Hydraulic and Water Quality Perspective of performance analysis of Greywater Treatment Filters

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Abstract. This paper conducts an experimental determination and assessment of the performance of greywater purification systems with varied filter media and observes their hydraulic behaviour in controlled conditions. Six laboratory-scale single-media and multi-layer column filtration experiments were conducted. Experiments on sand, gravel, activated carbon, biochar, zeolite, and ceramic media were conducted at the laboratory scale to determine the ability to eliminate physical, chemical and biological contaminants. Findings demonstrated turbidity removal efficiencies of 55 to 92 percent with activated carbon and biochar recording the best removal efficiencies. Multi-layer filter setups had a TSS removal rate of more than 80 percent with a reduction of 48 percent and 40 percent of BOD and COD, respectively. Hydraulic performance study revealed that the flow rates were stable ranging 0.8 to 1.5 L/min and the retention times of 20 to 35 minutes were identified as the optimum retention times to achieve efficient treatment. A monitoring system was also incorporated using IoT to monitor real-time flow and water quality parameters so that automated alerts could be taken, and maintenance was decreased by about 30%. The research assists in the construction of economical greywater treatment plant that can be used in the small-scale domestic and urban non-potable water consumption as irrigation and toilet flushing.

Keywords: Greywater treatment, IoT, water quality, Sustainable development, low carbon initiative.

1 Introduction

Greywater is water that is not wastewater that is used in homes or workplaces, including that in sinks, showers, and washing machines other than water that is flushed out of toilets

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or urinals. Washing machines, sinks, bathtubs, showers, dishwashers, etc. are considered as the sources of grey water which is much safer to use, easier to treat and can be utilized on-site to non-portable use like irrigation and use of toilet water as they contain very fewer pathogens. Greywater can contain pathogens despite the implementation of the relevant hygiene practices when one is bathing or trying to clean the dirty clothes.

The use of greywater in the modern urban water systems is favourable in both directions of wastewater and water supply subsystems since it reduces the volume of filtered and transferred wastewater and it also reduces the demand of a new clean water too. Greywater may be treated and applied in irrigation and toilet flushing.

Recent studies on decentralised greywater treatment systems have demonstrated their efficacy in urban and semi-urban settings, particularly where centralised infrastructure is limited [6,&7]. Filtration or chemical treatment is the most common method of grey water treatment in mechanical systems. The main purpose of filtration is to eliminate impurities through filtration. The chemical purification process is intended to add the substances that attach the pollutants. Mechanical treatment process can also include a settlement tank, and in this case, the sediments will be removed by settling them and draining them. It is passed through filters which may be sand and gravel and biological which may be peat or wood. Finally, the microbes that may remain are eliminated (where necessary) either by chemicals or UV light.

2 Critical Literature Review

Greywater is a significant portion of household wastewater and it is produced by shower, sinks, laundry washing, and kitchen operations, but not discharge of toilets. It is very variable in composition and usually contains suspended solids, surfactants, fats, oils, organic carbon as well as nutrients and microbial contaminants [1]. Even though the concentrations of pathogens are usually less than those of blackwater, the recycling of biodegradable organic materials and any remaining detergents requires treatment before reuse.

Perspectives of assessments at urban-scale have revealed that reusing greywater can greatly cut down on potable water consumption, especially in the less developed parts of the world where centralized infrastructure development is minimal [2]. At the home level, fresh water savings have been recorded to be quantifiable, when grey water reuse systems are installed in an orderly manner [3]. The thorough reviews also confirm that decentralized treatment as long as the quality of the effluent is maintained within acceptable levels [6,7].

But the greywater that is not treated or it is not treated properly can be dangerous when used in re-irrigation or landscaping processes such as soil degradation and risk of exposure to microbes [8,18]. The available treatment procedures are physical, biological, and chemical. The method of physical filtration is popular because of its simplicity and low operation cost, but it only works well in regard to particulate matter and not in totally removing dissolved organic contaminants [9]. The reliability of treatment and stability of effluents is very important in arid environments [10]. The economic analysis shows that the long-term viability of the decentralized systems is focused on the operational efficiency and the hydraulic performance aspects [11].

As a result, the choice of filtration media cannot be made according to the removal efficiency only; hydraulic behaviour, the possibility to be clogged, and resilience in operation should also be taken into consideration.

2. Filter Media and Hydraulic performance

Low-cost and natural filtration materials have become the subject of recent research as alternatives to more traditional media and are viewed as sustainable. Natural adsorbents and waste derived materials have demonstrated encouraging levels of turbidity and particulate removal at reasonable economic levels [4,5]. Singh and Kansal [21] indicated natural adsorbent had the potential to reduce COD and turbidity significantly though this was dependent on a surface chemistry and contact time.

The use of biochar has gained attention because of the high adsorption capacity and porosity. Li et al. [12] showed that biochar-based filters have greater removal of dissolved organic carbon than the traditional sand systems. On the same note, filtration-adsorption systems have also been demonstrated to be more effective than single-media systems in providing better quality effluents. Stable turbidity reduction and durability are also offered by ceramic filters to be used at the household level.

Although these improvements have been made, the hydraulic performance has remained as a thorn in its flesh. Clogging processes of granular media have been widely reported especially in sand filters of greywater that contains high suspended solids [13]. According to Nguyen and Tran, hydraulic loading rate affects the removal efficiency and the head loss development. Surveys taken over long terms show that the maintenance needs become considerably high when the clogging is not properly tracked [14].

The biological polishing processes like biofiltration improve the reduction of organic matter under controlled loading conditions, and the aerobic biofilters have been proved to be more effective in reducing biodegradable organic matter [15]. There is also the further need to strike a balance between hydraulic application rates and the protection of soils in agricultural reuse.

Digital monitoring technologies have also lately been incorporated in the decentralized systems in order to enhance reliability. IoT sensor networks can be used to detect performance changes in real time and preventive maintenance [16]. The development of hybrid treatment systems that consist of physical filtration, adsorption, and intelligent monitoring is the new trend of the greywater reuse studies [17].

3. Experimental Methodology

A column of filtration system was built on a laboratory scale to test its efficiency. An acrylic filtration column measured 1000 mm in height with an internal diameter of 100 mm. Media particle sizes ranged from 0.5-1 mm (biochar, zeolite) to 2-5 mm (oyster shell, Fe-sand), and were packed in sequence with gravel support layers at inlet and outlet.Separate collection of greywaters was done in kitchen, bathroom, and laundry water to indicate the compositional variability reported in previous research [1&6]. The filter media were biochar, zeolite, Fe-sand, oyster shell and Moringa seed-fabric, which were tested separately and under the same working conditions. Biochar was derived from coconut shell, pyrolyzed at 500°C for 2 hr and sieved to 0.5- 1 mm. Fe-san was prepared by coating river sand with 0.1 M $FeCl_3$ solution followed by oven-drying at 105°C. Oyster shell was crushed, rinsed and oven-dried to use.

Figure 1 shows the experimental set-up of the laboratory-scale filtration system. The system was created by a vertical acrylic column filled with the chosen filter media, an influent reservoir, controlled flow regulator and an effluent collection chamber. At the influent and effluent, sampling ports were installed so that the water quality can be analysed periodically.

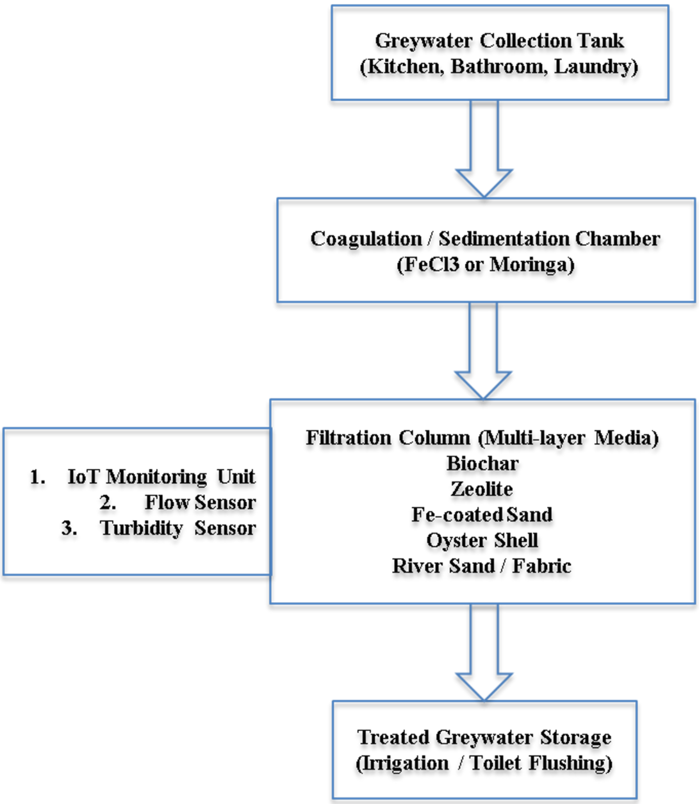


Fig 1.A schematic flow of the laboratory-scale greywater filtration system

Figure 1 is showing the laboratory scale greywater system design with: (1) influent reservoir, (2) flow regulator valve, (3) vertical acrylic filter column with layered media, (4) influent and effluent sampling ports and (5) effluent collection chamber.

Analyses done on the water quality included pH, turbidity, TSS, COD and BOD 5 using standard analysis procedures in line with known greywater characterization procedures [9]. The pre-treatment concentrations were taken to determine baseline variability especially that higher organic loads were observed in the kitchen greywater.

The summary of the initial physicochemical characteristics of greywater originating in the kitchen, bathroom, and laundry are shown in Table 1. (Note: All parameters in Table 1 are reported in Standard units). Turbidity in NTU; TSS, BOD and COD in mg/L and pH is dimensionless. As anticipated, kitchen greywater had high values of COD and turbidity because of the oils and food remains whereas the laundry greywater had high values of detergent-related suspended solids.

Parameters that described hydraulic conditions were monitored during operation. Flow rate was maintained at 0.8-1.5 L/min and retention time was determined by using media volume and rate of discharge. The development of the head loss was periodically documented to measure the clogging development, in line with techniques that have been used in earlier evaluations of hydraulic development [18].

The development of progressive head loss across the filter bed is shown in Figure 2. Biochar and Fe-sand, in its turn, had a steeper head loss increase with time, which is in line with the mechanisms of fine particle entrapment and pore blockage that have been reported in the literature of hydraulic studies [19].

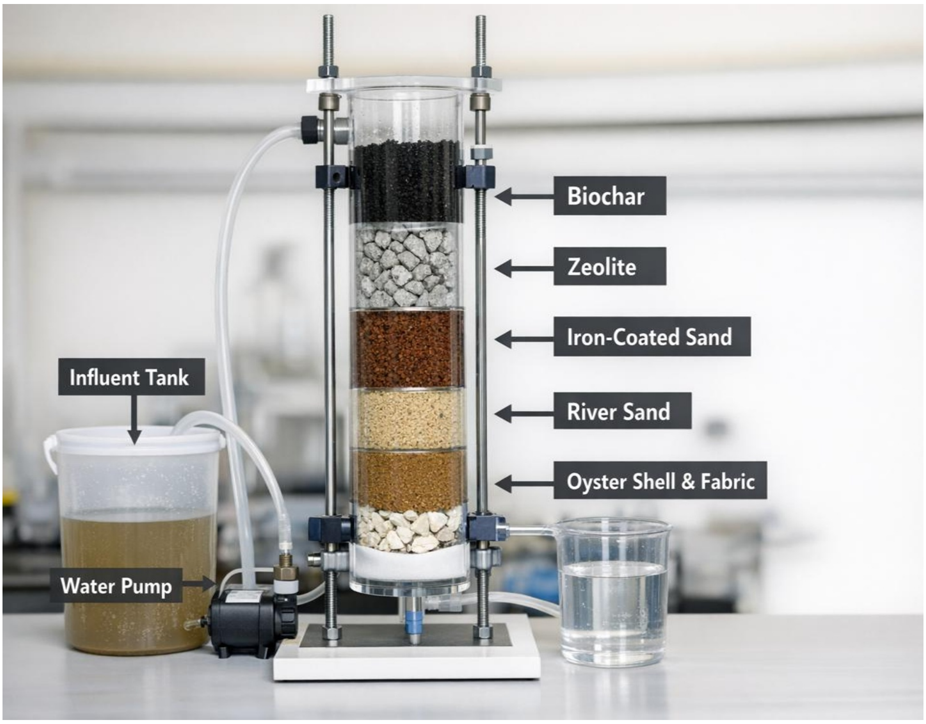
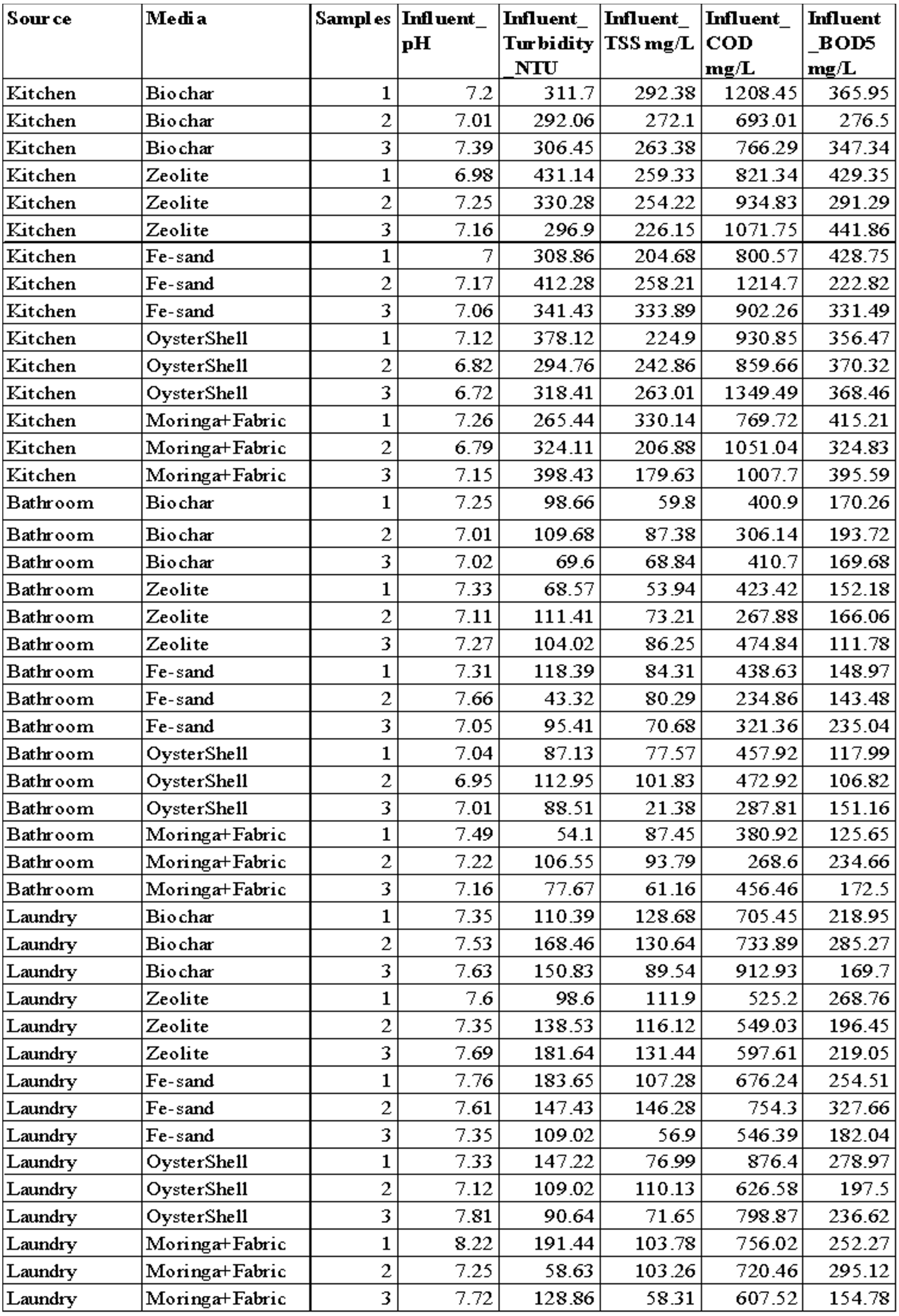


Fig 2. Laboratory scale filtration unit for greywater treatment

The outlet stream was fitted with an IoT module having a turbidity and flow sensor. The system comprised a nephelometric turbidity sensor (range: 0-1000 NTU), an ultrasonic flow meter, and a pH electrode connected via an ESP32 microcontroller that transmitted readings at 1-minute intervals to a cloud dashboard. Automated alerts were triggered when turbidity exceeded 5 NTU or flow rate deviated by more than 15% from the operating set-point. The ability to acquire data continuously enabled the realization of deviations in the performance of the base state, which is consistent with the concept of smart monitoring that is reported in the recent literature [20].

Table 1. Collected Greywater Characteristics before treatment



Source	Media	Samples	Influent_ pH	Influent_ Turbidity _NTU	Influent_ TSS mg/L	Influent_ COD mg/L	Influent _BOD5 mg/L
Kitchen	Biochar	1	7.2	311.7	292.38	1208.45	365.95
Kitchen	Biochar	2	7.01	292.06	272.1	693.01	276.5
Kitchen	Biochar	3	7.39	306.45	263.38	766.29	347.34
Kitchen	Zeolite	1	6.98	431.14	259.33	821.34	429.35
Kitchen	Zeolite	2	7.25	330.28	254.22	934.83	291.29
Kitchen	Zeolite	3	7.16	296.9	226.15	1071.75	441.86
Kitchen	Fe-sand	1	7	308.86	204.68	800.57	428.75
Kitchen	Fe-sand	2	7.17	412.28	258.21	1214.7	222.82
Kitchen	Fe-sand	3	7.06	341.43	333.89	902.26	331.49
Kitchen	OysterShell	1	7.12	378.12	224.9	930.85	356.47
Kitchen	OysterShell	2	6.82	294.76	242.86	859.66	370.32
Kitchen	OysterShell	3	6.72	318.41	263.01	1349.49	368.46
Kitchen	Moringa+Fabric	1	7.26	265.44	330.14	769.72	415.21
Kitchen	Moringa+Fabric	2	6.79	324.11	206.88	1051.04	324.83
Kitchen	Moringa+Fabric	3	7.15	398.43	179.63	1007.7	395.59
Bathroom	Biochar	1	7.25	98.66	59.8	400.9	170.26
Bathroom	Biochar	2	7.01	109.68	87.38	306.14	193.72
Bathroom	Biochar	3	7.02	69.6	68.84	410.7	169.68
Bathroom	Zeolite	1	7.33	68.57	53.94	423.42	152.18
Bathroom	Zeolite	2	7.11	111.41	73.21	267.88	166.06
Bathroom	Zeolite	3	7.27	104.02	86.25	474.84	111.78
Bathroom	Fe-sand	1	7.31	118.39	84.31	438.63	148.97
Bathroom	Fe-sand	2	7.66	43.32	80.29	234.86	143.48
Bathroom	Fe-sand	3	7.05	95.41	70.68	321.36	235.04
Bathroom	OysterShell	1	7.04	87.13	77.57	457.92	117.99
Bathroom	OysterShell	2	6.95	112.95	101.83	472.92	106.82
Bathroom	OysterShell	3	7.01	88.51	21.38	287.81	151.16
Bathroom	Moringa+Fabric	1	7.49	54.1	87.45	380.92	125.65
Bathroom	Moringa+Fabric	2	7.22	106.55	93.79	268.6	234.66
Bathroom	Moringa+Fabric	3	7.16	77.67	61.16	456.46	172.5
Laundry	Biochar	1	7.35	110.39	128.68	705.45	218.95
Laundry	Biochar	2	7.53	168.46	130.64	733.89	285.27
Laundry	Biochar	3	7.63	150.83	89.54	912.93	169.7
Laundry	Zeolite	1	7.6	98.6	111.9	525.2	268.76
Laundry	Zeolite	2	7.35	138.53	116.12	549.03	196.45
Laundry	Zeolite	3	7.69	181.64	131.44	597.61	219.05
Laundry	Fe-sand	1	7.76	183.65	107.28	676.24	254.51
Laundry	Fe-sand	2	7.61	147.43	146.28	754.3	327.66
Laundry	Fe-sand	3	7.35	109.02	56.9	546.39	182.04
Laundry	OysterShell	1	7.33	147.22	76.99	876.4	278.97
Laundry	OysterShell	2	7.12	109.02	110.13	626.58	197.5
Laundry	OysterShell	3	7.81	90.64	71.65	798.87	236.62
Laundry	Moringa+Fabric	1	8.22	191.44	103.78	756.02	252.27
Laundry	Moringa+Fabric	2	7.25	58.63	103.26	720.46	295.12
Laundry	Moringa+Fabric	3	7.72	128.86	58.31	607.52	154.78

Moringa was also used as a coagulant, hence it was placed in the coagulation/sedimentation department before the filtration column. At this point, moringa (or $FeCl_3$) was included to form floc. It is a pre-filter (previously biochar) by using a fabric cartridge (or cloth). In standard cases of practical systems, the fabric is put on the top as a pre-screen and the bottom above the outlet to avoid loss of sand.

In the case of a gravity-driven column of greywater filtration, the proposed order (top to bottom, direction of flow) is technically feasible as follows:

Layer 1 (topmost)- Biochar
Layer 2-Zeolite
Sand coated with a layer 3-Iron-oxides with River sand embedded in it and
Uniform shell (layer at base)

The first one should be biochar, as it achieves the dissolved matter adsorption and odour reduction. It is effective in cases where water initially comes in with greater organic content. The next step is zeolite to eliminate ammonium and perform ion exchange, following the partitioning of larger organics, which is reduced. Sand was added with an iron oxide coating, after which phosphate and metal adsorption occur. Sand of the river is a fine layer of filtration to hold back resistant solids and allow the bottom particles to settle. The bottom one should be oyster shell which is primarily a stabilizer of pH and a layer of structural support. As it is coarser, it enhances drainage, and it does not clog up at the outlet. It is not an important fine filtration medium, and therefore, it should not be positioned over sand.

4. Results and Discussions

All removal efficiency values reported below represent the mean of triplicate measurements; standard deviations were within 3-5% for all parameters, confirming acceptable reproducibility. The performance of the treatment was different based on the type of media as well as source of greywater. The post-treatment pH was maintained within the neutral range and oyster shell media provided significant buffering effects to the media because of the dissolution of the calcium carbonate. This stabilization effect could be helpful in irrigation reuse by reducing the aberration of soil pH though the removal capacity of pollutants was low.

The turbidity removal was 58-88 percent with the highest removal being recorded with the Moringa seed-fabric cartridge. This performance can be explained by the fact that the coagulation properties of the Moringa proteins spearhead the formation of floc formation before physical retention which is also in line with the research on natural coagulants [4,&5]. Fe-sand and biochar were also characterized by high levels of particulate removal but at high rates of hydraulic loading the efficiency decreased.

Table 2& Table 3-6show the removal efficiencies at the coagulation stage of the greywater and of each filter medium at the filtration stage. A comparative summary of removal efficiencies across all media is provided in Table 7 for direct cross-media assessment. Biochar had the greatest COD removal (62 percent) of the tested materials, whereas the Moringa seed-based fabric cartridge had the best turbidity reduction (88 percent). The moderately but consistent performance was exhibited by zeolite and Fe-sand in all parameters.

Table 2. Removal performance at Coagulation stage

Media	Moringa+Fabric at the coagulation stage								
Source	Laundry	Bathroom	Bathroom	Bathroom	Laundry	Kitchen	Kitchen	Kitchen	Laundry
Samples	2	3	1	2	3	2	1	3	1
Turbidity in NTU	92.14	91.6	88.8	87.39	85.83	82.87	82.04	81.05	79.18

Table 3. Removal performance by Biochar at layer 1 of greywater filtration unit

Media	**Biochar**								
Source	Kitchen	Bathroom	Bathroom	Kitchen	Laundry	Laundry	Bathroom	Laundry	Kitchen
Samples	3	1	2	1	1	3	3	2	2
Turbidity in NTU	72.25	91.33	86.11	85.9	83.67	82.95	82.07	80.09	72.94

Table 4. Removal performance by Fe-River sand at layer 2 of greywater filtration unit

Media	**Fe-River sand**								
Source	Kitchen	Bathroom	Laundry	Bathroom	Laundry	Kitchen	Laundry	Bathroom	Kitchen
Samples	3	2	2	1	3	1	1	3	2
Turbidity in NTU	76.58	76.32	75.23	72.14	72.05	71.64	71.34	65.87	72.44

Table 5. Removal performance by Zeolite at layer 3 of greywater filtration unit

Media	**Zeolite**								
Source	Bathroom	Bathroom	Kitchen	Bathroom	Kitchen	Laundry	Laundry	Laundry	Kitchen
Samples	3	1	1	2	2	3	1	2	3
Turbidity in NTU	75.09	74.84	69.25	66.7	65.24	65.89	61.05	57.31	62.96

Table 6. Removal performance by Oyster shell at 4thlayer, bottommost layer of greywater filtration unit

Media	**OysterShell**								
Source	Bathroom	Kitchen	Laundry	Bathroom	Kitchen	Bathroom	Kitchen	Laundry	Laundry
Samples	3	2	3	2	1	1	3	2	1
Turbidity in NTU	74.79	73.32	68.86	72.6	63.78	62.15	61.79	50.53	46.01

Table 7. Removal Efficiencies of Single filter media

Source	Media	Samples	Turbidity in NTU	Removal_TSS mg/L	COD in mg/L	BOD5 in mg/L	pH
Laundry	Moringa+Fabric	2	92.14	75.1	34.08	43.61	0.11
Bathroom	Moringa+Fabric	3	91.6	87.23	54.88	51.78	0.04
Bathroom	Biochar	1	91.33	82.37	50.85	59.6	0.09
Bathroom	Moringa+Fabric	1	88.8	83.6	50.42	45.69	0.14
Bathroom	Moringa+Fabric	2	87.39	88.35	51.69	44.26	-0.06
Bathroom	Biochar	2	86.11	89.48	56.53	49.72	0.18
Kitchen	Biochar	1	85.9	79.6	59.18	61.8	0.13
Laundry	Moringa+Fabric	3	85.83	77.3	42.4	36.59	0.15
Laundry	Biochar	1	83.67	70.45	57.83	48.58	0.16
Laundry	Biochar	3	82.95	78.75	58.37	54.4	0.05
Kitchen	Moringa+Fabric	2	82.87	82.71	56.88	41.61	0.22
Bathroom	Biochar	3	82.07	87.27	56.41	74.04	0.22
Kitchen	Moringa+Fabric	1	82.04	81.73	52.6	45.98	0.28
Kitchen	Moringa+Fabric	3	81.05	78.72	55.13	50.78	0.16
Laundry	Biochar	2	80.09	72.14	56.27	49.09	0.15
Laundry	Moringa+Fabric	1	79.18	85.43	53.41	31.69	0.21
Kitchen	Fe-sand	3	76.58	79.64	43.29	47.59	-0.09
Bathroom	Fe-sand	2	76.32	76.61	42.99	49.76	0.03
Laundry	Fe-sand	2	75.23	78.92	59.52	33.53	-0.1
Bathroom	Zeolite	3	75.09	73.08	46.12	70.82	0.04
Bathroom	Zeolite	1	74.84	69.56	35.23	27.88	0.14
Bathroom	OysterShell	3	74.79	57.42	32.92	35.92	0.23
Kitchen	OysterShell	2	73.32	61.05	36.8	31.48	0.39
Kitchen	Biochar	2	72.94	76.89	56.55	48.11	0.11
Bathroom	OysterShell	2	72.6	61.75	39.11	40.42	0.3
Kitchen	Fe-sand	2	72.44	76.5	47.64	30.09	0.01
Kitchen	Biochar	3	72.25	77.25	58.4	55.96	0.16
Bathroom	Fe-sand	1	72.14	80.82	44.6	45.57	0
Laundry	Fe-sand	3	72.05	87.38	49.6	35.38	-0.04
Kitchen	Fe-sand	1	71.64	83.02	49.53	39.48	0.04
Laundry	Fe-sand	1	71.34	78.06	42.78	33.82	-0.08
Kitchen	Zeolite	1	69.25	53.24	29.37	37.57	0.03
Laundry	OysterShell	3	68.86	60.69	39.43	30.54	0.28
Bathroom	Zeolite	2	66.7	70.92	42.47	30.86	0.12
Laundry	Zeolite	3	65.89	62.27	38.58	27.38	0.04
Bathroom	Fe-sand	3	65.87	82.93	43.37	50.97	-0.01
Kitchen	Zeolite	2	65.24	71.34	42.75	21.9	0.06
Kitchen	OysterShell	1	63.78	61.57	35.04	30.36	0.2
Kitchen	Zeolite	3	62.96	63.14	42.65	43.8	0.16
Bathroom	OysterShell	1	62.15	62.08	48.36	37.83	0.32
Kitchen	OysterShell	3	61.79	52.99	43	37.26	0.38
Laundry	Zeolite	1	61.05	62.07	39.3	29.49	0.09
Laundry	Zeolite	2	57.31	55.56	30.25	32.29	0.11
Laundry	OysterShell	2	50.53	59.15	30.96	34.12	0.41
Laundry	OysterShell	1	46.01	68.12	29.08	39.9	0.3

The removal of TSS also exhibited comparable patterns and went up to a maximum of 86. Nevertheless, finer media demonstrated faster head loss growth, especially in terms of using kitchen greywater which contains higher levels of grease content. This finding agrees with the clogging behaviour characterized in sand filter researches [21].

Removal of organic material was less intense. Biochar attained peak percentages of 62 and 58 of COD and BOD 5 respectively, which was indicative of its adsorption ability as previously reported. As much as these cuts are substantial, it means that adsorption by itself might not succeed to meet the effluent standards needed to ensure that the reuse can be done freely. Additional improvement of organic degradation under integration with biological polishing stages may be further enhanced [22].

Hydraulic analysis indicated that retention time was one of the determinants of removal efficiency. The highest performance was where there was a range of 20 to 35 minutes. The flow rates beyond this range minimized the time of contact and destabilized adsorption equilibrium, which validates findings on the sensitivity of hydraulic loading [23]. The progressive head loss indicates that operational sustainability is conditioned on the periodical backwashing or media replacement, which is stressed during the maintenance assessments. The correlation between the hydraulic retention time and the efficiency of the turbidity removal. The removal efficiency rose steeply within the initial 20 minutes and levelled past 30 minutes, implying that the equilibrium in an adsorption process has been attained in controlled loading conditions.

The IoT-based monitoring proved useful in detecting performance decline at early stages. On-site turbidity monitoring made it possible to respond on time, which facilitated the research that smart monitoring increases the reliability of decentralized systems.Table 3 gives a comparative performance analysis of all the media tested in terms of the removal efficiency, hydraulic stability and the maintenance implication.

5. Conclusions

The research paper has shown that filter media should be chosen based on the hydraulic stability primarily. Biochar was better than the Moringa seed -fabric cartridge in adsorbing dissolved organic matter, whereas the Moringa seed - fabric cartridge was effective in removing particulate matter by a combination of coagulation and filtration. Fe-sand had good performance but was prone to the development of head loss when loaded with high solids. Oyster shell was principally used as a pH stabilizing medium and not as the main treatment medium.

In addition to hydraulic retention time, over-loading decreased the effectiveness of treatment. Clogging is a major operation issue, which supports the significance of controlled flow conditions and monitoring strategies.

Smart sensing technology enhanced the level of operational transparency and minimized the reactive maintenance needs. Multi-stage systems which integrate the processes of coagulation, adsorption and controlled hydraulic operation can be considered as a technically valid method of decentralized reuse of greywater in non-portable hashes.

The principal technical contribution of this study is the systemic benchmarking of five low-cost filter media under controlled hydraulic conditions, with integrate IoT monitoring, demonstrating a practically viable approach for decentralised greywater reuse. Future work should prioritise field-scale validation under variable loading conditions, quantitative microbial risk assessment (QMRA) to evaluate pathogens removal, and household level economic analysis to confirm cost-effectiveness across diverse urban and semi-urban settings.

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References

1. E. Eriksson, K. Auffarth, M. Henze, A. Ledin, Characteristics of grey wastewater. Urban Water **4**, 85–104 (2002). https://doi.org/10.1016/S1462-0758(01)00064-4
2. D. Mandal, P. Labhasetwar, S. Dhone, A. S. Dubey, G. Shinde, S. Wate, Water conservation due to greywater treatment and reuse in urban setting with specific context to developing countries. Resour. Conserv. Recycl. **55**, 356–361 (2011). https://doi.org/10.1016/j.resconrec.2010.11.001
3. S. Muthukumaran, K. Baskaran, N. Sexton, Quantification of potable water savings by residential water conservation and reuse – a case study. Resour. Conserv. Recycl. **55**, 945–952 (2011). https://doi.org/10.1016/j.resconrec.2011.04.013
4. M. Afreen, Y. Suma, M. S. Sri, G. Rohit, J. D. Ashish Raju, Low cost water purifier using natural and waste material. J. Phys.: Conf. Ser. **2779**, 012091 (2024). https://doi.org/10.1088/1742-6596/2779/1/012091
5. A. Krishna, I. Muhammed, J. Mathew, M. Dhanya, Treatment of greywater using banana peel, corn cob and orange peel as major filter media – a review. Sustain. Agri. Food Environ. Res. **12**, Art. 788 (2023). https://doi.org/10.7770/safer-v12n-art788
6. M. Oteng-Peprah, M. A. Acheampong, N. K. deVries, Greywater characteristics, treatment systems, reuse strategies and user perception – a review. Water Air Soil Pollut. **229**, 255 (2018). https://doi.org/10.1007/s11270-018-3909-8
7. K. S. Oh, J. Y. Leong, P. E. Poh, M. N. Chong, E. V. Lau, A review of greywater recycling related issues: challenges and future prospects in Malaysia. J. Clean. Prod. **171**, 17–29 (2018). https://doi.org/10.1016/j.jclepro.2017.09.267
8. A. Gross, N. Azulai, G. Oron, Z. Ronen, Environmental impact and health risks associated with greywater irrigation: a case study. Water Sci. Technol. **52**, 161–169 (2005). https://doi.org/10.2166/wst.2005.0487
9. S. Boyjoo, V. Pareek, M. Ang, A review of greywater characteristics and treatment processes. Water Sci. Technol. **62**, 1403–1410 (2010). https://doi.org/10.2166/wst.2010.459
10. A. Jamrah, A. Al-Omari, M. Al-Mashaqbeh, Assessment of greywater reuse for irrigation in arid regions. Desalination **256**, 90–95 (2010). https://doi.org/10.1016/j.desal.2010.03.007
11. M. Friedler, R. Hadari, Economic feasibility of on-site greywater reuse in multi-storey buildings. Water Pract. Technol. **11**, 813–820 (2016). https://doi.org/10.2166/wpt.2016.093

12. S. Li, H. Ding, Y. Wang, Performance of biochar-based filters for decentralized greywater treatment. J. Environ. Manage. **240**, 310–318 (2019). https://doi.org/10.1016/j.jenvman.2019.03.092
13. R. B. Santos, L. F. Pires, A. P. Rosa, Hydraulic behaviour and clogging mechanisms in sand filters treating greywater. Water Res. **157**, 297–306 (2019). https://doi.org/10.1016/j.watres.2019.03.059
14. A. Bani-Melhem, M. Smith, Greywater treatment using aerobic biofilters: performance evaluation. Ecol. Eng. **62**, 241–246 (2014). https://doi.org/10.1016/j.ecoleng.2013.10.007
15. S. Al-Hamaiedeh, H. Bino, Effect of treated greywater reuse on soil and plants. Desalination **256**, 115–119 (2010). https://doi.org/10.1016/j.desal.2010.02.004
16. Y. Zhou, J. Li, X. Liu, Smart water quality monitoring using IoT-based sensors for decentralized treatment systems. J. Clean. Prod. **252**, 119785 (2020). https://doi.org/10.1016/j.jclepro.2019.119785
17. R. Singh, S. Kansal, Low-cost greywater treatment using natural adsorbents. Environ. Technol. **41**, 2741–2750 (2020). https://doi.org/10.1080/09593330.2019.1577501
18. T. Nguyen, H. Ngo, W. Guo, Emerging technologies in greywater reuse systems. Sci. Total Environ. **743**, 140613 (2020). https://doi.org/10.1016/j.scitotenv.2020.140613
19. A. El-Gohary, M. Kamel, Greywater treatment using combined filtration and adsorption processes. Alexandria Eng. J. **58**, 87–96 (2019). https://doi.org/10.1016/j.aej.2018.11.002
20. M. R. Amin, M. Rahman, Performance evaluation of ceramic filters for household greywater reuse. Water Pract. Technol. **15**, 905–914 (2020). https://doi.org/10.2166/wpt.2020.082
21. P. L. Nguyen, D. D. Tran, Hydraulic loading effects on greywater biofilters. J. Water Process Eng. **38**, 101612 (2020). https://doi.org/10.1016/j.jwpe.2020.101612
22. S. Shrestha, F. Kazama, Assessment of clogging and maintenance in household greywater systems. Water Sci. Technol. **74**, 1111–1120 (2016). https://doi.org/10.2166/wst.2016.317
23. L. Zhang, Q. Chen, Y. Xu, Real-time monitoring of water quality parameters using IoT for reuse applications. Measurement **164**, 108068 (2020). https://doi.org/10.1016/j.measurement.2020.108068