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Research Article

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A SCALABLE DECENTRALIZED GREYWATER TREATMENT FRAMEWORK FOR ACADEMIC INSTITUTIONS IN DEVELOPING REGIONS

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Abstract

Decentralized wastewater management in educational institutions offers a viable strategy to reduce freshwater demand and mitigate environmental pollution in developing regions. This study evaluates the performance of a multi-media packed-bed filtration system combining gravel, silica sand, and powdered activated carbon for treating institutional greywater generated at Hajee Mohammad Danesh Science and Technology University (HSTU), Bangladesh. Raw wastewater samples collected from drainage lines and campus storage ponds were evaluated for physicochemical characteristics, including pH, chemical oxygen demand (COD), nitrate-nitrogen (NO_3^--N), phosphorus, boron, total suspended solids (TSS), and total hardness. The filtration system demonstrated substantial pollutant removal efficiency, achieving reductions of 50%–70% in COD, 80%–90% in NO_3^--N, 80%–85% in boron, 75%–80% in TSS, and 40%–50% in phosphorus. Post-treatment effluent quality complied with Food and Agriculture Organization (FAO) standards for landscape and agricultural irrigation, as well as discharge guidelines for receiving water bodies, despite low residual dissolved oxygen (DO) levels. The proposed low-cost, scalable framework demonstrates how academic campuses can implement circular water management, lower reliance on local groundwater, and reduce environmental impact.

Keywords: Decentralized wastewater management, Greywater recycling, Activated carbon, Packed-bed filtration, Physicochemical analysis, Sustainable irrigation, Institutional water security

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Author Contribution
Rukaya Yasmin wrote the main manuscript, while Kundan Yadav collected the required data and information. All authors reviewed the manuscript.

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1 Introduction

1.1 General Background

Human activities, whether domestic or industrial, inevitably lead to the generation of waste (Kesalkar et al., 2012). A significant portion of the water used daily turns into wastewater, which, if not managed properly, can create serious environmental and health challenges. However, with a well-planned reuse strategy, wastewater can also serve as a valuable resource. Domestic wastewater is typically categorized into two types: grey water and black water (Jefferson et al., 2004; Omole et al., 2017). Black water mainly consists of human waste, including feces, urine, and sludge, whereas grey water originates from household activities such as washing, bathing, and kitchen use. Additionally, wastewater can also come from industries, laboratories, and agricultural processes, all of which contain different levels of organic and inorganic pollutants (Haering et al., 2018).

The level of treatment required for wastewater depends on its contamination load and the intended purpose of reuse. Treated wastewater can be repurposed for various applications, including irrigation, toilet flushing, fire control, vehicle washing, industrial cooling, and even recreational landscaping. Strict regulations and guidelines, such as those provided by the United States Environmental Protection Agency (USEPA, 2004) and the Food and Agriculture Organization (FAO, 2004), ensure that treated wastewater is safe for agricultural and domestic use, preventing potential health hazards (U.S. Environmental Protection Agency, 2004; Food and Agriculture Organization of the United Nations, 2004)).

Water plays a crucial role in every aspect of life, from consumption to hygiene and overall well-being. Its availability is essential for sustainable human development, particularly in residential areas such as university campuses, where water demand is high due to the presence of dormitories and academic buildings.

To establish a generalizable model for institutional greywater management, this study utilizes, Hajee Mohammad Danesh Science and Technology University (HSTU) in northern Bangladesh as a representative case study. The institution provides technical education to both undergraduate and postgraduate students, with approximately 10,000 students enrolled across 9 faculties and 45 departments. The total campus area spans 85 acres, generating a substantial amount of wastewater daily. Given this, research on wastewater management at HSTU is highly relevant.

Grey water refers to all wastewater discharged from households, excluding black water from toilets. This includes water from showers, bathtubs, dishwashers, kitchen sinks, and laundry machines, typically containing traces of soap, detergents, toothpaste, oils, and food particles (Abu-Orf et al., 2013; Sha et al., 2024). Grey water makes up the majority of household wastewater, accounting for about 80% of total domestic wastewater (Jefferson et al., 2004; Omole et al., 2017). The primary goal of grey water recycling is to replace potable water with non-drinking alternatives, such as irrigation, industrial use, laundry washing, and toilet flushing, depending on the level of treatment applied. Recycling grey water not only reduces freshwater consumption but also minimizes wastewater discharge and lowers water bills. Additionally, considering grey water as an alternative water source can enhance irrigation capacity, boosting agricultural productivity. Unlike rainwater harvesting, grey water reuse is not dependent on seasonal variations, making it a reliable and continuous water resource (Deshmukh et al., 2017).

Although northern Bangladesh does not suffer from severe water shortages, proper wastewater management remains a critical concern. HSTU, which relies entirely on natural groundwater resources, serves as an interesting case study for analyzing wastewater quality and exploring potential treatment and management strategies. This study aims to evaluate the characteristics of wastewater generated on the HSTU campus, with a focus on improving its treatment and sustainable utilization.

1.2 Research Objectives

The following objectives are going to be determined in this paper:

1. To evaluate the baseline physicochemical properties (pH, COD, DO, NO_3^--N, phosphorus, total hardness, TSS, and boron) of raw greywater generated across distinct campus discharge zones.
2. To design and construct a bench-scale multi-media packed-bed filtration system combining aggregate, silica sand, and powdered activated carbon.

3. To quantify the pollutant removal efficiencies of the system and evaluate the treated effluent quality against FAO standards for irrigation and national discharge guidelines for receiving water bodies.

2 Literature Review

For decades, environmental pollution has been a global concern, prompting extensive research, experiments, conferences, and policy discussions aimed at reducing its impact. Scientists worldwide have been working on various approaches to minimize pollution and develop sustainable management strategies.

Several studies have focused on smaller-scale areas such as factories, residential colonies, and university campuses, which contribute significantly to wastewater generation. These studies help in understanding the composition of wastewater and exploring effective treatment and management techniques. Kesalkar and Raisoni (2012) conducted research on effluent discharged from a paper production mill and found that the concentration of pollutants in the treated effluent exceeded Indian water quality standards (Kesalkar et al., 2012).

Similarly, Sonune (2015) analyzed the physico-chemical characteristics of domestic wastewater and reported that contamination levels were above the permissible limits set by the American Public Health Association (APHA, 1989). Based on their findings, they concluded that untreated wastewater should not be directly used for irrigation or discharged into natural water bodies without proper treatment (Sonune et al., 2015).

Another study by Falguni and Mishra (2012) focused on wastewater characteristics from a hostel building at NIT Rourkela. Their research revealed that contamination levels exceeded APHA standards, and in response, they designed a wastewater treatment system for the campus. The proposed system included components such as a clarifier tank, aeration tank, bar screen, collection pit, and sludge drying beds (Mishra & Mahanty, 2012). Similarly, Patil (2013) studied wastewater characteristics at the NMIMS campus and proposed a treatment plant based on sewage quality and demand. They suggested that the treated wastewater could be effectively reused for landscape irrigation (Patil et al., 2013).

In Ghana, Awuah (2014) assessed the chemical properties of domestic wastewater and emphasized the need for proper wastewater management (Awuah et al., 2014). To reduce the strain on freshwater resources, Deshmukh (2017) explored the use of sand filtration combined with activated charcoal, demonstrating that bathroom wastewater could be reused for gardening (Deshmukh et al., 2017).

A similar study was conducted at Alfred Akawe Torkula Hostel, University of Agriculture, Makurdi, where wastewater samples were collected and analyzed based on their strength (Vandefanterdoo, 2015). Effluent filtered through sand beds at varying depths showed changes in contaminant levels at each filtration stage (Aloo et al., 2014). Bench-scale treatability of domestic wastewater was examined using the Soil Aquifer Treatment (SAT) system, and the impact of treated wastewater on soil properties and crop yield was also analyzed (K et al., 2007; Singh et al., 2012).

These studies highlight the critical role of wastewater management in preserving water availability and quality. Without proper treatment and reuse strategies, wastewater disposal can contribute to environmental pollution and health risks. Therefore, research in this field continues to be essential for sustainable water resource management.

3 Methodology

3.1 Study Area

HSTU campus is situated in the Dinajpur district of Rangpur division, northern region of Bangladesh. It is just 13 kms north from Dinajpur town. It is developed over 135 acres of land and provides state-of-the-art facilities to students, faculty and its staff. It has 10000 plus population living on its area in daytime and 5000 plus population in whole day. The average volume of water pumped from the numbers of functional boreholes is around 1,125,000 liters for their day-to-day activities such as drinking, cooking, washing, flushing, bathing, housekeeping etc. The other water requirement in the campus is for water fountains, cleaning of roads, floors of office buildings, some laboratories, toilets and urinals and the landscape irrigation. According to the standard rule about 80 % of supplied water, i.e. 900,000 liters of water are generated per day as wastewater. Nearly all this wastewater coming from residential buildings passed through a constructed drainage line and discharged into a nearby pond and waterlogging area (Figure 1).

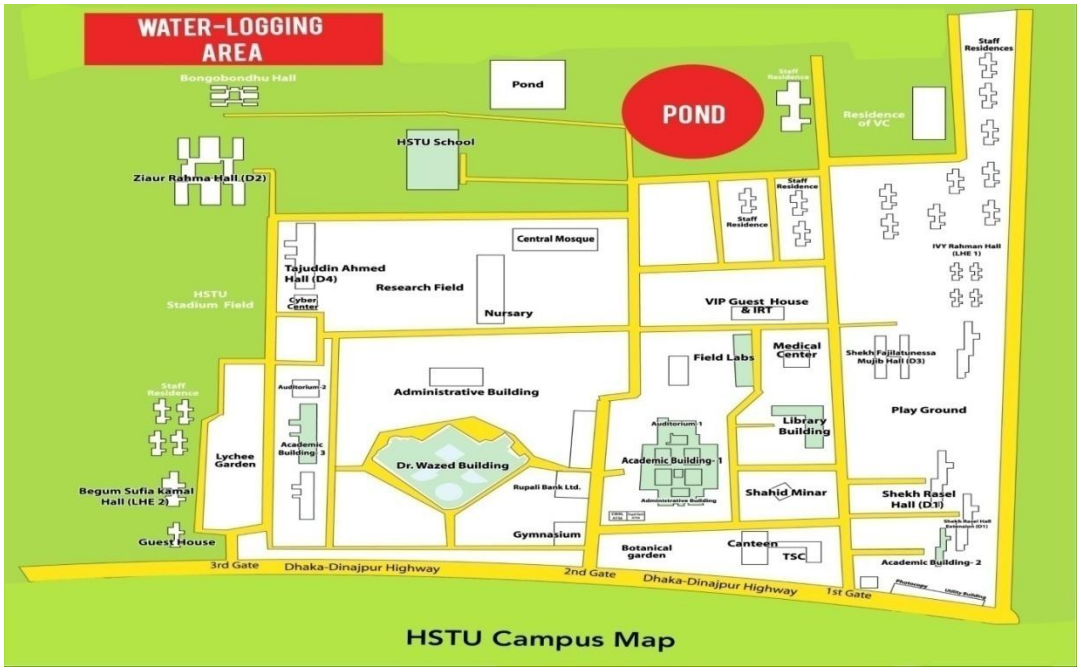


Figure 1: Layout map showing HSTU campus and its wastewater discharge sites, marked with red.

An aerial view of HSTU Campus (Figure 2), which shows wastewater is disposed into the Open area and Pond without any treatment. This may invite pollutants around campus areas which look inconvenient (Figure 3).



Figure 2: Aerial map showing HSTU campus and its wastewater discharge sites as red spot.

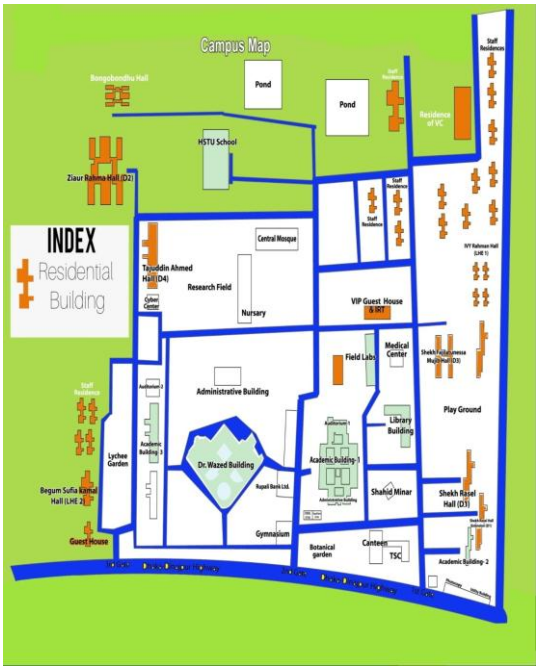


Figure 3: Layout map of HSTU campus showing Residential Buildings of campus.

Detailed research plan carried out during the study was as per the following. This shows the step-by-step procedure carried out during the research work shown in Figure 4.

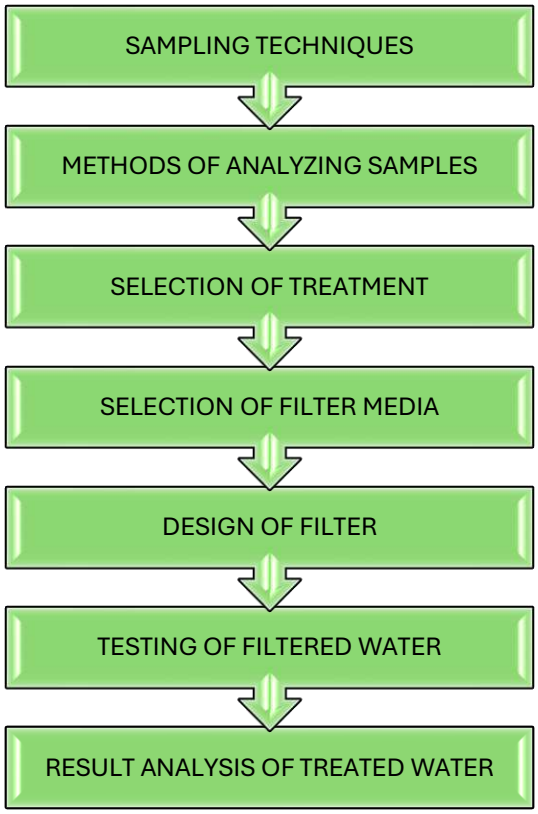


Figure 4: Step by step flow chart of research work.

3.2 Sampling Techniques

The samples are collected from different waste outlets, usually kitchen and bathroom wastewater from hostels and residential buildings as influent and from discharged site as effluent. The samples are collected in contamination free sampling bottles of 1000 ml. During sampling, hand gloves are used to prevent contamination. The samples are collected and transported to the laboratory for an appropriate test.

Table 1: Wastewater sample collection points for water quality assessment on campus.

S. No.	Sample Points	Sample No.	Location	Figures
1.	From the drainage line of waterlogging area beside Bangabandhu Sheikh Mujibur Rahman Hall.	S1, S2	25.695073° N 88.650149° E	
2.	From waterlogging area.	S3, S4	25.695504° N 88.650489° E	

3.	From the drainage line of central Pond.	S5, S6	25.698647° N 88.652173° E	
4.	From central Pond.	S7, S8	25.698226° N 88.651728° E	

Wastewater samples were collected from four different locations on campus to assess water quality and pollution levels (Table 1). The first sampling point (S1, S2) was from a drainage line near Bangabandhu Sheikh Mujibur Rahman Hall, where wastewater continuously flows, indicating significant daily water usage in nearby residential buildings. The second point (S3, S4) was from a waterlogged area that remains submerged in wastewater, making it difficult for students to walk around comfortably. The third location (S5, S6) was another drainage line that carries wastewater from the northern residential buildings into the central pond, running continuously and highlighting excessive water consumption. The final sampling point (S7, S8) was from the central pond itself, where wastewater from the northern part of the campus is discharged, leading to visible contamination. These findings reflect the ongoing wastewater issues on campus, underlining the urgent need for proper treatment and management to improve the overall environmental conditions.

3.3 Analysis of Physicochemical Parameters of Wastewater

All the parameters were analyzed following standard laboratory methods. Physical characteristics such as pH were determined using a pH meter, while total solids, including Total Suspended Solids (TSS) and Total Dissolved Solids (TDS), were measured using an electrically heated, temperature-controlled oven. The chemical parameters, including alkalinity, Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO), were tested using appropriate lab equipment like a DO meter. Other parameters, such as boron, nitrate, and phosphate, were analyzed using the spectrophotometric method following lab manual instructions (Association, 2017).

1. pH Measurement

To determine pH, the electrode of the pH meter was immersed in a beaker containing the sample. The measurement was taken after waiting for 2-3 minutes, allowing the reading to stabilize. The pH meter also provided the sample temperature along with the pH value.

2. TSS and TDS Determination

A clean and dry beaker was first heated at 103°C in an oven for one hour, then weighed, and the reading was recorded. A 100 ml sample of well-mixed wastewater was placed in the same beaker and kept in the oven at 103°C for 24 hours. After cooling, the beaker was reweighed. The Total Solids (TS) content was determined by subtracting the initial weight of the empty beaker from the final weight after drying.

For TDS, a 100 ml sample was passed through double-layered filter paper, and the filtrate was collected in a beaker. The filtrate was dried in the oven, and the remaining solids were measured. TDS was calculated by subtracting the weight of the clean beaker from the weight of the dried filtrate. The TSS was determined by subtracting TDS from TS.

3. Alkalinity Test

titration description with standard $KMnO_4$ / dichromate titration notation:

$$\text{COD (mg/L)} = \frac{(a - b) \times N \times 8000}{V_{\text{sample}}}$$

Where:

- a = Volume of titrant used for the wastewater sample (mL).
- b = Volume of titrant used for the blank sample (mL).
- N = Normality of the titrant.
- 8000 = Equivalent weight of oxygen (mg/eq).

$$\text{enolphthalein Alkalinity (mg/L as } CaCO_3) = \frac{V_1 \times N \times 50{,}000}{V_{\text{sample}}}$$

$$\text{Total Alkalinity (mg/L as } CaCO_3) = \frac{V_2 \times N \times 50{,}000}{V_{\text{sample}}}$$

Where:

- V_1 = Volume of standardized H_2SO_4 or HCl titrant used to reach pH 8.3 (mL).
- V_2 = Total volume of titrant used to reach pH 4.5 (mL).
- N = Normality of the acid titrant (eq/L).
- V_{sample} = Volume of the wastewater sample (mL).

4. Dissolved Oxygen (DO) Measurement

DO was measured using a DO meter by immersing the sensor probe in the wastewater sample. After allowing the meter to stabilize for 2-3 minutes, the reading was recorded.

5. Chemical Oxygen Demand (COD) Test

$$\text{COD (mg/L)} = \frac{(a - b) \times N \times 8000}{V_{\text{sample}}}$$

Where:

- a = Volume of titrant used for the wastewater sample (mL).
- b = Volume of titrant used for the blank sample (mL).
- N = Normality of the titrant.
- 8000 = Equivalent weight of oxygen (mg/eq).

6. Nitrate Determination

A 50 ml sample was taken in a Nessler tube, and 1 ml of 1.0N HCl was added and mixed well. The absorbance was measured using a spectrophotometer, set at a wavelength of 410 nm, using redistilled water as the blank reference.

7. Phosphorus Determination

Before starting the test, the following reagents were prepared:

i. Primary standard phosphate solution (50 ppm P)
ii. Secondary standard phosphate solutions (20 ppm and 2 ppm P)
iii. Phosphate standard series solution
iv. Sulphomolybdic acid solution (2.5%)
v. Stannous chloride solution

A 5 ml sample was taken in a 100 ml volumetric flask, and 4 ml of sulphomolybdic acid solution was added. Distilled water was then added to two-thirds of the flask volume. Next, 5-6 drops of stannous chloride solution were added and mixed well. The flask was filled to the mark with distilled water. After 3-4 minutes, the developed color intensity was measured at 660 nm using a spectrophotometer. A blank sample was prepared similarly, excluding phosphate solution.

The phosphate concentration was determined by plotting a calibration curve with absorbance (y-axis) Vs concentration (x-axis).

8. Boron Determination

Boron levels were estimated by treating the sample with a standard reagent, which altered its pH value. The boron concentration was determined using a manual reference table.

9. Hardness Test

A burette was filled with EDTA (Ethylenediaminetetraacetic acid) solution and calibrated to remove air bubbles. A 10 ml standard hard water sample was taken in a 100 ml conical flask, and the following reagents were added:

i. 3 ml of ammonia buffer solution
ii. 4 drops of Eriochrome Black-T (EBT) indicator (which turned the solution red-wine colored)

Titration was performed with EDTA solution from the burette until the red-wine color changed to blue, indicating the endpoint. The reading was recorded. The titration was repeated for accuracy.

For the actual hard water sample, the same process was followed, and the hardness was determined by comparing the EDTA volume used for the standard vs. the sample.

3.4 Selection of Treatment

Generally, for the treatment of wastewater the following methods are used:

a. Trickling filter
b. Rotating biological contactor
c. Lagoons and Wetlands
d. Anaerobic Digestion

For the selection of any type of treatment, we have to consider it economical aspects. But the above mentioned methods are used for large quantity treatment and also there is problem of odor and sludge disposal. So, taking these points into consideration, we prefer sand filters for the treatment of wastewater.

After analyzing the wastewater, we found that sand filter along with activated charcoal is capable to remove the impurities. So, with this consideration sand filter along with activated charcoal is finalized for treatment.

3.5 Selection of Filter Media

The selection of filter media is based on the characteristics of the wastewater being treated. The filter consists of three distinct layers: aggregate, sand, and activated charcoal (in powder form).

1. Aggregate

Filter gravel is used as the first filtration layer to remove larger sediments such as leaves, insects, and plastic debris. For optimal efficiency, the gravel must possess high hardness and be rounded rather than angular. River Sands Filter Gravel, a hard and predominantly quartz-based aggregate, is chosen for its durability and low breakdown rate, ensuring an extended filter media lifespan (Deshmukh et al., 2017).

The gravel used in this filter is screened into three standard sizes to provide effective support for the upper layers of the filter media. The selected aggregate size ranges from 5 mm to 30 mm.

2. **Sand**

Beneath the gravel layer, a sand bed is included to remove finer impurities from the wastewater. As the fluid percolates through the porous sand, particulates come into close contact with the sand grains and are captured through several mechanisms, including:

- **Direct collision** -Particles physically collide with sand grains and get trapped.
- **London force attraction** -Weak intermolecular forces attract particles to the sand surface.
- **Surface charge attraction** -Oppositely charged particles adhere to sand grains.
- **Diffusion** -Smaller particles move randomly and eventually adhere to sand grains.

However, repulsion may also occur if the surface charge of the sand matches that of the particulates. Additionally, previously captured particles may detach and either be recaptured at a deeper level or remain suspended in the water column. Over time, adhered particulates may alter the sand's surface charge, either increasing its attraction or repelling further particles (Deshmukh et al., 2017). The sand used in this filter has a particle size ranging from 1 mm to 1.36 mm.

3. **Activated Charcoal**

Activated charcoal is the final filtration layer, used to adsorb odorous and colored substances from the wastewater. Unlike regular charcoal, activated charcoal is treated with oxygen, creating a highly porous structure with an extensive surface area (300–2,000 square meters per gram). This vast surface provides numerous bonding sites for impurities to attach and become trapped.

Activated charcoal is particularly effective in adsorbing organic contaminants and chlorine. However, it does not remove all impurities, as certain substances like sodium and nitrates pass through without being retained (Mohan & Pittman, 2006; Shukla et al., 2020; Sulyman et al., 2017).

The activation of charcoal is achieved through superheating in the absence of oxygen at temperatures exceeding 1000°F (Musa et al., 2020). The process enhances the adsorption capacity of the charcoal, making it highly efficient in wastewater treatment. The procedure of making charcoal powder is shown in Figure 5.



Figure 5: Flow for Making Powdered Activated Charcoal Using Heat Treatment and Crushing

3.6 Design of Filtration Column

To evaluate the performance of the multi-media treatment system at a bench scale, a cylindrical packed-bed column reactor was assembled in the laboratory. The system incorporates three primary filter media arranged in sequential layers; gravel, sand, and activated charcoal, to achieve multi-stage physical straining and adsorption. While this laboratory-scale model was designed to establish proof-of-concept for small sample volumes, full-scale campus implementation would involve scaling these ratios into continuous-flow concrete or steel filtration tanks.

The media layers were packed sequentially into the column from bottom to top as follows:

- **Retention Matrix (Base):** A non-reactive synthetic fiber plug was fitted at the column outlet to retain the fine media and prevent powdered activated charcoal from eluting into the treated effluent.
- **Adsorptive Layer:** A consolidated bed of activated charcoal was placed directly above the base matrix to adsorb dissolved organic compounds, trace micro-pollutants, and odor-causing agents.
- **Granular Sand Layer:** A middle layer of graded silica sand was placed over the charcoal bed to trap fine suspended solids, protecting the downstream carbon pores from premature clogging.
- **Coarse Gravel Layer:** A top layer of coarse river gravel served as the primary filter to intercept larger floating debris, gross suspended solids, and organic particulate matter.

Once assembled, raw campus greywater was introduced from the top of the column under gravity head. The water percolated through the media bed, and continuous, steady effluent flow was established within 60 seconds. The treated effluent samples were immediately collected in sterile containers for detailed physicochemical characterization.

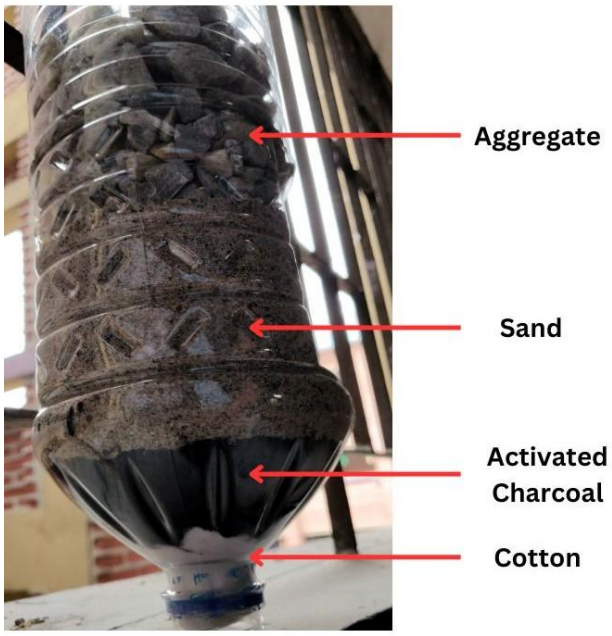


Figure 6: Visual representation of the filter sample utilized during wastewater treatment

3.7 Testing Filtered Water

Once the wastewater passed through the filtration bed, the filtered water was collected and analyzed in the laboratory to assess its physicochemical characteristics. The same parameters were tested again, including:

- Chemical Oxygen Demand (COD)
- Dissolved Oxygen (DO)
- Total Dissolved Solids (TDS)
- Total Suspended Solids (TSS)
- Boron
- Hardness
- Nitrate
- pH
- Alkalinity

The tests were conducted using the same instruments and methods as the initial wastewater analysis to ensure consistency. The results demonstrated notable improvements in water quality, validating the efficiency of the filtration system.

4 Data Analysis

4.1 Physico-chemical characteristics of wastewater samples

The physical and Chemical parameters of influent and effluent were tabulated in Table 2 and Table 3 after analysis respectively.

I. Before Filtration

Table 2: Physico-chemical characteristics of wastewater samples before filtration at different locations.

Parameters	Location 1		Location 2		Location 3		Location 4		**Average**
Samples	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	

pH	6.92	6.89	6.96	6.99	6.94
DO (mg/L)	0.35	0.50	0.55	0.30	0.43
TDS (mg/L)	4.04	5.10	7.90	8.70	6.44
NO_3^--N (mg/L)	42.20	36.20	19.36	18.45	29.05
P (mg/L)	10.20	6.71	5.72	5.53	7.04
Alkalinity (mg/L)	3.80	3.70	3.20	3.30	3.50
COD (mg/L)	169.0	159.00	109.60	120.50	139.53
Hardness (mg/L)	170.00	120.00	202.00	150.00	160.50
TSS (mg/L)	34.80	60.50	40.8	75.00	52.78
Boron (mg/L)	2.40	2.10	2.80	2.60	2.55

The pH of influent samples is low acidic in nature. Higher concentrations of NO_3-N and trace amount of nitrate nitrogen were noticed in wastewater. On the other hand, extensive epidemiological data supports the current guideline values for NO_3-N of 10.00 mg/L (U.S. Environmental Protection Agency, 2004). DO concentrations varied from 0.30 to 0.55 mg/L, which indicated that the samples were highly polluted. Phosphorus values were within suitable level from irrigation but as its average value was 7.04 mg/L which is not under permissible limit for aquatic life (Vandefanterdoo, 2015). The hardness of samples was 160.50 mg/L as average value which cannot affect the life of aquatic animals, but it affects the growth of plant (Patil et al., 2013).

II. After Filtration

Table 3: Physico-chemical characteristics of wastewater samples after filtration at different locations.

Parameters	Location 1		Location 2		Location 3		Location 4		**Average**
Samples	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	
pH	7.01		8.20		7.50		7.30		7.50
DO (mg/L)	0.28		0.32		0.32		0.30		0.31
TDS (mg/L)	4.03		5.10		7.85		8.90		6.47
NO_3^--N (mg/L)	4.83		4.48		5.00		4.14		4.61
P (mg/L)	3.87		5.38		1.93		4.37		3.89
Alkalinity (mg/L)	3.75		3.20		2.90		3.50		3.34
COD (mg/L)	40.00		65.00		45.00		46.00		49.00
Hardness (mg/L)	110.00		105.00		140.00		115.00		117.50
TSS (mg/L)	9.00		12.50		8.50		15.20		11.30
Boron (mg/L)	0.40		0.46		0.42		0.40		0.42

The pH of effluents ranged from 7.01 to 8.20. The pH of 6.o to 8.50 is acceptable for most pond life (Islam et al., 2013) and also it was under the permissible limit for irrigation. Alkalinity was found to be 3.34 mg/L on average after filtration. Hardness was reduced as compared to influent values, which changed from 160.50 mg/L to 117.50 mg/L. The NO3- concentration in the water samples of effluents ranged from 4.14 to 5.00 mg/L which were under the limit of 5.00 mg/L. COD, TSS, Boron and Phosphorus were all reduced as compared to influent values.

5 Results And Discussions

5.1 Results

In the present study, comparative analyses of physicochemical parameters of wastewater in HSTU Campus were carried out. Results obtained during the research work are presented by the graphs and tables and analysis was done on the basis of these results. This study is crucial for the management and treatment of wastewater in and around the HSTU campus. After collecting data from the selected area, different tests were conducted to determine the percentage of impurities in wastewater. The physicochemical parameters studied were pH, alkalinity, TSS,

TDS, DO, BOD, COD, nitrate, and phosphate. Each experiment was conducted using different methods and instruments, as described in the procedures above. The results are tabulated below:

SAMPLE S1/S2: Wastewater from the Drainage Line at a Waterlogged Area (Flowing Condition).

This sample was collected from a drainage line in a waterlogged area, receiving direct wastewater discharge from residential buildings. The test results before and after filtration are summarized in Table 4:

Table 4: Physicochemical Parameters of Wastewater Before and After Filtration for Sample S1/S2

S. No.	Parameters	Before Filter	After Filter
1	pH	6.92	7.01
2	DO	0.35 mg/L	0.28 mg/L
3	TDS	4.04 mg/L	4.03 mg/L
4	NO_3^--N	42.20 mg/L	4.83 mg/L
5	P	10.20 mg/L	3.87 mg/L
6	Alkalinity	3.80 mg/L	3.75 mg/L
7	COD	169.00 mg/L	40.00 mg/L
8	Hardness	170.00 mg/L	110.00 mg/L
9	TSS	34.80 mg/L	9.00 mg/L
10	Boron	2.40 mg/L	0.40 mg/L

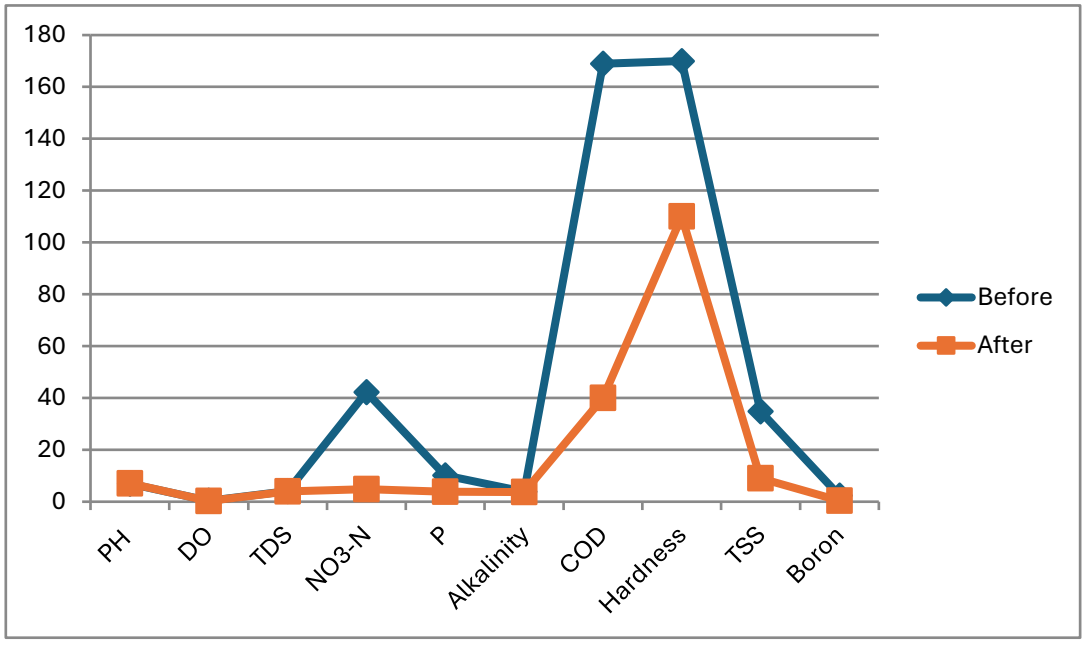


Figure 7: Line chart of wastewater physicochemical parameters at the waterlogged drainage line (flowing) before and after filtration.

The filtration process significantly reduced the concentration of several key pollutants which shown in Figure 7. The nitrate-nitrogen (NO_3-N) level dropped from 42.20 mg/L to 4.83 mg/L, reflecting an 88.5% reduction, while COD decreased from 169 mg/L to 40 mg/L—a sign of improved water quality. The hardness level also declined, though the dissolved oxygen (DO) concentration showed a slight reduction.

SAMPLE S3/S4: Wastewater from a Waterlogged Area (Stagnant Condition).

This sample was taken from a steady, non-flowing waterlogged area. The results are summarized in Table 5:

Table 5: Physicochemical Parameters of Wastewater Before and After Filtration for Sample S3/S4

S. No.	Parameters	Before Filter	After Filter
1	pH	6.89	8.20
2	DO	0.50 mg/L	0.32 mg/L
3	TDS	5.10 mg/L	5.10 mg/L
4	NO_3^--N	36.20 mg/L	4.48 mg/L
5	P	6.71 mg/L	5.38 mg/L
6	Alkalinity	3.70 mg/L	3.20 mg/L
7	COD	159.00 mg/L	65.00 mg/L
8	Hardness	120.00 mg/L	105.00 mg/L
9	TSS	60.50 mg/L	12.50 mg/L
10	Boron	2.10 mg/L	0.46 mg/L

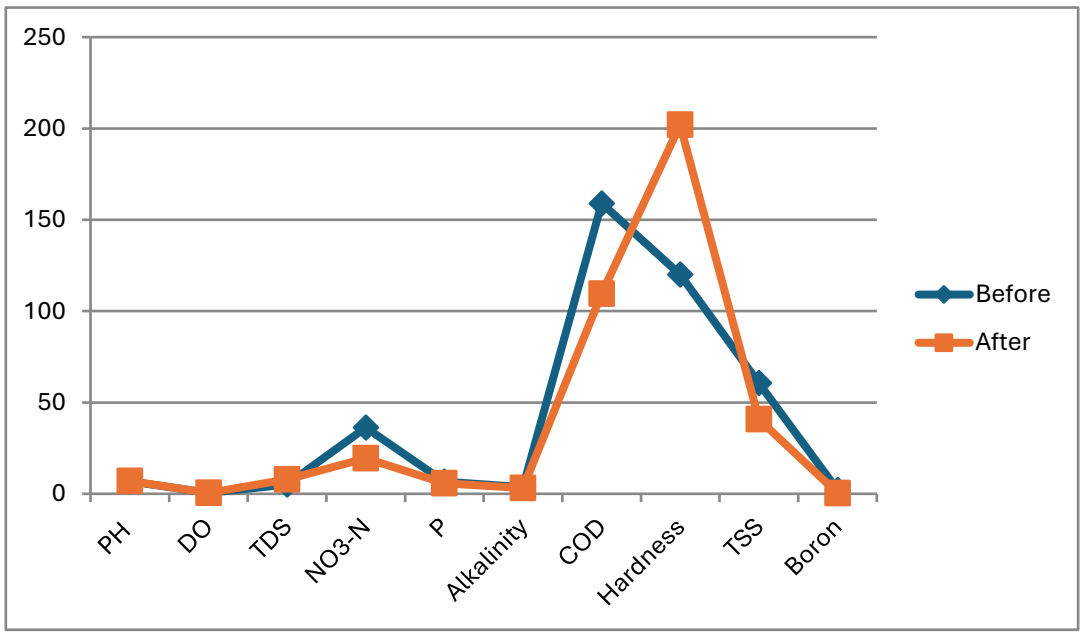


Figure 8: Line chart of wastewater physicochemical parameters at the waterlogged area (stagnant) before and after filtration.

After filtration, COD levels dropped by 59.1% (from 159 mg/L to 65 mg/L), and hardness was reduced from 120 mg/L to 105 mg/L. The results in Figure 8 also show a decline in NO_3-N concentration, indicating improved water quality. However, the TDS levels remained unchanged, suggesting that dissolved solids were not significantly removed by the filtration process.

SAMPLE S5/S6: Wastewater from Drainage Line at the Central Pond (Flowing Condition).

This sample represents wastewater flowing into the central pond, directly discharged from residential buildings summarized in Table 6.

Table 6: Physicochemical Parameters of Wastewater Before and After Filtration for Sample S5/S6

S. No.	Parameters	Before Filter	After Filter
1	pH	6.96	7.50
2	DO	0.55 mg/L	0.32 mg/L
3	TDS	7.90 mg/L	7.85 mg/L
4	NO_3^--N	19.36 mg/L	5.00 mg/L
5	P	5.72 mg/L	1.93 mg/L
6	Alkalinity	3.20 mg/L	2.90 mg/L
7	COD	109.60 mg/L	45.00 mg/L
8	Hardness	202.00 mg/L	140.00 mg/L
9	TSS	40.80 mg/L	8.50 mg/L
10	Boron	2.40 mg/L	0.50 mg/L

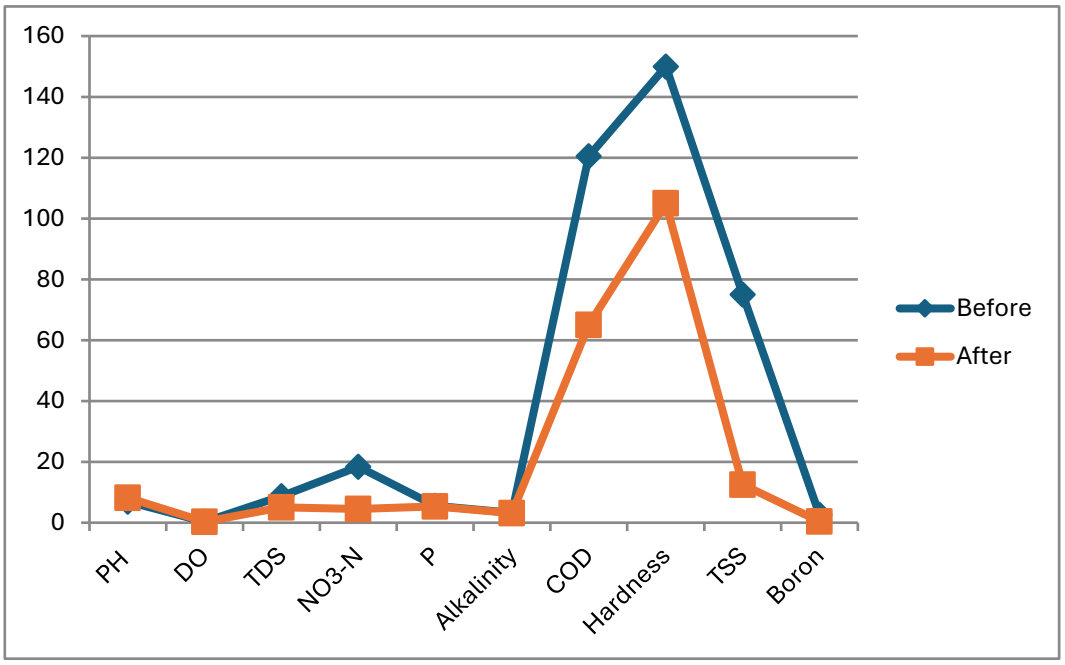


Figure 9: Line chart of wastewater physicochemical parameters at the drainage line of the central pond (flowing) before and after filtration.

After filtration, from Figure 9, it can be concluded that there is a significant change in total dissolved solids (TDS), which was not observed in other sample comparisons. The TDS level decreased from 7.90 mg/L to 7.85 mg/L, indicating a slight reduction. Additionally, the filtration process effectively lowered other pollutants, such as nitrate-nitrogen (NO_3-N), which dropped by 74.2%, and COD, which decreased from 109.60 mg/L to 45.00 mg/L.

Hardness also declined, while dissolved oxygen (DO) showed a slight reduction. Notably, boron levels increased after filtration.

SAMPLE S7/S8: Wastewater from Central Pond (Stagnant Condition).

This sample was taken from a steady, non-flowing Central Pond. The results are summarized in Table 7:

Table 7: Physicochemical Parameters of Wastewater Before and After Filtration for Sample S7/S8

S. No.	Parameters	Before Filter	After Filter
1	pH	6.99	7.30
2	DO	0.30 mg/L	0.30 mg/L
3	TDS	8.70 mg/L	8.90 mg/L
4	NO_3^--N	18.45 mg/L	4.14 mg/L
5	P	5.53 mg/L	4.37 mg/L
6	Alkalinity	3.30 mg/L	3.50 mg/L
7	COD	120.50 mg/L	46.00 mg/L
8	Hardness	150.00 mg/L	115.00 mg/L
9	TSS	75.00 mg/L	15.20 mg/L
10	Boron	2.60 mg/L	0.40 mg/L

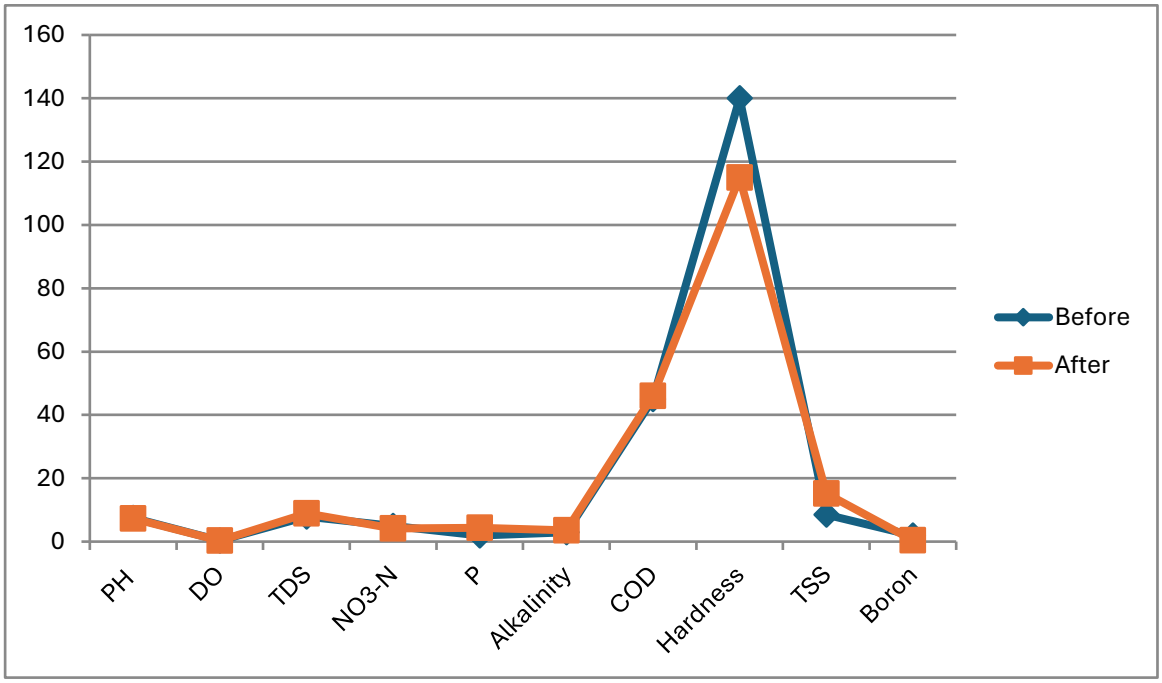


Figure 10: Line chart of wastewater physicochemical parameters at the central pond (stagnant) before and after filtration.

The phosphorus levels changed after filtration, unlike in the other charts where they remained relatively constant. The phosphorus (P) concentration dropped from 5.53 mg/L to 4.37 mg/L, indicating a noticeable reduction.

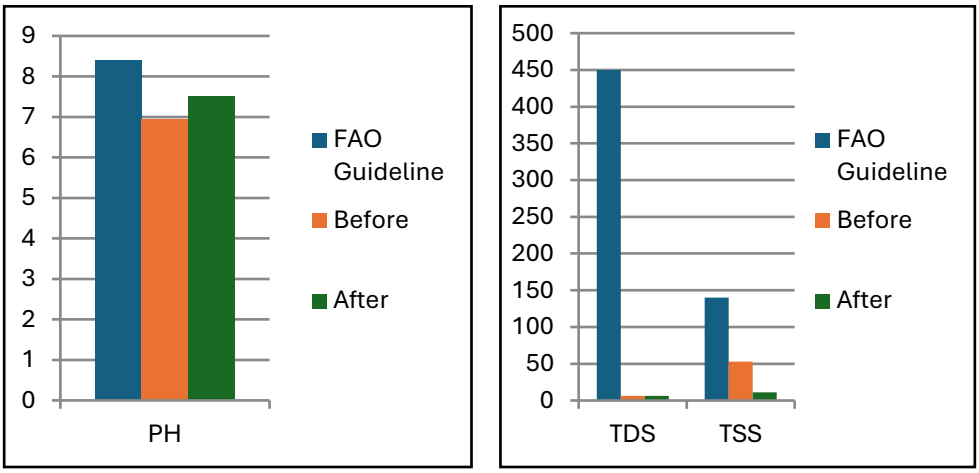
Additionally, the filtration process effectively lowered nitrate-nitrogen (NO_3-N) by 77.6% and reduced COD from 120.50 mg/L to 46.00 mg/L clearly shown in Figure 10. Hardness also declined, while dissolved oxygen (DO) remained unchanged. Notably, total dissolved solids (TDS) showed a slight increase after filtration, and boron levels significantly decreased.

5.2 Comparison of Water Quality Parameters with FAO and Pond Water Standards

Table 8: FAO Standard Water Quality Parameters for Irrigation Water.

Parameters	**Unit**	**Value**
pH		6.50-8.40
TDS	mg/L	<450.00
NO_3^--N	mg/L	<9.50
Boron	mg/L	<0.50
TSS	mg/L	<140.00

Using the value of FAO guideline for irrigation water (Table 8), line chart was drawn between Influent, Effluent and Standard values.



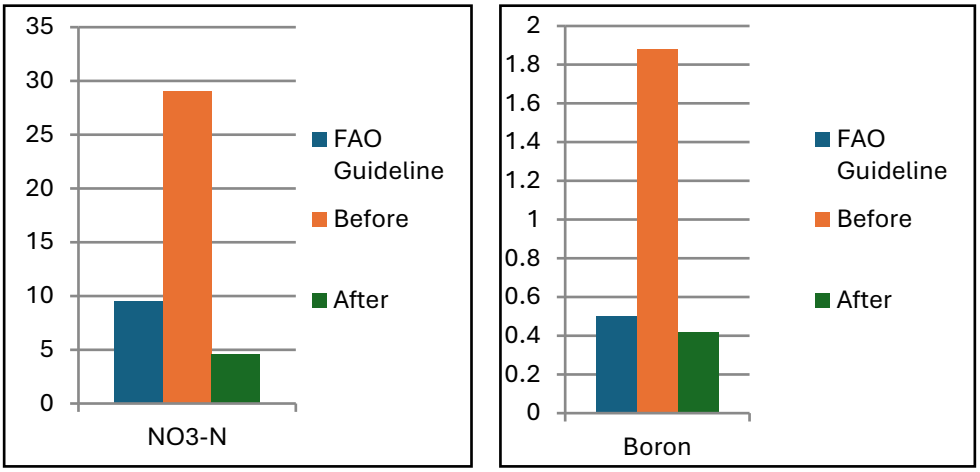


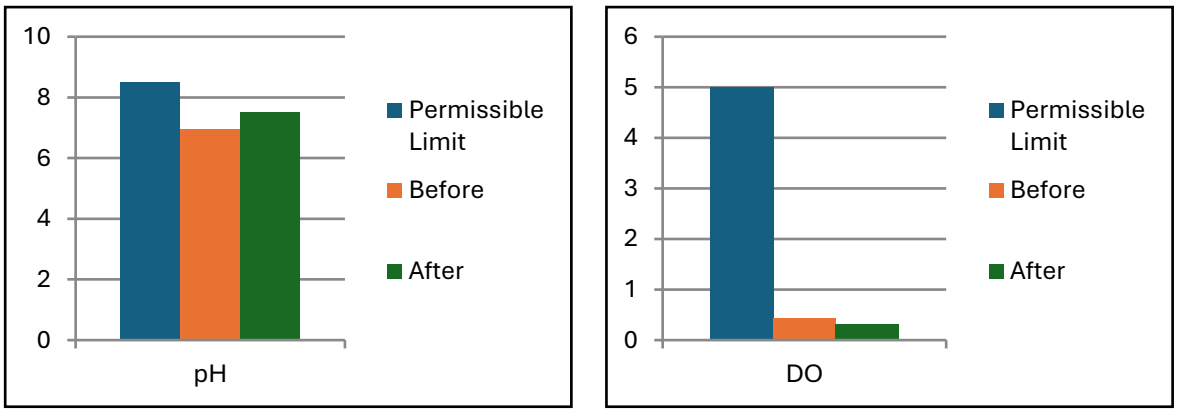
Figure 11: Column Bar Chart showing comparison of Water Quality Parameters with FAO Guidelines for Irrigation Water

The sample's parameters were under the FAO guideline after filtration with activated charcoal which can be reused in irrigation and gardening. The average parameters values of samples were compared with the standard value of FAO guideline in Figure 11. Boron and Nitrate-Nitrogen were huge amount in influence but got reduced and fell under guideline. Although pH value was increased, it is under FAO guideline.

Table 9: Permissible Water Quality Parameters for Pond Water.

Parameters	**Unit**	**Value**
pH		6.00-8.50
DO	mg/L	5.00
TDS	mg/L	<300.00
NO_3^--N	mg/L	<5.00
P	mg/L	<0.10
Alkalinity	mg/L	50.00-300.00
Hardness	mg/L	20.00-300.00

The line chart were drawn between Influent, Effluent and permissible Limit for Pond water quality (Table 9).



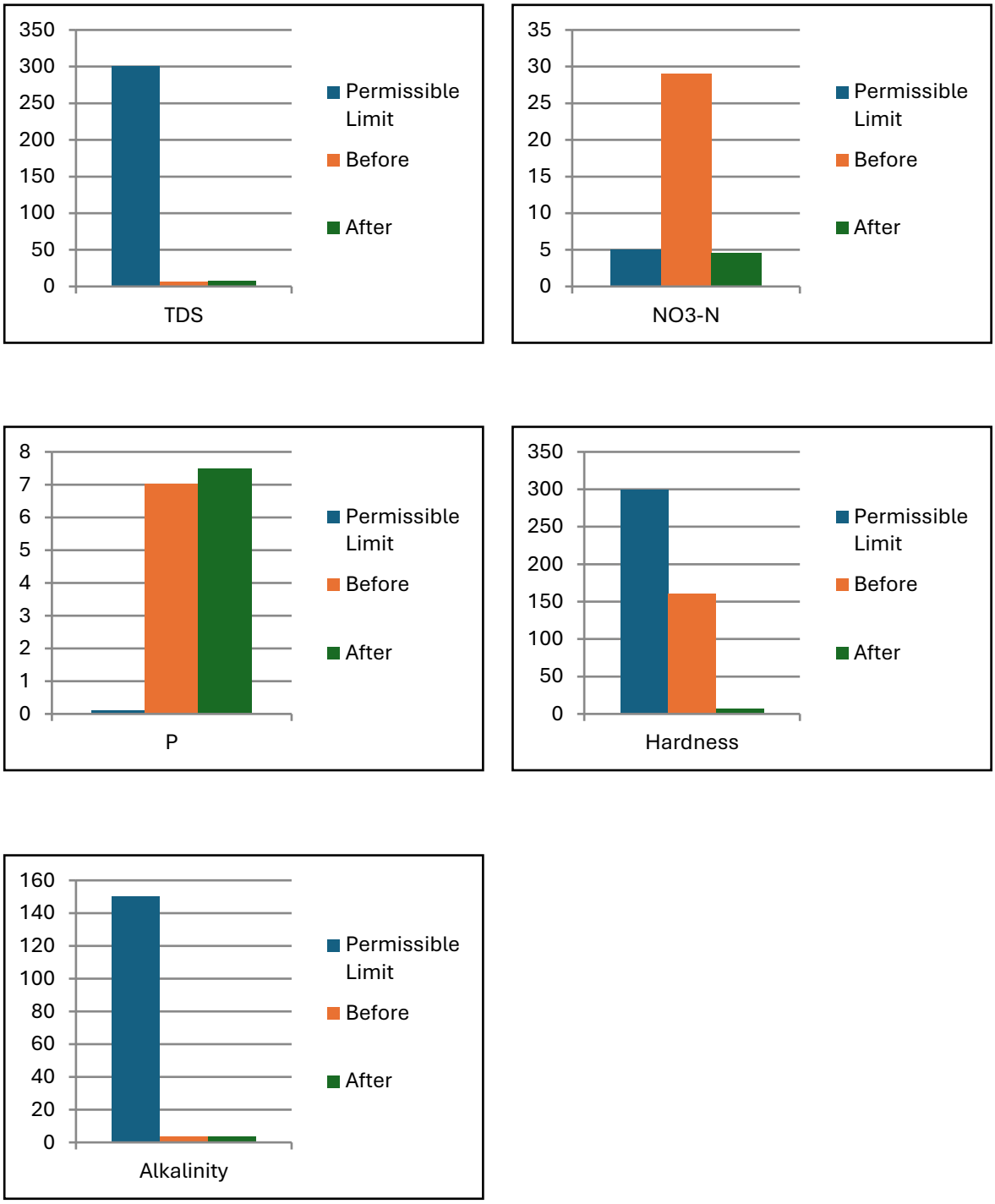


Figure 12: Column Bar Chart showing comparison of Water Quality Parameters with Permissible Limits for Pond Water Quality.

Some sample's parameters were under the permissible limit after filtration with activated charcoal shown in Figure 12. And some are above it but can be considered for dispose into pond.

5.3 Evaluation of Physicochemical Parameters Before and After Filtration

1. pH

The hydrogen-ion concentration (pH) is a key indicator of water quality for both discharge into water bodies and irrigation. Before filtration, the pH ranged from 6.92 to 6.99, while after filtration, it increased to 7.01 to 8.20. The range of 7.00 to 8.00 is generally suitable for irrigation and aquatic life. However, prolonged exposure to pH levels above 9.00 can cause stress and kidney damage in fish (Islam et al., 2013).

2. **Chemical Oxygen Demand (COD)**

COD measures the organic pollutant load in wastewater. Before filtration, COD levels ranged from 109.60 mg/L to 169.00 mg/L, exceeding acceptable limits for aquatic life and irrigation. After filtration, COD was significantly reduced to 49.00 mg/L, making the water more suitable for reuse.

3. **Color**

The color of wastewater is directly related to its pollutant load. Effective removal of color is crucial for improving water quality. Figure 13 illustrates the difference in color before and after filtration using activated charcoal.



Figure 13: Visual difference in color between untreated and treated water.

4. **Nitrate-Nitrogen**

Nitrate-Nitrogen concentrations ranged from 18.45 mg/L to 42.20 mg/L before filtration. At high pH levels, ammonia (NH_3) in wastewater becomes toxic to both aquatic and terrestrial organisms. Filtration reduced Nitrate-Nitrogen levels by 80% to 90%, significantly improving water safety.

5. **Suspended Solids (TSS)**

Suspended solids hinder photosynthesis by reducing light penetration and can suffocate benthic organisms. The influent contained 34.80 mg/L to 75.00 mg/L of suspended solids, but after filtration, levels dropped to 9.00 mg/L to 15.20 mg/L, achieving a 75% to 80% reduction.

6. **Total Dissolved Solids (TDS)**

TDS values before filtration ranged from 4.04 mg/L to 8.70 mg/L, and no significant change was observed after filtration. However, these values remained within permissible limits.

7. **Phosphate**

Phosphorus, primarily from cleaning agents, contributes to excessive algal growth when present in high concentrations. Before filtration, phosphate levels ranged from 5.53 mg/L to 10.20 mg/L. Filtration achieved a 40% to 50% reduction, mitigating potential ecological impacts.

8. **Alkalinity**

Alkalinity, determined by the presence of hydroxide (OH^-), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) ions, was found to be within permissible limits. Since the average pH was above 7, the samples were alkaline and may require additional treatment for irrigation purposes.

9. **Dissolved Oxygen (DO)**

DO is essential for wastewater treatment and aquatic life. The influent contained 0.30 mg/L to 0.55 mg/L of dissolved oxygen, which is below the permissible limit, indicating high organic pollution.

10. **Hardness**

Hardness in wastewater is primarily caused by detergents and soap residues. Before filtration, hardness ranged from 120.00 mg/L to 202.00 mg/L. Filtration reduced these values by 20% to 30%, making the water more suitable for reuse.

11. **Boron**

Boron is an essential micronutrient for plants but is required only in small amounts. Before filtration, boron levels ranged from 2.10 mg/L to 2.80 mg/L. After filtration, concentrations were reduced by 80% to 85%, ensuring safer levels for irrigation.

6 Conclusion

This study demonstrates that filtration treatment using activated charcoal is a simple, effective, and affordable method for improving wastewater quality. The multi-layer filtration system, consisting of gravel, sand, and activated charcoal, significantly reduced key pollutants, making the treated water suitable for safe disposal into water bodies and potential reuse for irrigation purposes. The filtration process successfully removed:

- COD: 50%-70%
- Hardness: 20%-30%
- Boron: 80%-85%
- Phosphate: 40%-50%
- Suspended Solids: 75%-80%
- Nitrate-Nitrogen: 80%-90%

These reductions help prevent groundwater contamination, mitigate environmental impacts, and support aquatic ecosystems. The slight increase in pH remained within acceptable limits, ensuring that the treated water is non-harmful to plant and aquatic life.

While the results are promising, the study also highlights limitations, such as the inability of the filter to reduce Total Dissolved Solids (TDS). Therefore, additional treatment methods may be needed for comprehensive wastewater purification. Nonetheless, implementing this low-cost, scalable solution on a larger scale could effectively manage campus wastewater, reducing reliance on freshwater sources for irrigation and promoting sustainable water resource management.

6.1 Implementation Insights and Limitations

While the proposed treatment framework proves effective for primary organic and nutrient reduction, key technical boundaries remain:

1. **Total Dissolved Solids (TDS):** The multi-media filter exhibited negligible impact on dissolved solids. For institutions operating in brackish groundwater zones, integrating secondary membrane or ion-exchange units may be required.
2. **Dissolved Oxygen (DO):** Effluent DO levels remained low post-filtration. Future iterations of this framework should incorporate passive cascade aeration or bio-retention steps prior to discharge into campus water bodies.

6.2 Broader Implications

Scaling this decentralized framework across academic institutions in resource-constrained environments provides a viable pathway toward institutional circular water management. Future research should focus on

optimizing long-term hydraulic loading rates, evaluating media regeneration cycles (specifically for activated charcoal), and conducting techno-economic life-cycle assessments (LCA) for full-scale campus deployment.

Declarations

- **Ethics Approval:** Not applicable. This study does not involve human participants, human biological materials, or animal experimentation. It is based solely on environmental water sample collection and laboratory filtration testing.
- **Consent to Participate:** Not applicable.
- **Consent to Publish:** Not applicable.
- **Competing Interests:** The authors declare that they have no competing interests.
- **Funding:** This research received no specific grant from any funding agency.
- **Availability of Data and Materials:** All data generated or analyzed during this study are included in this published article.

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