EFFECTIVENESS OF MODIFIED BIOSAND FILTERS (BY INCORPORATING BAMBOO ACTIVATED CHARCOAL, DIATOMITE, BONE CHAR, AND STEEL WOOL) IN REMOVAL OF FLUORIDE, AND *E. coli* FROM WATER.

OKADEMI NANCY

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DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or University of Eldoret.

Nancy Okademi

____________________________ Date_____________________

SENV/EBH/M/002/18

Declaration by the Supervisors

This thesis has been submitted with our approval as the University Supervisors.

______________________________ **Date**_____________________

Prof. Odipo Osano
School of Environmental Sciences and Natural Resources
University of Eldoret, Eldoret, Kenya

______________________________ **Date**_____________________

Dr. Judith Khazenzi
School of Environmental Sciences and Natural resources
University of Eldoret, Eldoret, Kenya

DEDICATION

This thesis is dedicated to my daughter Valentine Valarie Okademi. May she become a great scholar in her own right, my beloved Dad Fredrick Okademi Papa and Mum Antonina Amoo Okademi.

ABSTRACT

The Rift Valley contains the most significant sources of fluoride exposure. People in the Rift Valley have been confirmed to drink water containing up to 33mg/L of fluoride. The WHO has set the maximum allowable limit for fluoride in potable water at 1.5 mg/L. For millions of Kenyans, drinking water with a high fluoride content is a health risk such as dental fluorosis and skeletal fluorosis. Several studies on defluoridation have been conducted, and the majority of them concentrate on separate treatments for flouride, even though mixed contamination is common. Among Point of Use water treatment systems, the domestic Biosand filter (BSF) is a low-cost technology that has been implemented in Kenya. Several studies have shown that the BSF can reduce the turbidity and microbial contaminants effectively however, limited studies have focused on removal of fluoride. Various low-cost materials like bamboo activated charcoal, bone char, diatomite and steel wool were investigated to assess their capacity to remove fluorides from water by batch adsorption studies. Experiment was also conducted to determine the effect of the modified filter on bacteria reduction using E. *coli* as an indicator. The specifications of the standard Biosand filter were reduced, and four modified filters and one standard filter were designed. The 5 filters were replicated four times to produce a total of 20 filters. The filters were subjected to trials in the laboratory where 1.5, 2.26 and 3.0 mg/L initial fluoride concentration were subjected to 30 minutes, 60 minutes and 90-minutes contact time in order to reduce fluoride concentration to the recommended level of below 1.5 mg/L. *E. coli* was cultured and serially diluted into sterile saline deionised water and passed through modified Biosand filters. Data obtained was analysed using descriptive statistics, t-test and Analysis of Variance (ANOVA). The bamboo activated charcoal, diatomite, bone char and steel wool modified filters performed significantly better ($p<0.05$) than the standard filter, removing over 90% of fluoride after 24 hours and treating the water to below the WHO fluoride limit of 1.5mg/L. This study also indicated that the standard Biosand filter removed the highest amount of *E. coli* bacteria with removal rate of 96%. Bamboo activated charcoal, diatomite, bone char and iron oxide (Fe^0) removed 90, 85, 81 and 70% respectively. This study's findings indicate that the modified filters are effective in removing both fluoride and *E. coli* from water. The bone char modified biosand filter proved to be the most effective in removing fluoride, while the standard biosand filter was found to be the most effective in removing *E. coli.* The study recommends that bone char modified filters can be built with locally accessible materials (sand, gravel, coarse sand and bone char) and applied in communities that are exposed to both fluoride and *E. coli* pollution but cannot afford expensive fluoride and E .*coli* reduction approaches.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BSF	Bios and Filter
E. coli	*Escherichia coli*
ANOVA	Analysis of Variance
CFU	Colony Forming Unit(s)
Mg/L	Milligrams per litres
TISAB	Total Ionic Strength Adjustment Buffer
UOE	University of Eldoret
WHO	World Health Organization.

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May God Bless you all.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Water is crucial component of all forms of life (Bartik et al., 2011; Westall & Brack, 2018). Water, the most crucial in our planet as a natural resource covers about 70% of the earth surface (Abdullah-Al-Mamun et al., 2015; Dwivedi, 2017; Risse, 2014). At the most basic level, everyone requires clean water in ample amounts for drinking, cooking, personal hygiene, and sanitation without jeopardizing their health or dignity (Dinka, 2018; Velleman et al., 2014). As a result, humans have a fundamental/basic right to healthy and dependable (clean and fresh) water (Crawford, 2020; Khalifa & Bidaisee, 2018). However, owing to water contamination, 2.2 billion people worldwide do not have access to clean drinking water (WHO, 2019). Water dissolves a slew of minerals because it is a universal solvent that interacts with environmental materials (Reichardt & Timm, 2020). Water pollutants from both anthropogenic and natural causes include microorganisms such as viruses, protozoa, and bacteria; inorganics such as salts and metals; organic chemical emissions from industrial processes and agricultural use; pesticides and herbicides; and other contaminants (Singh et al., 2020; Stokdyk et al., 2020). Mineral elements present in a given area can naturally dissolve in varying amounts in water sources as a result of the geological composition of soils and bedrock (Binda et al., 2018; Gemitzi et al., 2017). Fluorides are among the mineral elements found in water that raise significant global concerns (Kamathi, 2017).

In humans and animals, fluoride is considered as an essential mineral but its importance depends on the concentration there is in drinking water or the amount that one consumes (Shukla et al., 2018). Fluoride is essential for the maintenance of strong and healthy bones (Ringe, 2004). About 260 million citizens that are from six different countries are believed to ingest a daily uptake of water that contains close to 1.0 mg/L of fluoride (Onipe et al., 2020).

Elevated concentrations of fluoride have been documented in many places of Kenya, including the Great Rift Valley and the slopes of Mount Kenya (Wambu & Muthakia, 2011; Mechal et al., 2022). The presence of dental fluorosis and skeletal fluorosis has been reported in these particular locations (Kahama et al., 1997). The study conducted by Gevera et al. (2019) found that the groundwater in Nakuru contains varying levels of fluoride, ranging from 0.1 to 72 mg/L.

For the past eight decades, dedicated efforts have been ongoing to develop suitable technologies aimed at mitigating fluoride pollution (Collivignarelli et al., 2020; Naseri et al., 2017). Drinking water defluoridation is normally achieved by precipitation or adsorption processes (Collivignarelli et al., 2020). Electro-dialysis, reverse osmosis, ion exchange, chemical precipitation, and adsorption are the most popular methods for defluoridating water (Brindha & Elango, 2011). The method for removing fluoride is dependent on factors such as capital and operating costs, environmental effects, and fluoride removal effectiveness (Halder et al., 2016; Karunanithi et al., 2019). Only a portion of the materials that have been examined contain activated alumina, activated charcoal, activated clay, bone char, clays, ion exchange membranes, laterite, magnesium compounds, phosphate rock, poly-aluminium salts, serpentine, and zeolite (Craig et al., 2015; Nabbou et al., 2019). Most defluoridation techniques are complicated, require skilled labor, have a high initial and ongoing expense, and are technically unfeasible due to strict pH and other experimental conditions, as well as the use of toxic chemicals, all of which are limiting factors for their use in water defluorination (Damtie et al., 2019; Karunanithi et al., 2019). Given their high efficacy in eliminating fluoride, this renders them unaffordable to most local communities. As a result, it is beneficial to find locally accessible defluoridation media that are clean, simple to use, and low in cost at both the household and small community levels (Marwa et al., 2018; Roy & Dass, 2013).

Because of its high removal performance, superior adsorption rate, ease of operation, and large range of adsorbents, adsorption has been identified as the most promising method for removing fluoride from water (Onyango & Matsuda, 2006; Habuda-Stanić et al., 2014). It also has the benefit of being adaptable to a decentralized water supply scheme (Prathna et al., 2018). Since different adsorbents are available in large quantities and at low prices, they are possible candidates for defluoridation in remote areas (Viswanathan et al., 2010). Activated carbon, cellulosic materials, zeolites aluminum, nanomaterials, diatomite, iron oxides (FeO), and biochar are only a few examples of adsorbent materials (Kalidindi et al., 2017; Karmakar et al., 2017; Rostamia et al., 2017).

Numerous studies have reported that activated carbon derived from bamboo (Wendimu et al., 2017), biochar (Mutheki et al. in 2011), diatomite (Akafu et al., 2019), and iron oxides (FeO) (García-Sánchez et al., 2013) can effectively eliminate fluoride from water. However, these materials are unable to address the issue of microbial contaminants. In contrast, the Biosand filter (BSF) has been documented to reduce water turbidity and microbial contaminants, as demonstrated in the research by Kennedy et al. in 2012. Consequently, combining the Biosand filter with fluoride removal materials holds promise as a viable solution for areas where high fluoride levels in water coexist with microbial contamination concerns.

1.2 Statement of the problem

The Biosand filter (BSF) is a low-cost, easy-to-use water treatment system that advances conventional slow-sand filters (Treacy, 2019; Shah et al., 2015). It is designed for intermittent use (Young-Rojanschi & Madramootoo, 2014). When compared to the global average, Kenya's unique geology results in some of the highest concentrations of fluoride in the earth's lithosphere, rivers, and bore water. The elevated fluoride in water occurs in some springs, wells, and Rift Valley lakes (Edmunds & Smedley, 2013). These areas with high levels of Fluoride are areas that have had a number of volcanic eruptions and are located in areas along the East African Rift. Most of the lakes in the Rift Valley system, according to Nair et al., (2020) have high fluoride concentrations, with amounts ranging from 1,640 mg/L to 2,800 mg/l in Lakes Elementaita and Nakuru, respectively. According to Njoroge (2014) the Kenyan government's Vision 2030 blueprint aims to provide safe and clean water to the entire country while emphasizing a stable and prosperous population.

According to a study conducted by Gevera et al. (2019), the groundwater supplied to residents of Nakuru contains varying levels of fluoride, ranging from 0.1 to 72 mg/L. Millions of people living along Rift Valley Escarpment in Kenya have been suffering from dental and skeletal fluorosis due to consuming water containing excessive fluoride

(Gevera et al., 2019; Mechal et al., 2022). Several strides have been done to remove fluoride from drinking water. However, most of these filters involve using a single defluorination media, which may remove fluoride but does not ensure the removal of other water contaminants such as bacteria. Some bacteria, such as pathogenic or disease-causing strains, can pose serious health risks when consumed in contaminated water. Ingesting these bacteria can lead to various waterborne diseases, including gastrointestinal infections, which can be particularly harmful to vulnerable populations such as children and the elderly.

Numerous studies have demonstrated the efficacy of various materials such as bamboo activated charcoal (Wendimu et al. in 2017; Bhatnagar et al. in 2013), bone char (Alkurdi et al., 2019; Medellin-Castillo et al., 2007; Delgadillo-Velasco et al., 2017, and Kaseva, 2006), steel wool (Ndé-Tchou et al., 2015 and Hildebrant et al., 2020), and diatomite (Yitbarek et al., 2019; Dong et al., 2021) for the removal or reduction of fluoride levels in water.

However, there is a noticeable gap in the existing literature when it comes to filters capable of simultaneously removing both fluoride and microbial contaminants from water. This research study aimed to address this gap through investigating the potential of different Biosand filters incorporating bamboo activated charcoal, diatomite, bone char, and steel wool in removing both fluoride and *E. coli* from water sources. This will be determined by finding out efficiency of the filters in removal of the two contaminants.

1.3 Objectives

1.3.1 General Objective

The main objective of the study was to determine the potential of Biosand filters modified with bamboo activated charcoal, diatomite, bone char, and steel wool in removal of fluoride, and *E. coli* in water

1.3.2 Specific Objectives

1. To determine percentage removal of fluoride from drinking water using biosand filters incorporated with diatomite, bone char, steel wool and bamboo activated charcoal
2. To determine percentage removal of *E coli* from drinking water using biosand filters incorporated with diatomite, bone char, steel wool and bamboo activated charcoal.

1.3.3 Null Hypothesis

Ho1: Biosand filters incorporated with diatomite, bone char, steel wool and bamboo activated charcoal do not remove fluoride from drinking water.

Ho2: Biosand filters incorporated with diatomite, bone char, steel wool and bamboo activated charcoal do not remove *E coli* from drinking water.

1.4 Justification

Between 1990 and 2015, the UN's Millennium Development Goals aimed to "halve the population without access to clean drinking water and basic sanitation” (Wests rate et al., 2019; Fukuda et al., 2019). A report released by WHO and UNICEF as part of their Joint Monitoring Programme (JMP) for water supply and sanitation showed that nearly 2.3 billion people currently have better drinking water (Armah et al., 2018). According to the report, substantial progress has been made in the last two decades, but much more remains to be done.

Under the social pillar of Kenya Vision 2030, water and sanitation aim for all to have access to clean water and healthy sanitation by 2030 (Ndung’u et al., 2011). The goal of the Ministry of Water and Sanitation strategic plan for 2018-2022 is to increase the percentage of the country's population with access to clean water from 60% in 2017 to 80% by 2022 (Mwai et al., 2022). Healthy drinking water is not only important for human development and well-being but also a recognized human right (WHO, 2015). The supply of safe drinking water is regarded as critical and pivotal to overall development (Francis et al., 2015). The presence of contaminants in water can cause economic burden to the population by treating water borne-related diseases caused by their toxicity. Therefore, it is vital to remove these water contaminants so as to reduce or eliminate economic and health burdens. The majority of defluoridation materials primarily target the removal of fluoride from water, often neglecting other waterborne contaminants. The results of this study contribute to the improvement of biosand filters.

Most methods for reducing fluoride levels are expensive and inefficient when dealing with small concentrations.

1.5 Significance of the study

The removal of fluoride and E. *coli* from drinking water has the potential to mitigate the prevalence of waterborne infections and dental fluorosis, thereby fostering improved public health outcomes, particularly among populations facing challenges in accessing clean water resources. This work will additionally contribute to the scientific comprehension of biosand filters and their potential for improved water treatment.

Traditional water treatment processes often involve multiple steps or technologies to target different contaminants. A modified Biosand filter capable of handling both fluoride and *E. coli* simplifies water treatment processes, making them more resource-efficient, cost effective, and accessible to communities with limited resources.

The findings of this research can inform policymakers, governmental agencies, and nongovernmental organizations (NGOs) in crafting targeted interventions and policies to combat water contamination issues in affected regions. It can serve as a basis for evidence based decision-making.

1.6 Scope and limitations of the study

The experiment was set at the biotechnology laboratory at the University of Eldoret. In addition to bamboo activated charcoal, diatomite, bone char and steel wool were used to modify the biosand filter separately. Water samples were collected from a borehole and spiked with flouride and *E. coli* for use in the study. Efficiency was measured as the percentage removal of the contaminants (fluoride and *E.coli)*. The study was limited to a short-term analysis of filter performance and therefore long-term effects, such as filter media degradation, clogging, or changes in removal efficiency over time, was not explored. Furthermore, an in-depth economic analysis, including the costs associated with implementing and maintaining these modified biosand filters, was not included in the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Sources of Fluoride in Kenya

For over 30 years in Kenya, Fluorosis has been shown to be endemic (Rango et al., 2014). Kenyan groundwater has shown to have high amounts of fluoride ranging from 0.1 ppm to more than 1ppm according to samples that were obtained from a long-term analysis. On surface water, they found that fluoride levels went up to 34ppm which is lethal to human health (Onipe et al., 2021).

Excessive fluoride levels of over 70 mg/L in surface and groundwater have been identified in the East African Rift Valley dating back to the colonial period (Marwa et al., 2018; NdéTchoupé et al., 2019; Ronoh, 2023). Many studies have been undertaken to address the fluorosis problem in this area since the early 1960s (Marwa et al., 2018; Pettenati et al., 2013; Wambu & Muthakia, 2011). This is because volcanic rocks contain fluorotic crystals, which contaminate groundwater resources and then pollute local water bodies with fluoride ions (Srivastav et al., 2018).

Consumers of water from Njoro, Gilgil, Nakuru town, Bahati, Solai and Rongai in Nakuru County drink water with fluoride levels (Wambu and Muthakia, 2011). This is similar to the population within lake Magadi, Bogoria and Baringo (Gikunju, 2002; Onindo and Mwangi, 2012; Malago et al., 2017), Laikipia and Muranga Counties (Gikunju et al., 2002).

Fluoride amounts as high as 1,640 mg/L and 2,800 mg/L were observed in lakes Elementaita and Nakuru (Kamathi (2017). In addition, they found that 61 % of 1,000 groundwater samples obtained around the world surpassed 1 mg/L, 20% surpassed 5 mg/L, and 12% surpassed 8 mg/L.

2.2 Health effects of fluoride

According to studies, the adverse effects that fluoride intake has on human health first came to light in the earlier years of 1910 but the claims were not taken seriously up until 1930 (Carstairs, 2015). According to WHO the set amount of fluoride intake that drinking water should have should be between 0.5 mg/L and 1.5mg/L (Egor & Birungi, 2020; Yami et al., 2015). Concentration between 1.5 mg/L and 4 mg/L is what defines dental fluorosis (Collivignarelli et al., 2020; Kimambo et al., 2019). On the other hand, Skeletal Fluorosis gets defined by concentrations from 4mg/L. According to the findings of Prystupa (2011) and Kimambo et al. (2019), they observed that concentrations exceeding 10 mg/L have a detrimental impact on the central nervous system, resulting in spinal cord injuries that lead to deformities in the spine.

Fluoride penetration disrupts collagen development and leads to collagen degradation of bone, tendon, muscle, skin, cartilage, the lungs, kidneys, and trachea (Katiyar et al., 2020). Fluoride diminishes the energy reserves of white blood cells and hampers their capacity to efficiently eliminate foreign intruders through the phagocytic process. Even at levels as low as 0.2 parts per million in serum, fluoride triggers significant oxide production in resting white blood cells, effectively hindering phagocytosis (Yan et al., 2015). Fluoride, at micromolar concentrations (much less than 1 ppm), can significantly impair the ability of white blood cells to combat pathogenic intruders, leading to a disruption in the immune response. Furthermore, fluoride causes the immune system to target the body's own tissues and increases the rate of tumor growth in individuals susceptible to cancer. Additionally, fluoride has a decelerating effect on thyroid activity (Liu et al., 2019).

2.3 Standards for Fluoride in Drinking Water

In Kenya, the normal dose of fluoride in water varies from 0.5 to 1.5 mg/L, which is the WHO, (2017) recommended amount (Nocella et al., 2022). According to the Water Services Regulatory Board Drinking Water Quality and Effluent Monitoring Guidelines (WASREB, 2015), fluoride concentrations of up to 1.5 mg/L are appropriate due to local climatic conditions, and in situations where more is needed, standard absorption can be extended to 3 mg/L.

2.4 Defluoridation

Electro dialysis, reverse osmosis, ion exchange, chemical precipitation, and adsorption are the most popular methods for defluoridating water (Waghmare & Arfin, 2015). The evaluation of fluoride reduction considers various factors, including capital and operational expenses, environmental impacts, and the efficiency of fluoride removal. For instance, distillation can eliminate ions from water but is associated with a considerably high cost.

2.5 Studies on Water Defluoridation

In 2006, Adora conducted a study on the removal of fluoride from water using chalk sourced from Muranga, Kenya. The mass of fluoride ions sorbed per unit mass of chalk, equilibrium adsorption capacity (Qe), was 0.08mg/g for column investigations and

0.096mg/g for batch studies. Batch fluoride removal was better, but a batch system is not optimal for industrial scale. Chalk removes fluoride from Kenyan water effectively.

Mutheki et al. (2011) analysed the field and laboratory performance of bone char filters and other filters based on a mix of bone char and calcium-phosphate pellets. They found that bone char filters performed better than the other filters. The study found out that the typical uptake capabilities for F were 1.2± 0.3 mg/g and 3.0 ± 1.0 mg/g, respectively.

Naliaka (2016) conducted a study to investigate the performance of locally accessible bone char in the removal of fluoride from water. The study findings indicated that the bone char adsorbent lowered fluoride concentration from 8.1 mg/L to under the threshold of 3 mg/L for high concentration of fluoride. In contrast, Mavura et al. (2004) devised a flow-through defluoridation system tailored for high-fluoride water. This system comprised a cartridge filled with bone char material that could be affixed to a residential faucet to serve as a defluoridizer. Their studies revealed that the optimal conditions for the fluoride filter, yielding the most effective fluoride removal from water, included the following parameters: a particle size with an average diameter of 0.2 mm, a flow rate equal to or less than 20 ml/L, and a cartridge length of 10 cm, containing 20 g of bone char material.

2.6 Use of biomaterials as adsorbents

The use of this process in removal of Fluoride in contaminated water has received a lot of praise. The reason is because the materials used to make the same are cheaper as compared to others and can get processed in very large amounts and also the materials for use in the making is from resources that can get renewed. The materials used are environmentally friendly hence get considered as efficient in removing contaminants to levels that are conducive to human beings.

According to research, it has got proven that biomass that comes from plants are most conducive for fluoride removal and they include rice husks, orange peels and papaya seeds among others (Brunson & Sabatini, 2014; Liu et al., 2019) the surface of the adsorbent and its characteristics is a greater contributor to the removal of Fluorides using biomaterials (Chidambaram et al., 2003; Mlilo et al., 2010).

The most significant challenge that these methods pose is the incorporation of secondary contaminants into water due to organic leaching and a lack of regeneration capabilities (Kikuchi & Tanaka, 2012). Numerous studies have indicated that the utilization of unprocessed natural components like fruit and vegetable residues presents various challenges, including limited pollutant removal efficiency and a significant cation exchange potential resulting from the release of soluble organic compounds from plant matter (Crini & Badot, 2010; Kikuchi & Tanaka, 2012). Consequently, it becomes necessary to treat plant waste materials before their utilization. de Quadros Melo et al. (2016) found that adding carboxylate groups to orange peels, bagasse, and peels mixed with bagasse with citric acid improved biomaterial properties and resulted in high lead removal ability.

2.6.1 Bamboo Charcoal

Bamboos are a complex group of evergreen annual flowering plants in the grass family Poaceae's subfamily Bambusoideae (Akinlabi et al., 2017). The root of the word "bamboo" is unclear, but it is most likely originating from the Dutch or Portuguese languages, which adopted it from Malay or Kannada (Mudoi et al., 2013). Bamboo is one of the most common plants in tropical and subtropical regions between 46°N and 47°S, and it is very hardy, not requiring pesticides or herbicides to survive. It is a grass that grows from its roots; when removed, it easily regrows, with most species maturing in 3-5 years (Akinlabi et al., 2017). Bamboo has been described as a superior herb due to characteristics such as rapid growth, high biomass, and harvest in a short period of time, as well as high performance in a few years. It is classified as a non-timber forest product (NTFP) plant (Mudoi et al., 2013).

Among the most significant aspects of bamboo is the accelerated rate at which it matures, which can be 3 years, while other trees need roughly 20 years. The bamboo growth rate is also impressive; in some instances, it has been recorded that it is nearly 2 inches per hour, as well as the height will exceed 60 feet in just three months (Akinlabi et al., 2017).

The porous surface of bamboo charcoal absorbs tap water and airborne impurities. Bamboo charcoal extracts chlorine, chloride, phosphate, mercury, toluene, nitrogen, residual chlorine (ammonia and chlorine compound applied to water to eliminate pathogens), and also contaminants including pesticides that may seep into drinking water while carbonized at high temperatures. In general, bamboos now play an important role in human life, meeting a broad variety of human needs ranging from environmental conservation to use as household appliances. The chemical composition and structural structure of bamboo charcoal all contribute greatly to its usefulness as a water filter. It is composed of 85-98 % carbon, and is the same material found in most modern filtration processes. With the exception of conventional carbon filters, bamboo charcoal has a built-in team of microbes that work to decompose poisonous compounds such as trihalomethane and chlorine. Despite bamboo's intrinsic antibacterial properties, which are peculiar to bamboo and are referred to as "Bamboo Kun," these harmless microbes can thrive in bamboo and bamboo charcoal. Bamboo Kun is an anti-bacterial and anti-fungal bio-agent that spontaneously binds to bamboo cellulose without destroying the microbes that live there (Nishida et al., 2017).

Activated carbon, often known as activated charcoal, is a kind of carbon used to filter impurities from air and water, among other applications. It is treated to have small, reduced pores that improve its surface area (Bhatnagar et al., 2013). Carbon got used as an adsorbent in the ancient times which were famously used by the Roman and the Chinese empires (Tshwenya, 2017). The Romans were the first to discover the use of carbon for water purification, and to this day, it continues to be employed for this purpose in some countries (Telgote & Patil, 2020). Although charcoal's discovery dates back quite early, it still required nearly 3,000 more years to refine the formula for effectively using it in pollutant removal. In 1863, a researcher Smit discovered that charcoal when left in open air, could strip off its oxygen for up to a month. However, they also made a discovery that the most effective coal to be used for the process is one made from animal bone remains as compared to that made of wood (Hagemann et al., 2018). This made researchers grow an interest in expanding their research into finding the characteristics of coal made from various items and their sorption abilities. It was not until the early years of the 19^{th} century that they discovered that charcoal components contain various sorbed organic compounds (Paul et al., 2016). As a result, the first "activation" techniques aimed to reduce the number of chemical species consumed after processing. According to Wang et al. (2012) thermal activation is the only way for extracting adsorbed organic compounds from the surface of the charcoal.

As a result, water is naturally cleansed of toxins, viruses, and fungi. Bamboo charcoal is also suitable for use in filtered water because it increases the flavor and provides the 'fizz' that means the water has been washed and mineralized. After filtering water, the bamboo charcoal can be reused by exposing it to direct sunlight for three hours to allow it to lose its impurities. In this way, charcoal can be reused for up to a year. Due to high adsorption capabilities of activated charcoal this study will modify the Biosand filter in order to increase the efficiency of fluoride removal.

2.6.2 Bone Char

Bone char was among the earliest materials suggested for eliminating fluoride from water, as noted by Alkurdi et al. in 2019. However, it has not gained widespread use due to issues such as the treated water's unpleasant taste, high costs, and limited availability. Nevertheless, the World Health Organization (WHO) in 1988 endorsed bone char as a viable technology for use in developing nations. Its porous and granular structure has made bone char a highly efficient option for absorbing various water contaminants. The purification process involves passing water through bone char, typically done through a drum or a column.

The process of making bone char involves taking bones from local butcheries then heating it up in kilns whereby there is no oxygen allowed in and the heat is maintained between 400 to 500^0c. But in some instances when the bones are lesser and the quality of bone is not the hard type, temperatures can get reduced to ensure they remain effective and temperatures can get increased for large batch sizes. After the heating process, the sorting process begins where they get graded according to their colour. Those that are black in color are collected together where when the next batch of bones are getting charred, they get added to it. The ones that get categorized as white and grey-brownish get crushed separately where they get sieved into three different particle sizes using a crushing machine. Calcium phosphate pellets for contact precipitation are made from powder and fine fraction (0.63 mm). the importance of sorting them up to different particle sizes is to ensure that water can flow through it effectively and if it's the required size to remove Fluoride. Washing is then done where different impurities that got absorbed are removed where in the end bone char then gets dried and stored safely for future use (Rojas-Mayorga et al., 2013). According to Delgadillo-Velasco et al. (2017), charring can be performed in two ways: calcinations, in which bones are heated in the presence of a continuous supply of oxygen from ambient air, or pyrolysis, in which no oxygen is available during heating. In calcinations, organic carbon is converted to CO_2, which is then extracted, while in pyrolysis, organic carbon is converted to inorganic carbon, which is then stored in the bone char. Calcined bones range in color from brown to grey to white depending on oxygen availability, whereas pyrolyzed bones are black.

According to Alkurdi et al. (2019), bone char has been utilized in the sugar industry as an absorbent for decolorization purposes. This is because it has a unique textural property and has a high content of hydroxyapatite, which contributes to the high pollutant removal quality. Bone char (Reynel-Avila et al., 2016; Rojas-Mayorga et al., 2016) is an inorganic material that has been recorded as a good material due to its use in the field of electrochemistry (Goodman et al., 2013), as a catalyst (Alkurdi et al., 2019; Oladipo et al., 2017; Yang et al., 2020). Several studies have been done on the effectiveness of defluoridation using bone char. In late 1998, bone char defluorination was first studied in Kenya in a laboratory in batches and columns. The Catholic Diocese of Nakuru Water Deflouridation company established and markets four separate types of defluorination filters, ranging from household filters to institutional, community, and waterworks filters (Kanyora, 2014). The process of defluoridation utilizing bone char is characterized by its simplicity, affordability, and suitability for decentralized water treatment applications.

According to a study by Mutheki et al. (2011) on the use of defluoridation treatment in East Africa, he concluded that bone char filtration is effective for fluoride removal. Bone char use particularly in remote areas have greatly helped in reduction of maintenance activities and improvement suitability. This has been enabled by increasing the uptake capacity of the bone char intake.

Ion exchange between fluoride in the solution and carbonate of the apatite that makes up bone char is thought to be the removal mechanism. From an initial fluoride concentration of 12.0 mg /L, the bone char media can produce water with a residual fluoride concentration of less than 0.1 mg/L. The materials are readily available in the area and can be handled by individuals at the household level for personal use or by a group of locals for resale to other locals. The bone char can also be prepared at a centralized station, where it can be mass processed and packed in numbered packets. The bones are charred in special kilns that use wood charcoal as a fuel source. The kiln has been designed and tested in various sizes. Devices for crushing and sieving have been created. Bone char defluoridation systems have been developed and tested on a household and community scale (Nigri et al., 2020). The packed bone char and columns could then be sold in fluorotic areas' local shops. The centralized processing of bone char, on the other hand, necessitates a larger expenditure. Capital for large-scale procurement of raw bones, transportation of raw bones to the processing station, larger kilns, and powered crushing and sieving equipment could all be included in the investment. Other specifications could include packaging materials and many plastic columns for storing bone char during water defluoridation. Another apparent expense is the transportation and distribution of manufactured bone char and columns to local shops in fluorotic areas. Since it is difficult for locals to know when to replace the media in their household defluoridation, data on the initial fluoride concentration can be used to predict when the media should be replaced (Ayoob et al., 2008).

2.6.3 Diatomite

Diatomite is a mineral found in nature which is believed to be fossilized remains of diatoms (Ghobara et al., 2019). Famously the mineral gets known as the diatomaceous earth which belongs to a family of Bacillariophyceae of the golden-brown algae (Khan, 2010). Made up of silica, the concentration of silica is higher because it makes up the sedimentary deposit (Lutyński et al., 2019). Diatomite was famously used for pottery by the Greeks 2000 years ago. Diatomite sedimentary properties have made it used as an adsorbent (Bakr, 2010).

Diatomite is a microscopic diatom alga with a size range of 0.75 to 1500 meters; it is also known as infusorial earth, kieselguhr, and mountain meal (Papadopoulos et al., 2008). The main components of the siliceous armor $SiO_2.nH_2O$ are silica hydrates with different degrees of water content (opals). Diatomite rock is classified as a silica-bearing stone. Diatomite is a siliceous sedimentary rock formed during the tertiary and quaternary periods from the fossilized skeletal remains of diatoms, a kind of unicellular aquatic plant similar to algae (Arik, 2003).

Diatomite is composed of a variety of diatom shapes and sizes varying in length from 10 to 200 mm in a formation of up to 80-90 % voids (Bakr, 2010). Diatomite's extremely porous composition, low density, and wide surface area have led to a variety of industrial applications, including filtration media for a variety of beverages and inorganic and organic chemicals, as well as an adsorbent for per litres and oil spills.

Diatomite is far more inexpensive as compared to other materials considered as adsorbent including carbon which is commercially activated which has globally now replaced the use of coal (Gupta et al., 2009). Diatomite has not only got used in water purification but its chemical and physical characteristics has made it of use in so many other industrial processes (Ediz et al., 2010). Moreover, it is customary for this substance to exhibit the capacity to accumulate heavy metals, which might potentially have detrimental effects on both human and animal health. Additionally, it possesses the ability to adsorb a wide range of pollutants present in drinking water. However, diatomite has received little attention as an adsorbent in wastewater treatment (de Namor et al., 2012; Ediz et al., 2010).

2.6.4 Steel Wool (Fe^0)

Metallic iron (Fe^0) is the parent of iron oxides and hydroxides and has been utilised in water treatment for more than 170 years (Noubactep, 2018). Small particles of F (iron filings, iron shavings, scrap iron, steel wool) are typically introduced to polluted water (Gheju, 2018). Steel wool (Fe^0) commonly known as an iron wool or a wire wool or wire sponge is defined as a bundle made up of sharp-edged filaments which are very fine which was defined as a novel product by studies in the year 1896 (Gasia et al., 2019). Steel wool has been used for various activities such as smoothening of rough surfaces of wood, metals and floors by smoothening its surfaces and has also been used in cleaning of utensils and cookware (Lv et al., 2022). This is because steel wool gets considered as abrasive having been made up of steel that has very low carbon components (Lu, 2002). In its making, they use heavy steel wire which then gets pulled through a toothed die which ensures it removes the small and sharp wire shavings. The ability of FeO-based filters to remove/inactivate various biological and chemical contaminants from water has been demonstrated. FeO type (intrinsic reactivity), FeO particle size, filter configuration (e.g., depth of the reactive layer, filter dimensions), complementary substrate type and concentration (e.g. FeO/sand ratio), water content (e.g. pH and presence of competing species), and operational conditions all impact individual filter operation (e.g. water flow, temperature) (Phenrat et al., 2009; NdéTchoupé et al., 2015; Loganathan et al., 2013). As a result, a wide range of operational factors can affect the FeO filter's performance. Since there is such a broad variety of significant variables, only a well-designed systematic approach will determine optimal operating conditions.

Iron oxide for use in household filters was introduced the same way that permeable reactive barriers made up of iron oxide for groundwater remediation (Hussam & Munir, 2007; Ngai et al., 2007). Results from different studies on the suitability of safe drinking water after the use of FeO filters have shown that it is effective (Noubactep et al., 2009). Biosand filters, which are made up of iron particles, residues and nails, have proven to be effective in aiding the removal of arsenics, bacteria and viruses (Parajuli, 2013). The Biosand filters traditionally were made when iron made equipment got added to the diffuser basins while some even added it directly to the sand bed of the BSF. While steel wool is effective for fluoride removal, its performance may vary based on factors such as pH, temperature, and the presence of other water constituents. Additionally, regular monitoring and replacement of the steel wool may be necessary to maintain its adsorption capacity. (Naseri et al., 2017; Tepong-Tsindé et al., 2015).

2.7 Different types of filters used to remove fluoride in water

In the pursuit to combat fluoride contamination in drinking water sources, various types of fluoride removal filters have been developed. Each of these filter types employs distinct mechanisms and materials, offering a unique set of benefits and drawbacks. To provide a comprehensive understanding of these filtration methods, this table 2.1

summarizes the different types of fluoride removal filters, highlighting their respective advantages and limitations.

Table 2.1: Types, Benefits and drawbacks of different filters used to remove fluorides

Filter	**Mechanism**	**Benefits**	**Drawbacks**	**Source**
Adsorbent-Based Filters	Various adsorbent materials, including clay minerals, zeolites, and synthetic adsorbents, can be used to remove fluoride through adsorption.	Diverse options for different water sources, costeffectiveness, and ease of use in decentralized water treatment systems.	Variable fluoride removal capacities and selectivity depending on the adsorbent material. Not effective in removing bacteria and viruses	Vinati et al., (2015); Amor et al. (2018); Margeta et al. (2013); Jagtap et al. (2011)
Activated alumina filters	Work through adsorption. The aluminum oxide surface of the filter media attracts and binds fluoride ions from the water.	Effective at removing fluoride, relatively low cost, and can be used in point of-use or point of-entry systems.	Requires periodic regeneration or replacement, and may release aluminum into the treated water. Not effective in removing bacteria and viruses	Tripathy et al (2006); Ahamad et al. (2018); Dhawane et al. (2018)

Bone Char Filters	Work through adsorption. Fluoride ions are adsorbed onto the hydroxyapatite surface.	Excellent fluoride removal capacity, cost effective, and long-lasting.	Limited availability of bone char, and may require pretreatment to remove turbidity. Not effective in removing bacteria and viruses	Alkurdi et al. (2019); Sorlini et al. (2011); Kanyora et al. (2015)
Ion-Exchange Resin Filters	Ion-exchange resins contain charged sites that exchange fluoride ions with other ions, such as chloride or hydroxide, as water flows through the resin bed.	Efficient fluoride removal, regenerable for multiple cycles, and minimal waste generation	Higher initial cost, the need for periodic regeneration with salt solutions, and potential for brine waste disposal. Not effective in removing bacteria and viruses	RodríguezIglesias et al. (2022); Singer & Bilyk, (2002)
Reverse Osmosis (RO) Filters	Use a semipermeable membrane to separate fluoride ions and other contaminants from water by applying pressure	Highly effective at removing fluoride and a wide range of other impurities, suitable for both point-of-use and point-of entry systems	Higher energy consumption, wastewater generation (concentrate), and regular maintenance required for the membrane. Expensive to purchase	Khairnar et al. (2018); Wimalawansa, (2013); Arora et al. (2004); Shen et al. (2016)

2.7.1 Biosand Filter Design

The BSF can be made out of concrete or plastic frames, with crushed rock from the local area serving as the filter media (Kerich, 2014). The rock is crushed into two layers of differing sizes: coarse and fine. The fine crushed rock (sand) sheet, which covers about 40 cm of the filter and has an effective size of 0.15 to 0.18 mm and a uniformity coefficient of 0.3, makes up the majority of the filter (Ahammed & Davra, 2011). The course layer of 5 cm has effective particle sizes ranging from 1.18 to 4.75 mm, and the gravel layer of 5 cm has size particles ranging from 4.75 to 12.0 mm (Figure 2.1).

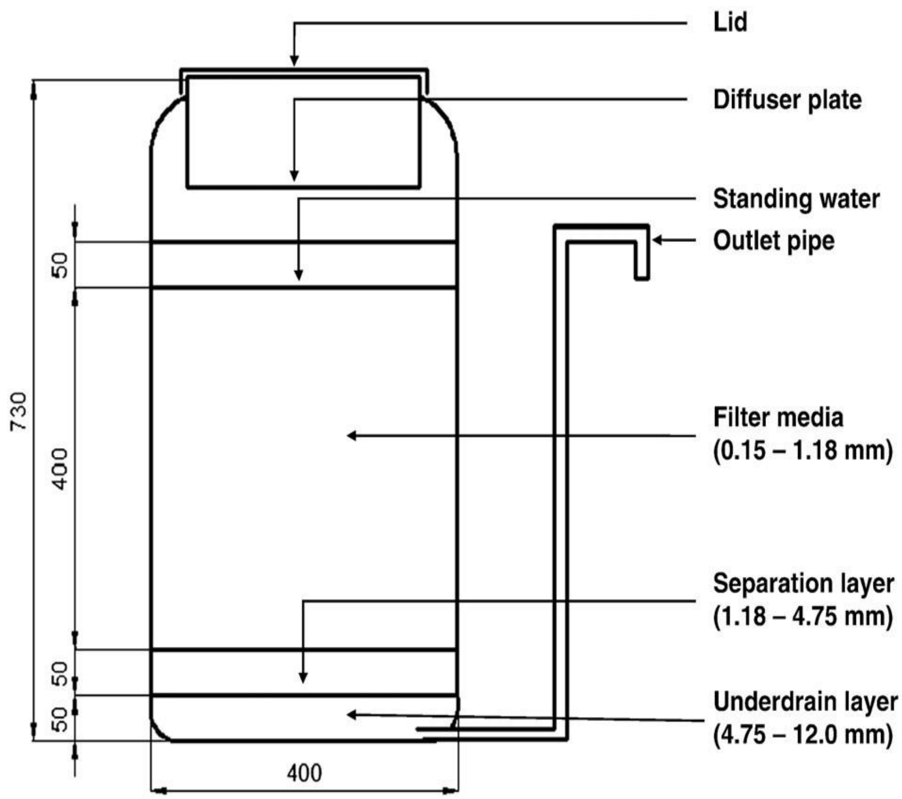

Figure 2.1: The Bio-Sand filter structure

Source: (Ahammed & Komal, 2011)

The two main mechanisms that regulate the performance of slow sand filters are physical removal mechanisms and biological removal mechanisms. Particles in the water are manually separated because they are too large to fit into the filter bed. Biological processing takes place mostly in the filter's top layer, where a biological film known as the schmutzdecke eliminates biological contaminants. The schmutzdecke is defined by Murphy et al. (2010) as a fine filter that removes small colloidal particles as well as a biological zone that degrades soluble organics and destroys harmful pathogens.

2.7.2 Biosand Filters Operation

Raw water is filtered within the BSF method by passing it through a sand filter. The raw water initial passes through the supernatant before passing through the fine sand layer. alga and alternative organic material from the raw water grow on the surface of the fine sand crust, forming a skinny slimed zoogleal layer (Wang & Wang, 2021), additionally called the schmutzdecke. The schmutzdecke is extremely active within the raw water, feeding dead alga and live microorganism and turning them to inorganic salts. an outsized proportion of inert suspended particles is automatically strained from the raw water at a similar time (Wang & Wang, 2021)

Since water flows through the sand and further through the filter, a sticky zoogleal mass of microorganisms, microbes, bacteriophages, rotifers, and protozoa known as the biofilm forms and covers the sand particles on the far side of the schmutzdecke. The species of biofilm seek adsorbable impurities and substitute organic material (including everything else) carried by raw water and attracted to the sand by mass attraction or electrical forces.

Organic matter decomposes into inorganic matter such as water, carbonic acid smoke, nitrates, phosphates, and substitute salts, all of which are washed out by flowing water (Wang & Wang, 2021).

During the pause method, once the filter is not being crammed, oxygen is reduced within the schmutzdecke and biofilm, and also the concentration of oxygen close to the sand bed's bottom might become too low to sustain aerobic respiration. Live pathogens that enter this sand depth ordinarily die and leave the BSF with the effluent (Ngai et al., 2007).

2.7.3 BSF Filter performance

Laboratory studies have shown that the BSF is capable of removing 100% of protozoa, 99.9% of viruses and 99.5% of bacteria once the bio-film has had time to mature. Since maintenance to the filter disturbs the bio-film, the removal rate of bacterial are often reduced to 60-70% (Mohanty & Boehm, 2014) almost like the rates expected of an unripen filter. Such laboratory studies have also shown the power of the BSF to supply filtrate quality.

A biosand filter has been shown to effectively reduce bacteria, virus, protozoa, and turbidity in previous studies, as stated in Centre for Affordable Water and Sanitation Technology (CAWST) Chan et al., (2015); Napotnik et al. (2021); Budeli et al. (2021). In laboratory experiments, bacteria could be reduced by up to 96.5%, and by 87.9–98.5% in the field. Based on laboratory tests, virus reduction ranged from 70 to over 99% (Kottutt, 2015). The turbidity of the influent water could be decreased by 95% to less than 1 NTU

(Duran Romero et al., 2020). While protozoa can be reduced by 99.9%, dissolved chemicals (organic pesticides) cannot be eliminated. Because of this, a customised biosand filter is required to remove impurities that a conventional biosand filter cannot eliminate. Additionally, the protozoa count could be reduced by an impressive 99.9%, as shown in Sizirici (2018) study. Nevertheless, it is worth noting that dissolved chemicals, such as organic pesticides or fluoride, are not completely eliminated.

2.8 *Escherichia coli (E. coli)*

Escherichia coli (E. coli) was first discovered in the year 1885 by Theodor Escherich who described it as Gram-negative, facultative anaerobic bacteria that is rod shaped (Acuff & Dickson, 2017; Liu, 2015). As part of the human beings and animals' natural flora, *E. coli* majorly is found in the gastrointestinal tract (Akpor et al., 2014). Although a majority of them are nonpathogenic, some strains have the ability of causing disease from the intestines and outside the intestines (Leimbach et al., 2013). The strains of *E. coli* considered as pathogenic get grouped further into different patho groups depending on the genes of virulence they possess (Gati et al., 2019). Many infections considered to be caused by the virulent strain have been considered as one that can get transmitted from one human to another (Sarowska et al., 2019). Examples are the Entero-invasive *E. coli* (EIEC), the Enteropathogenic *E. coli* (EPEC) and the Enteroaggregative *E. coli* (EAggEC) (Kabiru et al., 2015). There are also those strains that get transmitted to humans by taking contaminated water with the Enterixigenic *E. coli* (ETEC) or the Shiga toxin producing *E. coli* (STEC) (Lothigius et al., 2008). The United States Environmental Protection Agency USEPAs water guidelines states that in the United States to measure the amount of water bacterial contamination by fecal matter is by measuring the amount of *E. coli* in the water (Stepenuck et al., 2011). If the stipulated amount of *E. coli* required for drinking water exceeds what is accepted by USEPA, then that water is considered as toxic and poses a risk to the health of consumers (Oloruntoba et al., 2019).

Various studies have been done in Kenya and established presence of microbes in water. For instance, studies on Nairobi River (Musyoki et al., 2013) reported the presence of pathogenic microbes like; *E. coli*, Shigella flexneri, Salmonella paratyphi, Klebsiella aeroginosa and Enterococcus faecalis. A study by Waithaka et al. (2015) on water running in community taps and River Kandutura in Nakuru, established the presence of *E. coli,* Shigella spp and Salmonella spp. A study by Kemboi (2016) on water quality used by residents of Kabianga, Kericho County, in Kenya, identified *E. coli,* filamentous fungi and yeasts. Too et al. (2016) studied thermotolerant coliform-contaminated (TTC) home water contamination in Kericho District, Western Kenya. About 48 (46.6%) of the 103 houses surveyed had thermotolerant coliform-contaminated water (>10 cfu/100 mL). Five homes had pathogenic *E. coli,* including 40% enteroaggregative, 40% enterotoxigenic, and 20% enteropathogenic. Kericho District drinking water is contaminated with thermotolerant coliform-contaminated (TTCs), including multidrug-resistant *E. coli*. Opisa et al. (2012) studied faecal pollution in residential water sources in seven informal areas of Kisumu City, Kenya. Total and faecal (*Escherichia coli*) coliform bacteria in dams, rivers, springs, and wells were counted using membrane filtration. About 76 (95%) of 80 water sources were infected with *E coli*. All unprotected well samples (26) and 92.6% of protected well samples (25) contained *E. coli*. Dams and boreholes had the highest and lowest *E. coli* densities, respectively (p = 0.0321). *E. coli* coliform density in wells was negatively correlated with distance from pit latrines (r = -0.34, n = 53, p = 0.0142). Untreated well water may not be safe for human consumption, posing a health concern to informal community residents. Okoko et al. (2012) tested source and domestic water for faeces. Eight drinking-water draw-off stations along River Awach were sampled. *E. coli* densities along the river and in residential water samples differed significantly ($p<0.05$). Source and home water included faecal bacteria.

2.9 Removal of *Escherichia coli* bacteria from water

Indicator bacteria include total coliforms, *Escherichia coli (E. coli),* Enterococci, and Clostridium perfringens (Winkler et al., 2017). Animal or human faeces can contaminate drinking water with coliform and *E. coli (*Cho et al., 2020). *E. coli* indicates pathogens in natural and treated waters. *E. coli* can cause diarrhoea, UTI, meningitis, peritonitis, septicemia, and gram-negative bacterial pneumonia (Kunert Filho et al., 2015). Treatment plants have introduced numerous methods for removing *E. coli*, including membrane filtration soil aquifer treatment, slow sand filtering, granular activated carbon (GAC) adsorption, and advanced oxidation (Crittenden et al., 2012; García et al., 2018). All these water treatment procedures have long been used to remove microorganisms.

Franz (2005) investigated the efficacy of ceramic candle filters in Kenya, including coliphage removal experiments. The AquaMaster (Piedra candle), Doulton Super Sterasyl, and Pelikan filters removed considerably more total coliform and *E. coli* than the Pozzani filters, according to coliform removal trials conducted at MIT. All filters evaluated at MIT had removal rates ranging from 92% to 100%. Filter testing carried out in Kenya revealed removal rates of total coliform and *E. coli* of up to 99.99%.

Albert et al. (2010) studied Point of Use water treatment end-user preferences and performance among Kenya's rural poor. Dilute hypochlorite and filters were more popular than flocculant-disinfectant. Averaged across all participating houses, dilute hypochlorite solution reduced *Escherichia coli* in treated water the most. Dilute hypochlorite and flocculant-disinfectant reduce *E. coli* in self-reported households equally and more than filters. Filters were the most popular product among homes.

2.10 Modified Media

Because heavy drinking of fluoridated water is believed to cause fluorosis which is an irreversible risk and has no remedies for treatment, it is important to ensure that its toxic levels get eliminated in drinking water. By eliminating it from drinking water, it will help prevent ingestion which in return helps in eliminating accumulation in the body to high levels (Azbar & Türkman, 2000; Jagtap et al., 2012). There has been a development of several ways in which drinking water can get deflouridated majority of them being given the name “Best Available Technologies” Bats. The introduction of these new fluoridation techniques has brought many drawbacks to developing countries due to their ineffectiveness, especially in remote areas (Rostamia et al., 2017; Rugayah & Nuraini, 2014; Shen & Schäfer, 2014). Fluoride reduction techniques include the sorption process, coagulation-flocculation-filtration, touch precipitation, and membrane filtration

In batch studies, activated charcoal, diatomite, bone char, and steel wool have proven efficient as a defluoridant of water. Full-scale BSFs have been used to extract dissolved pollutants including arsenic and FIB using similar techniques and metal amendments. Arsenic biosand filters (ABF) are used to remove arsenic from water by adding an adsorbent layer over the standard sand layer, which is known as a Kanchan filter. Ngai et al. (2014) used an adsorbent layer with iron nails within the diffuser plate of a standard BSF for three months to extract 93% of arsenic, 58% of total coliforms, and 64% of *E. coli.* Studies have reported iron to extract arsenic using locally available and inexpensive materials by changing a conventional BSF in this way.

2.11 Biosand Filter Design Modifications

The BSF's conventional design consists of one container with three media layers, which can be purchased or rendered locally. According to the CAWST BSF construction manual, locally made BSFs are usually made of concrete. BSFs, but at the other side, can be made from a variety of materials such as injection formed plastic, PVC, ceramic tubes, large plastic barrels, and 20 L buckets (Ngai et al., 2014). Concrete BSFs weigh approximately 91 kg and require molds, which can be difficult to transport (Ahammed & Davra, 2011). This may not be a concern for aid organisations, but it may be a barrier for small developed countries. As a result, it would be beneficial to build a new BSF that is made of locally sourced materials. Smith's Sandstorm BSF design modification is encouraging (Smith, 2013). Sandstorm is made up of a cylindrical galvanized iron (GI) shell weighing 23 kg and an inverted jerry can. The water reaches the GI shell through the inverted jerry can, which retains a constant head of 7 cm above the filter media.

2.12 Knowledge Gaps

Numerous defluoridation techniques have been extensively examined and assessed, predominantly in laboratory settings. Nevertheless, many of these methods have proven to be ineffective in eliminating fluoride, require complex upkeep, and entail prohibitively high expenses, particularly in developing nations. According to the CCEFW (2010), when selecting a technology suitable for the Kenyan context, several factors must be taken into account, including potential adverse effects, such as the repercussions of incorrect chemical dosing, the potential presence of chemical residues in treated water, the overall cost of defluoridation methods (both initial capital investment and ongoing operational costs), as well as the extent of defluoridation or service coverage.

Various adsorbent materials, such as clay minerals, zeolites, and synthetic adsorbents, can be utilized for fluoride removal through adsorption. However, they demonstrate limited effectiveness in eliminating bacteria and viruses (Vinati et al., 2015; Amor et al., 2018; Margeta et al., 2013; Jagtap et al., 2011).

Activated alumina filters, on the other hand, prove efficient in fluoride removal, cost effectiveness, and suitability for both point-of-use and point-of-entry systems. Nevertheless, they necessitate periodic regeneration or replacement, which may result in the release of aluminum into treated water. Additionally, activated alumina filters are not effective in removing bacteria and viruses (Tripathy et al., 2006; Ahamad et al., 2018; Dhawane et al., 2018).

In contrast, Bone Char Filters exhibit exceptional fluoride removal capacity, cost effectiveness, and durability. However, they face limitations related to the limited availability of bone char and the prerequisite for water pretreatment to eliminate turbidity before filter usage. Like other methods, Bone Char Filters are not effective in removing bacteria and viruses (Alkurdi et al., 2019; Sorlini et al., 2011; Kanyora et al., 2015).

Ion-Exchange Resin Filters demonstrate high efficiency in fluoride removal, reusability for multiple cycles, and minimal waste generation. Nonetheless, they are associated with a higher initial cost, the necessity for periodic regeneration using salt solutions, and the potential for brine waste disposal. These filters are not effective in removing bacteria and viruses (Rodríguez-Iglesias et al., 2022; Singer & Bilyk, 2002).

Reverse Osmosis (RO) Filters prove highly effective in removing fluoride as well as a broad spectrum of other impurities, including bacteria and viruses. They are suitable for both point-of-use and point-of-entry systems. Nevertheless, RO filters entail higher energy consumption, wastewater generation in the form of concentrate, and regular membrane maintenance. Additionally, they are relatively expensive to purchase (Khairnar et al., 2018; Wimalawansa, 2013; Arora et al., 2004; Shen et al., 2016).

The inadequacy of existing water treatment methods to simultaneously remove both fluoride and *E. coli* bacteria is a significant challenge, particularly in regions where both contaminants are prevalent. This gap underscores the need for innovative and integrated water treatment solutions that can effectively address multiple types of contaminants in a cost-effective and sustainable manner. Developing such solutions is crucial for ensuring access to safe and clean drinking water for communities facing these dual challenges.

CHAPTER THREE

METHODOLOGY

3.1 Research Design

This study was based on an experimental design. It focused on the modification of standard biosand filter with activated charcoal from bamboo, diatomite, bone char, and steel wool and subsequent application of the modified biosand filter in removal of fluoride from model solutions and water samples. The study also focused on application of these modified and standard filter on removal of *E. coli* bacteria to assess its efficiency in removal of microbial contaminants. This involved installing the basic biosand filter and customizing the standard filter with bamboo, diatomite, bone char, and steel wool activated charcoal. Water was spiked with fluoride then passed through the modified biosand filters and standard biosand filter which acted as a control. The water filtrated was then taken for analysis.

3.2 Materials and Instrumentation

The following materials were used; distilled water, sodium hydroxide solutions, nitric acid, fluoride ion selective electrode, Bamboo, Bone char, Diatomite and Fe^0, plastic container, sand, course sand, gravel and plastic pipes. MacConkey Broth agar (Merck) plates were used to culture *E. coli* bacteria.

The fluoride content of the aqueous solutions was measured using a potentiometric method using a fluoride ion selective electrode (JENWAY 3345 Ion Meter). The experimental procedure involved the addition of 25 mL of the total ionic strength adjustment buffer (TISAB) to the test solution. This volume of TISAB was maintained at a constant ionic strength throughout the experiment.

3.3 Filter Construction and Design

The specifications of the standard Biosand filter were reduced, and four modified filters and one standard filter that acted as control were designed. The 5 filters were replicated four times to produce a total of 20 filters where A 10-litres plastic pipe, PVC pipe, and fittings were used to make the filters.

This design's bottom bucket has a valve under the outlet to help in the restoration of the adsorptive media. The gravel layers remained constant regardless of whether each bucket contained grit, activated charcoal from bamboo, Diatomite, Bone char or Steel wool, and were prepared in accordance with the CAWST Filter Construction Manual (2012). According to Manz's standard procedures for BSF, the sand was washed several times with tap water before the wash water became clear (2007). The filters were made from a plastic container purchased from a supermarket in Eldoret. The container was washed with tap water before being filled with 5 cm of deep under drain gravel, 5 cm of coarse sand, and 50 cm of fine sand. In order to maintain a water depth of 5 cm over the filter media for the normal BSF an outlet pipe was place after 5cm of water (figure 3.1). The modified biosand filter was built with 5 cm of drain gravel, 5 cm of coarse sand, 25 cm of fine sand, 10 cm of adsorbent media (activated charcoal from bamboo, diatomite, bone char, and steel wool), and pipe installed to keep a water depth of 5 cm (figure 3.2). A plastic diffuser plate was created on the filter's lip to avoid disrupting the top layer of sand during standard charging of the filter with raw water. Before using the filter, it was feed with 40 litres of water per day, 20 litres in the morning and 20 litres at night, for 21 days to allow the filter to mature (formation of biological film).

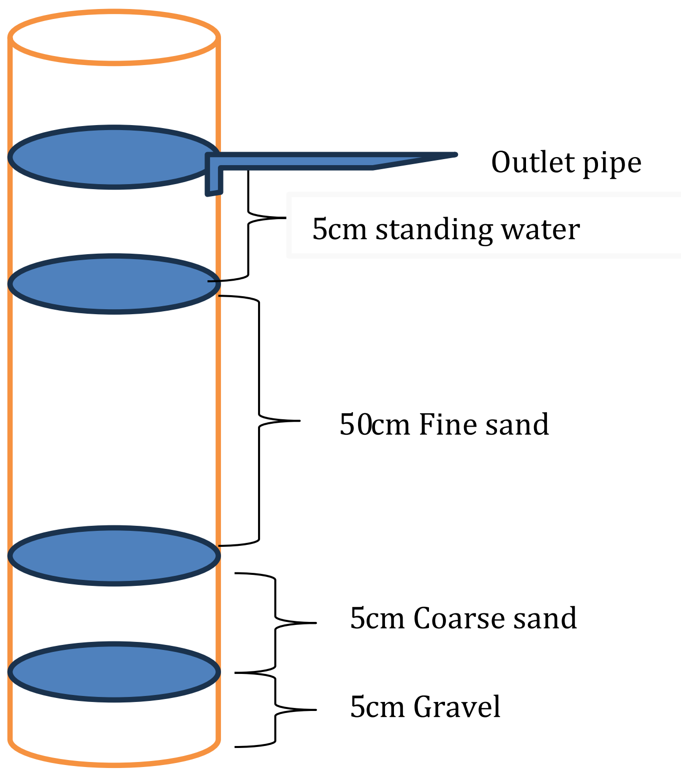

Figure 3.1: Standard Biosand Filter design

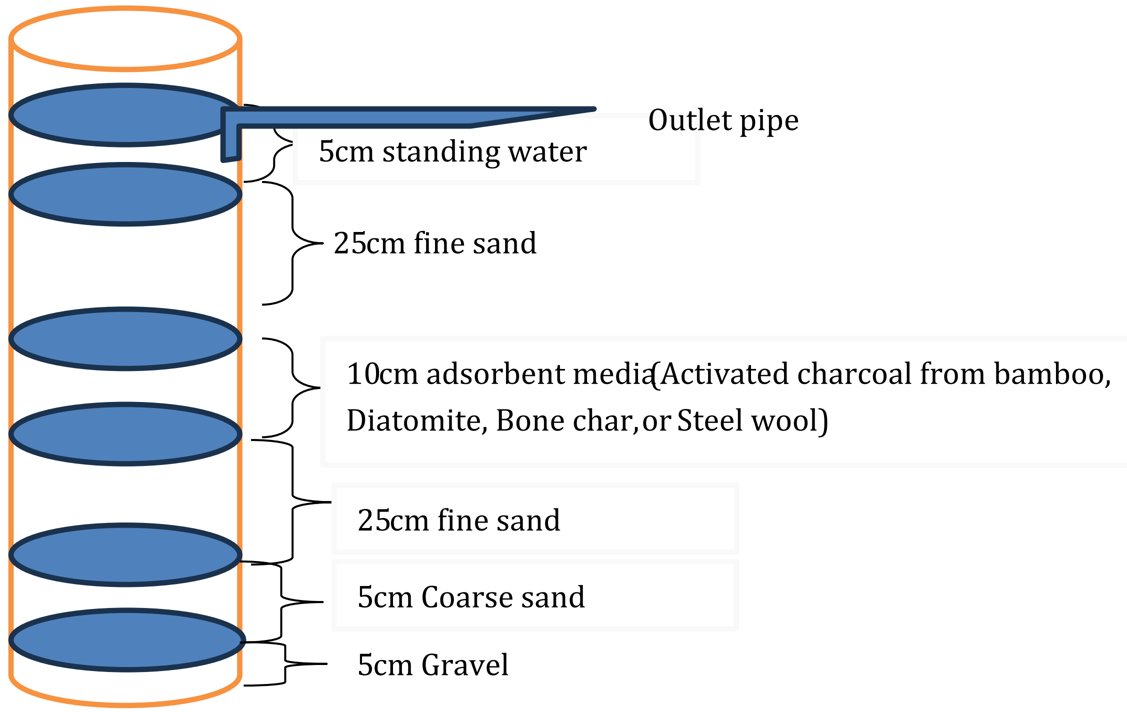

Figure 3.2: Modified Bios and Filter design

3.4 Adsorbents sourcing and preparation

3.4.1 Activated carbon preparation from Bamboo

Bamboo plant *(Arundinaria alpina)* was obtained from local resident in Elgon View area, Eldoret, Kenya, and identified using dichotomus key. The Bamboo was cut into small pieces 20cm long and 3-5 cm wide to allow uniform burning in the furnace, then dried for seven days in the sun. After sun drying, the resulting material was then heated in sealed oiled drums which was lit from the bottom. The material was successfully carbonized and charcoal was produced over the next two to three hours (Talat et al., 2018; Wang, 2012).

The prepared charcoal was then washed by distilled water to remove remaining organic material content and finally dried in an oven at 110^0C (Nishida et al., 2017; Wendimu et al., 2017). The product was broken down into tiny pieces ensuring it did not get ground to a fine powder. The parts were then soaked in a 25% solution of $CaCl_2$ or $NaCl_2$ for 24 hours. They were then thoroughly rinsed and dried in an oven set to 100°C for about an hour.

3.4.2 Bone char, Diatomite and Fe^0 sourcing

Two kilograms of bone char was sourced from the Catholic Diocese of Nakuru. A total of 2 kgs of diatomite was obtained from the Kariandusi mining facility, while 500 g of steel wool was purchased from local shops.

3.5 Determination of percentage removal of fluoride from water using the modified biosand filters

3.5.1 Stock solution preparation

All of the solutions were made with double distilled water and analytical grade reagents from Kobian Kenya Limited, a Sigma Aldrich's outlet in Kenya. A 2.26 g sodium fluoride was dissolved in 1000 ml water to make a fluoride standard stock solution with a concentration of 1000 mg/L. Subsequent working solutions were obtained from this stock solution. To change the working solutions' pH to the appropriate value of 4.8, 0.1 mol/L nitric (V) acid and 0.1 mol/L sodium hydroxide solutions were used. Prior to use, the stock solution was stirred for at least 10 minutes.

3.5.2 Experiment procedure

Fluoride concentrations of 1.5, 2.26, and 3 mg/L were prepared from the stock solution before being run through 5 pairs of filters modified with activated charcoal, bone char, steel wool and diatomite and the control for 30, 60, and 90 minutes as well as 24 hrs. The residual fluoride concentration in the filtrates after the different exposure times was determined in the laboratory by potentiometric (ion selective electrode [ISE] method. The difference in concentration was then determined and used to calculate the efficiency of the modified biosand filters. Standard solutions with concentrations of 0.1, 1, 3, 5, 7, 10, and 20 mg/L were used to calibrate the ISE (Ion selective electrode).

3.6 Determination of percentage removal of *Escherichia coli* from water using the modified biosand filters

3.6.1 *Escherichia coli* culture

Initially, the *Escherichia coli* strain was sourced from untreated sewage and grown on nutrient agar plates and incubated for 24 hours at 36.1 °C. One loop of this bacterial culture was inoculated into 100 mL sterile nutrient broth and incubated at 37 °C in a shaking incubator for 16 hours before being serially diluted in 9 mL sterile physiological water (0.9 % w/v NaCl) and spread-plated on MacConkey Broth agar (Merck) plates. The plates were incubated at 37°C for 24 hrs.

3.6.2 Experiment procedure

A total of 248 starting concentrations of *E. coli* bacteria in colony-forming units per milliliter (cfu/mL) were introduced into a final volume of 5 l of borehole water. The spiked water samples were shaken vigorously several times for 5 mins before being passed through the 5 types of filters.

A 0.45 um filter was used to filter the filtrate water from the standard BSF and modified filters. The media was prepared and nutrient agar was used to culture the *E. coli* bacteria that were gathered by resuctioning bacteria from filters. The plates were incubated at 37 °C for 24 hrs after the nutrient agar solidified, and the colonies were counted. The effectiveness was therefore determined by getting the difference between the *E. coli* bacteria in the filtrate before filtration and after filtration and calculating the percentage removed for each filter.

3.7 Statistical Analysis

Data obtained was analysed descriptively and results presented in tables and figures. Analysis of Variance (Anova) was used to determine significance difference between filters. To see if there was any correlation between the filtration material and Cfu's obtained, the Chi-square test of independence was used.

CHAPTER FOUR

RESULTS

4.1. Percentage removal of fluoride from water using the modified biosand filters

4.1.1 Fluoride adsorption percentage of the five filters at varying contact times for initial concentrations of 1.5 mg/L

Figure 4.1 depicted below illustrates the percentage of fluoride adsorption by the five filters at varying contact times for 1.5 mg/L fluoride initial concentration.

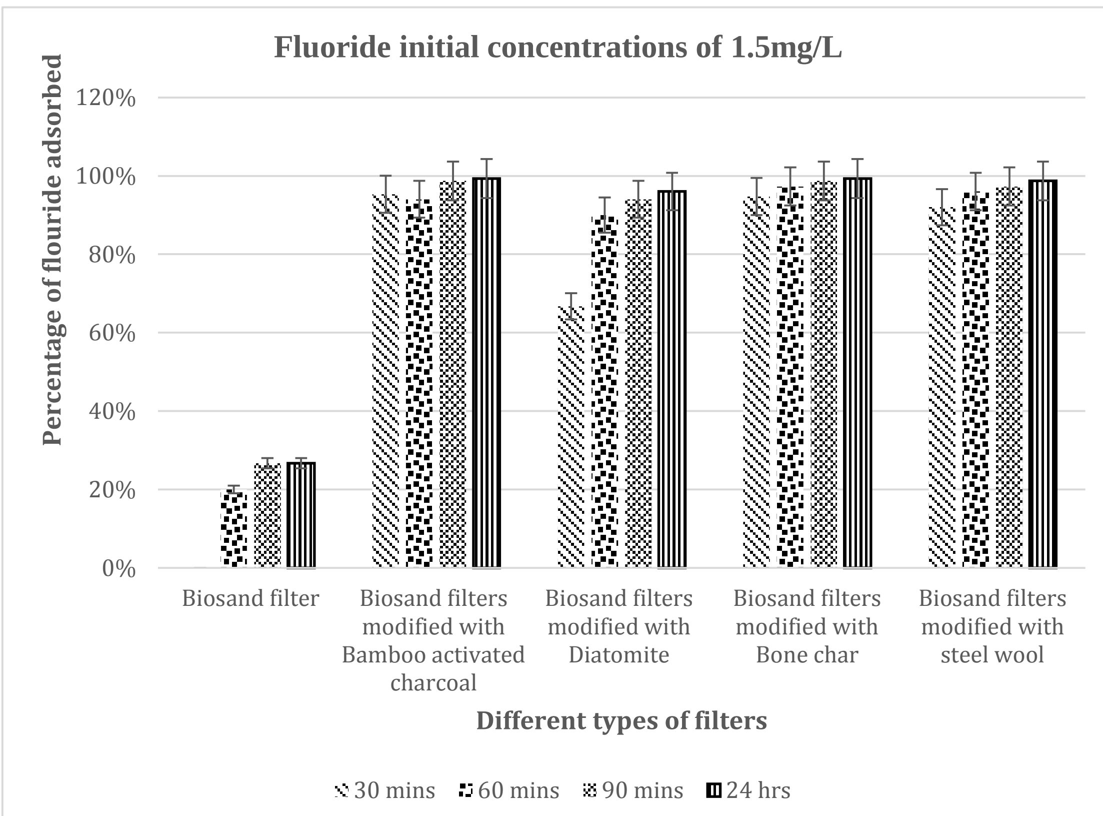

Figure 4.1: Percentage of fluoride concentration adsorbed from five filters at varying time intervals 1.5 mg/L initial concentrations

The results obtained from the study indicate that the Biosand filters tested showed little capacity for adsorbing fluoride, as no fluorides were absorbed after a 30-minute period of contact. On the other hand, bamboo activated charcoal, diatomite, bone char, and steel wool showed higher efficacy in removing fluoride, with an adsorption rate above 90% within contact times of 30 minutes, 60 minutes, 90 minutes, and 24 hours. The filtration system successfully achieved a reduction in fluoride levels to a value below the recommended threshold of 1.5 mg/L, as stated by the World Health Organization (2017).

4.1.2 Comparisons in adsorption efficacy of 1.5 mg/L initial fluoride from 5 filters for different contact time

To determine whether there existed any significant differences in adsorption of 1.5 mg/L initial fluoride from 5 filters for 30, 60, and 90 mins contact time in different filters, One-Way Analysis of Variance was conducted. The results are presented in table 4.1.

Table 4.1: ANOVA for fluoride adsorption levels among the five filters with 1.5 mg/L initial concentration

		Sum of Squares	df	Mean Square	F	Sig.
30 mins	Between Groups	2.990	4	.748	171.459	.000
	Within Groups	.022	5	.004		
	Total	3.012	9			
60 mins	Between Groups	2.003	4	.501	30.758	.001
	Within Groups	.081	5	.016		
	Total	2.084	9			
90 mins	Between Groups	1.796	4	.449	107.923	.000
	Within Groups	.021	5	.004		
	Total	1.817	9			
24 hours	Between Groups	1.852	4	.463	110.262	.000
	Within Groups	.021	5	.004		
	Total	1.873	9			

The mean of absorbed 1.5 mg/L initial fluoride concentration reported in 24 hrs, 30-, 60, and 90-minutes contact time was all ($p<0.05$) significantly different among the five filters tested; biosand filter, bamboo activated charcoal, diatomite, bone char, and steel wool (Fe^0) ($P=0.000$, $df=4$, $F=171.459$), ($P=0.001$, $df=4$, $F= 107.923$).

4.1.3 Fluoride adsorption percentage of the five filters at varying contact times for initial concentrations of 2.26 mg/L

The concentration of adsorbed fluoride by five filters after varying contact times at an initial fluoride concentration of 2.26 mg/L is depicted in Figure 4.2.

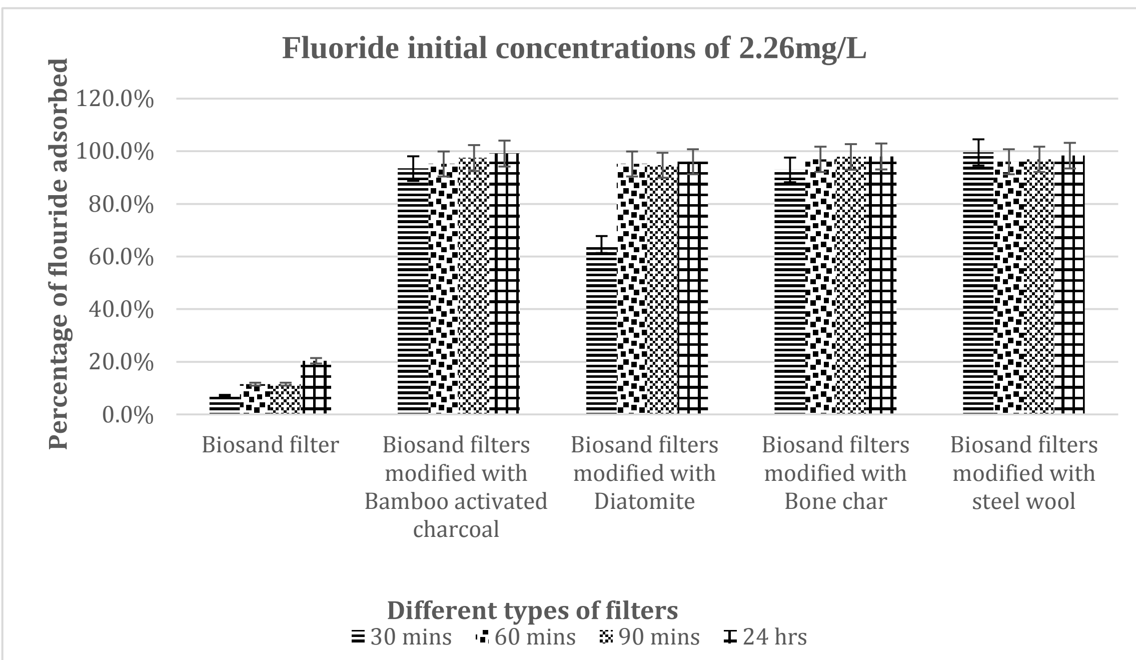

Figure 4.2: Percentage of fluoride concentration adsorbed from five filters at varying time intervals 2.26 mg/L initial concentrations

According to the findings above, biosand filters tested also showed little capacity for adsorbing fluoride. Bamboo activated charcoal, diatomite, bone char, and steel wool however shown a higher efficacy in removing fluoride, with an adsorption rate of majority of the filters above 90% within contact times of 30 minutes, 60 minutes, 90 minutes, and 24 hours. The filtration system also successfully achieved a reduction in fluoride levels to a value below the recommended threshold of 1.5 mg/L, as stated by the World Health Organization (2017).

4.1.4 Comparisons in adsorbed of 2.26 mg/L initial fluoride from 5 filters for different contact time

One-way analysis of variation was used to see if there were any major variations in the adsorbed of 2.26 mg/L initial fluoride from five filters after 30, 60, and 90 minutes of contact time. Table 4.2 shows the results.

Table 4.2: ANOVA for fluoride adsorption levels among the five filters with 2.26 mg/L initial concentration

		Sum of Squares	Df	Mean Square	F	Sig.
30 mins	Between Groups	5.834	4	1.458	72.200	.000
	Within Groups	.101	5	.020		
	Total	5.935	9			
60 mins	Between Groups	5.809	4	1.452	89.861	.000
	Within Groups	.081	5	.016		
	Total	5.889	9			
90 mins	Between Groups	5.935	4	1.484	90.470	.000
	Within Groups	.082	5	.016		
	Total	6.017	9			
24 hours	Between Groups	4.934	4	1.233	75.211	.000
	Within Groups	.082	5	.016		
	Total	5.016	9			

With the use of one-way analysis of variance of the adsorbed 2.26 mg/L initial fluoride concentration recorded in 24 hours, 30, 60 and 90 minutes contact time were all ($p < 0.05$) significantly different among the five filters tested biosand filter, bamboo activated charcoal, diatomite, bone char and steel wool (Fe^0) (P=0.000, df=4, F=72.200), (P=0.000, df=4, F=89.861), (P=0.000, df=4, F=90.470) and (P=0.000, df=4, F=75.211) for 30 mins, 60 mins, 90 mins and 24 hours contact time respectively.

4.1.5 Fluoride adsorption percentage of the five filters at varying contact times for initial concentrations of 3 mg/L

The figure 4.3 presents the fluoride adsorption percentages for five different filters at various contact times, focusing on an initial fluoride concentration of 3 mg/L.

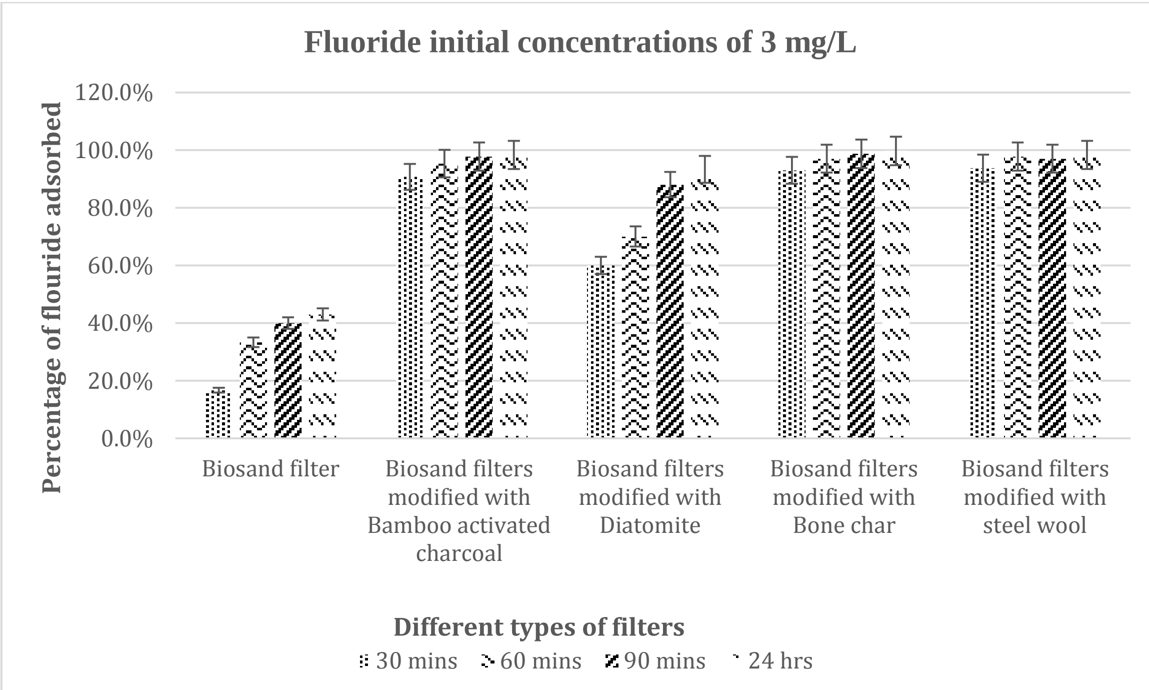

Figure 4.3: Percentage of fluoride concentration adsorbed from five filters at varying time intervals 3 mg/L initial concentrations

The results further revealed that the Biosand filters under examination exhibited limited ability to adsorb fluoride. In contrast, the four modified Biosand filters displayed high fluoride adsorption capacity of up to 99.7%, particularly when the contact time extended to 24 hours. Furthermore, the modified system consistently achieved a reduction in fluoride levels, ensuring that the fluoride concentration fell below the World Health Organization's recommended limit of 1.5 mg/L, as outlined in the 2017 guidelines.

4.1.6 Comparisons in adsorbed of 3 mg/L initial fluoride from 5 filters for different contact time

One-way analysis of variation was used test f there were any major variations in the adsorption of 3.0 mg/L initial fluoride from five filters after 30, 60, and 90 minutes of contact time. Table 4.3 presents the findings.

Table 4.3: ANOVA for fluoride adsorption levels among the five filters with 1.5 mg/L initial concentration

		Sum of Squares	df	Mean Square	F	Sig.
30 mins	Between Groups	8.023	4	2.006	98.520	.000
	Within Groups	.102	5	.020		
	Total	8.125	9			
60 mins	Between Groups	5.589	4	1.397	69.037	.000
	Within Groups	.101	5	.020		
	Total	5.690	9			
90 mins	Between Groups	4.541	4	1.135	69.216	.000
	Within Groups	.082	5	.016		
	Total	4.623	9			
24 hours	Between Groups	4.254	4	1.064	129.700	.000
	Within Groups	.041	5	.008		
	Total	4.295	9			

With the use of one-way analysis of variance of the unabsorbed 3.0 mg/L initial fluoride concentration recorded in 24 hours, 30, 60 and 90 minutes contact time were all ($p < 0.05$) significantly different among the five filters tested biosand filter, activated charcoal, diatomite, bone char and steel wool (Fe^0) (P=0.000, df=4, F=98.520), (P=0.000,df=4, F=69.037), (P=0.000,df=4, F=69.216) and (P=0.000,df=4, F=129.700) for 30, 60, 90 minutes and 24 hrs contact time respectively.

4.2. Percentage removal of *E. coli* from water using the modified biosand filters

Evaluation of *E. coli* only after 24 hrs was done as the Biosand filtered drinking water can be consumed only after 24 hrs. Activated charcoal, diatomite Bone char and steel wool (Fe^0) modified biosand filters were tested for the removal of *Escherichia coli* bacteria. The total number of the spiked *E. coli* bacteria was 248, results are presented in figure 4.4 below.

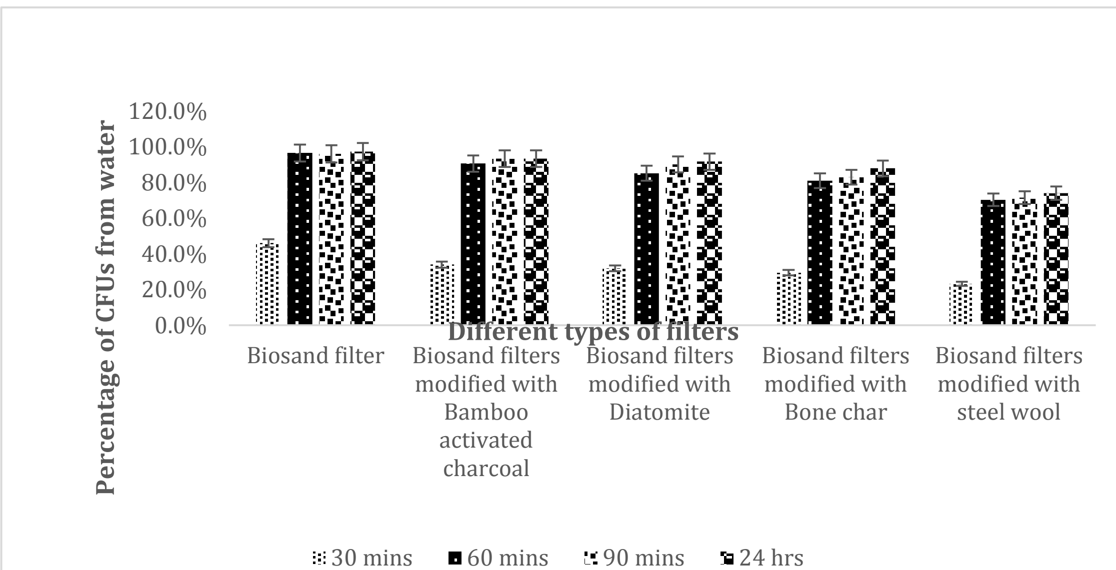

Figure 4.4: Removal of *Escherichia coli* bacteria by the five modified biosand filters

The results of this study indicated that the standard biosand filter removed the highest amount of *E. coli* bacteria with a removal rate of 96%. Activated Charcoal, diatomite and bone char removed 90, 85 and 81% respectively. Steel wool removed the lowest amount of *E. coli* bacteria (70%) in one-hour contact time. It was observed that 24 hours contact time allows more *E. coli* to be removed more effectively for all the filters.

4.2.1 Comparisons in removal of *E. coli* concentration from 5 filters for different contact time

One-way analysis of variation was also used to test if there were any major variations in the removal of *E.coli* from five filters after 30, 60, and 90 minutes of contact time. Table 4.3 presents the findings.

Table 4.4: ANOVA for removal of *E. coli* for different filters and different contact time

		Sum of Squares	df	Mean Square	F	Sig.
30 mins	Between Groups	9.023	4	1.070	92.400	.000
	Within Groups	.145	5	.030		
	Total	7.180	9			
60 mins	Between Groups	6.324	4	1.763	71.812	.000
	Within Groups	.196	5	.020		
	Total	12.810	9			
90 mins	Between Groups	8.391	4	9.761	95.340	.000
	Within Groups	.489	5	.034		
	Total	8.623	9			
24 hours	Between Groups	98.410	4	9.936	205.110	.000
	Within Groups	.894	5	.078		
	Total	16.705	9			

Based on ANOVA results, there was significant difference in removal of *e. coli* for the five filters ($p < 0.05$) for 30, 60, 90 minutes and 24 hrs contact time.

Chi-square test of independence was performed to find if there was any relationship between the filtration material and the number of Cfu's obtained. With the calculated chi square value (137.24) exceeding the tabulated value (5.99), there was a significant relationship between the material used for filtration and cfus obtained.

CHAPTER FIVE

DISCUSSIONS

5.1 Percentage removal of fluoride from water using the modified biosand filters

According to the results, standard biosand filters did not absorb a significant fluoride amount (figure 4.1). This may be due to a lack of fluoride ion binding sites in the sand. A similar study done by Gogoi (2018) observed that raw sand from the Kaliani river in the Kanaighat region of Golaghat district, Assam, India, reduced only 7% of fluoride from water. Results from this study also concurred with that of Rice (2020) who reported that raw sand did not completely remove fluoride when utilizing aluminum oxide coated media and a modified filter design.

High amount of fluoride was absorbed by the activated charcoal modified filters (figure 4.1, 4.2 and 4.3). The modified filter extracted 97% of fluoride after 24 hours and filtered the water to below the WHO fluoride limit of 1.5 mg/L, which was slightly better than the standard filter (WHO 2017). Similar results were obtained by Poudyal (2015) during defluoridation tests of granular activated carbon, where the highest fluoride removal for GAC at a concentration of 5 mg/L F- was 78%. Fito et al. (2019) also assessed the effectiveness of activated carbon extracted from the Catha edulis stem in extracting fluoride from aqueous solutions and reported 73% of fluoride was adsorbed. The study also observed an increase in fluoride removal from 30 min to 24 hrs contact time, which could be due to the available active site.

Diatomite from the study adsorbed 93% of fluoride after 24 hours (figure 4.1). Results of this study concurs with those of Yitbarek et al. (2019) who reported that after 24 hours of contact time, up to 93 % of fluoride was extracted using diatomaceous earth. Using diatomite modified with aluminum hydroxide, (Akafu et al., 2019) eliminated fluoride from drinking water.

The bone char modified biosand filter adsorbed fluoride to level below the WHO recommended concentrations of 1.5 mg/L(figure 4.1) . As fluoride is removed from water using bone char, the fluoride ion is known to exchange with the hydroxyl, carbonate, hydrogen carbonate, and phosphate ions (Medellin-Castillo et al., 2007; Rojas-Mayorga et al., 2013).

Kanyora et al. (2015) used regenerated bone char to strip fluoride from drinking water. The highest removal efficiency was found to be 97.63% which had an initial fluoride concentration of 100 ppm and a contact time of four hours. This result was similar to those of present study. Previous studies have shown that bone char has a high efficiency of 97.499.8% (Alkurdi et al., 2019; Goodman et al., 2013). This is an indication that the concentration was above the WHO guideline value of 1.5 ppm.

The steel wool modified filter outperformed the standard filter by eliminating 98% of fluoride after 24 hours (figure 4.1, 4.2 and 4.3). Tepong-Tsindé et al. (2019) reported that Fe^0-bearing materials, such as steel wool, hold good promise as low-cost, readily available and highly effective decentralized fluoride treatment materials. Characterizing a newly designed steel-wool based household filter for safe drinking water provision: Hydraulic conductivity and efficiency for pathogen removal

The activated charcoal and bone char modified BSF designs were found to have a higher capacity to extract fluoride than the other three adsorbents in the sample. The findings are consistent with those of (Naliaka, 2016), who found that bone char decreased fluoride concentration from 8.1 mg/L to below the WHO limit of 1.5 mg/L in 2 hrs.

5.2 Percentage *E. coli* removal for the five filters

The results of this study indicated that the standard biosand filter removed the highest amount of *E. coli* bacteria with a removal rate of 96%. Activated Charcoal, Diatomite and Bone char removed 90.85% and 81% respectively (figure 4.4). Steel wool removed the lowest amount of *E. coli* bacteria (70%) in one-hour contact time. Results from this study concur with those of Mwabi et al., (2012) who discovered that the biosand filter-standard (BSF-S); biosand filter-zeolite (BSF-Z); bucket filter (BF); ceramic candle filter (CCF) were found to eliminate up to 99% of *E. coli* bacteria in a sustainable solution for improving water quality. Collin (2009) also discovered that the dual sand layer biosand filter reduced *E. coli* by at least 85% and total coliforms by 95% in field tests, which was comparable to unmodified control filters. After filter maturation, laboratory tests revealed minimum average reductions of 93% turbidity, 97% *E. coli,* and 71% total coliform, which were equivalent to the results of unmodified control filters.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The standard biosand filter did not adsorb fluoride significantly. Fluoride was absorbed significantly by the activated charcoal, bone char, diatomite, and Fe^{o} biosand modified filters. The removal efficiencies were as follows; bone char> diatomite> bamboo activated charcoal> steel wool> standard Biosand filter. This means that standard biosand filter was the least effective in fluoride removal whereas bone char mas the most effective modified filter in fluoride removal. However, the removal efficiencies for *E. coli* were as follows;

standard biosand filter> bamboo activated charcoal> diatomite> bone char> steel wool.

This means that biosand filter modified with steel wool was the least effective for *E. coli* removal and standard biosand filter was the most effective filter to remove *E. coli* from water.

In both cases, the percentage of removal increased as the contact duration extended. This is due to the fact that a longer period of time allows fluoride to bind more effectively to active sites.

6.2 Recommendations

Based on the findings, the study makes the following recommendation;

1. In areas with elevated fluoride levels in water sources, it is advisable to consider bone char modified Biosand filters because it demonstrated significantly higher fluoride removal efficiency compared to the standard Biosand filter.
2. Further research is needed to assess the performance of these modified filters over a long period.

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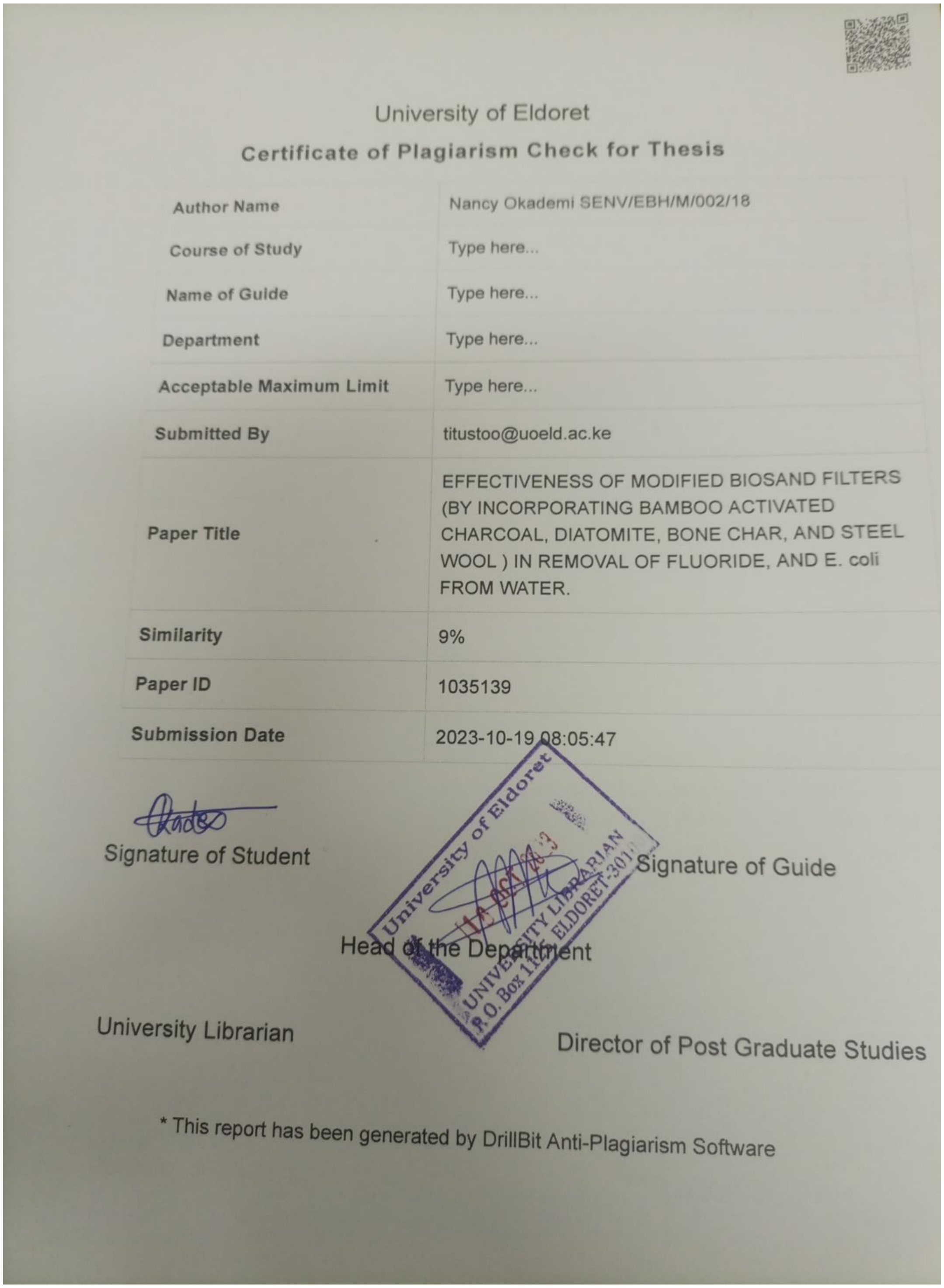
APPENDICES

Appendix I: Similarity Report



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