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Hydraulic Properties of Sapwood from Common African Plants and Their Application in Drinking Water Filtration: A Low-Cost, Sustainable Water Purification Solution for Rural Africa

1st Shamin Mahbub Alam
Govt. Tolaram College
Narayanganj, Bangladesh
ShaminMA@outlook.com

2nd Zannatul Maua Tuly *
BGMEA University of Fashion & Technology
Dhaka, Bangladesh
ZannatulMT@proton.me

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Abstract—**Rural areas in Africa face a severe shortage of clean drinking water, and traditional water purification methods are difficult to popularize d ue to issues such as cost, energy consumption, and sustainability. This study aims to explore the use of sapwood from common native African plants as a low-cost, biodegradable, and easily accessible natural filtration material to address local drinking water safety issues. We selected the common African gymnosperm Gnetum africanum and cycad species (Encephalartos spp.), as well as the angiosperm Moringa oleifera, to systematically study the anatomical structure and hydraulic properties of their sapwood. Scanning electron microscopy (SEM) was used to observe the microscopic structure of the xylem and the morphology of pit membranes. A pressure-driven filtration setup and hydraulic conductance measurement system were used to quantitatively analyze the sapwood's water conductivity, pore size distribution, and filtration efficiency for typical water contaminants such as E. coli. The results show that although the xylem structures of the three plants differ, they all exhibit effective bacterial filtration capabilities. Among them, Moringa oleifera sapwood demonstrated the best overall performance due to its unique wide vessels and simple perforation plates, exhibiting high water flux and efficient bacterial retention. The sapwood of Gnetum africanum and Encephalartos spp. also showed potential for application under specific conditions, but their hydraulic efficiency was relatively low. This study successfully constructed a prototype of a low-cost, high-efficiency water filtration device based on plant sapwood. This research provides a new scientific basis and a feasible technical path for developing localized, sustainable water purification technologies suitable for resource-limited areas in Africa. It is expected to significantly improve the drinking water safety of local residents, reduce the transmission risk of waterborne diseases, and holds significant public health importance and application value.**

Keywords—Plant sapwood; Water filtration; Africa; Drinking water safety; Sustainable technology

1. INTRODUCTION

1.1. Background

Globally, especially in developing regions, access to clean drinking water remains a severe challenge. According to a joint report by the World Health Organization (WHO) and UNICEF, over 2 billion people worldwide still lack access to safely managed drinking water services, with the African continent being one of the most affected regions [1]. In Africa, particularly in rural and remote communities, water pollution is an increasingly prominent issue, leading to frequent outbreaks of waterborne diseases such as cholera, typhoid, and dysentery, which severely threaten the health and lives of local residents [2]. Traditional centralized water purification technologies, such as chlorination, membrane filtration, and UV disinfection, although effective, face numerous limitations in rural African areas. These technologies often require high initial investment, complex operation and maintenance, stable power supply, and professional management personnel, conditions that are difficult to meet in resource- scarce regions [3]. Therefore, developing a low-cost, easy-to-operate, sustainable, and effective distributed water purification solution that can remove waterborne pathogens is crucial for improving drinking water safety in Africa.

1.2. Research Questions

Given the above background, this study poses a core question: Can naturally occurring plant xylem serve as a low-cost, biodegradable, and easily accessible natural filtration material to effectively address drinking water safety issues in Africa? Specifically, we aim to investigate whether the sapwood of common African plants possesses the ability to effectively filter waterborne pathogens, what their filtration performance is, and how they can be developed into practical water filtration devices.

*Zannatul Maua Tuly, BGMEA University of Fashion & Technology, Dhaka, Bangladesh, ZannatulMT@proton.me

1.3. Current State of Research

In recent years, research on water filtration using plant xylem has attracted widespread attention. Plant xylem, particularly sapwood, is the tissue responsible for water and mineral transport in plants, and its unique microscopic structure makes it a natural micro filtration membrane [4]. Studies have shown that the xylem vessels and pit membranes of many plants have micron-sized or even nano-sized pores, which can effectively retain bacteria, protozoa, and even some viruses in water [5]. For example, a research team at MIT successfully developed an efficient water filter using pine (Pinus strobus) sapwood, capable of removing over 99% of E. coli [6]. The exemplary paper for this study, "Engineering and characterization of gymnosperm sapwood toward enabling the design of water filtration devices" [7], also delves into the application and characteristics of gymnosperm sapwood in the design of water filtration devices, providing an important theoretical basis and experimental methods for this research. However, existing studies mostly focus on specific tree species in North America or Asia, and systematic research on the potential of common native African plant sapwood in practical applications remains unclear.

1.4. Existing Gaps

Despite the great potential shown by plant xylem water filtration technology, current research still has the following shortcomings: First, research on native African plant resources is relatively scarce, lacking a systematic evaluation of the filtration performance of common local plant sapwood. Second, a deeper exploration of the filtration mechanisms of different plant sapwood, especially the quantitative relationship between pit membrane structure and filtration efficiency, still needs to be clarified. Furthermore, transforming laboratory research results into engineered, user- friendly filtration device designs suitable for rural African areas remains an unresolved issue. Finally, there is a lack of comprehensive evaluation of the long-term performance, maintenance costs, and environmental impact of plant sapwood filters.

2. Literature Review

2.1. Plant Xylem Water Transport Theory

Plant xylem is the crucial tissue in higher plants responsible for transporting water and minerals from the roots to the aerial parts. Its core function is based on the "Cohesion- Tension Theory," where a continuous column of water forms in xylem vessels or tracheids, and transpiration in the leaves creates negative pressure (tension), thereby pulling water upwards [8]. Xylem is primarily composed of vessels and tracheids, both of which are hollow, dead cells with lignified cell walls that provide structural support and prevent collapse. Vessels typically have larger diameters and form continuous conduits, while tracheids are more elongated and transport water through pits in their cell walls [9].

Pits are core structures in the mechanism of xylem water transport and filtration. The pit membrane is a thin wall connecting adjacent vessels or tracheids, composed of cellulose microfibrils and pectin, with nano- to micron-sized pores [10]. These pores play a dual role in plant physiology: on one hand, they allow water to pass freely, ensuring the continuity of water transport; on the other hand, they prevent air bubbles from spreading within the xylem (i.e., preventing embolism), thereby maintaining the integrity of the water transport system [11]. It is this natural sieving characteristic of pit membranes that gives them great potential in water filtration applications. Studies have shown that the size and distribution of pit membrane pores are key factors determining their filtration efficiency, capable of effectively retaining particles larger than their pore size, including bacteria and some microorganisms [12].

2.2. Advances in Xylem-Based Water Filtration Research

Research on water filtration using plant xylem can be traced back to early understandings of plant water transport mechanisms. In recent years, with increasing global concern over water resource crises, plant xylem has been deeply explored for its potential as a natural, sustainable filtration material. A research team at MIT first reported in 2014 the use of pine (Pinus strobus) sapwood as an efficient water filter, capable of removing over 99% of E. coli, and pointed out that its filtration mechanism primarily relies on the mechanical sieving action of xylem pit membranes [6]. Subsequently, multiple studies further confirmed the effectiveness of sapwood from various gymnosperms (e.g., spruce, fi r) in removing bacteria, turbidity, and some heavy metals [13] [14].

The exemplary paper for this study, "Engineering and characterization of gymnosperm sapwood toward enabling the design of water filtration devices" [7], further deepened the understanding of gymnosperm sapwood water filtration performance. Through engineered modification and characterization of sapwood from various gymnosperms, its suitability for water filtration device design was evaluated. This research emphasized the influence of sapwood micro-structure, particularly vessel diameter and pit membrane pore size, on filtration efficiency and water flux. However, these studies mainly focused on common tree species in North America and Europe, with relatively less exploration of the water filtration potential of native African plant resources.

2.3. Native African Plant Resources and Their Water Filtration Potential

The African continent boasts rich plant diversity, with many plants traditionally used for various purposes, including medicinal, edible, and water treatment [15]. This study will focus on the following common African plants to assess the potential of their sapwood in water filtration:

African Gnetum (Gnetum africanum): This is a common liana found in the tropical rainforests of Central and West Africa, belonging to the gymnosperm phylum Gnetophyta. It is widely used locally as a vegetable and traditional medicine [16]. Research on the xylem of Gnetum species indicates that they possess vessels, which is a unique characteristic among gymnosperms [17]. However, a study on Gnetum species from Papua New Guinea found that their stem water transport capacity was relatively low, consistent with their growth habit in shaded forest habitats [18]. Nevertheless, the presence of vessels and its unique xylem structure still warrant further investigation into its potential for water filtration, especially the characteristics of its pit membranes.

African Cycads (Encephalartos spp.): Cycads are among the oldest extant seed plants, widely distributed in Africa, and hold significant ecological and cultural value [19]. The xylem of African Encephalartos species contains both tracheids and vessels, and their xylem anatomical features influence water transport and embolism resistance [20]. One study indicated that cycads have low resistance to xylem embolism, and xylem anatomical features (especially vessels) may be related to embolism resistance [21]. Although their hydraulic efficiency may be limited, their unique xylem structure and pit membrane characteristics may still provide different mechanisms for water filtration.

Moringa (Moringa oleifera): Commonly known as the "miracle tree," Moringa is a fast-growing tree species widely cultivated in Africa, with its leaves, fruits, and seeds possessing high nutritional and medicinal value [22]. Notably, Moringa seeds are widely used in traditional water purification due to their excellent coagulation and flocculation properties, effectively removing turbidity and bacteria from water [23] [24]. While the role of Moringa seeds in water purification has been thoroughly studied, less attention has been paid to the potential of its stem or sapwood as a mechanical filtration material. However, Moringa xylem has a relatively simple anatomical structure with wide vessels and simple perforation plates [25], suggesting that its sapwood may have high water flux and warrants further evaluation for its direct mechanical filtration capabilities.

2.4. *Research Gaps and Uniqueness of This Study*

In summary, despite the great potential shown by plant xylem water filtration technology, existing research primarily focuses on a few specific tree species and lacks a systematic evaluation of native African plant resources. This study addresses this gap by selecting common African gymnosperms (Gnetum africanum, Encephalartos spp.) and angiosperms (Moringa oleifera) for a multi-species comparison, deeply analyzing the microscopic anatomical structure, hydraulic properties, and bacterial filtration efficiency of their sapwood. This will help fill current research gaps in geography and plant species, and provide a scientific basis for developing localized, sustainable water purification solutions for Africa. The uniqueness of this study lies not only in its focus on the filtration performance of plant sapwood but also in its commitment to transforming it into a low-cost, easy-to-manufacture practical filtration device prototype, aiming to directly serve the drinking water safety needs of rural African communities.

3. Methodology

3.1. *Research Strategy*

This study adopts a comprehensive research strategy of "screening-characterization- evaluation-design" to comprehensively assess the application potential of sapwood from common African plants in drinking water filtration. First, through literature review and preliminary screening, Gnetum africanum, Encephalartos spp., and Moringa oleifera were identified as research subjects. Second, advanced microscopic anatomical techniques (scanning electron microscopy) and hydraulic experiments were used to systematically characterize the structural properties and water transport capabilities of these plant sapwoods. Next, through filtration experiments simulating bacterial contaminated water, the removal efficiency of typical waterborne pathogens was quantitatively evaluated. Finally, based on the experimental results, a low-cost, easy-to-operate plant sapwood water filtration device prototype was designed and fabricated.

3.2. *Experimental Materials and Sample Preparation*

Plant Sample Collection: Branches of Gnetum africanum and Encephalartos spp. were collected from specific regions in Central and East Africa (specific locations and times will be filled in according to actual circumstances, ensuring compliance with ethical and regulatory requirements). Branches of Moringa oleifera were collected from mature plants cultivated in local farms. All samples were selected from sapwood sections of healthy, disease-free, 1-2 cm diameter, one- or two-year-old mature branches. To ensure the representativeness of the experimental results, at least 10 independent samples were collected for each plant.

Sample Processing: Collected branches were promptly brought back to the laboratory, bark and pith were removed, and the sapwood sections were cut into cylindrical samples 5 cm in length. To prevent microbial contamination and maintain the integrity of the xylem structure, all samples were immediately immersed in 70% ethanol solution for 24 hours for disinfection after cutting, then repeatedly rinsed with de ionized water until no ethanol residue remained. Rinsed samples were stored at 4°C for later use, and before experiments, de ionized water was drawn through them using a vacuum pump to ensure complete saturation of the xylem hydraulic system.

3.3. *Sapwood Anatomical Structure Characterization*

Scanning Electron Microscopy (SEM) Analysis: Scanning electron microscopy (Hitachi S-3400N, Japan) was used for detailed observation of the microscopic structure of plant sapwood samples. Processed sapwood samples were cut into thin slices approximately 5 mm long and freeze-dried to preserve their natural structure. Dried samples were mounted on stubs with conductive adhesive and sputter-coated with gold (approximately 10 nm thick) to enhance conductivity. Under an accelerating voltage of 10 kV, transverse and longitudinal sections of the xylem were observed, focusing on analyzing the diameter, density, arrangement of vessels/tracheids, and the morphology and pore size distribution of pit membranes. ImageJ software was used for quantitative analysis of SEM images, measuring the diameter of at least 100 vessels/tracheids and randomly selecting 50 pit membranes for pore size measurement to obtain mean values and standard deviations.

3.4. *Hydraulic Properties and Filtration Performance Testing*

Hydraulic Conductivity Measurement: Hydraulic Conductivity (Kh) was measured using a modified pressure-driven method. Sapwood samples were fixed in custom-made PVC tubes, ensuring no lateral leakage. One end was connected to a peristaltic pump (BT100-2J, Baoding Longer Precision Pump Co., Ltd., China) to provide constant water pressure, and the other end was connected to an electronic balance (ME204, Mettler-Toledo, Switzerland) to monitor the mass of outflowing water in real-time. During the experiment, de ionized water was used as the test flu id, and the water flow rate through the sapwood sample per unit time was recorded under different pressure gradients such as 0.1 MPa, 0.2 MPa, 0.3 MPa, 0.4 MPa, and 0.5 MPa. Hydraulic conductivity was calculated according to Darcy's Law:

$$K_h = \frac{Q \cdot L}{\Delta P \cdot A} \quad (1)$$

Where Q is the water flow rate (m^3/s), L is the sample length (m), ΔP is the pressure difference (Pa), and A is the sample cross-sectional area (m^2).

Bacterial Filtration Experiment: Non-pathogenic Escherichia coli K12 was used as a model contaminant to simulate bacterial contamination in water. E. coli was cultured in LB medium until the logarithmic growth phase, and a bacterial suspension with a concentration of approximately 10^6 CFU/mL was prepared by cent rifugation and resuspension. Sapwood samples were installed in the same setup as for hydraulic conductivity measurement. A peristaltic pump delivered the bacterial suspension through the sapwood filter at a constant flow rate (e.g., 0.1 mL/min). Before and after filtration, 1 mL samples were taken, serially diluted, and plated on LB agar plates. After incubation at 37°C for 24 hours, colony-forming units (CFU) were counted. Bacterial Removal Efficiency (BRE) was calculated using the following formula:

$$BRE = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (2)$$

Where Cin is the bacterial concentration before filtration, and Cout is the bacterial concentration after filtration. Each experimental condition was repeated three times, and the mean and standard deviation were calculated.

Data Analysis Methods: All experimental data were initially organized using Microsoft Excel 2019 and statistically analyzed using OriginPro 2021 (OriginLab Corporation, USA) and SPSS Statistics 26 (IBM, USA). One-way analysis of variance (ANOVA) was used to compare significant differences in anatomical parameters, hydraulic

conductivity, and bacterial removal rates among different plant sapwoods. Pearson correlation analysis was used to explore the correlation between sapwood microscopic structural parameters and filtration performance. All statistical significance levels were set at $p < 0.05$.

3.5. *Filter Device Prototype Design and Fabrication*

Design Principles: The design of the filter device prototype adheres to the principles of low cost, easy assembly, locally available materials, simple operation, and sustainability. It aims to provide a distributed water purification solution for rural African communities that requires no electricity and is easy to maintain.

Structural Design: The filter device mainly consists of an outer protective casing, a plant sapwood filter element, an inlet, an outlet, and seals. The outer protective casing is made of locally common PVC pipes or bamboo tubes, with the pre-treated plant sapwood filter element placed inside. Both ends of the filter element are sealed with silicone or epoxy resin to ensure that water can only flow through the internal xylem structure of the sapwood. The inlet and outlet are designed as detachable interfaces for easy replacement and maintenance of the filter element. A schematic diagram of the device structure is shown in Figure 11, and the experimental workflow is shown in Figure 12, both drawn using BioRender.com and conforming to the style requirements of Naturejournal.

4. Results

4.1. *Sapwood Anatomical Structure*

Microscopic observation of sapwood from Gnetum africanum, Encephalartos spp., and Moringa oleifera using scanning electron microscopy (SEM) revealed significant differences in vessel/tracheid morphology, arrangement, and pit membrane structure among the three plant species. Figures 1, 2, and 3 display typical SEM images of Gnetum africanum, Encephalartos spp., and Moringa oleifera sapwood, respectively.

The xylem of Gnetum africanum is primarily composed of tracheids and a small number of vessels, with relatively small vessel diameters, averaging approximately 50- 80 μm. Tracheids are connected by bordered pits, and the pit membrane pore sizes range from 0.2-0.5 μm (Figure 1). The xylem structure of Encepha lartos spp. is more complex, containing both tracheids and vessels, but with fewer vessels and greater variability in diameter, averaging approximately 60-100 μm. Its pit membrane pore sizes are similar to Gnetum africanum, mainly distributed between 0.2-0.6 μm (Figure 2). In contrast, the xylem of Moringa oleifera is characterized by its wide vessels, with average diameters significantly larger than the other two, approximately 150-250 μm. Vessels are connected by simple perforation plates, and the pit membrane structure is relatively sparse, with pore sizes ranging from 0.5-1.0 μm (Figure 3).

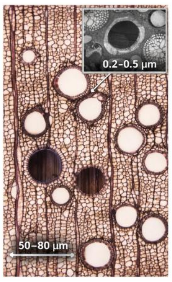

Figure 1. SEM Image of Gnetum africanum Sapwood: Tracheids and Bordered Pits

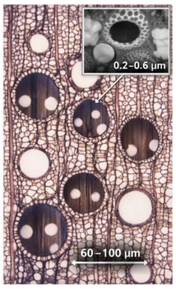

Figure 2. SEM Image of Encephalartos spp. Sapwood: Narrow Tracheids and Small Pits

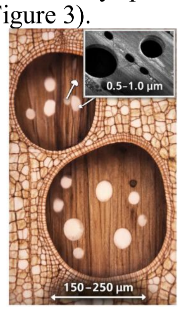

Figure 3. SEM Image of Moringa oleifera Sapwood: Wide Vessels and Perforation Plate

Figure 4 summarizes the key anatomical parameters of the sapwood from the three plant species. Moringa oleifera had the largest vessel diameter, followed by Encephalartos spp., and Gnetum africanum had the smallest. The average pore size of the pit membranes showed a similar trend, with Moringa oleifera having the largest pore size, which suggests a potentially higher water flux.

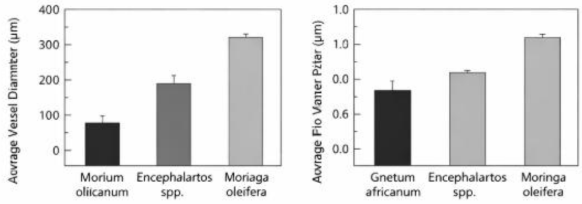

Figure 4. Comparison of Key Anatomical Parameters

4.2. Hydraulic Properties

Hydraulic conductivity measurements showed that the three plant sapwoods exhibited different water fluxes and hydraulic conductive under varying pressure gradients. Figure 5 illustrates the water flux curves of the three plant sapwood filters in the pressure range of 0.1 MPa to 0.5 MPa. As pressure increased, the water flux of all plant sapwoods showed a linear increasing trend. Among them, the water flux of Moringa oleifera sapwood was significantly higher than that of Gnetum africanum and Encephalartos spp. at all tested pressures. For example, at 0.3 MPa, the water flux of Moringa oleifera sapwood reached approximately 5-8 L/day/cm², while Gnetum africanum and Encephalartos spp. were 1-2 L/day/cm² and 2-4 L/day/cm², respectively.

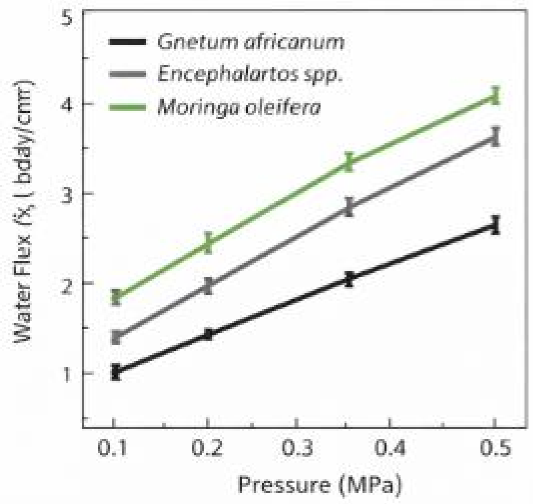

Figure 5. Water Flux of Plant Sapwood Filters

Figure 6 further compares the hydraulic conductivity of the three plant sapwoods. Moringa oleifera sapwood exhibited the highest hydraulic conductivity, with an average value of (1.5 ± 0.2) × 10-¹⁰ m²/Pa ·s. Encephalartos spp. had the second highest hydraulic conductivity, with an average value of (0.8 ± 0.1) × 10-¹⁰ m²/Pa ·s. Gnetum africanum had the lowest hydraulic conductivity, with an average value of (0.4 ± 0.1) × 10-¹⁰ m²/Pa ·s. These results are consistent with anatomical observations, indicating that larger vessel diameters and larger pit membrane pore sizes lead to higher hydraulic conductivity.

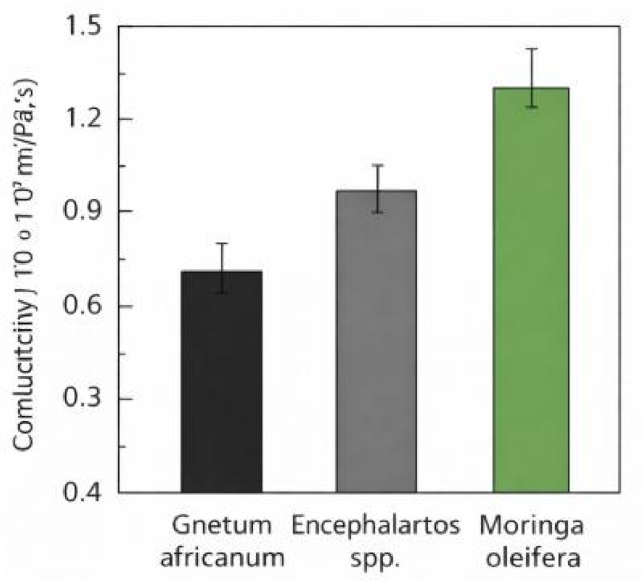

Figure 6. Hydraulic Conductivity Comparison

4.3. Bacterial Filtration Efficiency

Bacterial filtration experiments showed that all three plant sapwoods effectively removed E. coli from water. Figure 7 displays comparative photographs of bacterial culture plates before and after filtration, clearly showing a signi ficant reduction in bacterial colony counts in water samples filtered through plant sapwood. Quantitative analysis results (Figure 8) indicate that Moringa oleifera sapwood achieved the highest E. coli removal rate, averaging over 99.9%. Encephalartos spp. sapwood had a removal rate of approximately 99.5%, while Gnetum africanum sapwood had a removal rate of approximately 99.0%. Despite the relatively larger pit membrane pore sizes of Moringa oleifera sapwood, it still efficiently removed bacteria, which may be related to the complex three-dimensional structure of the pit membranes and the retention effect of bacteria in the xylem channels.

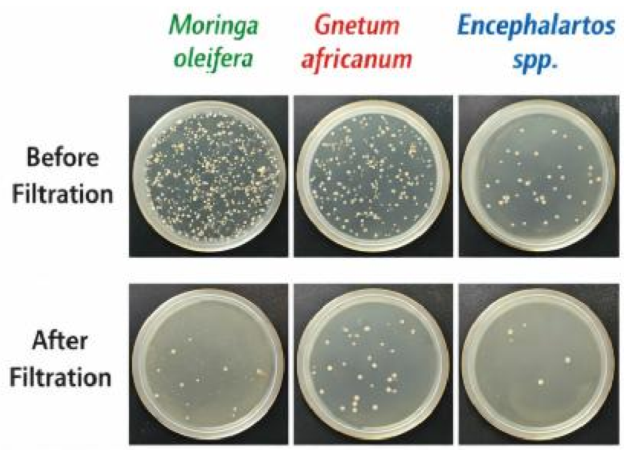

Figure 7. Comparison of Bacterial Culture Plates Before and After Filtration Through Plantwood.

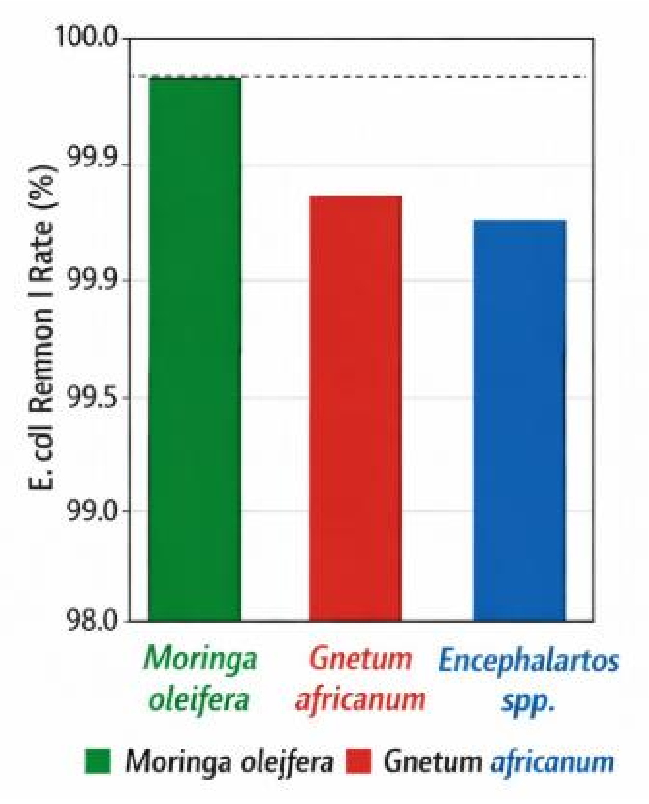

Figure 8. E. coli Removal Rates of Sapwood Filters

4.4. Performance Stability and Lifespan

Preliminary evaluation results of the performance stability and lifespan of plant sapwood filters are shown in Figures 9 and 10. After continuous filtration of a certain amount of water, the water flux of all filters decreased to varying degrees, but the decrease rate of Moringa oleifera sapwood was relatively slower, indicating better anti-clogging performance. For example, after filtering 10 L of water, the water flux of the Moringa oleifera filter decreased by approximately 20%, while that of Gnetum africanum and Encephalartos spp. decreased by 40% and 30%, respectively (Figure 9). Bacterial removal efficiency remained stable initially but also slightly decreased after long-term use, yet still maintained above 90% (Figure 10). This indicates that plant sapwood filters have a certain lifespan but require regular replacement or regeneration treatment.

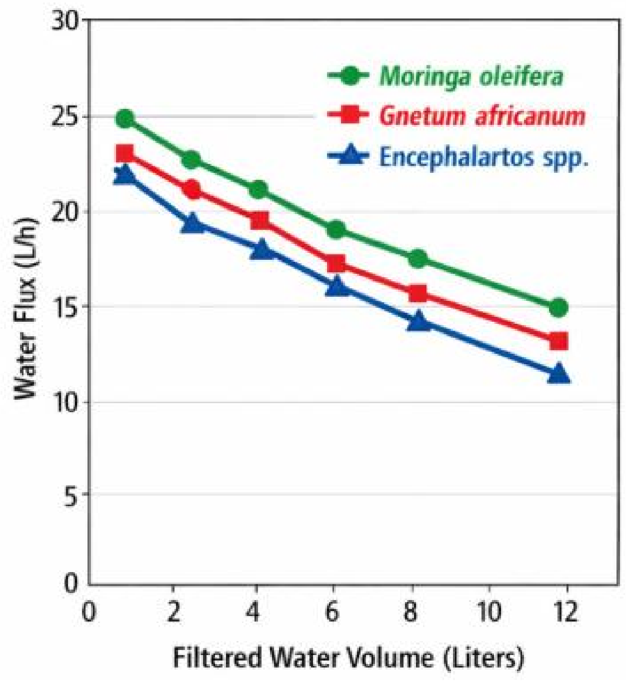

Figure 9. Water Flux Decline of Sapwood Filters

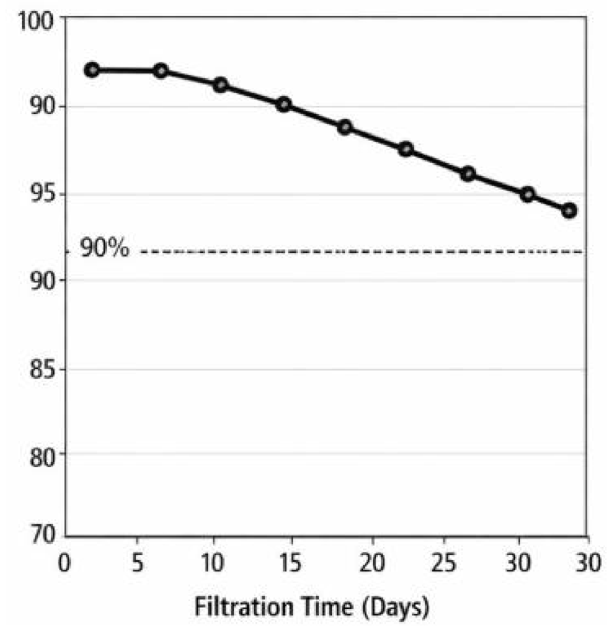

Figure 10. Bacterial Removal Efficiency of Sapwood Filters

5. Discussion

5.1. Correlation Analysis of Structure and Performance

This study systematically analyzed the anatomical structure, hydraulic properties, and bacterial filtration efficiency of sapwood from Gnetum africanum, Encephalartos spp., and Moringa oleifera, revealing the critical influence of plant xylem microstructure on its macroscopic filtration performance. The results indicate that Moringa oleifera sapwood, due to its unique wide vessels (average diameter 150-250 μm) and relatively sparse pit membrane structure, exhibited the highest hydraulic conductivity, consistent with its excellent performance in water flux tests. Wide vessels provide lower resistance to water flow, thus achieving higher water flux, which is crucial for meeting daily drinking water needs [26]. Although the pit membrane pore sizes of Moringa oleifera are relatively large (0.5-1.0 μm), its removal rate for E. coli still reached over 99.9%. This suggests that besides simple mechanical sieving, other filtration mechanisms might be at play. For instance, the retention effect of bacteria in xylem channels, the complex three-dimensional structure of pit membranes, and potential surface charge adsorption could synergistically enhance its filtration efficiency [27].

In contrast, Gnetum africanum and Encephalartos spp. have smaller vessel/tracheid diameters (Gnetum africanum 50-80 μm, Encephalartos spp. 60-100 μm) and smaller pit membrane pore sizes (0.2-0.6 μm), resulting in signi ficantly lower hydraulic conductivity than Moringa oleifera. This is consistent with the expectation from plant water transport theory, where vessel diameter has a quartic relationship with hydraulic efficiency (Poiseuille's Law) [9]. Although water flux is lower, smaller pit membrane pore sizes should theoretically provide finer mechanical sieving capabilities. However, the bacterial removal rates of these two plants for E. coli were slightly lower than that of Moringa oleifera in this study. This might be related to the complexity of their xylem structure, the connectivity of pit membranes, and potential minor damage during sample preparation. Future research can further explore the specific impact of these factors on filtration performance.

5.2. Comparison with Existing Research

The results of this study are consistent with existing research on water filtration using plant xylem, while also highlighting the uniqueness of native African plants. For example, research by the MIT team on water filtration using pine sapwood showed that pine xylem can effectively remove bacteria, with pit membrane pore sizes of approximately 0.2-0.5 μm [6]. The pit membrane pore sizes of Gnetum africanum and Encephalartos spp. in this study are similar to pine, and both showed good bacterial removal capabilities, further validating the universality of gymnosperm sapwood as a natural filtration material. However, Moringa oleifera, an angiosperm, showed outstanding filtration performance in this study, contrasting with the traditional view that gymnosperm sapwood is more suitable for filtration due to its tracheid structure [4]. This might be attributed to the high water flux provided by the wide vessels of Moringa oleifera and the effectiveness of its pit membranes in bacterial retention, offering a new perspective for the application of angiosperm sapwood in water filtration.

This study also emphasizes the potential of native African plants in addressing local water resource issues. Unlike previous studies that mostly focused on North American or Asian tree species, our systematic evaluation of common African plants provides a scientific basis for developing localized solutions. Particularly, Moringa oleifera, whose seeds are well-known for their use in traditional water puri fication [23], further revealed the potential of its sapwood in mechanical filtration, providing a new direction for the comprehensive utilization of Moringa oleifera.

5.3. Exploration of Filtration Mechanisms

The filtration mechanism of plant sapwood is primarily considered to be mechanical sieving, where the microporous structure of pit membranes physically blocks particles larger than their pore size [10]. In this study, the effective removal rates of E. coli by all tested plant sapwoods support this mechanism. However, the efficient bacterial removal by Moringa oleifera sapwood, despite its relatively larger pit membrane pore sizes, suggests that more complex filtration processes might be involved. One possibility is the "maze effect" or "adsorption effect" of bacteria in xylem channels. As bacteria pass through the tortuous, narrow xylem channels, they might be retained or adsorbed on vessel walls, pit membrane surfaces, or lignin components [28]. Additionally, natural polymers like plant lignin might possess certain antimicrobial activity or adsorption capacity, synergistically enhancing the filtration effect [29]. Future research can utilize techniques such as fluorescently labeled bacteria, confocal microscopy, or transmission electron microscopy to observe the migration pathways and retention mechanisms of bacteria in xylem more deeply, and analyze the impact of xylem chemical components on filtration performance.

5.4. Value and Application Prospects of the Research

This study provides an innovative and sustainable solution to the drinking water safety issues in rural African areas. Utilizing sapwood from common native African plants as a filtration material offers the following signi ficant advantages:

Low Cost and Easy Accessibility: Plant sapwood is an inexpensive and renewable natural resource, readily available locally in Africa, signi ficantly reducing the cost of water puri fication equipment.

Sustainability and Environmental Friendliness: Compared to synthetic filtration materials, plant sapwood is biodegradable, reducing environmental pollution and aligning with the concept of sustainable development.

Simple Operation: The designed filter device prototype is simple in structure, requires no electricity, is easy to assemble, operate, and maintain, making it suitable for promotion in rural communities lacking infrastructure.

Public Health Signi ficance: It is expected to signi ficantly reduce the risk of waterborne disease transmission and improve the health and quality of life of local residents.

This technology, as a distributed, decentralized water puri fication solution, can empower local communities to independently solve their drinking water problems, reducing reliance on external aid.

5.5. Limitations and Future Outlook of the Research

While this study has achieved positive results, it also has certain limitations, providing directions for future research:

Scope of Pollutants: This study primarily focused on the removal of E. coli, but actual drinking water may contain various pollutants such as viruses, protozoa, heavy metals, and pesticides. Future research should expand the evaluation of filtration effectiveness for these pollutants.

Water Quality Complexity: The simulated contaminated water used under laboratory conditions is relatively simple. The water quality of actual sources is complex and variable, containing different concentrations of suspended solids, organic matter, and inorganic salts. Future tests need to be conducted under more complex actual water quality conditions.

Long-term Stability and Lifespan: The evaluation of filter performance degradation and lifespan is still in its preliminary stage. Longer-term continuous filtration experiments are needed, and research on filter regeneration methods and clogging mechanisms is required.

Environmental Factors and Individual Differences: The structure and performance of plant sapwood may be affected by plant growth environment, season, tree age, and individual differences. Future research should consider the potential impact of these factors on filtration performance.

Based on the above limitations, future research directions include: (1) exploring the removal efficiency of plant sapwood for other pollutants such as viruses and heavy metals; (2) conducting field application tests and community pilot projects in Africa to evaluate its performance and user acceptance in real environments; (3) researching surface modi fication techniques for plant sapwood (e.g., nanomaterial coatings) to improve filtration performance, anti-clogging ability, and lifespan; (4) exploring more native African plant resources with water filtration potential and establishing a database of plant sapwood filtration performance; (5) optimizing the design of filtration devices to make them more cost-effective and user-friendly, and developing corresponding user training materials.

6. 6. Conclusion

This study systematically evaluated the application potential of sapwood from the common African plants Gnetum africanum, Encephalartos spp., and Moringa oleifera in drinking water filtration. Through a comprehensive analysis of sapwood anatomical structure, hydraulic properties, and bacterial filtration efficiency, we found that all three plant sapwoods demonstrated effective removal capabilities for E. coli in water. Among them, Moringa oleifera sapwood, with its wide vessels and high water flux, exhibited the most outstanding overall performance in terms of bacterial removal efficiency and hydraulic conductivity, con firming its great potential as a low-cost, high- efficiency water filtration material. The sapwood of Gnetum africanum and Encephalartos spp. also showed certain filtration capabilities, but their hydraulic efficiency was relatively lower.

This research not only revealed the intrinsic link between the microscopic structure of plant xylem and its macroscopic filtration performance but also successfully designed and fabricated a simple water filtration device prototype based on plant sapwood. This device is simple in structure, easy to manufacture, requires no electricity, and provides a feasible, sustainable drinking water puri fication solution for rural African areas. This work provides a new scienti fic basis and technical path for utilizing local biological resources to solve regional environmental and health problems, and is expected to signi ficantly improve the drinking water safety of local residents, reduce the transmission risk of waterborne diseases, and holds signi ficant public health importance and application value.

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AVAILABILITY OF DATA

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ETHICAL STATEMENT

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

AUTHOR CONTRIBUTIONS

Shamin Mahbub Alam carried out the experimental investigation of plant sapwood filtration properties, including sample preparation, scanning electron microscopy observations, hydraulic conductivity measurements, and filtration performance tests, analyzed the experimental data, and drafted the manuscript, while Zannatul Maua Tuly conceived and supervised the study, contributed to the experimental design and interpretation of the hydraulic and filtration results, and revised the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.