required to lower initial fluoride concentration of 10mg/L to 1.5 mg/L.

<sup>b</sup> This dimension is for one of the four EDF compartments. The depth includes a free board of 20 cm and 10cm slope for sludge removal. Runs 1 and 2 indicate that the EDF system was run twice (for two days consecutively).

Ethiopia. Further, it evaluates the feasibility of the EDF system for fluoride removal from drinking water using natural groundwater in the Rift Valley of Ethiopia.

## Research questions

The research questions evaluated in this work are:

- (1) Can the addition of bone char powder (waste material from bone char production) and aluminum hydro (oxide) (AO) to the Nalgonda system enhance its fluoride removal capacity?
- (2) Does the electrolytic defluoridation (EDF) system developed in India produce similar fluoride removal efficiency in natural groundwater in the Ethiopian Rift Valley?
- (3) Is the water treated using EDF system suitable for public consumption?

## MATERIALS AND METHODS

### Nalgonda

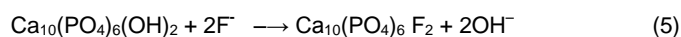
In Dodo Wadera village, a Nalgonda-based water treatment system in the Rift Valley of Ethiopia was selected in collaboration with the National Fluorosis Mitigation Project office of the Ethiopian Ministry of Water, Irrigation and Electricity as a site to evaluate the potential for enhancing the fluoride removal capacity of the Nalgonda system. The community level defluoridation system consists of raw water tanker, reactor tanker with a mixer shaft, treated water tanker, sludge storage tank, water distribution point and the powerhouse. The capacity of the reactor tanker (one batch) is 5000 Liters. The Nalgonda system uses aluminum sulfate (alum) and calcium oxide (lime) chemicals added to the reactor tanker and mixed rapidly with high fluoride concentration water. The motor agitated mixing and reactions of chemicals are conducted for 20 min and the treated water is stored in treated water storage tanker.

The aluminum and lime used in the Nalgonda system were purchased from Melkassa Aluminum Sulfate Production Company in Ethiopia. Based on the working manual of the Fluorosis Mitigation Project Office of the Ethiopian Ministry of Water, Irrigation

and Electricity, the amount of alum and lime used to treat 5000 liters of water per batch was 5.85 and 2.93 kg, respectively (Table 1 and SI-1). The quantity of lime added was assumed to be 50% of the alum needed for the treatment which agrees with the quantity of lime recommended as 20 to 50% of the alum dosage by Dahi et al. (1996). The quantity of alum and lime recommended in this study was targeted to achieve the WHO guideline value of 1.5 mg/L. Dahi et al. (1996) indicated that an alum dosage of 12.8 and 6.4 g lime (50% of alum quantity) reduced the fluoride concentration to  $2.1 \pm 0.7$  mg/L based on the findings from studies conducted in 76 families. Lime is added to alum to maintain neutral pH since the hydrolysis of aluminum hydroxide releases  $H^+$  ions and to facilitate formation of dense floc for rapid settling (Shrivastava and Rani, 2009). Both alum and lime were dissolved in separate buckets and poured into the Nalgonda system as slurry and stirred for 20 min until it reaches equilibration within 2 h.

In this study, efforts were made to improve the performance of the existing Nalgonda system considering the modality of operation by the local community, that is, the quantity of alum and lime added and the duration of mixing. The second option was using a hybrid system (the existing Nalgonda system and adding aluminum hydro(oxide) (AO)) prepared by the National Fluorosis Mitigation Project Office, Ministry of Water, Irrigation and Electricity, Ethiopia. The third option was using the existing Nalgonda system and adding cow bone char powder which is a byproduct of bone char produced by Oromo Self-Help Organization (OSHO), Ethiopia.

AO was prepared by adding 100g  $Al_2(SO_4)_3 \cdot 14 H_2O$  in 500 mL of Deionized water (DI) and NaOH solution that gives 2.7 OH:Al ratio due to its highest performance and surface properties (Mulugeta et al., 2014). The resulting pH 2.7 was raised to neutral pH using 2 M NaOH. In this study, 4.5 kg alum, 0.75 kg lime and 250 g AO (Table 1) were mixed in a bucket and poured into the Nalgonda system as slurry and stirred for 15 min until it reaches equilibration within 2 h. Thermally activated cow bone (bone char) was prepared by heating cow bone in a furnace at 500°C to remove volatile and organic matters. Bone chars have been widely used as an adsorbent for removal of excess fluoride concentrations. The fluoride removal mechanisms of bone chars are direct adsorption of fluoride on bone char surfaces and ion exchange mechanisms where fluoride ions exchange with hydroxyl ion (Equation 5) (Kawasaki et al., 2009). Bone char powder used in this study was obtained from OSHO bone charring site located in Modjo town in the Ethiopian Rift Valley. The quantity of alum, lime and cow bone char powder added to the Nalgonda system was 4.5 and 1.6 kg and 300 g, respectively (Table 1).



### Electrolytic defluoridation (EDF)

The feasibility study of EDF system for removal of fluoride from drinking water under the context of groundwater quality in the Rift Valley of Ethiopia was conducted in July 2014. An existing incomplete EDF system (finishing work remains on system's construction) at Berta Semi village in the Rift Valley of Ethiopia was used to conduct this study. The EDF system has four tankers to conduct the electrolysis. In this study, the aluminum plates were installed in one of the EDF tanker compartments to run the pilot testing work. The aluminum plates, electrical wires, and other accessories were purchased from Modjo town in the Rift Valley. The dimensions of the EDF system, Aluminum plate and the electrolysis time of the EDF system is summarized in supplemental data (Table 1 and SI-II).

The generator installed to pump raw water from Berta Semi drilled well was used as a power source to run the EDF system. The AC current was converted to DC current to run the electrolysis using BK Precision, Model 1796- high current DC power supply 0-16 V/0-50A with 800-watt output. Water pump (model 6000-125E, 3/4" Barb, 230V/240V, Laing Thermotech, USA) was used for mixing and recirculation of the treated water.

## RESULTS AND DISCUSSION

### Nalgonda

The separate addition of cow bone char powder and aluminum hydro(oxide) into the existing Nalgonda system (Aluminum sulfate and lime) significantly enhanced the fluoride removal capacity. The existing Nalgonda system (alum and lime) lowered the initial fluoride concentration of 9.3 to 7.0 mg/L, which is significantly higher than the WHO guideline value of 1.5 mg/L. The treated water fluoride concentration in the reactor tanker increased to 8.0 mg/L after 20 h of treatment due to the higher dosage of lime added above the design requirement for the treatment. This situation raised the pH which resulted in competition between  $\text{OH}^-$  and  $\text{F}^-$  and thereby reduced the fluoride removal capacity. Thus, the inappropriate ratio of alum and lime used by the local scheme operator in the Nalgonda reactor raised the pH and reduced the fluoride removal capacity of the system. The design requires the addition of a specific proportion of alum and lime (lime = 50% alum quantity). According to the field level observation of the Nalgonda system operation by local community, steel plates and bowls were used to measure the quantity of alum and lime added to Nalgonda reactor tanker. The OU WaTER Center's study conducted in July 2014 on the operation of Dodo Wadera Nalgonda-based treatment system indicated that 7 kg alum and 5 kg of lime (71% of the alum quantity) was added by the community, which is more than the recommended lime dosage level (50% of alum).

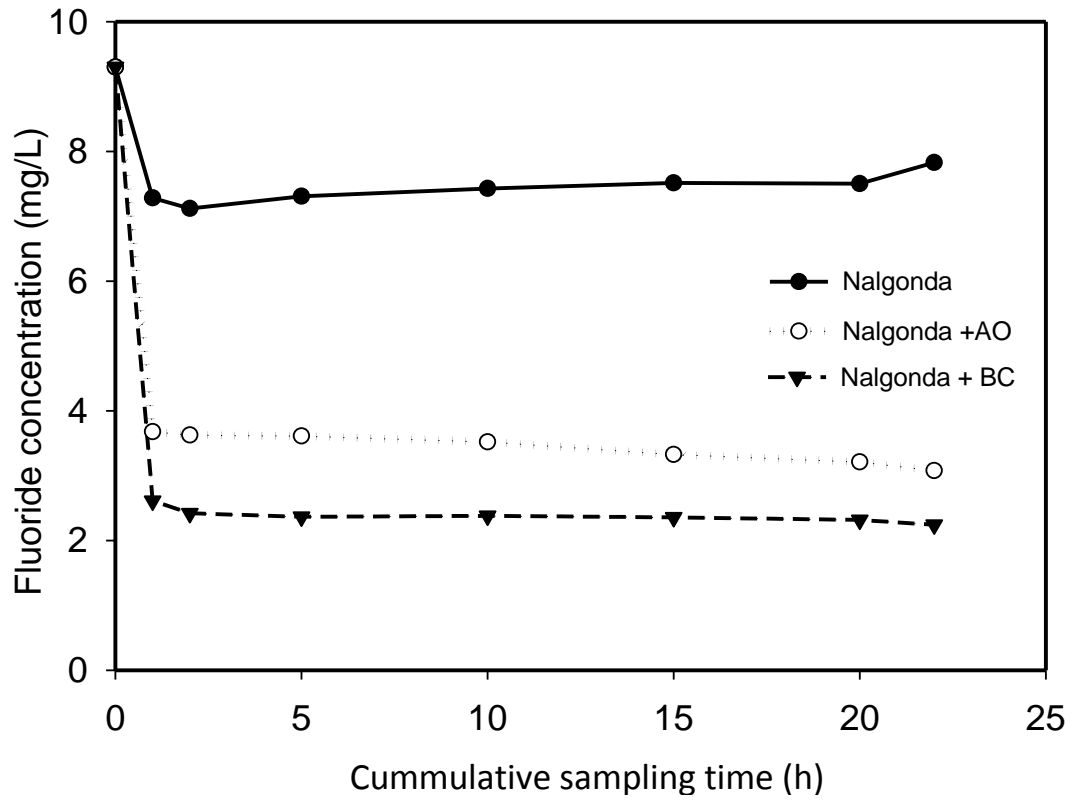
Further, since a separate tanker for treated water was not installed, the treated water stays in the treatment tank and the sludge releases  $\text{OH}^-$  back to the system and thereby raising the pH which reduced the fluoride removal capacity. It was observed that the Nalgonda system produced large quantity of sludge which required

labor to clean it before the next round of water treatment. Up on the addition of AO to the existing Nalgonda system, initial fluoride concentration of 9.3 mg/L was reduced to 2.8 mg/L (Figure 3). The treated water samples were collected at 5 h interval after the addition of AO and analyzed for fluoride and pH. Besides the improved performance of the treatment system, the addition of AO resulted in a lower quantity of sludge produced. Cow bone char powder (BC) added to the Nalgonda system could lower the initial fluoride concentration to 2.1 mg/L (Figure 3). This study demonstrated that both AO and cow bone char powder added to the existing system could be used to enhance the fluoride removal capacity of Nalgonda techniques. The treated water fluoride concentration met the US standard for fluoride of 4.0 mg/L. However, the treated fluoride level is still slightly above the WHO guideline value of 1.5 mg/L thus requiring further optimization of chemicals dosage (alum, lime and AO) and pH to meet the standard. Further, these two media (AO and cow bone char powder) produced significantly lower quantities of sludge which was one of the common problems of the existing Nalgonda systems.

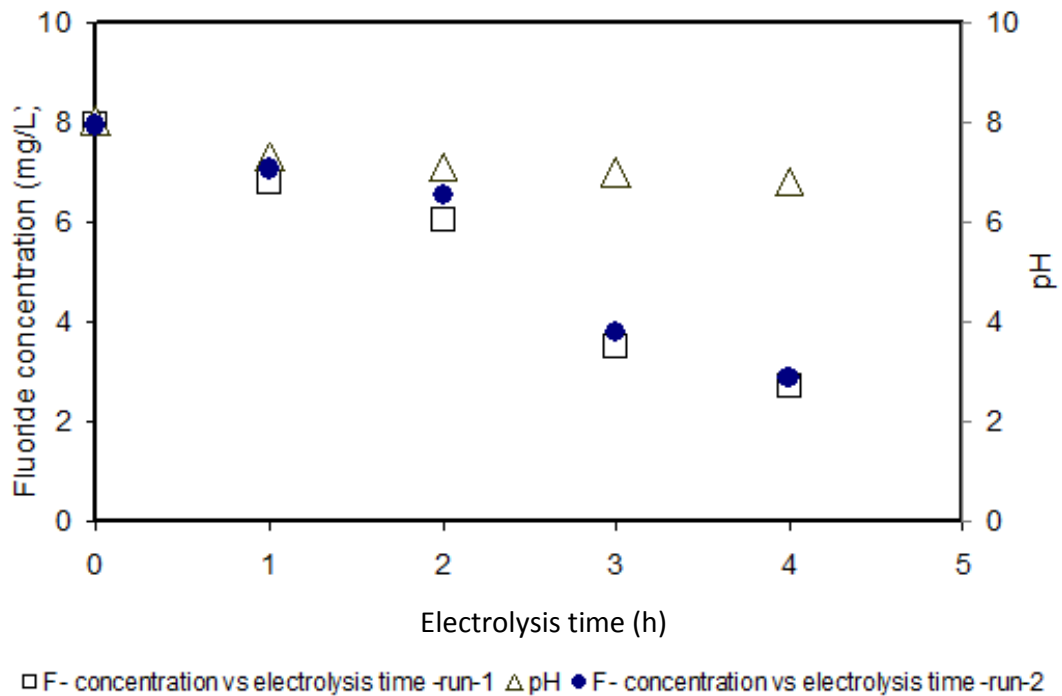
The combination of the alum/AO and cow bone char powder has a beneficial effect on the properties of the treated water by reducing the quantities of alum and lime needed to treat the water. Upon the addition of AO/cow bone char powder into the Nalgonda Technique, less sludge was produced, and the treated water quality met the WHO guideline values compared to the Nalgonda Technique alone. The addition of these media into the Nalgonda Technique enhances the formation of aluminum hydroxide flocs which is responsible for the co-precipitation of the fluoride ions. Further, the combined AO/cow bone char powder and alum/lime is low-cost and the treated water is affordable to the rural communities.

### Electrolytic defluoridation (EDF)

The pilot electrolytic defluoridation system installed at Berta Semi community in the Rift Valley of Ethiopia significantly reduced the fluoride concentration from 7.9 to 2.8 mg/L (Figure 4). The initial pH of raw water (8.02) was reduced to an average of 7 during the electrolysis process. The calculated electrolysis time was 3 h (SI-II) although it was increased to 4 h to further lower the fluoride concentration. The EDF system was run in two batches and the result of the fluoride removal versus the electrolysis time was consistent, that is, it did not show a statistically significant difference. During operation of the EDF system, it was observed that bubbles (hydrogen gas) formed at the electrode probably due to the highly acidic surface nature. Optimization of the operational voltage and current may help overcome the problem associated with the bubble formation. To further reduce the fluoride concentration in the treated water to the WHO guideline value (WHO, 2004) of 1.5 mg/L, it is also



**Figure 3.** Treated water fluoride level for samples collected at five-hour interval from the Nalgonda system.



**Figure 4.** Fluoride level of treated water over four hours of electrolysis time from the pilot tested EDF system in the Rift Valley of Ethiopia (Summer 2015).

**Table 2.** Treated water quality parameters for Berta Semi EDF site.

Water Quality Parameters	Unit	Pilot project site	
		Berta semi (EDF site)	Standards
pH	Dimensionless	7.0	6.5 – 8.5 <sup>1</sup>
Fluoride	mg/L	2.8	2 <sup>1</sup>
Arsenic, Total	mg/L	0.00414	0.01 MCL <sup>1</sup>
Sulfate	mg/L	1.73	250 <sup>1</sup>
Aluminum, Total	mg/L	32.1	0.05-0.2 <sup>1</sup>
Calcium	mg/L	9.95	50 <sup>2</sup>
Magnesium, Total	mg/L	2.05	50 <sup>2</sup>
Total Hardness Ca/Mg Eq. CaCO <sub>3</sub>	mg/L	33.3	75 <sup>2</sup>

Note: <sup>1</sup>WHO (2008), <sup>2</sup>Canadian Health act safe drinking water regulation BC Reg 230/92, and 390, Sch 120, 2001 .

necessary to further optimize the size of the aluminum plate and the electrolysis time. It is also of paramount importance to understand what is happening at the surface of the electrode as well. For example, scaling formation at the surface of the electrode reduces the performance of the system and it is difficult to regenerate the plate after scaling formation.

The aluminum concentration of the treated water using the EDF system was 32.1 mg/L (Table 2) which is higher than the WHO guideline value of 0.2 mg/L (WHO 2008). To lower the treated water aluminum concentration, configuration of the electrode during installation of the EDF system needs due consideration to avoid alkaline or acidic formation which reduces the performance of the system and posing treated water quality problem due to leaching of the A<sup>+</sup>. The fluoride concentration of the treated water of 2.8 mg/L was slightly higher than 1.5 mg/L of WHO guideline value. Therefore, optimization of the number and size of the aluminum electrodes used in the EDF system, duration of electrolysis time, and the electric current/voltage may help lower the treated water fluoride concentration to achieve the treatment goal of 1.5 mg/L. Other water quality parameters such as arsenic, sulfate, calcium, magnesium and total hardness are lower than the WHO guideline values (Table 2). Nonetheless, this first ever implementation of EDF in Ethiopia shows the great promise of this approach to addressing fluoride impacted groundwater in Ethiopia.

To ensure the sustainability of both the Nalgonda and EDF based- fluoride treatment systems, business model logic plays significant roles in achieving financial and operational sustainability of the systems (Yami et al., 2017). Engagement of the private sector/ local service providers can also significantly contribute towards scaling up of defluoridation technologies by actively engaging in production and installation of treatment systems, and supply of equipment and chemicals. The private sector/ service providers can produce adsorbents, treat fluoride impacted water, and distribute treated water and undertake operation and management works. Therefore,

using business model logic can help solve the prevailing shortage of raw materials, chemicals and equipment and ensure sustainability of the defluoridation systems.

## CONCLUSION AND RECOMMENDATIONS

This study demonstrated that the poor performance of Nalgonda-based water treatment system implemented in the Rift Valley of Ethiopia was due to the community's lack of necessary skill to manage and operate the system. The user community added an inappropriate ratio of alum and lime which raised the pH and thereby affected the fluoride removal capacity. Further, lack of supply chain for chemicals and equipments affected the sustainability of the Nalgonda systems. Upon addition of AO and cow bone char powder, the final fluoride concentration of the treated water was 2.8 mg/L and 2.1 mg/L, respectively compared to 7 mg/L for the Nalgonda system alone. This study has thus shown that the performance of the Nalgonda system can be significantly enhanced by adding AO and cow bone char powder into the existing Nalgonda techniques. Besides increased capacity, the addition of AO and cow bone char powder of the Nalgonda techniques reduced the amount of sludge produced and the labor cost required to clean the reaction tanker.

The raw water fluoride concentration of 7.9 mg/L considered in the pilot testing of the EDF system was reduced to 2.8 mg/L at an electrolysis time of 4 h. Thus, the EDF system was proven to be effective at removing the excess fluoride concentration in drinking water in the Rift Valley of Ethiopia. Significant reduction of the initial fluoride level was achieved meeting the US standard but further optimization of the size of the aluminum plate, electrolysis time and voltage is needed to further reduce the fluoride concentration of the treated water to the reach the WHO treatment goal of 1.5 mg/L and thereby eliminate the leaching of aluminum ion. Furthermore, to ensure the continuity of operation of the EDF system,



installation of solar power source is of paramount importance to fill the gaps in electric power supply. Monitoring water quality also needs attention to reduce the impact of chemicals leaching into treated water. Thus, the pilot testing of the EDF system using natural water in the Rift Valley has shown good potential to provide access to safe water supply to communities and thereby reduce the negative health impact of excess fluoride concentration in the Rift Valley of Ethiopia and beyond. To ensure sustainability of fluoride treatment systems, giving equal attention to the hardware and software component of the treatment system is important.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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## Supplemental Data

### SI-1- Design of Nalgonda Technique (Dodo Wadera site in the Rift Valley of Ethiopia)

Raw water fluoride concentration ( $C_0$ ) = 9.3 mg/L  
 Treated water fluoride concentration = 1.5 mg/L (WHO 1984).  
 Present project users = 3000 persons  
 Growth rate ( $r$ ) = 3%  
 Project life ( $n$ ) = 10 years

$$\text{Projected population (P)} = P_0 (1 + r)^n \quad (1)$$

$$P = 3000 (1 + 3\%)^{10} = 4000 \text{ persons} \quad (2)$$

$$\begin{aligned} \text{Quantity of treated water consumption per day} = \\ \text{water consumed per person per day} \times \text{number of people} \end{aligned} \quad (3)$$

$$= 4 \text{ L/P/D} \times 4000 \text{ persons} = 16,000 \text{ L/day} \quad (4)$$

Two reactors of each with 5000 Liters capacity are needed to treat the 16,000 Liters of water to meet the daily demand. Each reactor produces two batches of treated water daily i.e., one reactor produces 10,000 L/day.

### Quantity of chemicals required

$$\text{Quantity of fluoride removed per batch} = (C_0 - C_i) \times V \quad (5)$$

Where,  $C_0$  = initial fluoride concentration (mg/L)

$C_i$  = treated water fluoride concentration (mg/L)

$V$  = volume of treated water per batch (4000 L)

$$= (9.3 - 1.5 \text{ mg/L}) \times 5000 \text{ L}$$

$$= 39.0 \text{ g F}^- \text{ per batch} \quad (6)$$

The quantity of fluoride removed to treat the daily water demand of 16,000 L:

$$= 4 \text{ batches per day} \times 39.0 \text{ g F}^- \text{ per batch}$$

$$= 156 \text{ g F}^- \text{ day} \quad (7)$$

According to Ethiopian Ministry of Water and Energy, fluoride treatment design manual, 150 g alum ( $\text{Al}_2(\text{SO}_4)_3$ ) required to remove 1 g fluoride. The amount of lime required is 50% of the alum quantity.

Quantity of alum required per batch of treated water is,

$$= 39 \text{ g F}^- \times 150 \text{ g} / 1 \text{ g F}^- \quad (8)$$

$$= 5.85 \text{ kg alum} \quad (9)$$

$$\text{Quantity of lime per batch} = 50\% \times 5.85 \text{ kg} = 2.93 \text{ kg} \quad (10)$$

$$\begin{aligned} \text{Quantity of alum required per day (to treat 16,000 L)} &= 4 \text{ batches} \times 5.85 \text{ kg alum/batch} \\ &= 23.4 \text{ kg/day} \end{aligned} \quad (11)$$

$$\text{Quantity of lime per day} = 4 \text{ batches} \times 2.93 \text{ kg lime/batch} = 11.72 \text{ kg lime/day} \quad (12)$$

### SI-II Design of Electrolytic Defluoridation System (EDF)

Raw water fluoride concentration ( $C_0$ ) = 7.93 mg/L  
 Treated water fluoride concentration = 1.5 mg/L (WHO 1984).  
 Present project users = 3000 persons  
 Growth rate ( $r$ ) = 3%  
 Project life ( $n$ ) = 10 years  
 Projected population ( $P$ ) =  $P_0 (1 + r)^n$  (1)

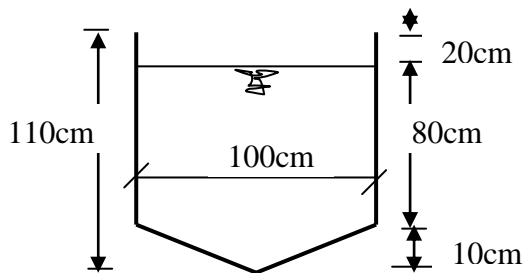
$$P = 3000 (1+3\%)^{10} = 4000 \text{ persons} \quad (2)$$

$$\begin{aligned} \text{Quantity of treated water consumption per day} = \\ \text{water consumed per person per day} \times \text{number of people} \end{aligned} \quad (3)$$

$$= 4 \text{ L/P/D} \times 4000 \text{ persons} = 16,000 \text{ L/day} \quad (4)$$

Four tankers of each with 1000 L capacity are needed to treat the 16,000 Liters of water in four batches to meet the daily demand.

The dimension of the defluoridation tank is 100 cm (wide), 105 cm (length) and 110 cm (depth). The net height of the tanker after provision of slope for sludge removal (10cm) and free board (20 cm) is 80cm. The dimension of one compartment (tanker) of the EDF system is shown in Figure S2-1 below.



**Figure S2-1.** Dimension of one compartment (tanker) of the EDF system. The bottom wedge is for sludge removal.

Volume of the tanker is calculated below:

Volume of the rectangular section of the tanker:

$$= 1.0 \text{ m} \times 0.9 \text{ m} \times 1.05 \text{ m} = 0.945 \text{ m}^3 \quad (5)$$

$$\text{Volume of the triangular section} = (0.5 \times 1.0 \text{ m} \times 0.1 \text{ m}) \times 1.05 \text{ m} = 0.0525 \text{ m}^3 \quad (6)$$

The total of volume of one compartment of the EDF system is  $1.0 \text{ m}^3$  (1000 L).

Dimensions of aluminum plate (electrode) fitting to the tanker:

= 90 cm (length)  $\times$  80 cm (high)  $\times$  2 mm (thick)

Number of aluminum plate used in each tanker = 3, where the first and the third plates are used as cathodes and the central plate is anode. The distance between the electrodes is 1cm.

$$\text{Weight of Aluminum plate} = \rho_{\text{aluminum}} \times V \quad (7)$$

Where,  $\rho$  is density of aluminum ( $\text{kg/m}^3$ ), and  $V$  is the volume aluminum plate ( $\text{m}^3$ )

$$= 2700 \text{ kg/m}^3 \times (0.9 \text{ m} \times 0.80 \text{ m} \times 0.002 \text{ m})$$

$$= 3.9 \text{ kg} \quad (8)$$

Using Faraday's law, the weight of aluminum dissolved (m) can be calculated as:

$$m = KIt \quad (9)$$

$$m = (C_o - C_i) \times V \times (\text{Al/F ratio}) \quad (10)$$

$$m = (7.93 - 1.5 \text{ mg/L}) \times 1000 \text{ L} \times 4 = 25.72 \text{ mg per tank} \quad (11)$$

In Equation 9,  $K$  is a constant determined using,

$$K = M/ZF \quad (12)$$

where,  $M$  is atomic weight of aluminum,  $Z$  is valency of aluminum and  $F$  is Faraday's constant = 96500.

$$K = \left(\frac{27}{3 \times 96500}\right) = 9.326 \times 10^{-5} \quad (13)$$

Therefore, from  $m = KIt$ ,

$$It = m/k = 25.72 / (9.326 \times 10^{-5}) = 275,788 \quad (14)$$

Considering current,  $I = 25$  Amp,  
Electrolysis time,

$$t = 275,788 / 25 = 11,031.5 \text{ s} = 184 \text{ min} = 3 \text{ h} \quad (15)$$