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THE USE OF LIGNITE AS PORE FORMERS IN CERAMIC WATER FILTERS FOR THE TREATMENT OF COLIFORM IN DRINKING WATER

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ABSTRACT

Due to the poor quality of generally available drinking water sources and the obvious lack of adequate centralized systems for the delivery of safe water to households in Nigeria, it became expedient to research low-cost ceramic household biological (coliform) filters in order to provide an affordable and accessible means for citizens to improve their drinking water quality to acceptable standards. This work seeks to ascertain the suitability of lignite as an organic additive (pore former) in ceramic clay filters for water purification in comparison with the commonly used sawdust. In this study, clay and lateritic soil samples were collected from Igo Village near Benin City, Edo State, while lignite samples were collected from Azagba-Ogwuashi, Aniocha South Local Government Area of Delta State. Sawdust from hardwood (pore former) and lateritic soil (flux and plasticity reducer) were collected from Benin City, Edo State. The raw materials were weighed and combined in various ratios with a certain percentage of water to produce a homogeneous plastic body. This was thoroughly kneaded to remove any available pores in the clay and then molded into discs. The various samples were allowed to dry for four weeks to remove any free water in the samples and were then fired in an electric kiln to a temperature of 900 °C. The average diameter, thickness, and weight of the discs were 9.9 cm, 2.4 cm, and 332.5 g, respectively, and they were designated D1–D6. The flow rates of the fired discs ranged from 341 mL/h for D1 to 850 mL/h for D5. The total coliform bacteria removal efficiency of the discs ranged from 60.2% for D2 to 80.1% for D6. Although this does not meet the WHO standard of 0 cfu/mL, it is still appreciable. D5 contained 10% sawdust mixed with Igo clay and laterite, while D6 contained 10% lignite. D5 and D6 outperformed the other discs due to their constituents. D5 recorded a flow rate of 850 mL/h and a coliform removal efficiency of 78.5%, while D6 recorded a flow rate of 756 mL/h and a coliform bacterial removal efficiency of 80.1%. It is recommended for further work that colloidal silver be added to the formulation of the filter disc, as it is a strong antibacterial agent, in order to improve the coliform removal efficiency of the filter.

KEYWORDS: Ceramic water filter; Lignite; Sawdust; Coliform bacteria; Household water treatment, Clay.

1.0 INTRODUCTION

A filter is defined as a device, instrument, or material that removes unwanted substances from whatever passes through it. In the context of water treatment, filtration is a fundamental process aimed at improving water quality by removing physical, chemical, or biological contaminants. Ceramic water filtration, as defined by Brown, Sobsey and Proum (2007), is the process that utilizes a porous ceramic (fired clay) medium to remove microbes and other contaminants from water. The effectiveness of ceramic filtration largely depends on the pore structure of the ceramic medium, as the pore sizes are sometimes sufficiently small to trap particles and organisms larger than water molecules, including bacteria and suspended solids.

From ancient times to the present day, water filtration technologies have evolved out of necessity. Initially, filtration methods were developed to remove materials that affected the appearance of water, such as turbidity and suspended particles. Over time, these methods advanced to address issues related to unpleasant taste and odor, and eventually to remove contaminants capable of causing disease and illness (The Water Exchange, 2012). Early practices included boiling water to improve taste and safety, followed by rudimentary filtration through cloth bags. These simple techniques gradually evolved into more advanced systems, such as ceramic cartridges designed specifically for the removal of bacteria from water. A major milestone in the development of ceramic water filtration was the invention of the ceramic pot filter by Dr. Fernando Mazariegos of the Central American Industrial Research Institute (ICAITI) in Guatemala, which was designed to render bacterially contaminated water safe for drinking.

Ceramic filters were initially employed mainly for centralized water treatment systems. However, in recent times, their application has expanded significantly, and they are now widely manufactured for Point of Use (POU) applications, particularly in low-income and rural communities (National Academy of Sciences, 2008). The World Health Organisation (WHO) also encourages the use of ceramic filters as Household Water Treatment Systems (HWTS) for the effective treatment of drinking water at the household level. These porous ceramic water filters, which vary widely in design, effectiveness, and cost, are often treated with a silver solution that acts as a microbiocide to inactivate bacteria. The incorporation of silver has contributed substantially to the improved performance and microbial removal efficiency of ceramic water filters. Despite these advantages, ceramic filters have been shown to have limitations, particularly in their inability to effectively treat viral contaminants and chemical pollutants present in drinking water.

While diarrhea is recognized as the most predominant waterborne disease globally, infectious diseases caused by pathogenic bacteria, viruses, protozoa, and fungi are considered the most common and widespread health risks associated with drinking water consumption (WHO, 2011). In addition to microbial contamination, chemical contamination of drinking water sources remains a significant concern. Millions of people worldwide are exposed to unsafe levels of chemical contaminants in their drinking water (WHO, 2011), and prolonged exposure to such pollutants can result in serious health implications, including chronic illnesses and long-term physiological damage.

In Nigeria, water supply challenges are particularly severe in rural areas, where water availability often falls short of demand due to infrastructural failure and inadequate maintenance. Public water supply systems are frequently erratic, intermittently unreliable, and in some cases completely inaccessible. As a result, there is a high dependence on supplementary water sources such as boreholes, wells, brooks, rainwater, springs, and streams (Aribigbola, 2010). This limited access to safe and reliable water sources poses significant challenges to public health and has far-reaching implications for sustainable development.

Due to the generally poor quality of available drinking water sources and the obvious lack of adequate centralized systems for the delivery of safe water to households in Nigeria, it became necessary to explore low-cost ceramic household water treatment options capable of improving water quality. Such systems are intended to provide affordable and accessible means for households to enhance their drinking water quality to acceptable standards. This work therefore seeks to ascertain the suitability of lignite as an organic additive (pore former) in ceramic clay filters for water purification, in comparison with the commonly used sawdust, with the aim of improving filtration performance while maintaining affordability and local availability of materials.

2.0 Geological setting / Study area

2.1 Local Geology of the Study Area

The lignite-bearing sequence, commonly referred to as the Azagba-Ogwashi Formation (Reyment, 1965), occurs along the continental margin of southern Nigeria as a belt approximately 16-20 km wide and extending for about 240 km. Lignite horizons have also been encountered within the lowermost units of the Ameki Group and the uppermost strata of the Benin Formation, as revealed by drill holes, stream and river bank exposures, and road-cut outcrops (Okezie & Onuogu, 1985).

The sedimentary basin of southern Nigeria originated during the Early Cretaceous. The Benue-Abakaliki Trough represents a failed arm of a rift system formed during the separation of the African and South American plates and the consequent opening of the South Atlantic Ocean (Murat, 1970). During the Albian-Santonian infilling of the Benue-Abakaliki segment, the proto-Anambra Basin existed as a platform. East-west–oriented Coniacian–Santonian compressional forces subsequently uplifted the Abakaliki sector, resulting in a westward shift of the depositional axis.

As a consequence of Santonian tectonism, the platform areas flanking the Benue Trough-namely the Anambra Platform to the west and the Afikpo Platform to the east-underwent down-warping, leading to the development of the Anambra Basin and the Afikpo Syncline, respectively (Benkhelil, 1989; Murat, 1970). The Anambra Basin contains an approximately 6-km-thick sedimentary succession of Cretaceous to Tertiary age and serves as the structural transition between the Cretaceous Benue Trough and the Tertiary Niger Delta (Mohammed, 2005).

Sedimentation within the basin occurred in three major depositional cycles (Reyment & Mörner, 1977), corresponding to major marine transgressions during the Campanian, Paleocene, and Eocene. The Campanian marine incursion led primarily to the deposition of prodelta shales with subordinate sands, forming the Nkporo Group. This phase was followed by slow subsidence and a Maastrichtian regression, during which deltaic floodplain and forest swamp environments developed, giving rise to the coal-bearing Mamu, Ajali, and Nsukka Formations.

The progradation of the modern Niger Delta lithofacies commenced with a large-scale Paleocene transgression that resulted in the deposition of the Imo Shale. Subsequent marine regression during the Eocene led to the accumulation of the Ameki Group, including the Nanka Sand, which is overlain by the Oligocene-Miocene lignite-bearing Azagba-Ogwashi Formation. While Reyment (1965) assigned an Oligocene-Miocene age to this formation, palynological evidence presented by Jan du Chêne et al. (1978) suggests a Middle Eocene age for its basal units.

The Benin Formation constitutes the uppermost stratigraphic unit of the Niger Delta. The Azagba-Ogwashi Formation is characterized by a sequence of coarse-grained sandstone, light-coloured clay, and carbonaceous shale with interbedded lignite seams. The lignite occurs as two principal thick seams-an upper and a lower seam-averaging approximately 3 m and 6 m in thickness, respectively, and separated by an intervening shale layer about 4 m thick. Outcrops of the Azagba–Ogwashi lignite are exposed along river valleys, streams, and springs at no fewer than seven locations, extending from Obomkpa and Isele-Uku in the northwest to Nnewi in the southeast. The average overburden-to-lignite ratio is approximately 6:1, a condition that largely precludes the feasibility of open-cast mining (De Swardt & Piper, 1957).

2.2 Tectonic evolution of the Niger Delta Basin

Several authors, including Burke et al. (1971), Whiteman (1982), and Olade (1975), have described the structural and tectonic framework of the Niger Delta. These studies indicate that the tectonic evolution of the Niger Delta commenced during the Early Cretaceous with the development of the Benue Trough, which represents a failed arm of a triple rift junction associated with the opening of the South Atlantic Ocean. Olade (1975) proposed that the initial stage of this evolution involved the upwelling of a mantle plume beneath the present Niger Delta region. This mantle activity caused regional doming and rifting in the Benue area, leading to the formation of an RRR (ridge-ridge-ridge) triple junction.

Murat (1970) identified three major tectonic phases, or epirogenic movements, that significantly influenced the geological evolution of the Benue Trough system. He subdivided the system into three paleogeographic units: The Abakaliki–Benue Trough, the Anambra Basin, and the Niger Delta Basin. The initial rifting phase was characterized by rapid subsidence and the deposition of the Asu River Group during the Albian. In the Cenomanian, a mild deformational episode resulted in compressional folding of the Asu River Group and restricted the deposition of the Odukpani Formation to the Calabar Flank. Continued mantle upwelling and rifting during the Early Turonian led to the deposition of the Ezeaku Formation. By the Santonian, mantle upwelling had ceased and migrated westward, resulting in the collapse of the trough.

The second tectonic phase began in the Santonian, marked by gentle but widespread compressional folding that uplifted the Abakaliki–Benue Trough. This tectonic event caused the Anambra Basin and the Afikpo Syncline to subside, where they were subsequently infilled by two deltaic sedimentary cycles extending into the Paleocene. The third tectonic phase occurred during the Paleocene to Early Eocene, involving uplift of the Benin and Calabar Flanks (Murat, 1970). These movements initiated subsidence and the progressive outbuilding of Eocene to Holocene sediments of the Niger Delta along the northeast–southwest structural trend of the Benue Trough.

The structural development of the Niger Delta has been largely controlled by basement tectonics, related to crustal divergence and lateral translation during Late Jurassic to Cretaceous continental rifting. Additionally, the basin's evolution has been strongly influenced by the isostatic response of the crust to sediment loading. Rapid subsidence of the Niger Delta has occurred as a result of continuous sediment accumulation, flexural loading, and thermal contraction of the lithosphere (Onuoha, 1982, 1986; Onuoha & Ofoegbu, 1988). According to Caillet and Batiot (2003), the delta's structure and stratigraphy throughout its geological history have been governed by the dynamic interplay between sediment supply and subsidence rates. Subsidence itself has been controlled by both basement-driven tectonic processes and differential sediment loading and compaction of mechanically unstable shales.

2.2.1 Location of Study Area

Lignite was collected from Azagba-Ogwashi Formation, Delta state located in the West of the state capital Asaba and is the headquarter for the local government area Aniocha South, Anambra Basin, with geographical coordinates 06°10' 59.06" N 06° 31' 27.72" E Azagba-Ogwashi area (Lignite exposed between Latitude 06° 14' 33"Nand Longitude 006° 35' 48'E'). Clay and lateritic soil were collected from Igo community (Ovia North East Local Government Area) of Delta State in the Benin Formation of the Niger Delta Basin with geographical coordinates of 6.267 and 5.517 and N 6° 16' 0"E5° 31'0".

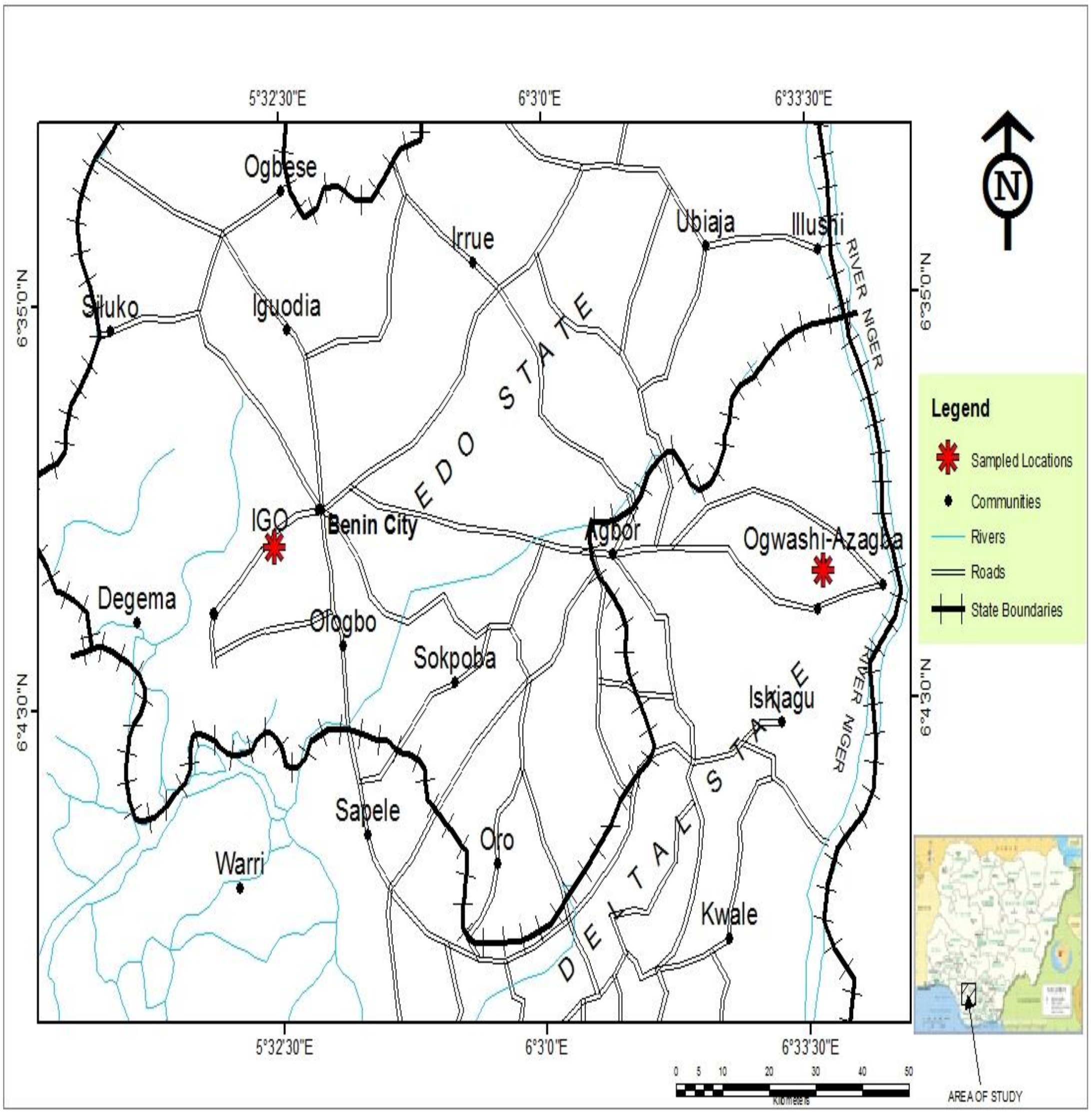

Fig 1.0 Map of the study area showing sampled locations.

3.0 MATERIALS AND METHODS

3.1 Field Sampling/ Sourcing of Materials

A field excursion was undertaken to collect rock samples. Lignite was obtained from Aniocha South (Azagba-Ogwashi Formation) in Delta State, while clay and lateritic soil samples were gathered from Igo community in Ovia North East Local Government Area, near Benin City, Edo State. Sawdust was sourced from a sawmill in Benin City, and water samples were taken from both tap and rainwater in Igo community.

The following materials facilitated the collection of these samples:

1. **Global Positioning System (GPS):** Used to receive satellite signals and determine the precise location of the receiver through coordinates.

2. **Sampling bags:** Polythene and sack bags were employed to store the collected field samples.
3. **Camera:** Utilized for capturing photographs of the study area.
4. **Cutlass:** Handy for clearing bush paths.
5. **Geologic hammer:** Essential for splitting and breaking rocks. It was used to expose fresh rock surfaces for examining composition, bedding orientation, mineralogy, and strength. The hammer also served as a photographic scale and allowed geologists to assess rock granularity, soundness, and resistance to fracturing.
6. **Chisel:** Useful for splitting rocks along bedding or foliation and for extracting fossils or specific mineral samples from unfoliated rocks.
7. **Field notebook and pen:** Employed to record field observations.
8. **Sampling cans:** Plastic containers were used to collect water samples, sealed tightly to prevent contamination, and carefully labeled to avoid mix-ups.

After collection, the rock samples were placed in polythene bags, properly labeled, and stored in a sack.

3.2 Moulding and Firing of Disc

Pulverized clay and lignites samples were mixed in varying ratio to produce filter disc. Clay was mixed with lignite, sawdust, laterite and water which were then molded to produce the various filter discs.

After the filter disc and pellets were produced, they were then sun-dried for four (4) weeks to remove moisture. They were then taken to a kiln to fire at temperatures of about 900^{o}C to enhance the hardening of the sun dried disc and prevent breakage (cracking) during filtration. A colour comparison was taken for the filter disc before and after firing using the Mussel colour chart.

Six filter discs (designated **D1, D2, D3, D4, D5 and D6**) were reported for the purpose of this research and their constituents are analysed below (Table 1)

Table 1: Analysis of the six (6) filter disc.

Disc	Clay (gram)	Lignite (gram)	Sawdust (gram)	Laterite (gram)	Diameter (cm)	Thickness (cm)	Weight after firing(gram)
D1	180	170	NA	NA	9.96	2.31	319
D2	170	180	NA	NA	9.95	2.34	320
D3	150	150	50	NA	9.85	2.38	305
D4	150	140	60	NA	9.92	2.56	320
D5	125	125	50	50	9.92	2.52	375

D6	130	120	50	50	9.93	2.51	356

Plate 1: Sieved sawdust.

Plate 2: Six (6) Moulded filter disc.

3.3 Filtration experimental Set Up

The instrumental set up for the filtration process was done using PVC pipes. The filter disc is inserted into the top PVC which holds it firm as it was moulded using the size of the pipe. Coliform contaminated water is then poured through the top pipe containing the filter disc. The filtration process of the water is observed and monitored to determine the flow rate of the process and ascertain the level of purity before and after the filtration.

The flow rate was calculated by dividing the volume of water measured in the lower container by the time at which the volumetric measurement was taken

$$\textbf{Flow rate} = \frac{\text{Volume of water measured at time T (mL)}}{\text{Elapsed time, T, from start of test (hours)}}$$

Elapsed time, T, from start of test (3hours)

3.3.1 Microbial Removal Test

The contaminated water was diluted with sterilize water at 110ºC in 1:1000 ratio by taking 1mL of the contaminated water with 999mLsterilized water. The common indicator microorganisms used were *E. coli* and total coliform. A membrane filtration technique was used to detect and enumerate total coliform and *E. coli* from both source water and filtered water samples. The membrane in membrane filtration has uniformly sized holes or pores of diameter 0.45 μm. This pore size is slightly smaller than the diameter of type, meal total coliform or other bacteria of interest. As the water sample was drawn through the filter, pure water passed through the pores, but the total coliform, *E. coli* and anything larger in size than 0.45 μm were caught on the surface or trapped in the pores of the membrane. The filters were tested for the removal efficiency of microbiological indicators (total coliform and *E. coli*).

Filter paper with 0.45 μm pore size was placed on the filter support base by using sterile tweezers. The whole apparatus was moved in a swirling motion to stir the sample by pouring 100 ml of the diluted river water. Filtration was sprinted and the funnel was rinsed with about 30 ml of distilled water twice. The filter membrane was removed carefully with sterilized tweezers and the membrane was then transferred to Membrane Lauryl Sulphate Broth media on metal Petri dish for in a rolling motion. The Petri dishes were inverted and placed into incubator set at 32 °C and 40 °C for 16 h for growth of colony of total coliform and *E. coli*.

The number of coliform forming units (CFU) were counted under magnifying glass and were expressed as CFU/100 ml. Microbial removal efficiency were calculated in terms of percent removal efficiency by the formula below:

$$\% \text{ E. coli removal efficiency} = \frac{(\text{E. coli before filtration} - \text{E. coli after filtration})}{\text{E. coli before filtration}} \times 100$$

3.3.2 Determination of the Porosity of the Disc Filters

Porosity of the ceramic filters was determined using the water absorption test (direct) method. It was a destructive method because three different samples weighing (50 g, 60 g and 100 g) were taken and the average porosity of these three samples was the apparent porosity of a ceramic filter. The samples were weighed when dry in air then saturated in distilled water at room temperature for 20 h. The water with the samples was then boiled for about two hours and allowed to cool to room temperature for another 20 h. This was done to ensure that the air in the open pores of the filter samples was replaced by the distilled water. The soaked samples were weighed under distilled water then removed and surface wiped with tissue paper and weighed in air. The weight of the wire is subtracted from the value obtained while determining the weight of the sample suspended in water. Apparent porosity (P) was then calculated using the expression given below (D'ujanda 2015).

Plate 3: Filtration set up.

$$P = \frac{(W_{\text{saturate}} - W_{\text{dry}}) \times 100}{W_{\text{saturate}} - W_{\text{underwater}}}$$

Where W saturated is the weight of the disc filter when saturated in water, W dry is the weight of the dry filter disc and W underwater is the weight of the filter disc under water.

3.4 DEDUCTION AND CONCLUSION

The various filter discs are carefully monitored in order to ascertain the flow rate of the water filtration process. The flow rate for each filter disc is recorded. Also the filtered water is poured into plastic containers which are then sent back to a water laboratory in order to evaluate the water quality after filtration. The water quality after filtration forms the basis of judgment for the various filter disc.

4.0 RESULTS AND DISCUSSIONS

4.1 Water Quality Analysis and Interpretation

Table 1: Microbial water quality before and after filtration.

Water Quality (CF/U/100 mL)	**Disc 1**	**Disc 2**	**Disc 3**	**Disc 4**	**Disc 5**	**Disc 6**
Before filtration e-coli	18	14	14	18	21	22
After Filtration e-coli	5.4	3.92	2.94	3.24	1.89	1.76
% e-coli removal efficiency	70	72	79	82	91	92
Before filtration Total coliform	40	45	38	46	68	60
After filtration Total coliform	15.92	18.45	14.44	16.5	14.62	11.4
% Total coliform removal efficiency	60.2	59	62	64.1	78.5	80.1

Table 2: Summarized characteristics of ceramic filter disc.

Disc name	**E-coli Removal Efficiency %**	**Total Coliform Removal Efficiency %**	**Flow rate ml/hr.**	**Porosity (%)**
1	70	60.2	341	20.1
2	72	59	353	20.4
3	79	62	412	30.1
4	82	64.1	377	30.4
5	91	78.5	850	40.1
6	92	80.1	756	43.1

Table 3: Comparison of Ceramic Filter Performance with WHO Standards.

Disc	**E. coli (CFU/100 mL) After Filtration**	**Total Coliform (CFU/100 mL) After Filtration**	**E. coli Removal Efficiency (%)**	**Total Coliform Removal Efficiency (%)**	**Meets WHO Standard?**
D1	5.4	15.92	70	60.2	✗ No
D2	3.92	18.45	72	59	✗ No

D3	2.94	14.44	79	62	✗ No
D4	3.24	16.5	82	64.1	✗ No
D5	1.89	14.62	91	78.5	✗ No
D6	1.76	11.4	92	80.1	✗ No
WHO Limit	0	0	–	–	

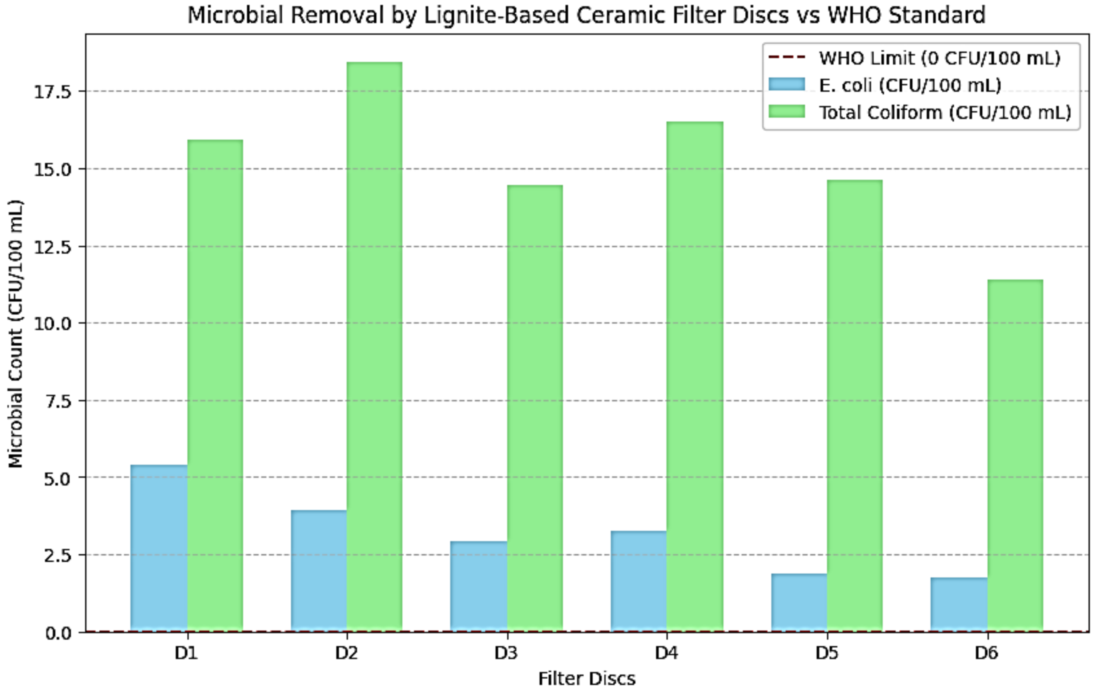

Fig 1. Graph comparing E. coli and total coliform removal by the six discs with the WHO limit.

4.2 DISCUSSION

The data presented in Tables 1 and 2 highlight the impact of filter composition, particularly the inclusion of lignite, on the microbial removal efficiency, flow rate, and porosity of ceramic water filters. The filters designed with lignite as a pore-forming material (Discs 5 and 6) consistently exhibited the highest removal efficiencies for both *E. coli* (91-92%) and total coliform (78.5-80.1%). In contrast, discs without lignite (Discs 1-4) demonstrated lower removal efficiencies, ranging from 70-82% for *E. coli* and 59-64.1% for total coliform.

The superior performance of lignite-containing discs can be attributed to the role of lignite in creating a well-connected pore network during the firing process. Lignite, an organic material, combusts during firing, leaving behind voids that act as micropores within the ceramic matrix. These pores increase the surface area and tortuosity of the filtration path, enhancing the physical trapping of microorganisms and improving microbial retention.

Consequently, the inclusion of lignite improves both porosity and flow characteristics, as evidenced by the higher flow rates (850 mL/hr for Disc 5 and 756 mL/hr for Disc 6) and increased porosity values (40.1% and 43.1%, respectively).

The data also suggest a balance between porosity and flow rate is essential. While higher porosity increases microbial removal by providing more sites for physical entrapment and adsorption, excessive porosity could compromise structural integrity or allow bypassing of microorganisms if pores become too large. In this study, the ratios of clay, lignite, sawdust, and laterite in Discs 5 and 6 appear optimized to create a microstructure that maximizes both filtration efficiency and practical flow rate.

In addition, the results indicate that lignite, when combined with sawdust and laterite, produces pores that are uniform and well-distributed, promoting consistent filtration performance. Discs 3 and 4, which included sawdust but no lignite, had moderate porosity (30.1–30.4%) and removal efficiencies, reinforcing that lignite is a more effective pore-former compared to sawdust alone.

Overall, this study confirms that lignite is a highly effective pore-forming material for ceramic water filters. Its use enhances microbial removal efficiency against both *E. coli* and total coliform, while maintaining an acceptable flow rate for practical household water treatment. This aligns with previous studies emphasizing that organic pore formers, such as lignite and sawdust, improve ceramic microstructure for drinking water purification (Clasen et al., 2007; Sobsey et al., 2008).

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study demonstrates that the incorporation of lignite as a pore-forming material in ceramic water filters significantly enhances their structural and functional performance for microbial removal. Filters containing lignite (Discs 5 and 6) exhibited superior porosity, optimal flow rates, and higher removal efficiencies for *E. coli* (91-92%) and total coliform (78-80%), compared to discs without lignite. The combustion of lignite during firing effectively generates a well-connected pore network, promoting physical entrapment of microorganisms and improving overall filtration efficiency.

Despite these improvements, post-filtration microbial counts for both *E. coli* and total coliform remained above WHO-recommended limits for safe drinking water (0 CFU/100 mL) Table 3 and Figure 1. This indicates that while lignite-based ceramic filters substantially reduce microbial contamination, additional treatment methods, such as boiling or chemical disinfection, are necessary to achieve fully compliant drinking water.

Overall, the study reveals that lignite is an effective pore-forming additive for ceramic water filters, providing a low-cost, locally-sourced solution to improve household water quality. Optimized formulations combining lignite, sawdust, clay, and laterite can serve as a practical basis for producing efficient and sustainable ceramic filters, particularly in resource-limited communities.

5.2 RECOMMENDATIONS

1. **Adopt Optimal Formulations:**

Discs 5 and 6, with a Clay:Lignite:Sawdust:Laterite ratio of ~2.5:2.5:1:1, arerecommended for local production. These formulations demonstrated superior porosity, flow rate, and microbial removal, confirming the effectiveness of lignite as a pore-forming material.

2. **Leverage Lignite for Improved Filtration:**

The study confirms that lignite significantly enhances pore connectivity and tortuosity, improving microbial retention. Future ceramic filter designs should include lignite in combination with sawdust and laterite to maximize performance.

3. **Enhance Safety through Complementary Measures:**

While lignite-based ceramic filters substantially reduce microbial contamination, minor post-filtration treatment (e.g., boiling, solar disinfection) can be applied to ensure compliance with WHO drinking water standards. This is a practical measure to complement the already high performance of the filters.

4. **Standardize Production Practices:**

Consistency in mixing ratios, firing temperatures, and burn-out times is essential to ensure reproducible filter performance, allowing households and small-scale manufacturers to reliably produce high-quality filters.

5. **Future Research and Development:**

- Explore long-term durability and clogging behavior of lignite-based filters under field conditions.
- Investigate additional low-cost pore-formers to optimize filtration further.
- Assess the removal of other contaminants (heavy metals, turbidity) to expand the application scope of ceramic filters.

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