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Effectiveness of Natural Zeolite and Geo-fabric as Single and Dual Media in Biologically Aerated Filters (BAFs) for Greywater Treatment

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ABSTRACT

The performance of a dual-media biologically aerated filter (NZGF-BAF) incorporating natural zeolite and geo-fabric was studied and compared with single-media BAF systems using only natural zeolite (NZ-BAF) or geo-fabric (GF-BAF) in batch mode. The study examined how hydraulic retention time (HRT), carbon-to-nitrogen (C/N) ratio, aeration rate, and filter depth affected the removal of contaminants such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia-nitrogen (NH3-N), turbidity, and total dissolved solids (TDS). Results showed that under similar conditions, NZ-BAF and GF-BAF performed similarly in removing COD, BOD, and turbidity, thanks to their larger surface areas, biofilm development, and absorption and adsorption capacities. NZ-BAF was more effective at removing NH3-N due to its ion-exchange properties, while GF-BAF excelled in TDS removal through permeability, adsorption, and bacterial activity. The dual-media NZGF-BAF demonstrated improved removal efficiencies across all contaminants. An optimization study using Response Surface Methodology (RSM) under optimal conditions revealed maximum removal rates of 93% for COD, 98% for BOD, 94% for NH3-N, 93% for turbidity, and 67% for TDS.

1. INTRODUCTION

Aerobic biological processes have been developed in wastewater treatment to lower environmental contaminant levels and efficiently remove most dissolved and suspended organic pollutants through mechanisms such as organic decomposition, surface adsorption, and sedimentation (Huang et al. 2017). Aerobic treatment methods include activated sludge processes, trickling filters, membrane bioreactors (MBRs), moving bed biofilm reactors (MBBRs), and biologically aerated filters (BAF). Both traditional activated sludge and carrier-added activated sludge (CAS) produce excess sludge that must be routinely removed, requiring large liquid-solid separation units. Fixed film techniques tend to nitrify wastewater more effectively than activated sludge methods. Treatment systems like trickling filters and bio-towers also need secondary sedimentation to settle waste sludge, making them larger and costlier (Doelle et al. 2020). MBRs are increasingly favored due to their compact size and high effluent quality (Van de Staey et al. 2015), though they face challenges such as membrane fouling, aeration limitations, and high costs. Membranes require frequent chemical cleaning and eventual replacement due to abrasion and declining efficiency (Krzeminski et al. 2012). MBBR systems, despite their benefits, can cause foaming and turbidity from filament growth, which can lead to excessive biomass and reduce void space, impairing oxygen transfer and substrate diffusion. Additionally, the plastic media will eventually need replacement because of wear (Krzeminski et al. 2012).

The BAF system's capability to effectively remove solids, carbon, nitrogen, and phosphorus from wastewaters has established it as a prominent technology in wastewater treatment. This is achieved through the integration of biological and physical processes, resulting in an effluent suitable for reuse or safe environmental discharge (Mendoza-Espinosa et al. 1999, Jacob et al. 1997). Its compact design, versatility in treating various wastewater types, ease of operation and maintenance, energy efficiency compared to other methods, and its ability to simultaneously eliminate multiple contaminants are some of its key advantages. BAF systems excel at removing organic matter from wastewater due to the high biomass attached to the filter media. This biological treatment efficiently decomposes organic pollutants within a single unit, greatly reducing the organic load (Fu et al. 2016). Additionally, bio-filter systems demonstrate adaptability, functioning effectively across a range of environmental conditions such as pH and temperature changes. This versatility allows their use in diverse climates and geographic regions. The operational flexibility of BAF systems permits modifications to accommodate different influent characteristics, including variations in wastewater composition and flow rates. They typically produce less sludge, simplifying residual sludge management and disposal while reducing environmental impact. Another advantage is that bio-filter systems are environmentally friendly and operate quietly (Nacheva et al. 2008).

Selecting an appropriate support medium is crucial when designing and operating a BAF system. To ensure the discharged effluent is environmentally safe and complies with health and environmental regulations, regulatory bodies establish effluent quality standards. Choosing the right filter media is vital for meeting these standards (Tan et al. 2008). For effective wastewater treatment, media characteristics such as permeability, pore size, and type are essential (Kent et al. 2000, Spychała et al. 2013).

Natural zeolite–based biologically aerated filters (NZ-BAFs) represent an advanced type of submerged biofilter, where natural zeolite serves as the primary support medium. Composed of hydrated alumino-silicates with a honeycomb structure, natural zeolite's three-dimensional network is formed by interconnected tetrahedra of SiO4 and AlO4 linked through shared oxygen atoms (Adam et al. 2023). The substitution of Al3+ ions for Si4+ ions within the lattice creates a negative charge within the tiny pores, establishing effective cation exchange sites (Widiastuti et al. 2011). This property makes natural zeolites particularly selective for cations such as ammonium ions in wastewater. With a high specific surface area and porosity, natural zeolite enhances adsorption capacity and supports biofilm development through bacterial attachment. Larger organic molecules, whether dissolved or colloidal, cannot pass through the zeolite's narrow pores and instead adhere to its surface. Microorganisms, including bacteria, become entrapped within the pores, facilitating microbial activity. Consequently, the extensive surface area allows for a substantial population of active bacteria responsible for degrading organic contaminants in wastewater. The performance of a BAF system is also influenced by the media's size, shape, and surface roughness. The rough surface of zeolite media provides more area for bacterial attachment and biofilm formation (Spychała et al. 2013). Furthermore, the uneven surface of zeolite outperforms spherical media in efficiency. Due to its inertness, low cost, non-metallic, and non-toxic characteristics, natural zeolite is an excellent support medium for wastewater treatment. Although the long-term operation may reduce its effectiveness, natural zeolite's regenerative properties—restored through treatments with NaCl, KCl, acids, or heat—offer additional advantages.

Geo-fabrics are durable polymeric materials designed for a variety of environmental and civil engineering uses. In wastewater treatment, particularly within biofilm reactors, the application of geo-fabrics as support media is an emerging research area. Commonly fabricated from synthetic polymers such as polyester (PET) and polypropylene (PP), geo-fabrics are produced in both woven and non-woven forms. The complex fiber structure of non-woven, needle-punched geo-fabrics has demonstrated exceptional efficiency in capturing suspended solids and larger particles. Due to their superior strength, porosity, flexibility, durability, resistance to environmental factors, and ability to withstand stresses, geo-fabrics are preferred over alternative media such as sand, crushed rock, river gravel, granular activated carbon (GAC), or certain plastics and ceramics (Praveen et al. 2008, Revathi et al. 2016). The large specific surface area of geo-fabrics enhances their effectiveness in filtration and adsorption processes. Their filamentous structure promotes rapid bacterial adhesion and biofilm formation (Alimahmoodi et al. 2012). In wastewater treatments where bacteria play a role in breaking down organic materials, the hydrophilic nature of geo-fabrics further facilitates bacterial attachment. Additionally, the biodegradable and eco-friendly qualities of geo-fabrics help to mitigate environmental impact.

Oxygen plays a crucial role in the decomposition of organic matter (COD and BOD) and in the nitrification process (NH_3-N removal). The efficiency of aerobic bacteria that eliminate pollutants is directly linked to the level of aeration supplied. The BAF system depends on a robust aeration setup, regardless of the support media used, to ensure optimal performance of biological processes, prevent operational issues, and produce high-quality effluent. Proper aeration maintains dissolved oxygen levels and supports the development of bacterial biofilms.

The backwash mechanism in a BAF system is essential for removing biomass and particles from the media surface, preventing clogging, and avoiding mechanical compaction that could reduce porosity. This process also helps maintain bacterial activity within the biofilm (Charchalac et al. 2015). Proper backwashing reduces energy consumption and extends the treatment cycle. It is important to carefully regulate the frequency of backwashing, as excessive cleaning can decrease biomass and impair bio-filter function. Conversely, infrequent backwashing may limit the removal of BOD and total nitrogen (Xie et al. 2004). Typically, backwashing intervals for some secondary treatment bio-filters range from 24 to 48 hours (Bacquet et al. 1991), while others may only require backwashing every 1-2 weeks to effectively remove excess biomass (Jacob et al. 1997).

This study systematically examines how key operational parameters influence the performance of a bio-adsorption filter (BAF) system that uses dual media—natural zeolite and geo-fabric—compared to single-media setups utilizing only natural zeolite or geo-fabric as biofilm support materials. The treatment effectiveness was evaluated based on the removal of COD, BOD, NH_3–N, turbidity, and TDS from greywater under batch experimental conditions. While most conventional biofilter media achieved satisfactory removal rates for COD, BOD, and turbidity, the efficiencies for NH_3–N and TDS were generally lower and often did not meet permissible discharge standards. The BAF system explored in this research is designed to be a compact, efficient, and cost-effective solution for household greywater treatment, reducing dependence on more advanced and expensive technologies such as ion exchange, ultrafiltration, nanofiltration, distillation, or reverse osmosis.

The operational parameters for the BAF system under investigation include HRT, C/N ratio, aeration rate, and media depth. The system's efficiency under different hydraulic conditions can be assessed by examining fluctuations in HRT, which reflects the contact time between water and microbial biofilm. Monitoring the C/N ratio helps understand nutrient availability and its influence on microbial activity and treatment performance in the dual media BAF. Aeration is vital for maintaining aerobic conditions within the biological filter and promoting the growth of aerobic microorganisms. Optimizing treatment efficiency involves studying how changes in aeration rates impact BAF performance. Additionally, the depth of the filter bed affects microorganism distribution and the contact time between greywater and biofilm. Analyzing the influence of filter depth provides valuable insights into the biofilter's functionality and system design considerations.

The system's optimization was analyzed using Minitab 19, a software that provides a range of data analysis tools through its Response Surface Model (RSM). By applying statistical techniques, mathematical problems are modeled and examined to enhance system performance. RSM offers the key advantage of requiring fewer experimental trials to evaluate multiple factors and their interactions (Jasni et al. 2020, Lin et al. 2010). It is an effective method for understanding how different factors interact and for identifying optimal operating parameters for the BAF system.

2. MATERIALS AND METHODS

2.1. Lab-Scale Setup

A lab-scale bio-filter system was employed to evaluate the feasibility of the proposed single and dual media-based bio-filter configurations. This system was built as a transparent, rigid glass column, allowing visual observation of internal processes. Measuring 150 mm × 150 mm in cross-section and 1200 mm in height, the column's square design provides sufficient capacity for testing. An inlet situated 50 mm from the top and an outlet 50 mm from the bottom enable controlled influent distribution and effluent collection. To ensure uniform distribution of influent and backwash water and to prevent washout, perforated plates are installed at both the top and bottom of the column. Two cubic glass tanks, each measuring 300 mm × 300 mm with a depth of 300 mm, were utilized: one as an equalization tank to supply a steady, regulated flow of greywater to the biofilter, and the other as a settling basin for the collection of treated greywater, allowing suspended solids to settle before disposal or reuse. Influent is pumped into the biofilter column via a submersible pump. Adequate aeration is maintained by an aerator and four evenly spaced air diffusers along the column's depth. To sustain system performance and prevent clogging, a backwash mechanism periodically removes excess biomass and accumulated solids, using the effluent from the settling basin as backwash water, thereby enhancing overall sustainability and efficiency. The schematic of the experimental setup for the BAF system is illustrated in Fig. 1.

2.2. BAF Media

Batch experiments were performed using single- and dual-media BAF filters, comprised of natural zeolite and/or geo-fabric as the filtering media. Natural zeolite, sized between 1-3 mm, was sourced from G. M. Biochem Pvt. Ltd. in Ahmedabad, Gujarat. The non-woven, needle-punched geo-fabric with a GSM of 500 was manufactured by Manas Geo Tech India Pvt. Ltd. in New Delhi, India. Natural zeolites possess a tetrahedral structure, offering high cation exchange, adsorption, and absorption capacities, along with the ability to develop a biofilm on their surface. Geo-fabrics feature a complex, porous structure with high permeability, tensile strength, and porosity, which facilitates microbial growth.

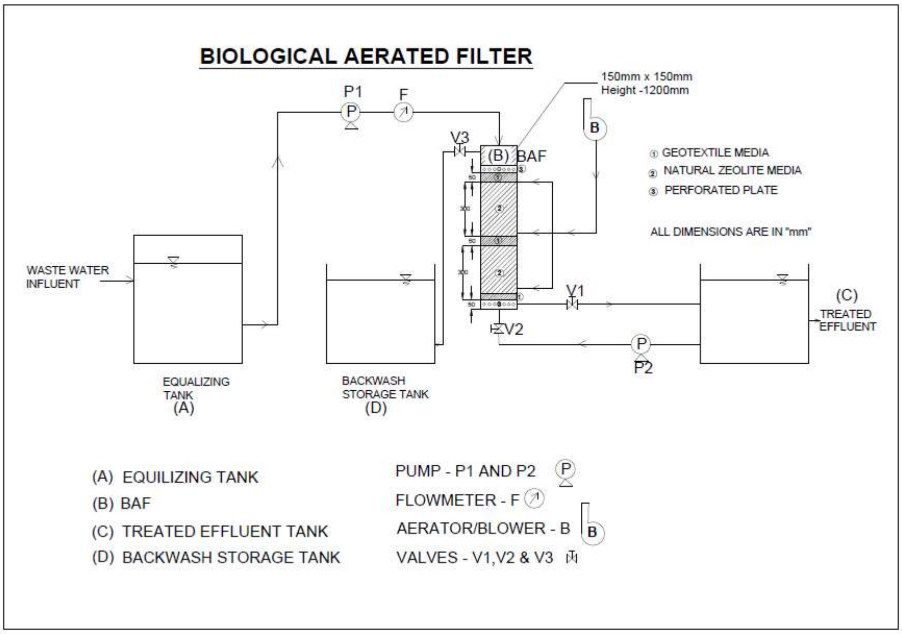


Fig. 1: Experimental setup of the BAF system.

Both materials enable water flow while effectively retaining suspended solids, making them excellent, cost-effective filter media that are easy to handle and install, and resilient against biological degradation and environmental factors.

In the initial series of batch experiments, the BAF system was operated using natural zeolite particles measuring 1-3 mm as the sole filter medium, designated as NZ-BAF. The second series employed only geo-fabric with a density of 500 GSM as the filter medium, labeled GF-BAF. In the third series, a dual media comprising natural zeolite (1-3 mm) and geo-fabric (500 GSM) was used in the BAF system, referred to as NZGF-BAF. The operational conditions remained consistent across all three experimental series.

2.3. Synthetic Greywater Preparation and Analysis

For this study, synthetic greywater was used as the influent to maintain consistent composition and eliminate variability in influent characteristics across the experimental runs conducted for NZ-BAF, GF-BAF, and NZGF-BAF systems. The synthetic greywater was prepared by mixing precise amounts of chemicals such as glucose (300 $mg.L^{-1}$), sodium acetate trihydrate (400 $mg.L^{-1}$), ammonium chloride (225 $mg.L^{-1}$), disodium hydrogen phosphate (150 $mg.L^{-1}$), potassium dihydrogen phosphate (75 $mg.L^{-1}$), and magnesium sulphate (50 $mg.L^{-1}$) with one liter of distilled water. The physicochemical properties of the synthetic greywater, along with their variability—low, high, mean, and standard deviation—are summarized in Table 1. Subsequently, physicochemical parameters were measured before and after treatment to determine the percentage removal of contaminants, following accepted standard methods (APHA 2017).

2.4. Bacterial Inoculation and Acclimation

The prepared synthetic greywater was combined with seed inoculum from the activated sludge of the sewage treatment plant to reduce startup time and promote microbial growth.

Table 1: Characteristics of synthetic greywater used as influent.

Process Parameter	Unit	Number of Samples	Influent Value			
			Low	High	Mean	Standard Deviation
COD	$mg.L^{-1}$	33	368	527	446.2	71.7
BOD	$mg.L^{-1}$	33	203	231	216.2	11.3
NH_3-N	$mg.L^{-1}$	33	15	18	16.42	1.19
Turbidity	NTU	33	46	85	63.5	14
TDS	$mg.L^{-1}$	33	547	609	575.8	24.1

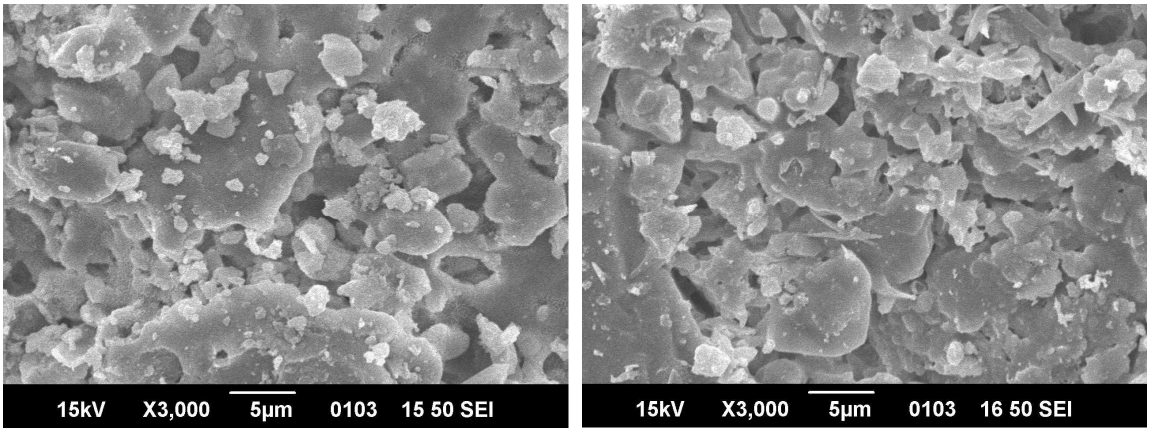
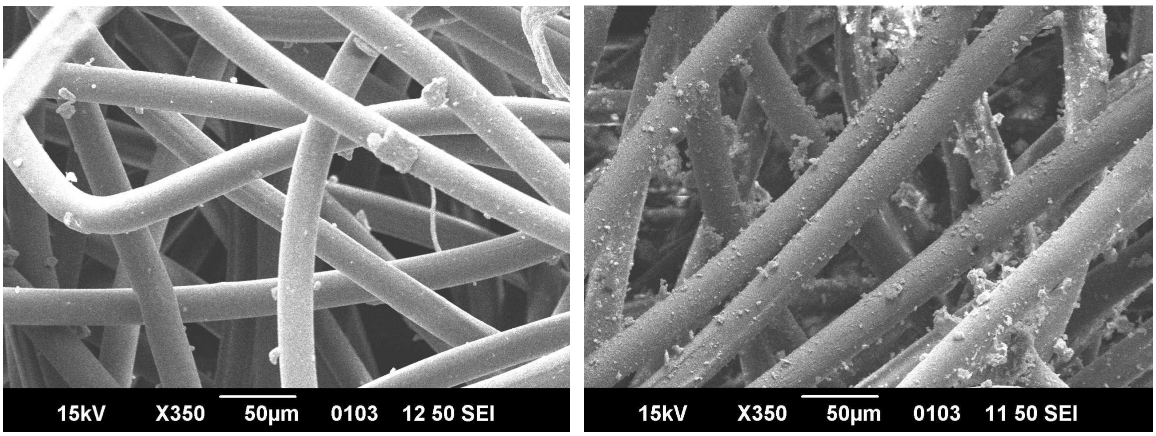


Fig. 2: SEM of natural zeolite 1-3 mm (a) Before treatment (b) After treatment.



(a) (b)

Fig. 3: SEM of geo-fabric media of 500 GSM (a) Before treatment (b) After treatment.

Additionally, nutrients for aerobic bacteria were added to the mixture. Before each experimental series, the respective media underwent a 21-day bacterial acclimation period to support biofilm formation and stabilization. To ensure sufficient oxygen supply, aeration was initially provided at a rate of 15 $L.h^{-1}$. After acclimation, the effluent COD levels remained low and stable, indicating the development of a biofilm on the media.

After the acclimatization phase, each system was operated under various conditions to enhance treatment efficiency and understand the system's sensitivity. The system was maintained at an organic loading rate of 3.95–4.5 kg $BOD.m^{-3}.day^{-1}$, based on initial BOD concentrations of 203 $mg.L^{-1}$ (low) and 231 $mg.L^{-1}$ (high) for synthetic greywater. The performance of single and dual media BAFs was evaluated under similar operational conditions, with variations in HRT, C/N ratio, aeration rate, and filter depth. The following section discusses the results and observations obtained.

3. RESULTS AND DISCUSSION

Batch experiments were conducted using BAF systems with various media configurations, specifically NZ-BAF, GF-BAF, and NZGF-BAF, to compare their treatment effectiveness. Each reactor operated independently under different operational parameters such as HRT, C/N ratio, aeration rate, and filter media depth. The system's performance was evaluated based on removal efficiencies of key parameters, including COD, BOD, NH_3–N, turbidity, and TDS.

To gain a deeper understanding of how media characteristics influence pollutant removal, scanning electron microscopy (SEM) analysis was performed on natural zeolite (particle size 1–3 mm) and geo-fabric (500 GSM) both before and after treatment. The SEM micrographs of natural zeolite and geo-fabric, shown in Fig. 2(a–b) and Fig. 3(a–b), respectively, clearly reveal distinct surface modifications post-treatment, indicating structural changes linked to biofilm development and contaminant accumulation.

3.1. Assessment of the Performance of BAF Using Single and Dual Media with Natural Zeolite of Size 1-3 mm and/or Geo-fabric of 500 GSM Under Varying Operational Conditions

3.1.1. HRT

For each BAF type—NZ-BAF, GF-BAF, and NZGF-BAF—to assess the impact of HRT on performance and identify the optimal HRT, all other variables such as C/N ratio, aeration rate, and filter medium depth were maintained constant at 6, 65 $L.h^{-1}$, and 70 cm, respectively. In single-media systems, natural zeolite and geo-fabric each occupied a 70 cm filter depth in the NZ-BAF and GF-BAF reactors. The dual-media NZGF-BAF featured a stratified setup, with a 30 cm bottom layer of natural zeolite and a 40 cm top layer of geo-fabric, totaling a 70 cm filter depth. After each operational period, the effluent properties were analyzed. The NZ-BAF was operated by systematically varying HRT values—1 h, 2 h, 3 h, 4 h, and 5 h—repeating the process for GF-BAF and NZGF-BAF. Performance was evaluated based on key process parameters influencing biological treatment: COD, BOD, NH3-N, turbidity, and TDS removal. The highest percentage removal of these parameters was observed at an HRT of 3 h across all BAF systems. At this HRT, removal efficiencies were 85%, 86%, 95%, 76%, and 30% for COD, BOD, NH3-N, turbidity, and TDS in NZ-BAF; 86%, 94%, 77%, 86%, and 63% in GF-BAF; and 91%, 98%, 92%, 91%, and 63% in NZGF-BAF. The variations in removal efficiencies for these parameters at different HRTs for each BAF type are depicted in Fig. 4 (a-c).

In BAF systems, pollutant removal efficiency improves when the HRT is increased from 1 hour to 3 hours. Extending the HRT further to 4 or 5 hours does not significantly enhance pollutant removal, indicating that the optimal HRT is around 3 hours. Initially, organic matter is rapidly eliminated due to the availability of absorbent sites on the filter media, which facilitate efficient adsorption of contaminants. Over time, the removal rate decreases as the active sites become saturated

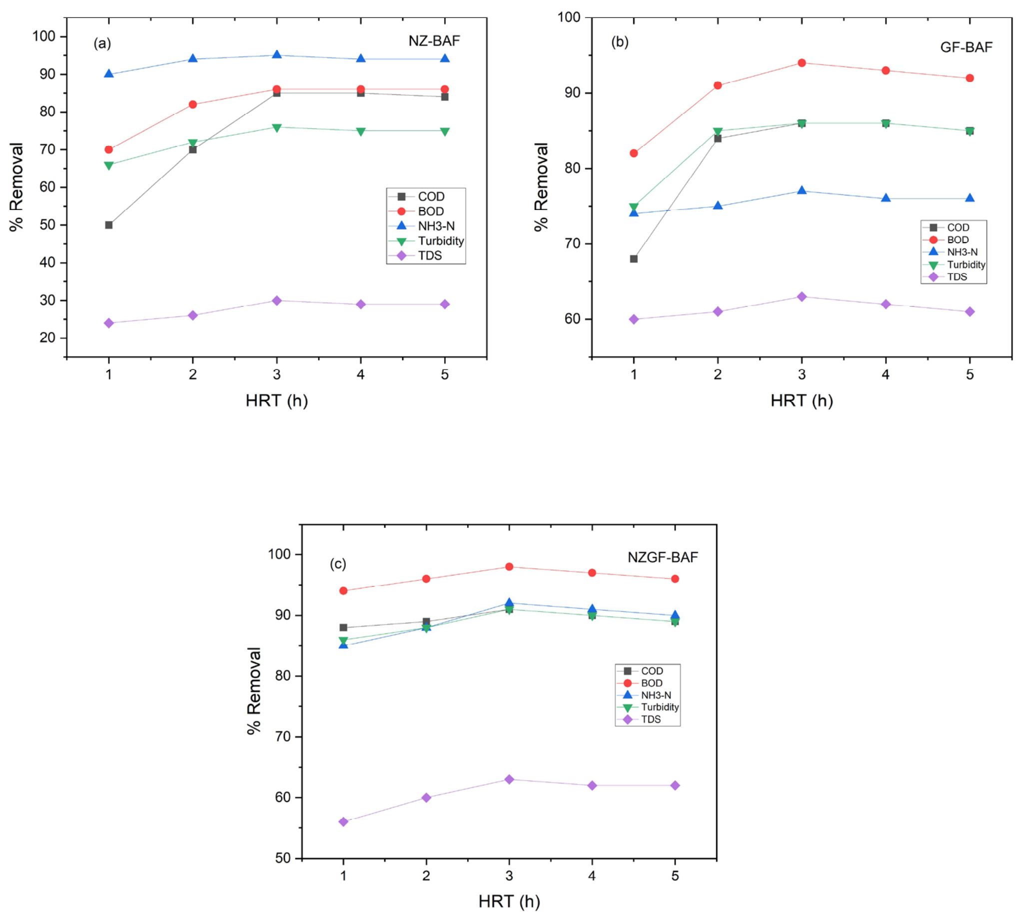


Fig. 4: Effect of the variation in HRT for (a) NZ-BAF, (b) GF-BAF (c) NZGF-BAF.

or deactivated, reducing pollutant removal effectiveness. Shorter HRTs are advantageous because they occupy less space for biofilters, potentially leading to lower building costs for biofiltration systems.

3.1.2. C/N Ratio

The experiments on NZ-BAF, GF-BAF, and NZGF-BAF were carried out with different C/N ratio values, specifically 4, 5, 6, 7, and 8, while maintaining a constant HRT of 3 hours, an aeration rate of 65 $L.h^{-1}$, and a filter depth of 70 cm. These conditions were set to investigate how variations in C/N ratios influence the properties of the effluent. The effluent characteristics were analyzed after each experimental run.

Based on the test results, the highest removal efficiency of contaminants was achieved at a C/N ratio of 6 for NZGF-BAF, NZ-BAF, and GF-BAF. Specifically, for NZGF-BAF, the maximum percentage removals were 93% for COD, 98% for BOD, 92% for NH_3-N, 91% for turbidity, and 66% for TDS. In the NZ-BAF system, the highest removals were 85% for COD, 85% for BOD, 89% for NH_3-N, 78% for turbidity, and 30% for TDS. Meanwhile, the GF-BAF system showed maximum removals of 84% for COD, 91% for BOD, 75% for NH_3-N, 85% for turbidity, and 61% for TDS. The data on contaminant removal across various BAFs and C/N ratios are displayed in Fig. 5(a–c).

Pollutant removal efficiency of the BAFs increased as the C/N ratio rose from 4 to 6. However, removal efficiency began to decline as the C/N ratio reached 6. Consequently, the optimal C/N ratio was found to be 6. The porous nature and large surface area of the natural zeolite and geo-fabric media, which provide ample space for bacterial colonization and pollutant breakdown, enabled effective interaction between organic matter and the media. However, beyond a certain point, the bio-filter's effectiveness declined as organic loading increased.

3.1.3. Rate of Aeration

The systems were operated at various aeration rates (15, 40, 65, 90, and 105 $L.h^{-1}$), with an optimal HRT of 3 hours and a C/N ratio of 6. The media depth remained at 70 cm, consistent with earlier experiments. When compared to NZ-BAF and GF-BAF, the NZGF-BAF system with dual media demonstrated

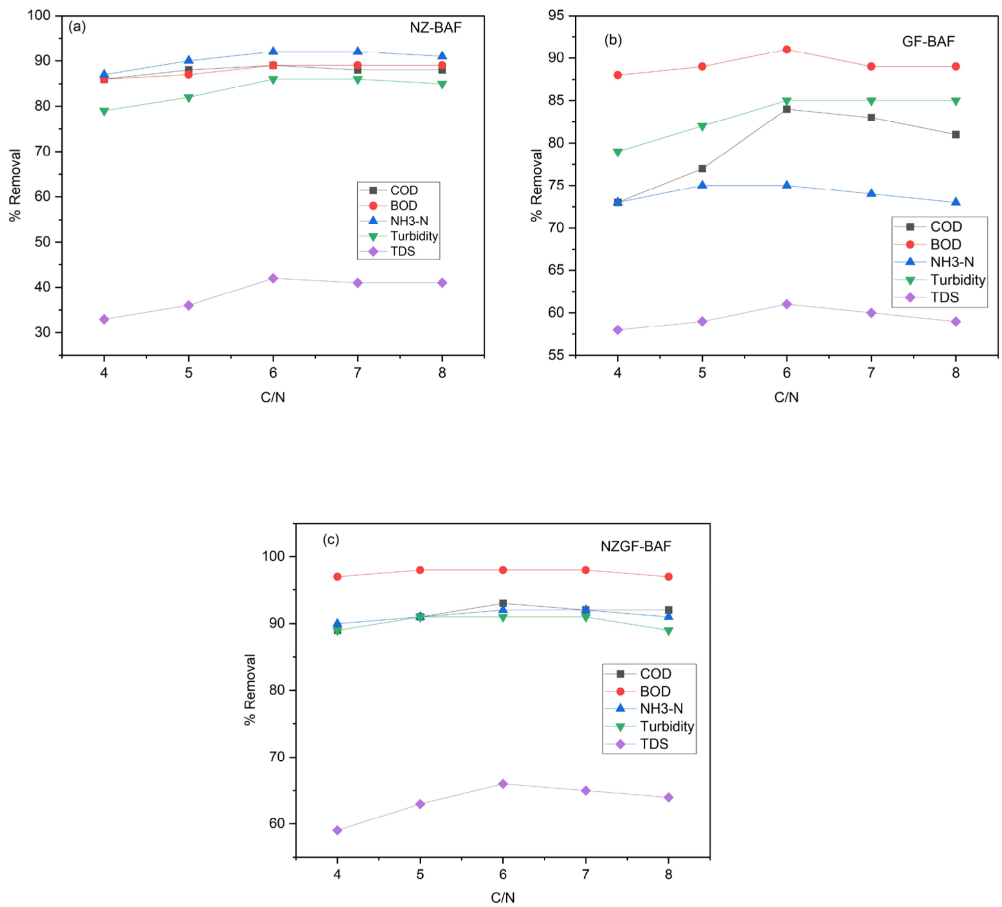


Fig. 5: Effect of various C/N ratios on (a) NZ-BAF, (b) GF-BAF (c) NZGF-BAF.

superior performance at an ideal aeration rate of 65 $L.h^{-1}$. The percentage removal efficiencies for different process parameters across various filter media types and aeration rates are depicted in Fig. 6 (a–c). The NZ-BAF achieved maximum removal rates of 90%, 92%, 96%, 92%, and 49% for COD, BOD, NH_3-N, turbidity, and TDS, respectively. The GF-BAF reported peak removal efficiencies of 90%, 95%, 84%, 88%, and 67% for the same parameters. Notably, the NZGF-BAF yielded the highest removal percentages for COD, BOD, NH_3-N, turbidity, and TDS, which were 93%, 98%, 92%, 91%, and 66%, respectively.

All BAF systems demonstrated improved removal efficiency when aeration was supplied at the optimal rate of 65 $L.h^{-1}$. Increasing the aeration rate to 90 or 115 $L.h^{-1}$ did not yield any noticeable enhancement in system performance. Based on the experimental data, the aeration rate was set at 65 $L.h^{-1}$, indicating that sufficient airflow boosts the metabolic activity of the bacteria.

3.1.4. Depth of Filter

The performance of the BAF system is significantly affected by the choice and properties of the filter media. To investigate how variations in filter depth impact treatment efficiency, reactors were operated with media depths of 60, 70, 80, 90, and 100 cm.

All systems were maintained under previously optimized conditions, including a 3-hour HRT, a C/N ratio of 6, and an aeration rate of 65 $L.h^{-1}$. In the single-media configurations (NZ-BAF and GF-BAF), natural zeolite and geo-fabric, respectively, filled the entire filter depth from 60 to 100 cm. Conversely, the dual-media NZGF-BAF system comprised a fixed 30 cm bottom layer of natural zeolite, with the thickness of the overlying geo-fabric layer varied (30, 40, 50, 60, and 70 cm) to achieve total depths of 60 to 100 cm.

At a filter depth of 80 cm, all three systems demonstrated the highest contaminant removal efficiencies. Fig. 7 (a-c) illustrates the percentage removal of various parameters in relation to filter depth for each system.

At a depth of 80 cm, NZGF-BAF demonstrated superior contaminant removal percentages compared to NZ-BAF and GF-BAF. Specifically, at this total filter depth, NZ-BAF

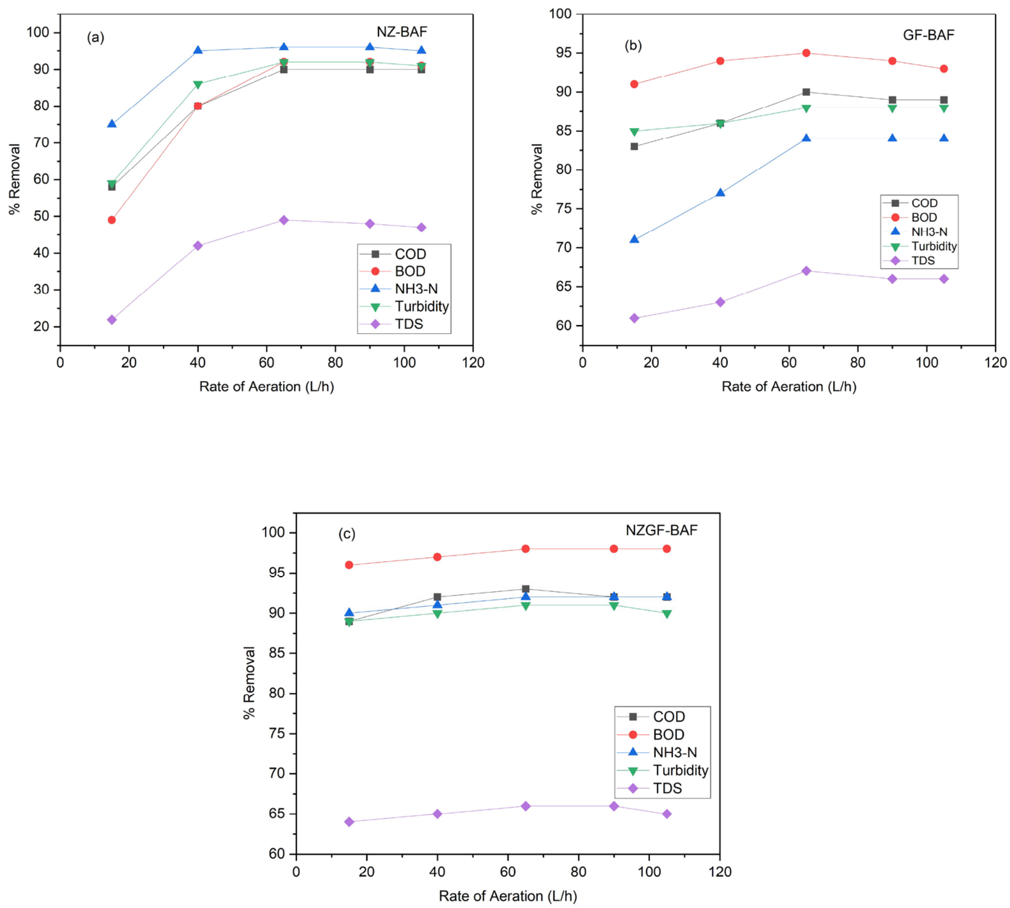


Fig. 6: Effect of various rates of aeration on (a) NZ-BAF, (b) GF-BAF, (c) NZGF-BAF.

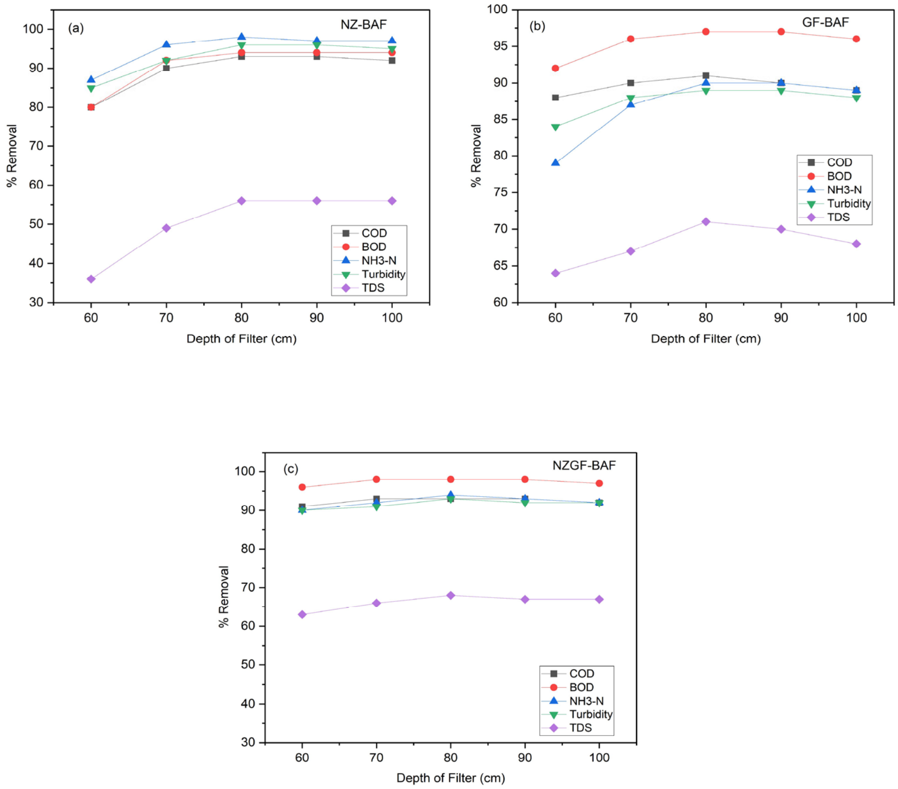


Fig. 7: Effect of variation in the depth of filter on (a) NZ-BAF, (b) GF-BAF, (c) NZGF-BAF.

achieved maximum removal efficiencies of 93% for COD, 96% for BOD, 98% for NH_3-N, 96% for turbidity, and 56% for TDS. GF-BAF recorded removal efficiencies of 91% for COD, 97% for BOD, 90% for NH_3-N, 89% for turbidity, and 71% for TDS. Meanwhile, NZGF-BAF with combined media exhibited maximum removal efficiencies of 93% for COD, 98% for BOD, 94% for NH_3-N, 93% for turbidity, and 68% for TDS.

A higher percentage removal was observed across all process parameters in the BAF systems when the filter bed's depth was increased from 60 cm to 80 cm. However, the improvement in removal efficiency was not significant beyond a depth of 80 cm. Over time, biomass accumulation in the filter bed leads to a decline in the bio-filter's performance. Organic matter buildup in the deeper filter bed results in increased pressure, which can cause uneven distribution of influent and air within the filter bed, as noted by Qamaruz-Zaman et al. (2020).

3.1.5. Media Type

Compared to NZ-BAF and GF-BAF, the NZGF-BAF with dual media exhibited strong performance. The optimal results for NZGF-BAF were achieved at an HRT of 3 hours, a C/N ratio of 6, an aeration rate of 65 $L.h^{-1}$, and a filter depth of 80 cm. Table 2 presents a comparison of the performance of the BAFs based on media types.

The percentage removal of COD, BOD, NH_3-N, turbidity, and TDS for NZ-BAF at an HRT of 3 hours, a C/N ratio of 6, an aeration rate of 65 $L.h^{-1}$, and a filter depth of 80 cm was 93%, 96%, 98%, 96%, and 56%, respectively. Under the same operational conditions, GF-BAF achieved removal efficiencies of 91%, 97%, 90%, 89%, and 71%, respectively. The NZGF-BAF demonstrated the highest removal percentages for COD, BOD, NH3-N, turbidity, and TDS, reaching 93%, 98%, 94%, 93%, and 67%, respectively. Although COD and BOD removals were comparable across NZ-BAF, GF-BAF, and NZGF-BAF, NH_3-N and turbidity removal efficiencies were higher in NZ-BAF due to its ion-exchange properties. Conversely, TDS removal was greater in GF-BAF, attributable to biofilm formation and bacterial

Table 2: Comparison of the performance of BAFs based on media types.

Media Type	Process Parameters				
	COD	BOD	NH_3-N	Turbidity	TDS
NZ-BAF	93%	96%	98%	96%	56%
GF-BAF	91%	97%	90%	89%	71%
NZGF-BAF	93%	98%	94%	93%	67%

activity within the finer pores of the media. Overall, the dual-media NZGF-BAF, combining natural zeolite and geo-fabric, exhibited superior performance in removing all process parameters, leading to further optimization using RSM in Minitab 19.

3.2. Optimization of NZGF-BAF System

Minitab 19 software was utilized to analyze and optimize the performance of the NZGF-BAF system. This version of Minitab supports regression modeling, statistical analysis, and the visualization of relationships between variables. To assess the impact of key independent variables, namely HRT, C/N ratio, aeration rate, and filter depth, on system performance, a total of 30 systematically designed experimental runs were conducted using Central Composite Design (CCD). This approach enables the development of a response surface model (RSM) and facilitates understanding the interactions between critical operational parameters and process parameter removal. The five coded levels and their corresponding experimental ranges for the independent variables are summarized in Table 3.

A regression model is employed to mathematically express the response as a function of the independent variables. The following general quadratic model equation (1) is used to predict and obtain the optimal response.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k}\sum_{j=1}^{k} \beta_{ij} X_i X_j + \varepsilon \quad \ldots(1)$$

where Y represents the predicted response (% removal), β0 denotes the constant regression coefficient (intercept), βi is the linear coefficient, βii is the quadratic coefficient, and βij signifies the interaction coefficient. Variables i and j are coded values for the independent variables, while k indicates the total number of process variables included in the study.

The equations (2), (3), (4), (5), and (6) represents the second-order quadratic regression models developed using RSM to predict the percentage removal of COD, BOD, NH_3–N, turbidity, and TDS in the NZGF-BAF system as functions of HRT, C/N (C/N ratio), ROA (Rate of Aeration), and DOF (Depth of Filter).

% Removal of COD = 77 + 59.1 HRT - 11.4 C/N - 6.73 ROA+ 4.01 DOF - 8.817 HRT * HRT + 0.065 C/N * C/N + 0.0252 ROA * ROA - 0.02457 DOF * DOF - 1.175 HRT * C/N + 0.390 HRT * ROA - 0.1262 HRT * DOF + 0.179 C/N * ROA + 0.0445 C/N * DOF + 0.0060 ROA * DOF …(2)

% Removal of BOD = 93 + 21.7 HRT - 0.2 C/N- 7.41 ROA+ 5.10 DOF - 9.218 HRT * HRT+ 0.523 C/N * C/N + 0.0370 ROA * ROA - 0.03320 DOF * DOF - 1.225 HRT * C/N + 0.610 HRT * ROA + 0.1900 HRT * DOF + 0.007 C/N * ROA - 0.0055 C/N * DOF - 0.0025 ROA * DOF …(3)

% Removal of NH_3-N = 91+ 21.3 HRT- 1.4 C/N - 7.30 ROA+ 5.07 DOF - 9.211 HRT * HRT+ 0.467 C/N * C/N + 0.0350 ROA * ROA - 0.03298 DOF * DOF - 1.210 HRT * C/N + 0.615 HRT * ROA+ 0.1895 HRT * DOF + 0.036 C/N * ROA - 0.0090 C/N * DOF - 0.0023 ROA * DOF …(4)

% Removal of Turbidity = 76+ 22.4 HRT + 1.1 C/N - 7.13 ROA + 5.03 DOF - 9.220 HRT * HRT+ 0.422 C/N *C/N + 0.0350 ROA * ROA - 0.03268 DOF * DOF - 1.347 HRT * C/N+ 0.611 HRT * ROA+ 0.1903 HRT * DOF + 0.011 C/N * ROA - 0.0063 C/N * DOF - 0.0027 ROA * DOF …(5)

% Removal of TDS = 79 + 36.5 HRT - 5.8 C/N - 5.08 ROA + 2.49 DOF - 10.389 HRT * HRT + 0.636 C/N * C/N + 0.0018 ROA * ROA - 0.02303 DOF * DOF - 4.77 HRT * C/N + 0.834 HRT * ROA + 0.167 HRT * DOF + 0.177 C/N * ROA + 0.069 C/N * DOF + 0.0062 ROA * DOF …(6)

Analysis of Variance (ANOVA) was employed to assess the performance of the NZGF-BAF system utilizing dual media, with results presented in Tables 4 to 8. The developed equation was validated through ANOVA and model adequacy diagnostics, confirming its statistical significance and predictive accuracy.

The p-values derived from the ANOVA tables are instrumental in assessing the significance of the model within the statistical analysis. In this research, all regression models for the process parameters exhibited p-values below the predetermined significance threshold ($\alpha = 0.05$). Additionally, the linear and quadratic terms for COD, BOD, NH_3-N, turbidity, and TDS each had p-values of 0.000, underscoring the importance of both the primary and quadratic effects of these operating parameters on

Table 3: Five levels and experimental range of independent variables α.

Symbol Coded	Independent Variables (Operational Parameters)	Unit	Range of actual independent variables				
			-α	-1	0	+1	+α
HRT	HRT	h	1.5	2.5	3.5	4.5	5.5
C/N	C/N Ratio	-	4.5	5.5	6.5	7.5	8.5
ROA	Rate of Aeration	$L.h^{-1}$	55	60	65	70	75
DOF	Depth of Filter	cm	60	70	80	90	100

Table 4: ANOVA for percentage removal of COD.

Source of variation	Degrees of freedom [DF]	Sum of squares [SS]	F-value	p-value
Regression	14	1526.77	32.41	0.000
Linear	4	971.17	72.16	0.000
Square	4	524.13	38.94	0.000
Interaction	6	31.46	1.56	0.241
Residual error	12	40.38		
Lack of Fit	10	37.96	3.14	0.266
Pure Error	2	2.42		
Total	26	1567.14		

Table 5: ANOVA for percentage removal of BOD.

Source of variation	Degrees of freedom [DF]	Sum of squares [SS]	F-value	p-value
Regression	14	1618.40	66.26	0.000
Linear	4	947.62	135.79	0.000
Square	4	613.05	87.85	0.000
Interaction	6	57.73	5.52	0.006
Residual error	12	20.94		
Lack of Fit	10	18.52	1.53	0.459
Pure Error	2	2.42		
Total	26	1639.34		

Table 6: ANOVA for percentage removal of NH_3-N.

Source of variation	Degrees of freedom [DF]	Sum of squares [SS]	F-value	p-value
Regression	14	1610.56	63.04	0.000
Linear	4	945.01	129.45	0.000
Square	4	607.29	83.19	0.000
Interaction	6	58.26	5.32	0.007
Residual error	12	21.90		
Lack of Fit	10	19.48	1.61	0.443
Pure Error	2	2.42		
Total	26	1632.46		

treatment performance. Conversely, the interaction term for COD demonstrated less statistical significance ($p = 0.241$), indicating that the combined effects of the factors are comparatively less impactful. The lack-of-fit p-values for COD (0.266), BOD (0.459), NH_3–N (0.443), turbidity (0.439), and TDS (0.205) exceeded 0.05, which suggests that the lack of fit is statistically non-significant and that the quadratic model reliably represents the experimental data. Overall, the developed models are statistically significant, confirming that the chosen independent variables significantly influence the responses—specifically, the removal efficiencies of COD, BOD, NH_3–N, turbidity, and TDS.

Table 7: ANOVA for percentage removal of turbidity.

Source of variation	Degrees of freedom [DF]	Sum of squares [SS]	F-value	p-value
Regression	14	1619.40	60.43	0.000
Linear	4	954.18	124.61	0.000
Square	4	606.10	79.16	0.000
Interaction	6	59.11	5.15x	0.008
Residual error	12	22.97		
Lack of Fit	10	20.46	1.63	0.439
Pure Error	2	2.51		
Total	26	1642.37		

Table 8: ANOVA for percentage removal of TDS.

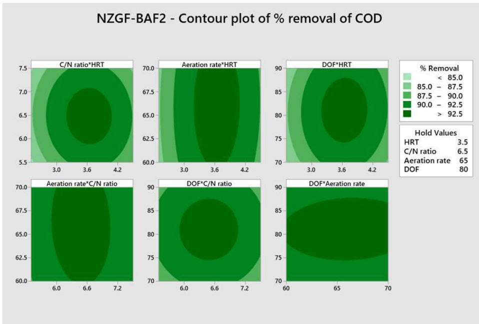
Source of variation	Degrees of freedom [DF]	Sum of squares [SS]	F-value	p-value
Regression	14	2109.27	33.58	0.000
Linear	4	1215.54	67.73	0.000
Square	4	716.78	39.94	0.000
Interaction	6	176.95	6.57	0.003
Residual error	12	53.84		
Lack of Fit	10	51.42	4.25	0.205
Pure Error	2	2.42		
Total	26	2163.11		

Table 9 displays the model summary for the removal efficiencies of COD, BOD, NH_3-N, turbidity, and TDS. The coefficient of determination (R^2) is a statistical metric that assesses how well a model explains the variability in the data. Higher R^2 values indicate better model fit. The models achieved R^2 values of 97.43%, 98.72%, 98.66%, 98.6%, and 97.5% for the removal of COD, BOD, NH_3-N, turbidity, and TDS, respectively. These high R^2 values demonstrate that the models effectively capture the variance in the percentage removal of each parameter. The adjusted R^2 values closely aligned with the R^2 values across all responses, indicating that the models are not overfitted and that the included factors are statistically significant. Similarly, the predicted R^2 values showed reasonable agreement with the adjusted R^2, confirming the models' good predictive ability. Although the predicted R^2 for COD (85.70%) and TDS (86.06%) was slightly lower than for other responses, they still fall within acceptable limits, indicating satisfactory external predictability.

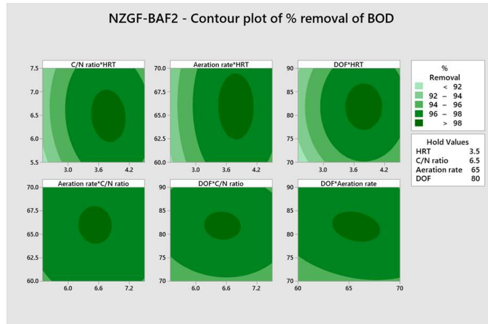
Contour plots derived from the experimental results were utilized to illustrate the responses generated by RSM. These plots depict the simultaneous effects of two variables or operational parameters on the responses. The specific correlations examined include HRT versus C/N ratio, rate of aeration versus C/N ratio, depth of filter versus C/N ratio,

Table 9: Model summary for percentage removal of COD, BOD, NH_3–N, turbidity, and TDS

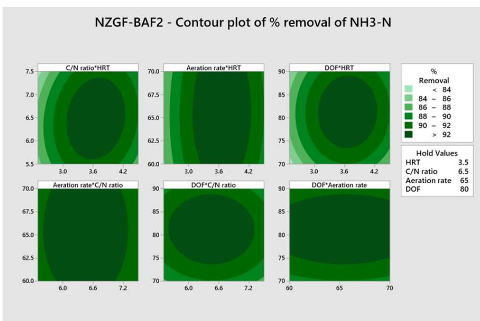
Model Summary for % removal of	Standard Deviation	R^2 [%]	Adjusted R^2 [%]	Estimated R^2 [%]
COD	1.83	97.43	94.42	85.70
BOD	1.32	98.72	97.23	93.16
NH_3–N	1.35	98.66	97.09	92.79
Turbidity	1.38	98.60	96.97	92.48
TDS	2.12	97.50	94.61	86.06



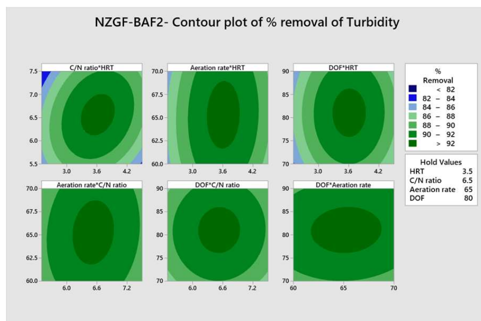
(a)



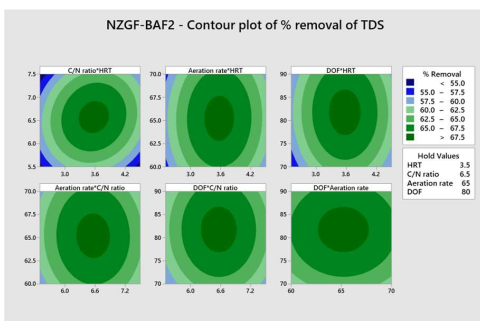
(b)



(c)



(d)

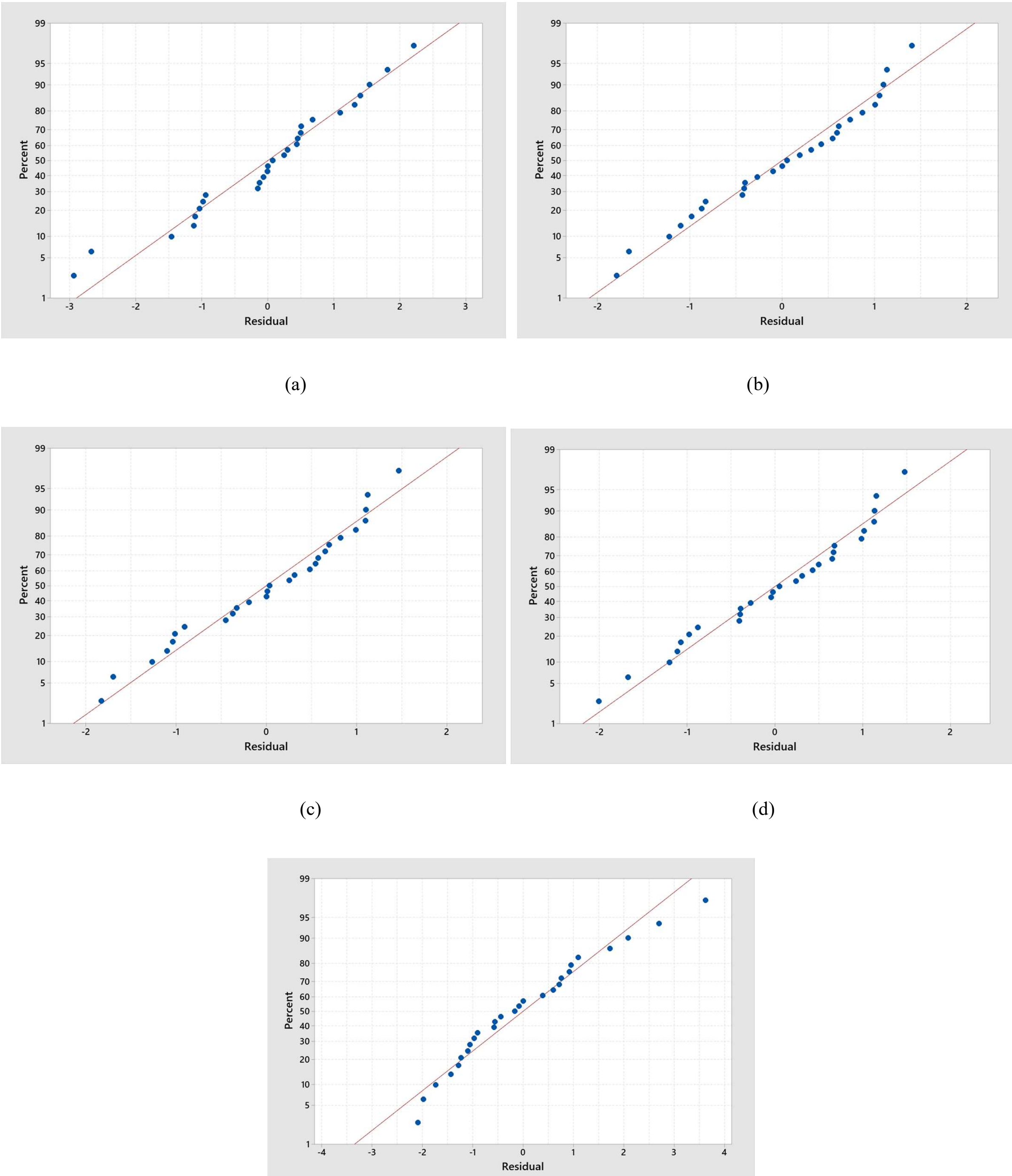


(e)

Fig. 8: Contour plot for percentage removal of (a) COD, (b) BOD, (c) NH_3–N, (d) turbidity, and (e) TDS.

rate of aeration versus HRT, depth of filter versus HRT, and depth of filter versus rate of aeration. These contour plots are shown in Fig. 8 (a–e).

The residual plots in RSM were analyzed to evaluate the adequacy of the model. The normal probability plots for various process parameters are displayed in Fig. 9 (a-e),



(a) (b) (c) (d) (e)

Fig. 9: Residual plot for removal of (a) COD, (b) BOD, (c) NH_3-N, (d) Turbidity and (e) TDS.

indicating that the residuals exhibit a linear pattern. This suggests that the residuals are roughly normally distributed, fulfilling a fundamental assumption of ANOVA and regression analysis.

3.3. Optimized Condition Validation

Based on the results obtained from the RSM optimizer, the maximum percentage removal was achieved for COD, BOD,

Table 10: Comparison of percentage removal for predicted values and experimental results for NZGF-BAF.

Percentage Removal	Process Parameters				
	COD	BOD	NH_3-N	Turbidity	TDS
Theoretically Predicted Value by RSM (%)	94	98	94	93	68
Experimental Value (%)	93	98	94	93	67

NH_3-N, turbidity, and TDS at 93%, 98%, 94%, 93%, and 68%, respectively, under conditions of 3.7 hours HRT, a C/N ratio of 6.5, an aeration rate of 66.2 $L.h^{-1}$, and a filter depth of 81.7 cm. An additional laboratory experiment was conducted under these optimal conditions predicted by the RSM model to evaluate the performance of NZGF-BAF. The final test was performed with the same parameters: HRT of 3.7 h, C/N of 6.5, aeration rate of 66.2 $L.h^{-1}$, and filter depth of 81.7 cm. The experimental results were analyzed and compared to the predicted removal efficiencies provided by the RSM model. These removal percentages are summarized in Table 10. This comparison allows for an assessment of how closely the experimental outcomes align with the model's predictions under optimal conditions. The accuracy of the RSM model in representing system performance can be evaluated by comparing the predicted and experimental data.

4. CONCLUSIONS

The effectiveness of a dual-media biologically aerated filter (BAF), comprising geo-fabric and natural zeolite (NZGF-BAF), was evaluated in this study in comparison to single-media BAFs containing either natural zeolite (NZ-BAF) or geo-fabric (GF-BAF). The performance of these BAF systems in greywater treatment depends on various operational parameters such as hydraulic retention time (HRT), carbon-to-nitrogen (C/N) ratio, aeration rate, and filter depth. The NZ-BAF, using natural zeolite particles of 1-3 mm, and the GF-BAF, with geo-fabric of 500 GSM, showed comparable results in removing COD, BOD, and turbidity. However, due to ion-exchange capabilities, NZ-BAF achieved higher removal of NH_3-N, while GF-BAF excelled in TDS removal owing to permeability, adsorption, biofilm formation, and bacterial activity within the finer pores of its media. The dual media filter, NZGF-BAF, promotes processes such as absorption, adsorption, ion exchange, and biofilm development, leading to enhanced contaminant removal. To optimize the treatment process, Response Surface Methodology (RSM) was employed to determine the optimal operational parameters—HRT, C/N ratio, aeration rate, and filter depth—for maximum removal efficiency of contaminants including COD, BOD, NH_3-N, turbidity, and TDS. Under optimized conditions (HRT of 3.7 hours, C/N ratio of 6.5, aeration rate of 66.2 $L.h^{-1}$, and filter depth of 81.7 cm), the NZGF-BAF system achieved removal efficiencies of 93% for COD, 98% for BOD, 94% for NH_3-N, 93% for turbidity, and 67% for TDS. These results demonstrate that the NZGF-BAF system has significant potential for efficient greywater treatment in controlled laboratory settings. Nevertheless, given the variability of actual greywater composition, further studies involving real greywater under practical conditions are necessary to validate its applicability in real-world scenarios.

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