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# To Design Composite Clay Filter Using Clay Sand and Charcoal for Rural Areas

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***Abstract***— Access to safe drinking water remains a significant challenge in rural areas where conventional purification systems such as reverse osmosis and UV sterilization are often unaffordable or impractical. This study evaluates the performance of a low-cost composite clay filter made from locally available clay, sand, and activated charcoal for rural water purification. Six filter mixtures (75% clay with 5–20% sand and 5–20% charcoal) were fabricated and tested for pH, turbidity, total dissolved solids (TDS), hardness, chloride, and bacterial removal. The optimal composition (75% clay, 12% sand, 13% charcoal) achieved balanced performance, reducing turbidity from 450 NTU to 3.9 NTU, TDS from 413 mg/L to 390 mg/L, hardness 170 to 155 mg/L, chloride 122 to 108 mg/L, achieving complete bacterial removal (0 CFU/100 mL, representing 100% reduction).. The treated water met WHO and Pakistan Standards for Drinking Water Quality. These findings suggest composite clay filters are an effective, sustainable, and affordable solution for rural communities lacking access to advanced water treatment systems.

***Index Terms***— Composite clay filter; Sand; activated charcoal; Water purification; Low-cost filtration; Rural areas.

## I. INTRODUCTION

Globally, access to clean drinking water remains a significant issue, especially in rural areas and low-income communities. Diseases caused by contaminated water include cholera, dysentery, and heavy metal toxicity. Despite the existence of commercial filters (like RO systems), their high cost and maintenance prevent many households from affording them. Low-cost filtering systems that use readily available materials like clay, sand, and activated charcoal provide an economical and eco-friendly alternative. Water is a natural resource that is necessary for all living things, including plants, animals, and people [1]. The problem is particularly concerning in emerging countries like Pakistan. According to reports, around 40% of people do not have access to clean drinking water, with rural and peri-urban areas being disproportionately affected. Rivers, ponds, and shallow groundwater are examples of sources of drinking water that are frequently severely contaminated with chemical and biological contaminants. According to a 2020 Pakistan Council of Research in Water Resources (PCRWR) investigation, high microbiological loads, excessive turbidity, or chemical contamination rendered over 70% of water samples from rural hand pumps and wells unfit for human use [2]. One of the main causes of child mortality in the nation is diarrheal infections, which are widely prevalent due to these conditions. Households frequently use commercial water sources, like bottled mineral water, to deal with this situation. Even if bottled water constantly satisfies strict quality criteria, it remains unaffordable for many rural households. The objective of this study is to develop and evaluate a low-cost composite filter using locally available clay, sand, and activated charcoal that can effectively treat drinking water for rural communities in Pakistan [3-5].

## II. LITERATURE REVIEW

Access to clean drinking water remains one of the critical global issues of the twenty-first century. The World Health Organization (WHO) estimates that 2 billion people globally drink water tainted with excrement, which exposes them to fatal infections. Low- and middle-income nations bear the brunt of the problem of contaminated water [6]. The problem is particularly concerning in emerging countries like Pakistan. According to reports, about 40% of people do not have access to clean drinking water, with rural areas being disproportionately affected [7]. Due to their high cost, energy needs, and complicated maintenance, conventional purification methods like reverse osmosis (RO) and ultraviolet (UV) sterilization are sometimes unsuitable for widespread implementation in these areas [6]. Low-cost, locally accessible and sustainable home filtration solutions are now desperately needed. Because of their unique filtration qualities cost and accessibility, natural materials like clay, sand, and activated charcoal have garnered much study attention in this regard [8, 9].

### *A. Sand and Bio-sand Filtration*

One of the best and most popular techniques for purifying water is sand filtration. To successfully lower turbidity and pathogens slow sand filters (SSF) rely on both physical straining and biological activity inside the sand bed [1]. Their propensity to clog fast, which results in decreasing flow rates is a major drawback [10, 11]. Additionally, the integrity of the sand substrate and operating circumstances have a significant impact on their efficacy [12]. SSFs are comparatively less successful in eliminating dissolved salts and total dissolved solids (TDS), despite achieving turbidity below 5 NTU [1]. Studies conducted in North Vietnam revealed that domestic sand filters were essentially useless against certain pollutants, such as arsenic, with 65% of treated samples still surpassing WHO criteria [13, 14].

### B. *Clay-Based Filtration*

The elimination of microorganisms is especially successful with clay ceramics. Bacteria and tiny suspended particles can be physically trapped by the porous microstructure that clay forms when it is burnt [3]. The type of clay, the firing temperature, and the use of burnout materials all have a significant impact on their efficacy [5]. Research has demonstrated the excellent effectiveness of clay filters, withnatural clay varieties eliminating up to 99% of total coliforms and E. coli [15]. They are a workable approach for enhancing water quality in developing nations due to their affordability and ease of local production [14]. However, a major drawback is the slow decrease in flow rate brought on by clogging and the impact of filter shape on performance, which calls for routine maintenance [16].

### C. *Activated Charcoal Filtration:*

Because of its high porosity and vast surface area, activated charcoal which is made from materials like wood or coconut shells is very effective at adsorbing dissolved organic pollutants, chlorine, and offensive odors [4]. It is essential for improving the acceptability and flavor of water [17, 18]. According to research adding activated carbon to sand filtration columns can greatly increase the removal effectiveness of a variety of pollutants, including micro-plastics; some tests have shown removal rates of over 96% [17]. Granular Activated Carbon (GAC) is not effective against all inorganic chemicals and salts, and biofilm formation, competitive adsorption, and the requirement for frequent replacement can eventually reduce its effectiveness [19].

### D. *Composite and Localized Filtration Solutions*

To maximize the advantages of each component, recent research highlights the advantages of composite filters that combine charcoal, sand, and clay [9]. For example, it has been demonstrated that integrated, multi-stage filtering systems may reduce heavy metals by over 95% and remove microbial contaminants [13]. Localized solutions, such as the Nadi (biosand) filter are commonly used in rural Sindh and have shown social acceptance by effectively lowering microbiological contamination and turbidity [8]. According to field research the prevalence of waterborne illnesses in rural Pakistan can be considerably decreased by using such Bio-sand Filters (BSFs) in conjunction with hygiene education [20]. However, there are obvious drawbacks to many popular low-cost methods. While Moringa oleifera coagulation is less effective against infections and may leave a lingering flavor, solar disinfection (SODIS) is restricted to modest volumes and sunny circumstances. Bio-sand filters are space-consuming and only partially remove chemical pollutants, whereas ceramic pots provide uneven removal of microorganisms and dissolved salts [8].

## III. Research Gap and Contribution

According to the literature, integrated composite filters offer a more comprehensive solution, whereas discrete filter media handle particular problems. Optimizing material ratios to balance turbidity reduction and microbial elimination, however, continues to be a crucial research concern [9]. Higher charcoal content enhances turbidity and flavor but slows flow, while higher sand content increases flow at the expense of microbial clearance [11]. Systematic research is required to address this trade-off. To determine the ideal composition that maximizes overall filtering performance for household usage in underserved regions, this project will fabricate and assess six composite clay-sand-charcoal filters.

## IV. Research Methodology

### A. *Materials*

The following materials were used for the fabrication of the composite filters:

i. *Clay:* Locally available clay was collected from nearby deposits and sieved to remove coarse particles and organic impurities. Water was added to obtain a uniform and workable consistency.
ii. *Sand:* Clean river sand was thoroughly washed to remove dust and unwanted contaminants, graded to obtain a uniform particle size, and oven-dried before use.
iii. *Activated Charcoal:* Activated charcoal prepared from wood or coconut shells was ground into a fine powder (0.5–1.0 mm) and sieved to achieve a uniform particle size before mixing.
iv. *Water:* Clean water was used for preparing the composite mixture.

### B. *Filter Preparation*

The composite filters were fabricated using the following procedure:

i. Six different filter mixtures were prepared as shown in Fig. 1. The selection of these six compositions was based on a systematic approach to investigate the effect of varying sand and activated charcoal proportions on filtration performance while maintaining a constant clay content of 75%. Preliminary trials indicated that clay contents below 70% resulted in inadequate structural integrity during firing, while contents above 80% caused excessive shrinkage and cracking. The sand and charcoal proportions were varied between 5% and 20% in 5% increments to create a balanced experimental matrix, as recommended in previous studies [9], [11]. This range and increment size allowed clear identification of optimal proportions while maintaining practical limits for material availability and filter fabrication.

ii. The required quantities of clay, sand, and activated charcoal were weighed accurately according to the selected mix proportions.
iii. All materials were thoroughly mixed with water to obtain a homogeneous paste.
iv. The prepared mixture was placed into a cylindrical metal mold having dimensions of 10 inches in height and 2.5 inches in diameter.
v. The molded filters were air-dried for 48–72 hours to remove excess moisture and minimize shrinkage during firing.
vi. After drying, the filters were fired in a kiln at 900°C for 6–8 hours to produce a rigid porous structure by burning out the organic particles as shown in Fig. 2.
vii. All filter samples were fabricated using the same procedure to ensure consistency throughout the experimental program as shown in Fig. 3.

Sand Clay Activated Charcoal

Fig. 1. Preparation of Composite Mixture.

Fig. 2. Kiln Firing of Composite Filters.

Fig. 3. Fabricated Composite Clay Filter.

## C. *Water Sample Preparation*

The water sample preparation involved the following steps:

i. Raw water samples were collected from the Karachi Canal, Jamshoro (Indus River System), which is widely used as a domestic water source in rural Sindh (Table I).
ii. The collected water was stored in clean containers to prevent contamination before testing (see Fig. 4).
iii. Initial physicochemical and microbiological characteristics of the raw water were determined prior to filtration.
iv. The same source water was used for all experimental trials to ensure consistency and allow a fair comparison of the performance of each filter mixture.

Fig. 4. Water Sample.

TABLE I
CHARACTERISTICS OF RAW WATER SAMPLE FROM KARACHI CANAL, JAMSHORO (PRE-FILTRATION)

| SR # | Water Sample | pH | Turbidity (NTU) | TDS (PPM) | Bacterial Counts (CFU\100) | Chlorides (mg/L) | Hardness (mg/L) |
|---|---|---|---|---|---|---|---|
| 1 | Karachi canal, Sindh | 7.9 | 450 | 413 | 280 | 122 | 170 |

## D. *Testing Procedure*

Each filter was tested for key water quality parameters:

i. *pH:* The pH of the filtered water was determined using a calibrated digital pH meter to evaluate the acidity or alkalinity of each water sample (see Fig. 5). Before each measurement, the instrument was calibrated using standard buffer solutions to ensure reliable and accurate readings. The obtained values were compared with the WHO and Pakistan Standards for Drinking Water Quality (PSDWQ).
ii. *Total Dissolved Solids (TDS, ppm):* Total Dissolved Solids (TDS) were measured using a conductivity-based digital TDS meter to determine the concentration of dissolved inorganic and organic substances in the filtered water. The readings were expressed in parts per million (ppm) and compared with the permissible limits recommended by WHO and PSDWQ to evaluate water suitability for drinking (see Fig. 6).
iii. *Bacterial Removal Efficiency (CFU/100mL):* The bacterial concentration was determined using the Most Probable Number (MPN) method for Escherichia coli (E. coli). The MPN method provides a statistical estimate of bacterial density based on the pattern of positive tubes. Results were expressed in CFU/100 mL (Colony Forming

Units per 100 millilitres) to maintain consistency with WHO and PSDWQ reporting standards. The MPN procedure involved inoculating water samples into lauryl tryptose broth tubes, incubating at 37°C for 48 hours, and confirming positive results in brilliant green lactose bile broth. The MPN index was then converted to CFU/100 mL using standard MPN tables. This method estimated the concentration of bacterial contamination before and after filtration, allowing the effectiveness of each composite filter in reducing microbial contaminants to be assessed.

iv. C*hlorides (mg/L):* The chloride concentration in the filtered water was determined using the standard argentometric (silver nitrate) titration method. The results, expressed in milligrams per litre (mg/L), were used to assess the effectiveness of the filter in reducing chloride ions and were compared with the recommended drinking water standards (see Fig. 7).

v. *Turbidity (NTU):* Turbidity was measured using a nephelometer to assess the clarity of the filtered water by determining the concentration of suspended particles. The instrument was calibrated before testing, and the results were recorded in nephelometric Turbidity Units (NTU). Lower turbidity values indicated improved filtration efficiency and better water quality (see Fig. 8).

vi. *Flow Rate (L/h):* The flow rate of each composite filter was determined by measuring the volume of filtered water collected over a known period using a graduated measuring cylinder and a stopwatch. The flow rate was calculated by dividing the volume of water collected by the filtration time and was expressed in liters per hour (L/h). This parameter was used to evaluate the filtration capacity and practical applicability of the developed filters for household water treatment.

$$\text{Formula: } Q = \frac{V}{t} \tag{1}$$

vii. *Quality Assurance:* Each parameter was tested in triplicate, and the average values were recorded to improve the reliability and accuracy of the experimental results (see Fig. 9).

viii. *Experimental Replicates:* For each of the six compositions, three independent filter samples (n=3) were fabricated using the same procedure to ensure reproducibility. All water quality parameters were tested in triplicate for each filter sample, yielding a total of nine measurements per composition per parameter (3 filters × 3 replicates). For microbiological testing using the MPN method, each water sample was inoculated into three sets of five tubes (3 × 5 configuration) as per standard MPN protocols. The results presented in Tables II, III and IV represent the average values across all replicates.

ix. *Hardness (mg/L):* Total hardness was determined using the standard EDTA complexometric titration method to estimate the concentration of calcium and magnesium ions present in the filtered water as shown in Fig. 10. The measured values were expressed in milligrams per liter (mg/L) and compared with the permissible limits specified by WHO and PSDWQ.

## E. *Benchmarking*

The performance of the six mixtures was compared to WHO standards and Pakistan standard for drinking water quality for safe drinking water. Parameters included pH, turbidity, TDS, chlorides, hardness and bacterial contamination. This comparison provided both a regulatory and practical benchmark for the evaluation of household water filters (see Fig. 11).

## F. *Performance of Composite Filters*

The six filter mixtures exhibited distinct performance characteristics depending on the proportions of sand and charcoal.

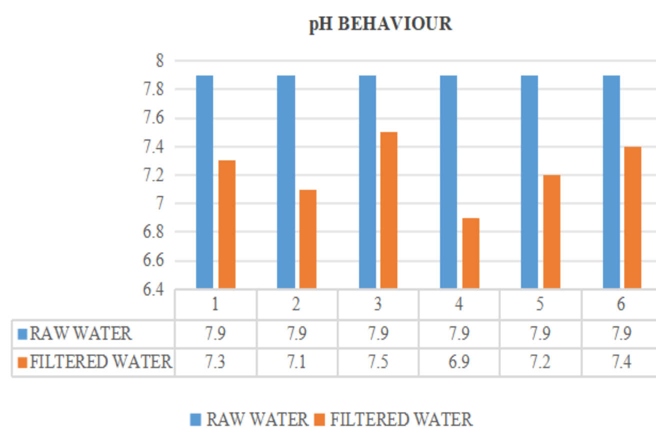


Fig. 5. Effect of Filter composition on pH.

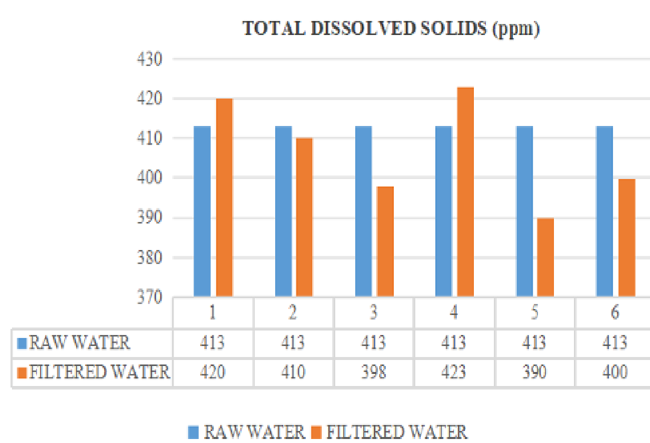


Fig. 6. Effect of Filter composition on TDS.

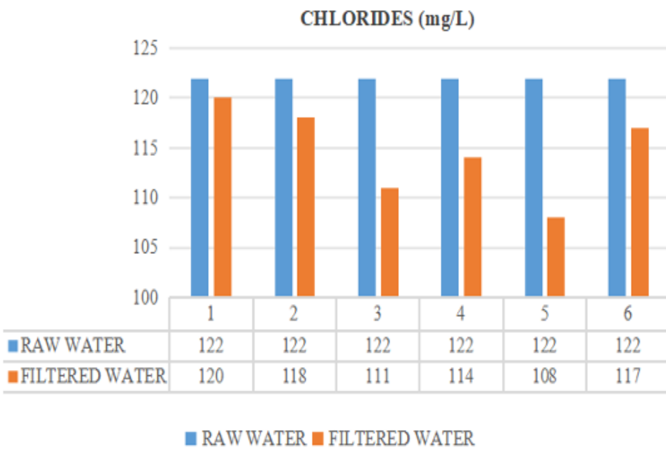


Fig. 7. Effect of Filter composition on Chlorides.

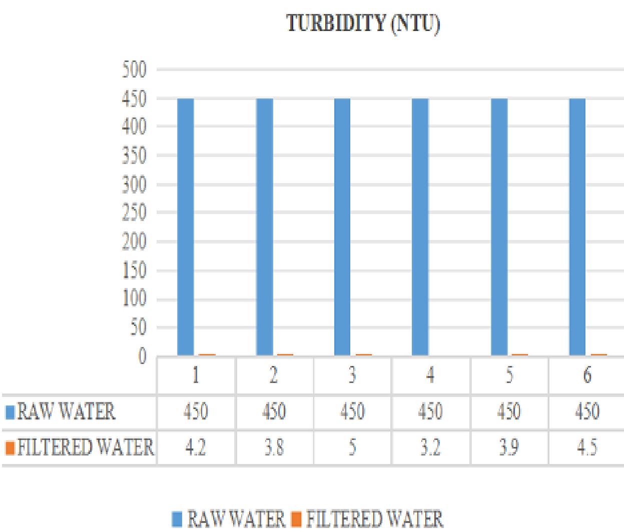


Fig. 8. Effect of Filter composition on Turbidity.

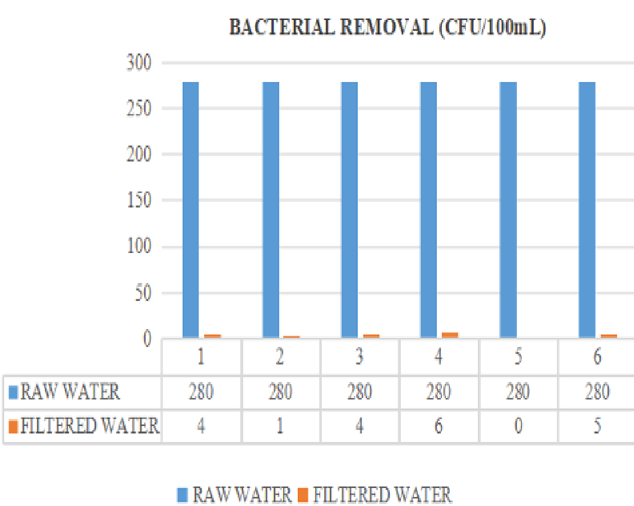


Fig. 9. Effect of Filter composition on Bacterial removal.

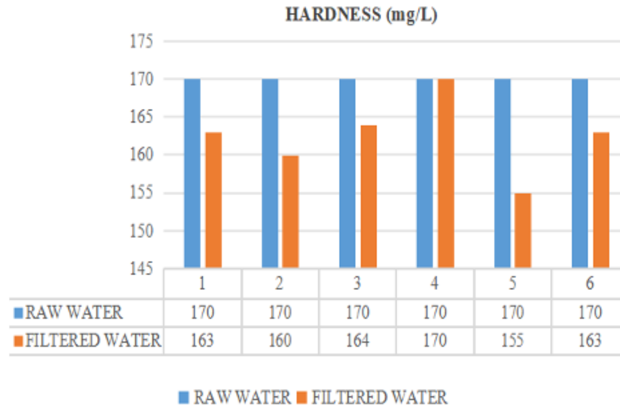


Fig. 10. Effect of Filter composition on Hardness.

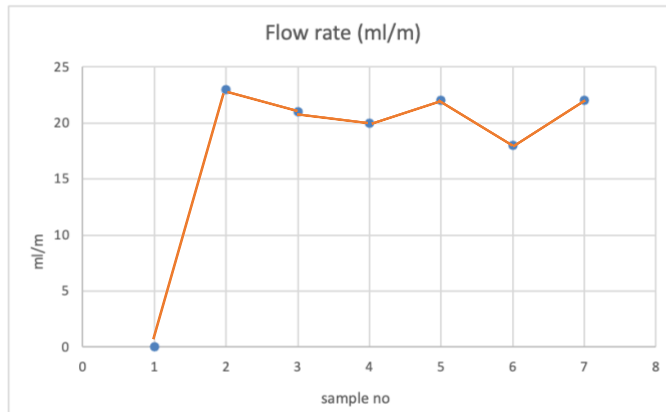


Fig. 11. The flow rate.

## V. RESULT AND DISCUSSIONS

### *A. Filtration Mechanisms:*

The observed filtration performance can be attributed to the distinct mechanisms of each component. The clay matrix, when fired at 900°C, develops a porous microstructure that physically traps suspended particles and bacteria through size exclusion and depth filtration [3], [15]. The sand particles within the composite create additional tortuous pathways that enhance particle capture while maintaining structural integrity [11]. The activated charcoal, with its high porosity and large surface area, adsorbs dissolved organic matter, chlorine, and compounds responsible for unpleasant taste and odor [4], [18]. The optimal composition (75:12:13) balances these mechanisms, achieving maximum microbial removal without compromising flow rate. Comparison with WHO Standards and Pakistan standard for drinking water quality. < 500 To benchmark the results, the best-performing filter (sample 5) was compared with WHO standards and Pakistan standard for drinking water quality. (Table II). Table II. Comparison of Composite Filter (sample 5) WHO Standards and Pakistan standard for drinking water quality. The composite clay–sand–charcoal filter showed effective reduction in turbidity and bacterial contamination, bringing values within WHO and Pakistan standards.The optimal mixture (75% clay, 12% sand, 13% charcoal) achieved complete bacterial removal (0 CFU/100 mL, representing 100% reduction) and turbidity reduction from 450 NTU to 3.9 NTU. However, reductions in TDS (from 413 to 390 mg/L), hardness (from 170 to 155 mg/L), and chloride (from 122 to 108 mg/L) were minimal, confirming that the filter primarily targets suspended and microbial contaminants rather than dissolved ions (see Fig. 12). The filtered water met all WHO and PSDWQ drinking water standards for pH, turbidity, TDS, chlorides, hardness, and bacterial contamination.

### B. *Flow Rate Analysis:*

The flow rate is a critical parameter for practical household applicability. As shown in Table III, the flow rates ranged from 18 to 23 mL/h (approximately 0.43 to 0.55 L/day) for the tested compositions. Sample 5 (75% clay, 12% sand, 13% charcoal) exhibited a flow rate of 22 mL/h (0.53 L/day), which is sufficient for a small household's daily drinking water needs. The flow rate decreased with increasing charcoal content (Sample 5: 18 mL/h at 15% charcoal) due to the higher surface area and finer pore structure of activated charcoal [11]. Conversely, higher sand content improved flow rates but reduced microbial removal efficiency (Sample 3: 23 mL/h but only 4 CFU/100 mL removal). These findings highlight the trade-off between flow rate and treatment efficiency, with Sample 5 providing an optimal balance for rural household applications. Future studies should investigate methods to improve flow rates, such as optimizing particle size distribution or incorporating additional filter layers [8].

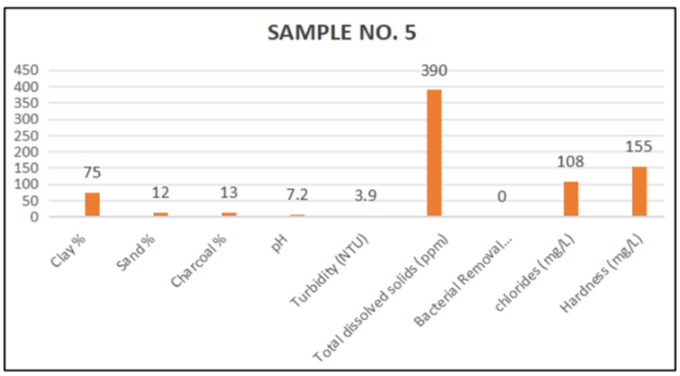


Fig. 12. Parameters analysis on the given sample.

## VI. CONCLUSION AND FUTURE WORK

This study evaluated six composite clay–sand–activated charcoal filter mixtures for improving drinking water quality using locally available materials. Among the tested compositions, the filter containing *75% clay, 12% sand, and 13% activated charcoal (Sample 5)* demonstrated the best overall performance. The filtered water met the WHO and Pakistan Standards for Drinking Water Quality (PSDWQ), achieving complete *E. coli* removal (0 CFU/100 mL), reducing turbidity to **3.9 NTU**, and maintaining acceptable pH, TDS, chloride, and hardness levels. These findings indicate that the developed composite filter is a simple, economical, and effective option for household water treatment in rural communities.

### A. *Study Limitations:*

While the composite filter demonstrated excellent performance in laboratory-scale testing, several limitations should be acknowledged. First, the study did not evaluate heavy metal removal efficiency, which is an important consideration for water sources contaminated with industrial or agricultural runoff [14]. Second, the long-term durability and operational lifespan of the filters under continuous use were not assessed; factors such as clogging, biofilm formation, and physical wear may affect performance over extended periods [16]. Third, the laboratory-scale testing conditions may not fully replicate field conditions, including variations in raw water quality, user handling, and environmental factors. Finally, the flow rate (22 mL/h) may be insufficient for larger households, suggesting the need for larger filter designs or multiple units.

### B. *Future Work:*

However, this study was limited to laboratory-scale evaluation. Future research should investigate the long-term durability, heavy metal removal efficiency, and field-scale performance of the filter under different water quality conditions. Studies should also focus on optimizing the flow rate through particle size modification or filter design improvements. Further enhancement using antimicrobial materials such as colloidal silver [3] or silver nanoparticles may improve the filter's long-term performance and operational reliability. Additionally, field trials in rural communities are recommended to assess social acceptance, user satisfaction, and actual health impacts.

## CONFLICTS OF INTEREST

The authors declare no conflicts of interest to report regarding the present study.

## AUTHOR CONTRIBUTIONS

Conceptualization, N.A., T.M., U.A., and A.Q.M.; methodology, N.A., T.M., U.A., and U.A.; software, U.A., A.Q.M. and N.A.; validation, N.A., T.M., U.A., and A.Q.M.; writing—original draft preparation, N.A., T.M., U.A.; writing—review and editing, T.M., U.A., and T.M.

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## INFORMED CONSENT STATEMENT

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## DATA AVAILABILITY STATEMENT

Data is available on reasonable request.

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TABLE II

| Samples | Clay (%) | Sand (%) | Charcoal (%) | pH | Turbidity (NTU) | Total dissolved solids (ppm) | Bacterial Removal (CFU/100mL) | chlorides (mg/L) | Hardness (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 75 | 15 | 10 | 7.3 | 4.2 | 420 | 4 | 120 | 163 |
| 2 | 75 | 10 | 15 | 7.1 | 3.8 | 410 | 1 | 118 | 160 |
| 3 | 75 | 20 | 5 | 7.5 | 5.0 | 398 | 4 | 111 | 164 |
| 4 | 75 | 5 | 20 | 6.9 | 3.2 | 423 | 6 | 114 | 170 |
| 5 | 75 | 12 | 13 | 7.2 | 3.9 | 390 | 0 | 108 | 155 |
| 6 | 75 | 18 | 12 | 7.4 | 4.5 | 400 | 5 | 117 | 163 |

COMPARATIVE FILTRATION RESULTS FOR SIX COMPOSITE FILTER MIXTURES

TABLE III
FLOW RATE MEASUREMENTS FOR COMPOSITE FILTER SAMPLES

| **Samples No.** | **Clay %** | **Sand %** | **Charcoal %** | **Volume filtered (ml)** | **Time (hours)** | **Flow rate (ml/m)** |
|---|---|---|---|---|---|---|
| 1 | 100 | 0 | 0 | 0 | 24 | 0 |
| 2 | 75 | 20 | 5 | 550 | 24 | 23 |
| 3 | 75 | 18 | 7 | 500 | 24 | 21 |
| 4 | 75 | 15 | 10 | 480 | 24 | 20 |
| 5 | 75 | 12 | 13 | 530 | 24 | 22 |
| 6 | 75 | 10 | 15 | 435 | 24 | 18 |
| 7 | 75 | 5 | 20 | 550 | 24 | 22 |

TABLE IV
PERFORMANCE OF OPTIMAL FILTER (SAMPLE 5) COMPARED WITH WHO AND PSDWQ STANDARDS

| Parameter | Composite Filter Sample 5 | WHO Standard (2022) | PSDWQ Standard (2008) |
|---|---|---|---|
| pH | 7.2 | 6.5 – 8.5 | 6.5-8.5 |
| Turbidity (NTU) | 3.9 | < 5 | < 5 |
| TDS (ppm) | 390 | < 1000 | < 1000 |
| Bacteria (E. coli) | 0 | 0 CFU/100mL | 0 CFU/100mL |
| Chlorides (mg/L) | 108 | 250 | <250 |
| Hardness (mg/L) | 155 | < 500 | < 500 |
| Flow Rate (ml/h) | 22 | - | - |