

Original Research

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 treatment performance of a dual-media biologically aerated filter (BAF) incorporating natural zeolite and geo-fabric (NZGF-BAF) was investigated and compared with single-media BAF systems using natural zeolite (NZ-BAF) or geo-fabric (GF-BAF) when operated in batch mode. The effect of hydraulic retention time (HRT), carbon-to-nitrogen (C/N) ratio, rate of aeration, and depth of filter on the single and dual media BAF system's performance for removal of contaminants like chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia-nitrogen (NH₃-N), turbidity, and total dissolved solids (TDS) was studied. According to the experimental results, under similar conditions, the NZ-BAF and GF-BAF showed comparable results for removal of COD, BOD, and turbidity due to larger surface areas, biofilm formation, absorption, and adsorption potential. The removal of NH₃-N was higher for NZ-BAF due to its ion-exchange property and GF-BAF showed better removal of TDS due to the permeability, adsorption and bacterial activity. The NZGF-BAF with dual media showed improved performance with respect to the removal of all the contaminants. Further, an optimization study conducted on NZGF-BAF using Response Surface Methodology (RSM) under optimal conditions achieved maximum removal rates of COD, BOD, NH₃-N, turbidity, and TDS as 93%, 98%, 94%, 93% and 67%, respectively.

1. INTRODUCTION

Aerobic biological processes have been developed in wastewater treatment to reduce environmental contaminant discharge levels and to economically remove the bulk of dissolved and suspended organic pollutants using mechanisms such as organic decomposition, surface adsorption, and sedimentation (Huang et al. 2017).

Aerobic biological treatment methods include activated sludge processes, trickling filters, membrane bioreactors (MBR), moving bed biofilm reactors (MBBR), biologically aerated filters (BAF), etc. Both the traditional activated sludge process and the carrier-added activated sludge (CAS) method generate excess sludge as a byproduct that must be routinely removed from the system, necessitating the use of a large liquid-solid separation unit. Furthermore, wastewater is nitrified more successfully by fixed film techniques than by activated sludge techniques. In order to settle the sludge that is wasted due to sloughing, treatment systems like trickling filters and bio-towers also require secondary sedimentation, which makes them larger and more expensive wastewater treatment systems (Doelle et al. 2020). Membrane bioreactors (MBR) have been used more and more over the years due to their advantages over CAS, including their compact footprint and good effluent quality (Van de Staey et al. 2015). Membrane fouling, aeration limitations, and high construction and operating costs are some of the disadvantages of MBR systems. The membrane needs to be chemically cleaned frequently in order to stay permeable. Additionally, because of abrasion and reduced efficiency, the membranes will eventually need to be replaced (Krzeminski et al. 2012). Even though MBBR systems have many advantages, they can also cause foaming and turbidity by growing filaments in the free liquid. Under these conditions, excessive biomass accumulation can lead to a reduction in void space, which in turn impedes oxygen transfer and substrate diffusion within the biomass. Furthermore, the plastic media will eventually need to be replaced because it is prone to abrasion.

The ability of the BAF system to effectively remove solids, carbon, nitrogen, and phosphorus from wastewaters has made it a significant wastewater treatment technology. This is accomplished by combining biological and physical processes to produce an effluent that can be reused or safely released into the environment (Mendoza-Espinosa et al. 1999, Jacob et al. 1997). The compact design of a BAF system, its ability to treat a variety of wastewater types, ease of operation and maintenance, energy efficiency when compared to other treatment methods and ability to remove multiple contaminants simultaneously are some of its main advantages. BAF systems are excellent at eliminating organic matter from wastewater since they have a high biomass concentration affixed to the filter media. Organic pollutants are efficiently broken down in a single unit by the biological treatment process, which significantly lowers the organic content of wastewater (Fu et al. 2016). Bio-filter systems exhibit adaptability by functioning well in a variety of environmental circumstances, such as changes in pH and temperature. Because of their versatility, they can be used in a variety of climates and geographical areas. The operational flexibility of BAF systems enables modifications to account for different influent characteristics, such as variations in wastewater composition and flow rates. These systems usually produce less sludge, which can make residual sludge management and disposal easier and lessen the environmental impact of sludge handling. Another benefit of bio-filter systems is that they are non-polluting and run quietly (Nacheva et al. 2008).

When designing and operating a BAF system, selecting an appropriate support medium is essential. In order to guarantee that the discharged effluent is safe for the environment and conforms with health and

environmental regulations, regulatory bodies set effluent quality standards, and choosing the appropriate filter media is crucial in meeting these standards (Tan et al. 2008). For wastewater treatment to be effective, media characteristics such as permeability, pore size, and type are essential (Kent et al. 2000, Sychała et al. 2013).

Natural zeolite-based biologically aerated filters (NZ-BAFs) are an advanced form of submerged biofilters, utilizing natural zeolite as the principal support medium. Natural zeolite consists of hydrated alumino-silicates having a honeycomb structure. Tetrahedra of SiO_4 and AlO_4 make up the three-dimensional structure of the zeolite, which are interconnected by common oxygen atoms (Adam et al. 2023). A negative charge density is produced inside the tiny pores by the isomorphous substitution of Al^{3+} ions for Si^{4+} ions, which serves as effective cation exchange sites (Widiastuti et al. 2011). For wastewater contaminants like ammonium ions, they act as selective cation exchange materials. Natural zeolites have a large specific surface area and high porosity, which facilitates adsorption and the capacity to form biofilms through bacterial attachment. Larger organic molecules that are found in dissolved or colloidal forms are unable to pass through the zeolite's tiny pores and adhere to its surface. Microorganisms such as bacteria become caught between the pores of the intraparticle. As a result, the vast surface area aids in sustaining a high number of active bacteria for the breakdown of organic materials in wastewater. The size, shape, and surface roughness of the media also affect how well the BAF system performs. Zeolite media's rough surface gives bacteria more surface area on which it adheres and form biofilms (Sychała et al. 2013). Additionally, the zeolite media's uneven surface shows enhanced performance as compared to any other spherical media. Natural zeolite is a very effective support medium for wastewater treatment because of its inertness, low cost, non-metallic character, and non-toxic nature. Natural zeolite-based BAF loses its efficiency only after operation for a long duration. The regenerative property of natural zeolites using NaCl , KCl , acids and by heating is a further advantage.

Geo-fabrics are long-lasting polymeric materials made for a range of environmental and civil engineering applications. In wastewater treatment, namely in bio-film reactors, the use of geo-fabric as support media is a newly emerging area of research. Synthetic polymers like polyester (PET) and polypropylene (PP) are commonly used to make geo-fabric. They are available in both woven and non-woven forms. The intricate fiber structure of non-woven needle-punched geo-fabrics has shown remarkable effectiveness in trapping suspended solids and other large materials. Due to their superior strength, porosity, flexibility, durability, resistance to environmental conditions, and capacity to endure the stresses, geo-fabrics are preferred over alternative media like sand, crushed rock, river gravel, granular activated carbon (GAC), or some type of plastic or ceramic material (Praveen et al. 2008, Revathi et al. 2016). The large specific area of geo-fabrics makes them effective media in filtration and adsorption applications. Its filamentous structure facilitates the quick bacterial adhesion and biofilm development (Alimahmoodi et al. 2012). In processes where bacteria aid in the breakdown of organic matter in wastewater, the wetting ability of geo-fabrics also promotes bacterial adherence. The environmental impact is also reduced by the biodegradable and eco-friendly nature of geo-fabric.

Oxygen is essential for the breakdown of organic matter (COD and BOD) and the nitrification process ($\text{NH}_3\text{-N}$ removal), so the effectiveness of the aerobic bacteria that remove pollutants is directly correlated with the amount of aeration that is provided. The BAF system requires an effective aeration system with any kind of support media in order to guarantee the best possible performance of the biological processes involved, avoid operational problems, and produce high-quality effluent. Maintaining dissolved oxygen levels and promoting bacterial biofilm development depend on aeration.

The backwash mechanism in a BAF system is crucial for eliminating biomass and particle buildup from the surface of the media, avoiding clogging, preventing mechanical compaction from reducing the media's porosity, and preserving bacterial activity on the biofilm (Charchalac et al. 2015). Energy consumption is reduced and the treatment cycle is prolonged with proper backwashing. Backwashing frequency needs to be carefully controlled. A decrease in biomass due to excessive backwashing may decrease the functionality of the bio-filter. The removal of both BOD and total nitrogen, however, may be diminished by infrequent backwashing (Xie et al. 2004). Backwashing intervals for some bio-filter systems used in secondary treatment might range from 24 to 48 hours (Bacquet et al. 1991), while for other systems, backwashing every 1-2 weeks is adequate (Jacob et al. 1997) to remove extra biomass.

The present study systematically investigates the impact of key operational parameters on the performance of a BAF system employing dual media (natural zeolite and geo-fabric), in comparison with single media configurations (natural zeolite or geo-fabric alone) as biofilm support materials. Treatment efficiency was assessed in terms of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS removal from greywater under batch experimental conditions. While most conventional biofilter media demonstrate satisfactory removal of COD, BOD, and turbidity, the removal efficiencies of $\text{NH}_3\text{-N}$ and TDS are generally lower and often fail to meet permissible discharge standards. The BAF system investigated in this study is designed to function as a compact, efficient, and cost-effective solution for household greywater treatment, minimizing reliance on advanced and expensive treatment technologies such as ion exchange, ultrafiltration, nanofiltration, distillation, or reverse osmosis.

The operational parameters for the operation of the BAF system under research comprise of HRT, C/N ratio, rate of aeration, and depth of media. The efficiency of the system under various hydraulic circumstances can be inferred from the fluctuation in HRT, or the contact time between water and the microbial biofilm. Understanding nutrient availability and how it affects microbial activity and treatment effectiveness is made easier by tracking the effect of the C/N ratio on the dual media BAF. In order to sustain aerobic conditions in the biological filter and encourage the growth of aerobic microorganisms, aeration is crucial. Optimizing the treatment process requires examining how aeration rates affect the effectiveness of BAF. The distribution of microorganisms and the duration of greywater-biofilm contact can be influenced by the filter bed's depth. Analysing the filter's depth affects the bio-filter's functionality and offers information on system design factors.

The system's optimization was examined with the aid of Minitab 19, a program that offers a variety of data analysis features through its Response Surface Model (RSM). Through the use of statistical techniques, mathematical problems are modelled and analysed, allowing for system performance optimization. RSM has the main advantage of requiring fewer experimental trials to assess a greater number of factors and their interactions (Jasni et al. 2020, Lin et al. 2010). RSM is an effective technique for comprehending how various factors interact and determine the ideal operating parameters for the BAF system.

2. MATERIALS AND METHODS

2.1. Lab-scale Setup

A lab-scale bio-filter system was used to assess the feasibility of the proposed single and dual media-based bio-filter system. This system was constructed as a rigid, clear glass column that made it possible to visually observe and track interior operations. With dimensions of 150 mm × 150 mm and a height of 1200 mm, the column's square cross-section offers an appropriate capacity for testing. Controlled influent distribution and effluent collection are made possible by the placement of an inlet 50 mm from the top of the column and an outlet 50 mm from the bottom. In addition to preventing washout, perforated plates at the top and bottom of the column are utilized to distribute influent and backwash water uniformly. Two cubical glass tanks with dimensions of 300 mm × 300 mm and 300 mm in depth were used. One of them was used as an equalization tank to feed influent, which keeps the greywater flow to the BAF steady and regulated. The second cubical glass tank functioned as a settling basin for the collection of the treated greywater. This makes it possible for suspended materials to separate and settle before the effluent is gathered for safe disposal or reuse. The influent is pumped into the bio-filter column using a submersible pump. An aerator and four air diffusers were positioned equally along the depth of the filter to guarantee adequate aeration throughout the bio-filter column. To avoid clogging and maintain system efficiency, a backwash mechanism is included to periodically remove extra biomass and accumulated solid material. The collected effluent in the settling basin is used as backwash water, which enhances the system's overall sustainability and effectiveness. The experimental setup for the BAF system is schematically represented in Fig. 1.

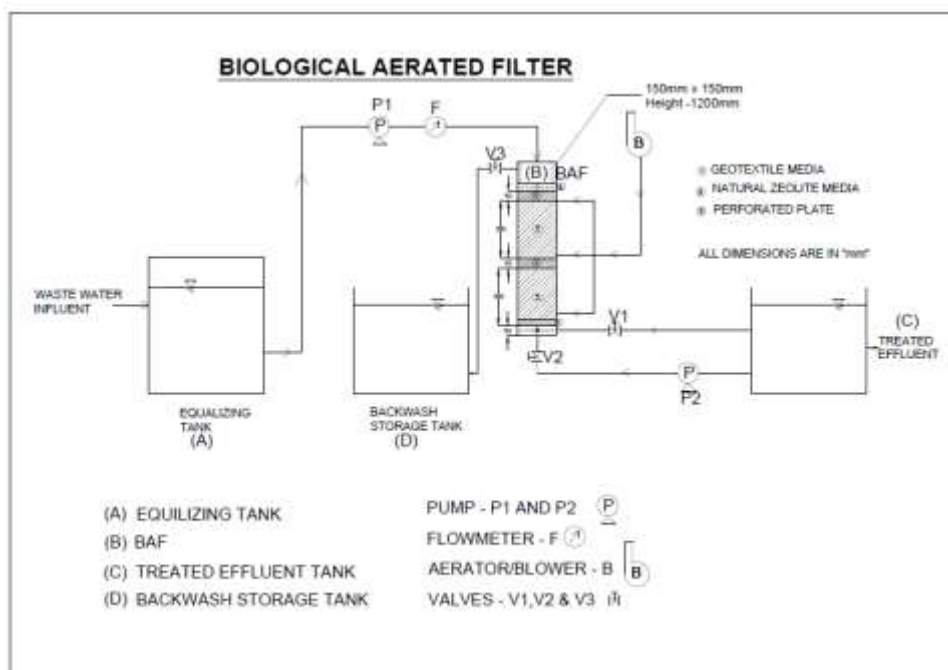


Fig. 1: Experimental setup of the BAF system

2.2. BAF Media

Batch experiments were conducted using a single and dual media BAF filters consisting of natural zeolite and/or geo-fabric as filter media. Natural zeolite of size ranging from 1-3 mm was procured from G. M. Biochem Pvt. Ltd. located at Ahmedabad, Gujarat and non-woven type needle-punched geo-fabric of 500 GSM was produced by Manas Geo Tech India Pvt. Ltd, located in New Delhi, India. Natural zeolites have a tetrahedral structure, having a high cation exchange, adsorption, and absorption capabilities with the ability to form a bio-film on their surface. Geo-fabrics have a complex structure, high porosity, permeability, and high tensile strength. Its fibrous and porous character also fosters the growth of microorganisms. Both materials allow the movement of water through the media while retaining suspended solids and act as excellent filter media. They are cheap, easy to handle and install, and resistant to biological deterioration and other environmental factors.

In the first series of batch experiments, the BAF system is operated using natural zeolite of 1-3 mm particle size as the only filter media, and it is designated as NZ-BAF; in the second series, only geo-fabric of 500 GSM is used as the filter media in the BAF i.e., GF-BAF; and in the third series, a dual media consisting of a combination of natural zeolite (1-3 mm) and geo-fabric (500 GSM) is used in the BAF system i.e., NZGF-BAF. All the operational conditions were similar for the three series of experiments.

2.3. Synthetic Greywater Preparation and Analysis

For the present study, synthetic greywater was employed as the influent to ensure consistency in composition and to eliminate fluctuations in influent characteristics across the experimental runs carried out for NZ-

BAF, GF-BAF, and NZGF-BAF systems. The synthetic greywater was prepared by combining definite quantities of chemical products such as glucose (300 mg/L), sodium acetate trihydrate (400 mg/L), ammonium chloride (225 mg/L), disodium hydrogen phosphate (150 mg/L), potassium dihydrogen phosphate (75 mg/L), and magnesium sulphate (50 mg/L) with one litre of distilled water. The physicochemical characteristics of the synthetic greywater used as influent, along with its variability in terms of low, high, mean, and standard deviation values, are presented in Table 1. Then, physicochemical parameters were examined before and after treatment to assess the percentage removal of the contaminants. The analysis was carried out in compliance with accepted Standard Methods (APHA, 2017).

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	33	368	527	446.2	71.7
BOD	mg/L	33	203	231	216.2	11.3
NH ₃ -N	mg/L	33	15	18	16.42	1.19
Turbidity	NTU	33	46	85	63.5	14
TDS	mg/L	33	547	609	575.8	24.1

2.4. Bacterial Inoculation and Acclimation

The synthetic greywater prepared was combined with seed inoculum from the activated sludge of the sewage treatment plant in order to shorten the startup time and encourage the growth of microorganisms. Additionally, the mixture was supplemented with nutrients for aerobic bacteria. Prior to the commencement of each experimental series, the respective media were subjected to a 21-day bacterial acclimation period to facilitate biofilm development and stabilization. To ensure that the system had enough oxygen, aeration was supplied initially at a rate of 15 L/h. The effluent COD level stayed low and stable after the acclimation period, suggesting the development of a possible bio-film on the media.

Following the acclimatization phase, each system was operated under various operating conditions in order to maximize treatment efficiency and comprehend the sensitivity of the system. The system was operated at an organic loading rate of 3.95 – 4.5 kg BOD/m³·day, calculated based on an initial BOD concentration of 203 mg/l (low) and 231 mg/L (high) for the synthetic greywater. The performance of single and dual media BAFs was examined under similar operational conditions by varying the HRT, C/N ratio, rate of aeration, and depth of filter medium. The following section presents and discusses the results and observations obtained.

3. RESULTS AND DISCUSSION

Batch experiments were carried out using BAF systems with different media configurations, namely NZ-BAF, GF-BAF, and NZGF-BAF to evaluate their comparative treatment performance. The reactors were operated independently under varying operational parameters, including HRT, C/N ratio, aeration rate, and filter

media depth. The system performance was assessed based on the removal efficiencies of key process parameters, namely COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS.

To further understand the role of media characteristics in pollutant removal, scanning electron microscopy (SEM) analysis was conducted on natural zeolite (1–3 mm particle size) and geo-fabric (500 GSM) before and after treatment. The SEM micrographs of natural zeolite and geo-fabric, presented in Fig. 2(a–b) and Fig. 3(a–b), respectively, clearly exhibit distinct surface modifications after operation, indicating structural changes associated with biofilm growth and contaminant deposition.

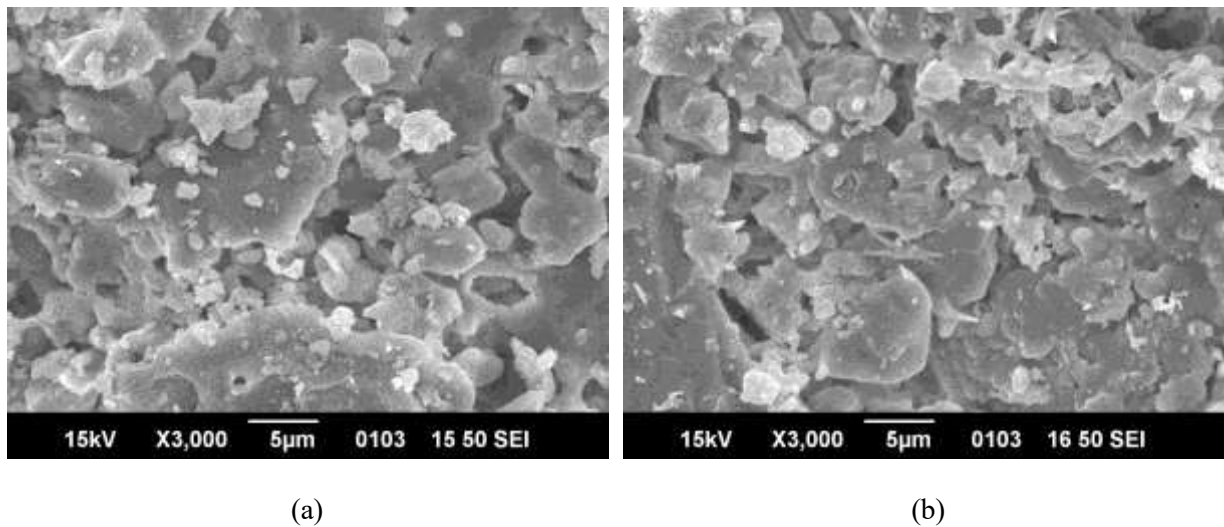


Fig. 2: SEM of natural zeolite 1-3 mm (a) Before treatment (b) After treatment

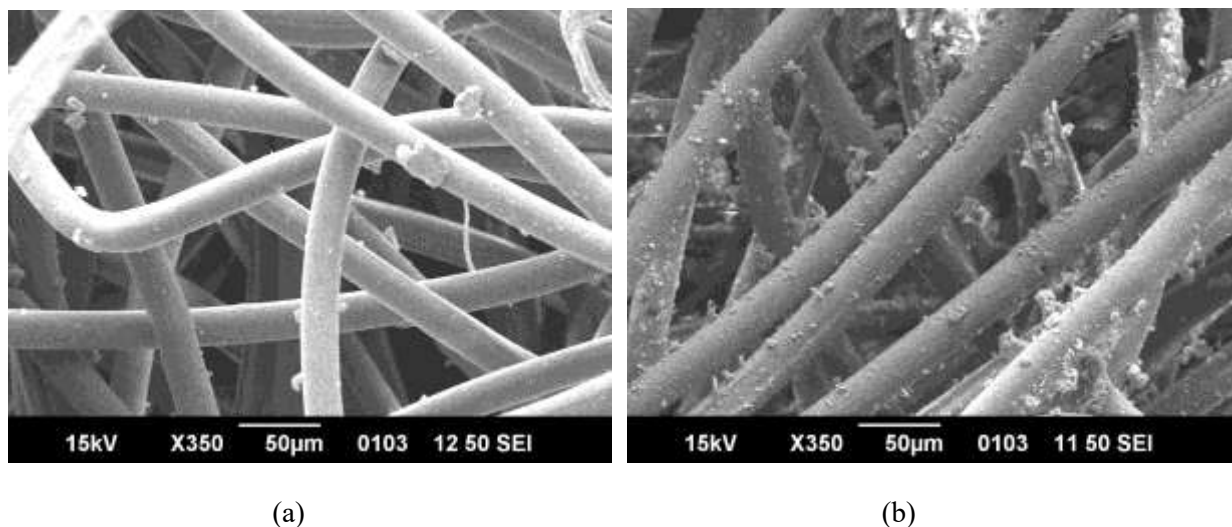


Fig. 3: SEM of geo-fabric media of 500 GSM (a) Before treatment (b) After treatment

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 type of BAF, i.e., NZ-BAF, GF-BAF, and NZGF-BAF, in order to evaluate the impact of HRT on the BAF's performance and determine the optimum HRT, all other variables, including the C/N ratio, aeration rate, and depth of filter medium, were kept constant at 6, 65 L/h, and 70 cm, respectively. In the single media systems, natural zeolite and geo-fabric each occupied the filter depth of 70 cm in the NZ-BAF and GF-BAF reactors, respectively. In contrast, the dual media NZGF-BAF configuration consisted of a stratified arrangement, with a 30 cm bottom layer of natural zeolite and a 40 cm top layer of geo-fabric, maintaining a total filter depth of 70 cm. After every operational period, the effluent's properties are ascertained. Initially, the NZ-BAF was operated by systematically changing the HRT values, i.e., 1 h, 2 h, 3 h, 4 h, and 5 h. This process was repeated for GF-BAF and NZGF-BAF, and the bio-filter's performance was evaluated in terms of the key process parameters that affect the biological treatment, such as the removal of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS. The maximum percentage removal of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS was recorded at an HRT of 3 h for all the BAF systems. At HRT of 3 h, the percentage removal of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS was found to be 85%, 86%, 95%, 76% and 30% respectively for NZ-BAF, 86%, 94%, 77%, 86% and 63% for GF-BAF and 91%, 98%, 92%, 91%, and 63% for NZGF-BAF. The percentage removal for the process parameters with NZ-BAF, GF-BAF, and NZGF-BAF at different HRTs is displayed in Fig. 4 (a-c).

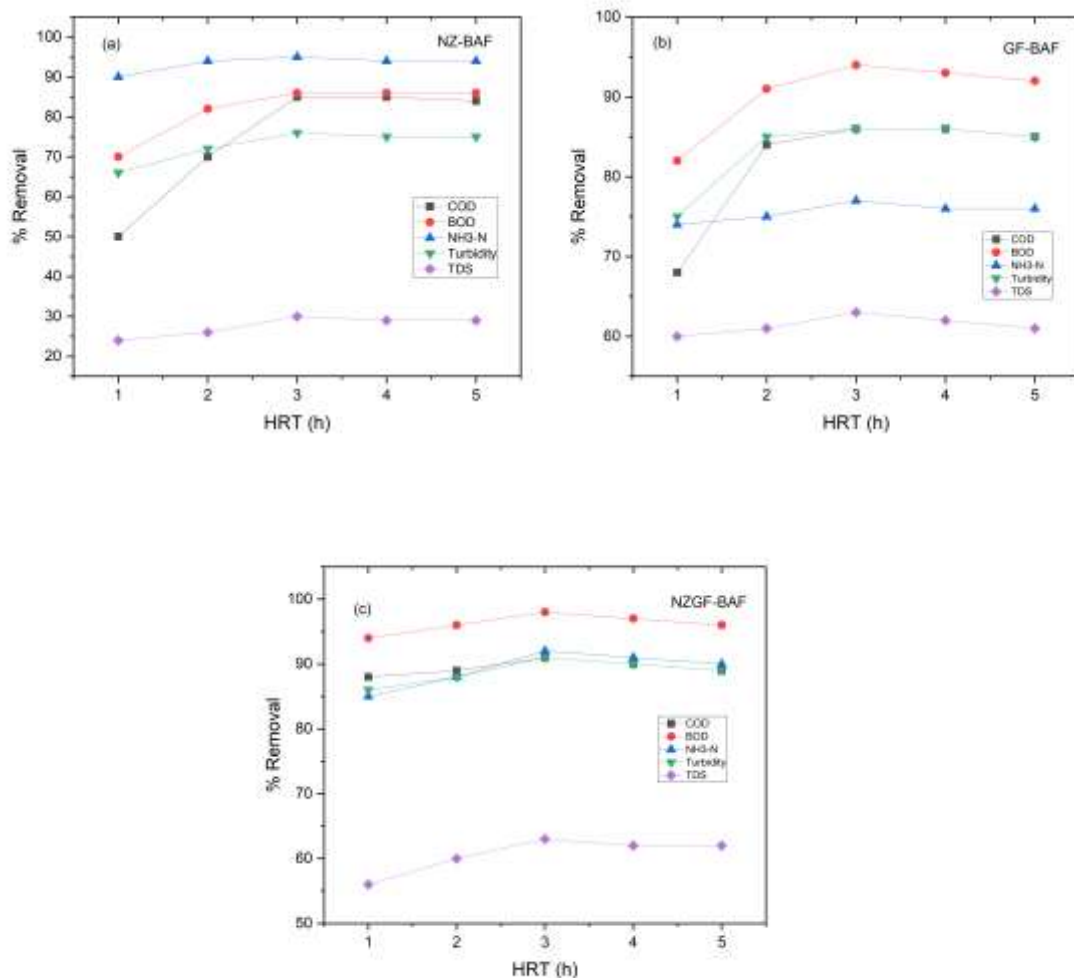


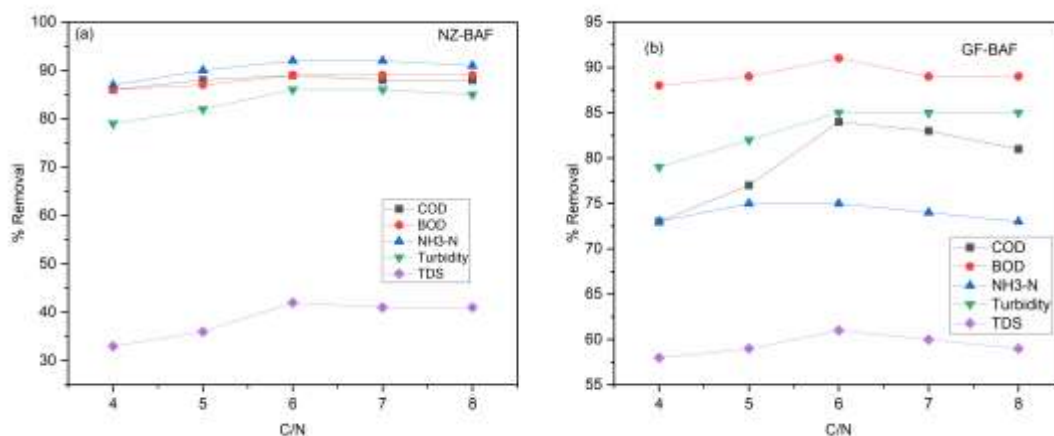
Fig. 4: Effect of the variation in HRT for (a) NZ-BAF, (b) GF-BAF (c) NZGF-BAF

For the BAF systems, pollutant removal efficiency increased when the HRT was extended from 1 h to 3 h. Increasing the HRT further to 4 or 5 h had no discernible effect on pollutant removal. According to this, the optimal removal occurred at 3 h HRT. At first, organic matter was removed rapidly. The absorbent sites available on filter media enable the efficient adsorption of organic contaminants. The rate of organic matter removal declined over time as a result of fewer active sites available. Pollutant removal effectiveness declines as these sites get saturated or deactivated. The benefit of shorter HRTs is that they require less space for bio-filters, which can indirectly result in lower building costs for biofiltration systems.

3.1.2. C/N Ratio

The experiments on NZ-BAF, GF-BAF, and NZGF-BAF were conducted using varying C/N ratio values, namely 4, 5, 6, 7, and 8, with a constant HRT of 3 h, a rate of aeration of 65 L/h, and a filter depth of 70 cm in order to examine the impact of the C/N ratios on the effluent's properties. The effluent properties were examined at the conclusion of each experiment.

According to the test results, the highest percentage removal of contaminants was obtained at a C/N ratio of 6 for NZGF-BAF, NZ-BAF, and GF-BAF. For NZGF-BAF, the highest percentage removals of COD, BOD, NH₃-N, turbidity, and TDS were found to be 93%, 98%, 92%, 91%, and 66%, respectively. The maximum removal of COD, BOD, NH₃-N, turbidity, and TDS was 85%, 85%, 89%, 78% and 30%, respectively, in the NZ-BAF system and was 84%, 91%, 75%, 85% and 61%, respectively for the GF-BAF system. The removal of contaminants for various BAFs at different C/N ratios is shown in Fig. 5(a–c).



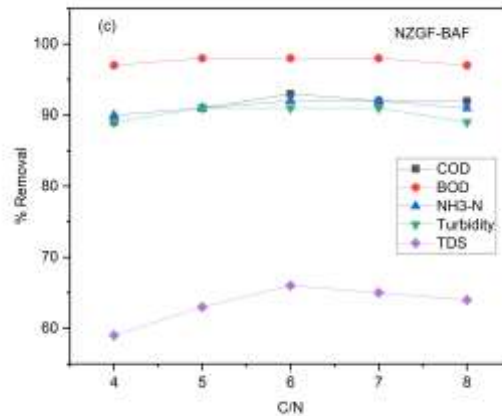


Fig. 5: Effect of various C/N ratios on (a) NZ-BAF, (b) GF-BAF (c) NZGF-BAF

Pollutant removal efficiency of the BAFs was positively impacted by increasing the C/N ratio from 4 to 6. However, the removal efficiency began to decline as the C/N ratio reached 6. Consequently, it was found that the optimal C/N ratio was 6. The porous nature and large surface area of the natural zeolite and geo-fabric media, which offer plenty of room for bacterial colonization and pollutant breakdown, enabled organic matter to effectively interact with 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 now run at various aeration rates (15, 40, 65, 90, and 105 L/h), with the optimum HRT of 3 h and C/N ratio at 6. The media depth was maintained at 70 cm as in earlier experiments. When compared to NZ-BAF and GF-BAF, the performance of NZGF-BAF with dual media was superior at an ideal aeration rate of 65 L/h. The percentage removal of the different process parameters for various filter media types at varying aeration rates is shown in Fig. 6 (a–c). The NZ-BAF had maximum removal values of 90%, 92%, 96%, 92% and 49% for COD, BOD, NH₃-N, turbidity, and TDS, respectively. The GF-BAF reported the highest percentage removal values as 90%, 95%, 84%, 88% and 67% for COD, BOD, NH₃-N, turbidity, and TDS, respectively. The highest removal for COD, BOD, NH₃-N, turbidity, and TDS was obtained for NZGF-BAF, and the corresponding values were 93%, 98%, 92%, 91% and 66%.

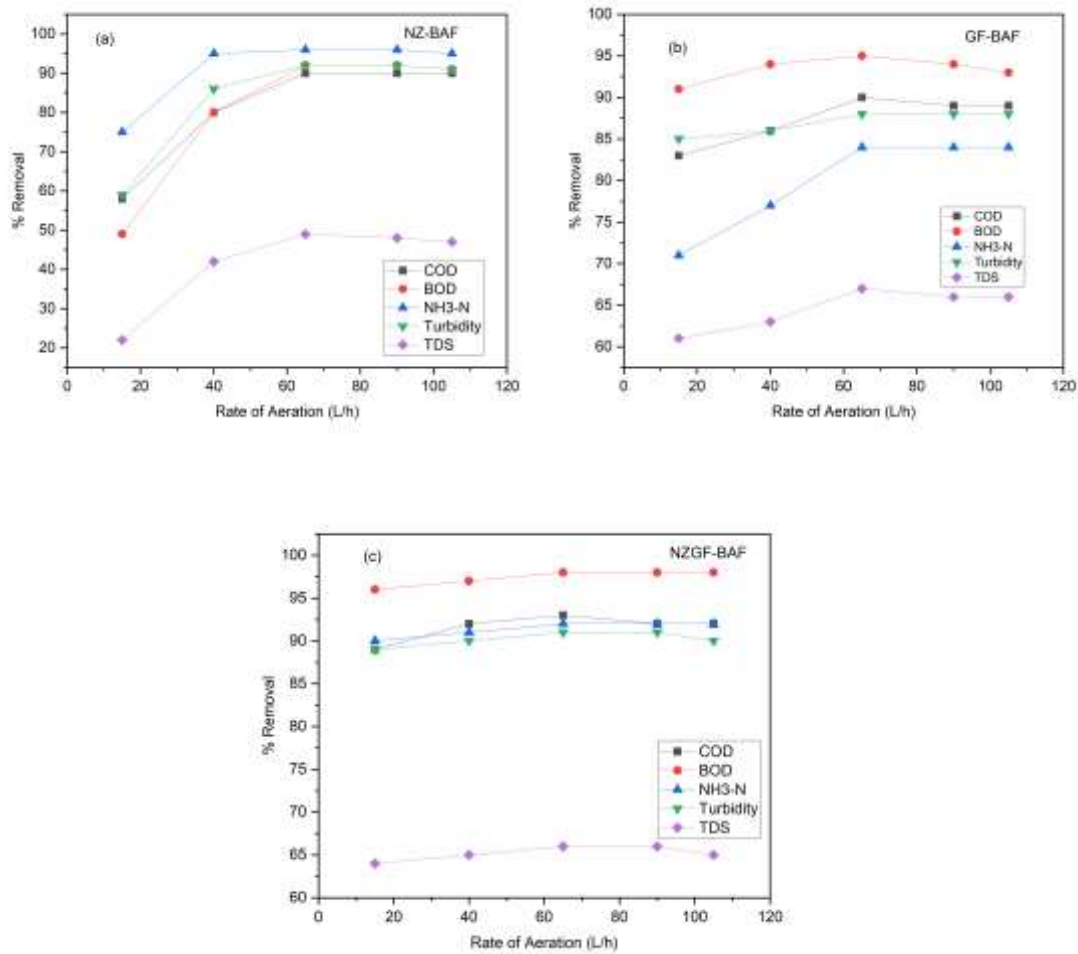


Fig. 6: Effect of various rates of aeration on (a) NZ-BAF, (b) GF-BAF, (c) NZGF-BAF

For all BAF systems, better removal efficiency was shown when aeration was provided at the optimum rate of 65 L/h. There was no discernible improvement in the system's performance when the aeration rate was further increased to 90 or 115 L/h. The experimental data led to the setting of the aeration rate at 65 L/h. This suggests that when there was enough air available to the system, the metabolic activity of the bacteria increased.

3.1.4. Depth of Filter

The performance of the BAF system is strongly influenced by the selection and characteristics of the filter media. To evaluate the effect of filter depth variation on treatment efficiency, the reactors were operated at total media depths of 60, 70, 80, 90, and 100 cm. All systems were maintained at the previously optimized operating conditions of 3 h HRT, a C/N ratio of 6, and an aeration rate of 65 L/h.

In the single media configurations (NZ-BAF and GF-BAF), natural zeolite and geo-fabric, respectively, occupied the entire filter depth corresponding to 60–100 cm. In contrast, the dual-media NZGF-BAF system consisted of a fixed 30 cm bottom layer of natural zeolite, while the thickness of the overlying geo-fabric layer was varied (30, 40, 50, 60, and 70 cm) to achieve total filter depths of 60, 70, 80, 90, and 100 cm, respectively.

At 80 cm of filter depth, all three systems showed maximum removal of contaminants. Fig. 7 (a-c) shows the percentage removal of various process parameters as per the variation in the filter depth for the three systems.

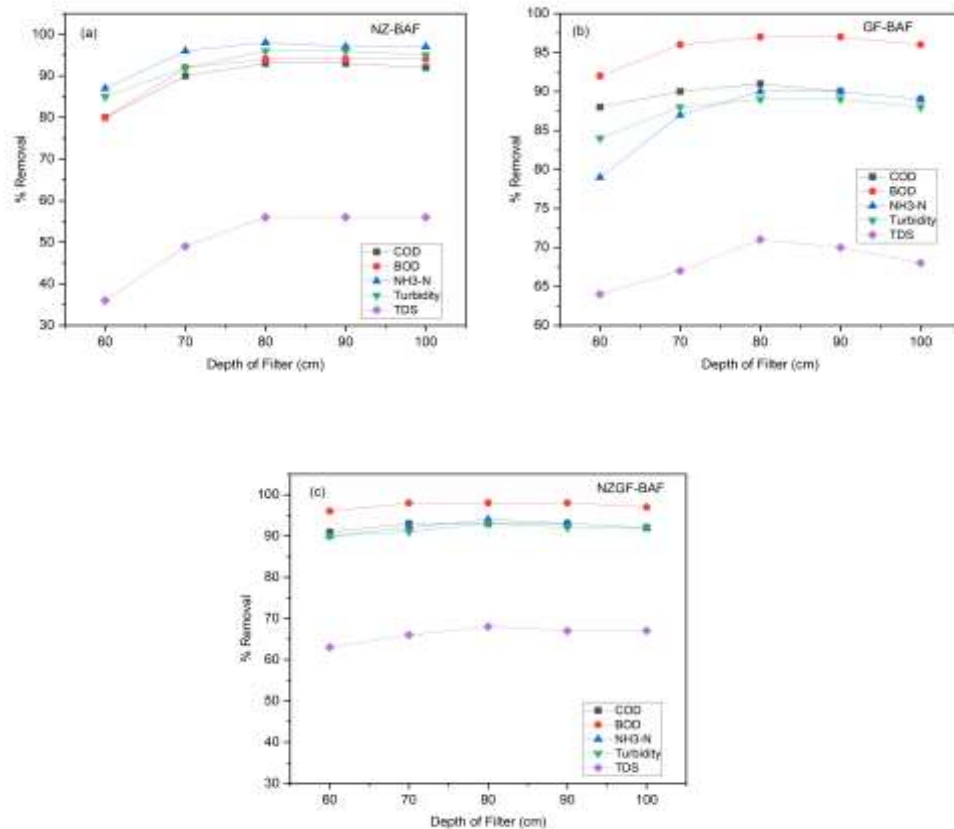


Fig. 7: Effect of variation in the depth of filter on (a) NZ-BAF, (b) GF-BAF (c) NZGF-BAF

The percentage removal of contaminants at 80 cm depth was better for NZGF-BAF than NZ-BAF and GF-BAF. At a total filter depth of 80 cm, the maximum percentage removal of COD, BOD, NH₃-N, turbidity, and TDS using NZ-BAF was found to be 93%, 96%, 98%, 96%, and 56%, respectively. With GF-BAF, the recorded values were 91%, 97%, 90%, 89%, and 71%, respectively. NZGF-BAF with combined media recorded maximum removal efficiency of 93 %, 98 %, 94 %, 93 %, and 68 % for COD, BOD, NH₃-N, turbidity, and TDS, respectively.

Higher percentage removal was achieved for all process parameters in the BAF systems when the filter bed's depth was increased from 60 cm to 80 cm. The percentage removal was not considerable beyond a depth of 80 cm. Over time, biomass buildup in the filter bed causes the bio-filter's performance to decline. The accumulation of organic matter in the deeper filter bed causes the pressure in the filter bed to rise. Pressure buildup in deep filters may result in an uneven distribution of influent and air within the filter bed, according to Qamaruz-Zaman et al. (2020).

3.1.5. Media Type

When compared to NZ-BAF and GF-BAF, the NZGF-BAF with dual media demonstrated good results. For NZGF-BAF, the best results were obtained at an HRT of 3 h, a C/N ratio of 6, an aeration rate of 65 L/h, and a filter depth of 80 cm. Table 2 displays the comparison of the BAFs' performance based on media types.

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%

The percentage removal of COD, BOD, NH₃-N, turbidity, and TDS for NZ-BAF at an HRT of 3 h, a C/N ratio of 6, an aeration rate of 65 L/h, and a filter depth of 80 cm was 93%, 96%, 98%, 96%, and 56%, respectively. For GF-BAF, under the same operational conditions, the removal attained was 91%, 97%, 90%, 89%, and 71%, respectively, and for NZGF-BAF, the highest percentage removal of COD, BOD, NH₃-N, turbidity, and TDS was 93%, 98%, 94%, 93%, and 67%, respectively. Though the COD and BOD removal were comparable for NZ-BAF, GF-BAF, and NZGF-BAF, the NH₃-N and turbidity removal were higher for NZ-BAF due to its ion-exchange properties, while the TDS removal was higher for GF-BAF due to the bio-film formation and bacterial activity in the finer pores of the media. So, the dual media NZGF-BAF with the combined properties of natural zeolite and geo-fabric exhibited superior combined efficiency in terms of percentage removal of all the process parameters and was considered for further optimization using RSM of Minitab 19.

3.2. Optimization of NZGF-BAF System

Minitab 19 software was used to analyse and improve the performance of the NZGF-BAF system. Minitab 19 facilitates regression modelling, statistical analysis, and the visualization of variable relationships. To evaluate the effects of the key independent variables or operational parameters, i.e., HRT, C/N ratio, rate of aeration, and depth of filter on the performance of the NZGF-BAF system, a total of 30 systematically designed experimental runs were carried out using Central Composite Design (CCD). This method makes it possible to construct a response surface model (RSM) and comprehend the connections between important operational parameters and the removal of different process parameters. The five coded levels and corresponding experimental ranges of the independent variables are presented in Table 3.

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

Symbol Coded	Independent Variables (Operational Parameters)	Unit	Range of actual independent variables				
			$-\alpha$	-1	0	+1	$+\alpha$
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	55	60	65	70	75
DOF	Depth of Filter	cm	60	70	80	90	100

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.

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

where Y is the predicted response (% removal), β_0 is the constant regression coefficient for the intercept, β_i is the linear coefficient, β_{ii} is the quadratic coefficient, β_{ij} is the interaction coefficient, X_i and X_j are coded values for independent variables, and k is the number of process variables considered 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, $\text{NH}_3\text{-N}$, 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).

$$\begin{aligned} \% \text{ Removal of COD} = & 77 + 59.1 \text{ HRT} - 11.4 \text{ C/N} - 6.73 \text{ ROA} + 4.01 \text{ DOF} - 8.817 \text{ HRT} * \text{HRT} + 0.065 \text{ C/N} * \text{C/N} \\ & + 0.0252 \text{ ROA} * \text{ROA} - 0.02457 \text{ DOF} * \text{DOF} - 1.175 \text{ HRT} * \text{C/N} + 0.390 \text{ HRT} * \text{ROA} - 0.1262 \text{ HRT} * \text{DOF} + 0.179 \text{ C/N} * \\ & \text{ROA} + 0.0445 \text{ C/N} * \text{DOF} + 0.0060 \text{ ROA} * \text{DOF} \end{aligned} \quad (2)$$

$$\begin{aligned} \% \text{ Removal of BOD} = & 93 + 21.7 \text{ HRT} - 0.2 \text{ C/N} - 7.41 \text{ ROA} + 5.10 \text{ DOF} - 9.218 \text{ HRT} * \text{HRT} + 0.523 \text{ C/N} * \text{C/N} \\ & + 0.0370 \text{ ROA} * \text{ROA} - 0.03320 \text{ DOF} * \text{DOF} - 1.225 \text{ HRT} * \text{C/N} + 0.610 \text{ HRT} * \text{ROA} + 0.1900 \text{ HRT} * \text{DOF} + 0.007 \text{ C/N} * \\ & \text{ROA} - 0.0055 \text{ C/N} * \text{DOF} - 0.0025 \text{ ROA} * \text{DOF} \end{aligned} \quad (3)$$

$$\begin{aligned} \% \text{ Removal of } \text{NH}_3\text{-N} = & 91 + 21.3 \text{ HRT} - 1.4 \text{ C/N} - 7.30 \text{ ROA} + 5.07 \text{ DOF} - 9.211 \text{ HRT} * \text{HRT} + 0.467 \text{ C/N} * \text{C/N} \\ & + 0.0350 \text{ ROA} * \text{ROA} - 0.03298 \text{ DOF} * \text{DOF} - 1.210 \text{ HRT} * \text{C/N} + 0.615 \text{ HRT} * \text{ROA} + 0.1895 \text{ HRT} * \text{DOF} + 0.036 \text{ C/N} * \\ & \text{ROA} - 0.0090 \text{ C/N} * \text{DOF} - 0.0023 \text{ ROA} * \text{DOF} \end{aligned} \quad (4)$$

$$\begin{aligned} \% \text{ Removal of Turbidity} = & 76 + 22.4 \text{ HRT} + 1.1 \text{ C/N} - 7.13 \text{ ROA} + 5.03 \text{ DOF} - 9.220 \text{ HRT} * \text{HRT} + 0.422 \text{ C/N} * \text{C/N} \\ & + 0.0350 \text{ ROA} * \text{ROA} - 0.03268 \text{ DOF} * \text{DOF} - 1.347 \text{ HRT} * \text{C/N} + 0.611 \text{ HRT} * \text{ROA} + 0.1903 \text{ HRT} * \text{DOF} + 0.011 \text{ C/N} * \\ & \text{ROA} - 0.0063 \text{ C/N} * \text{DOF} - 0.0027 \text{ ROA} * \text{DOF} \end{aligned} \quad (5)$$

$$\begin{aligned} \% \text{ Removal of TDS} = & 79 + 36.5 \text{ HRT} - 5.8 \text{ C/N} - 5.08 \text{ ROA} + 2.49 \text{ DOF} - 10.389 \text{ HRT} * \text{HRT} + 0.636 \text{ C/N} * \text{C/N} \\ & + 0.0018 \text{ ROA} * \text{ROA} - 0.02303 \text{ DOF} * \text{DOF} - 4.77 \text{ HRT} * \text{C/N} + 0.834 \text{ HRT} * \text{ROA} + 0.167 \text{ HRT} * \text{DOF} + 0.177 \text{ C/N} * \\ & \text{ROA} + 0.069 \text{ C/N} * \text{DOF} + 0.0062 \text{ ROA} * \text{DOF} \end{aligned} \quad (6)$$

Analysis of Variance (ANOVA) was used to evaluate and interpret the NZGF-BAF system's performance utilizing dual media, and the findings are displayed in Tables 4 to 8. The developed equation was validated using ANOVA and model adequacy diagnostics, confirming its statistical significance and predictive reliability.

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 NH₃-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		

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		

The p-values of the ANOVA tables aid in determining the relevance of the model in statistical analysis. In this study, the p-values for the regression models of all process parameters were less than the chosen significance level ($\alpha = 0.05$). The linear and square terms for COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS also had p-values of 0.000, confirming that both primary effects and quadratic effects of the operating parameters play an important role in the treatment performance. However, the interaction term for COD was statistically less significant ($p = 0.241$), suggesting that the combined effects of the factors were comparatively less influential. The lack-of-fit p-values obtained for COD (0.266), BOD (0.459), $\text{NH}_3\text{-N}$ (0.443), turbidity (0.439), and TDS (0.205) were all greater than 0.05, indicating that the lack of fit was statistically non-significant and the developed quadratic model adequately fits the experimental data. The developed models are statistically significant and confirm that the selected independent variables exert a significant influence on the responses, namely the removal efficiencies of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS.

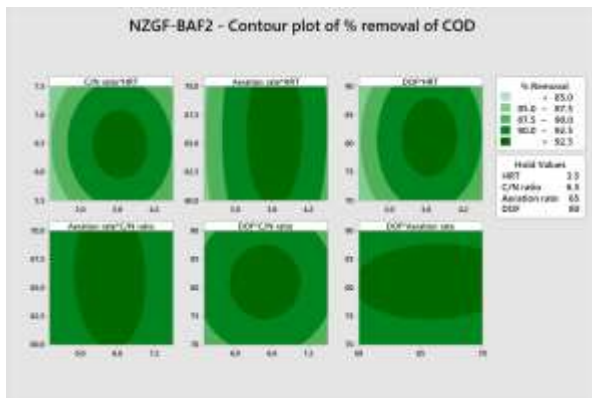
Table 9 presents the model summary for the removal efficiencies of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS. The coefficient of determination (R^2) is a statistical measure that evaluates how well a model explains the variability in the data. Models that fit better are indicated by higher R^2 values. R^2 values of 97.43%, 98.72%, 98.66%, 98.6%, and 97.5% were attained for the removal of COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS, respectively. These high R^2 values show that the model correctly captures the variance in the percentage removal of all process parameters. The adjusted R^2 values were in close agreement with the corresponding R^2 values for all responses, suggesting that the models are not overfitted and that the included terms are statistically meaningful. Similarly, the predicted R^2 values showed reasonable agreement with the adjusted R^2 values, confirming good predictive capability of the models. Although the predicted R^2 values for COD (85.70%) and TDS (86.06%) were slightly

lower compared to other responses, they remain within acceptable limits, indicating satisfactory external predictability.

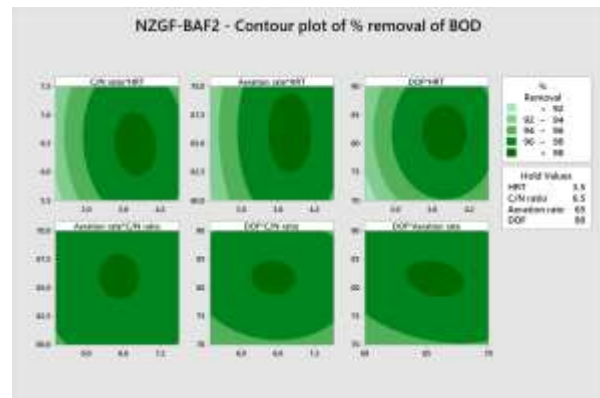
Table 9: Model summary for percentage removal of COD, BOD, NH₃-N, turbidity, and TDS

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

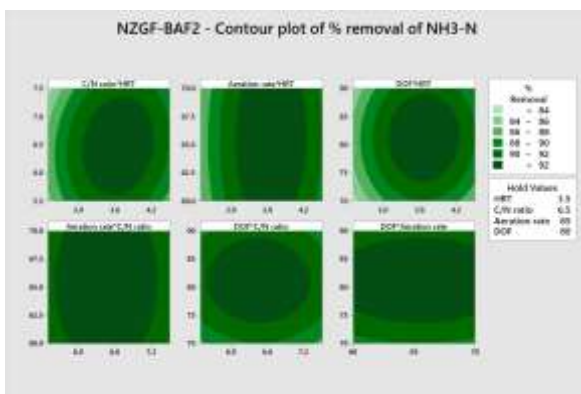
Contour plots based on the experimental results were used to illustrate the responses generated by RSM. The simultaneous effects of two variables or operational parameters on the responses were depicted in these plots. HRT versus C/N ratio, rate of aeration versus C/N ratio, depth of filter versus C/N ratio, rate of aeration versus HRT, depth of filter versus HRT, and depth of filter versus rate of aeration were the specific correlations that were investigated. Fig. 8 (a–e) show these contour plots, respectively.



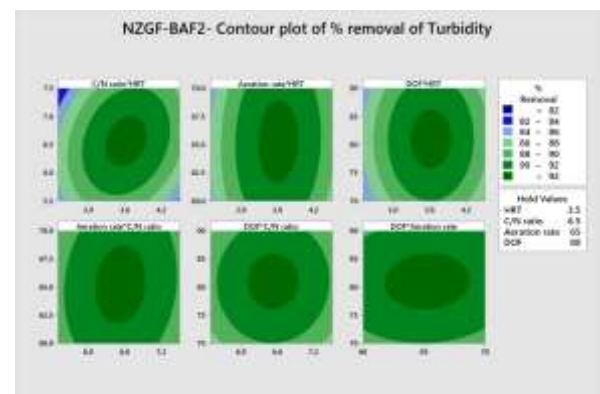
(a)



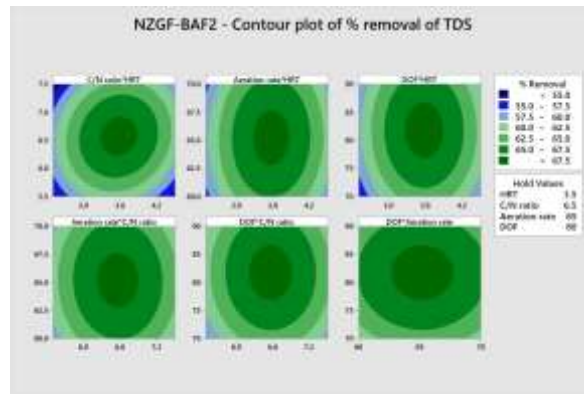
(b)



(c)



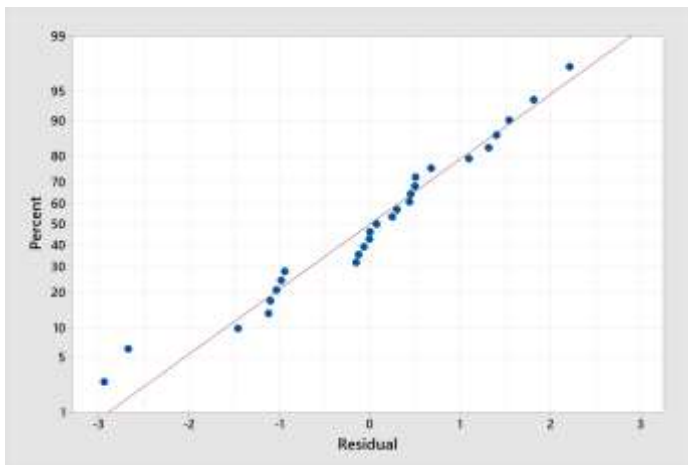
(d)



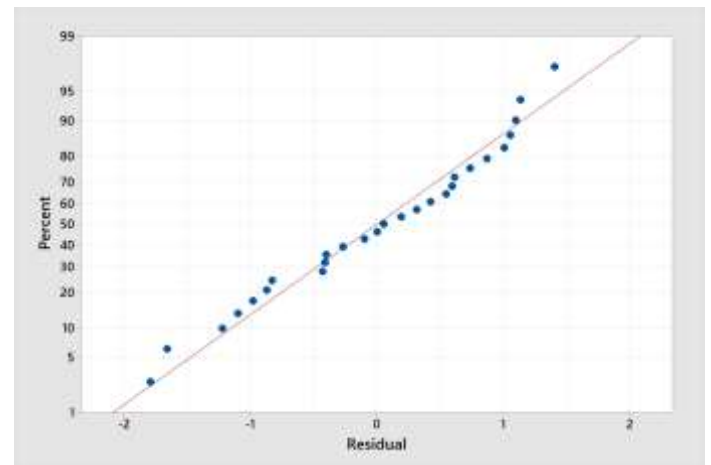
(e)

Fig. 8: Contour plot for percentage removal of (a) COD, (b) BOD, (c) NH₃-N, (d) turbidity, and (e) TDS.

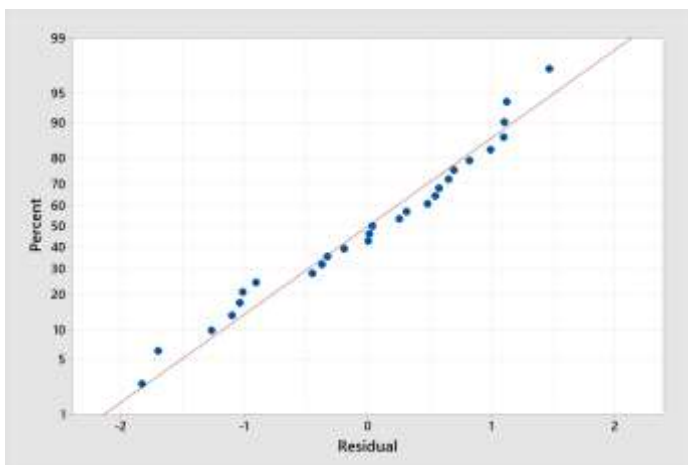
The residual plots in RSM were examined to assess model adequacy. The normal probability plots for the various process parameters are shown in Fig. 9 (a-e) and suggest that residuals followed a straight-line pattern. This pattern indicates that the residuals are approximately normally distributed, satisfying one of the key assumptions of ANOVA and regression analysis.



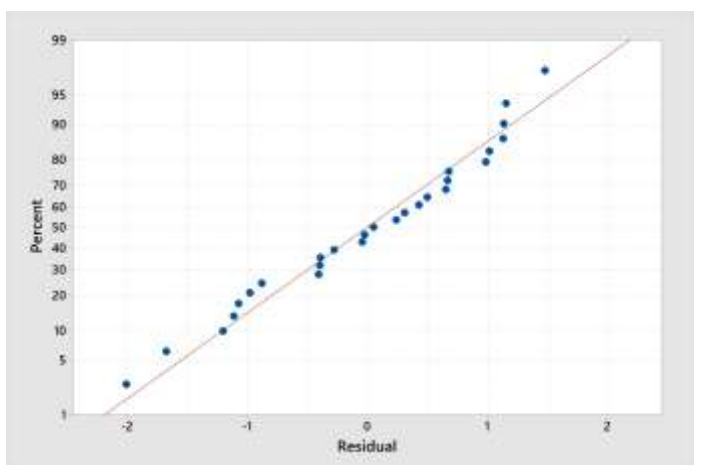
(a)



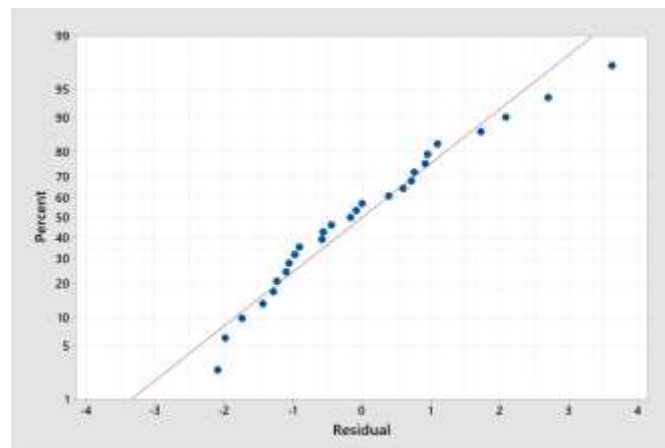
(b)



(c)



(d)



(e)

Fig 9: Residual plot for removal of (a) COD, (b) BOD, (c) NH₃-N, (d) Turbidity and (e) TDS

3.3. Optimized Condition Validation

Based on the RSM optimizer results, the highest percentage removal of COD, BOD, NH₃-N, turbidity, and TDS of 93%, 98%, 94%, 93%, and 68%, respectively, was attained at an HRT of 3.7 h, a C/N of 6.5, a rate of aeration of 66.2 L/h, a depth of filter of 81.7 cm. An additional experiment was carried out in the laboratory under the optimum conditions derived from the RSM model in order to assess the performance of NZGF-BAF. The final run was conducted at HRT of 3.7 h, C/N of 6.5, rate of aeration of 66.2 L/h, and a depth of filter of 81.7 cm. The experimental data were examined and compared with the predicted theoretical percentage removal values of the RSM model. The percentage removal of the process parameters derived from these experiments is summarized in Table 10. This information enables a direct comparison between the experimental outcomes attained under optimal conditions and the values predicted by the RSM model. The accuracy with which the RSM model captures the system's performance under optimal conditions can be ascertained by comparing the predicted and experimental values.

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

4. CONCLUSIONS

The treatment effectiveness of a dual media biologically aerated filter (BAF) comprising of geo-fabric and natural zeolite (NZGF-BAF) was examined in this study in comparison to a single media BAF, which contains either natural zeolite only (NZ-BAF) or geo-fabric (GF-BAF). The effectiveness of greywater treatment in the BAF systems under study is influenced by various operational parameters such as the HRT, C/N ratio, rate of

aeration, and depth of the filter. The NZ-BAF, composed of natural zeolite of 1-3 mm, and GF-BAF, with geofabric of 500 GSM, demonstrated equivalent results for the removal of COD, BOD, and turbidity. While NZ-BAF's ion-exchange characteristics resulted in a higher removal of $\text{NH}_3\text{-N}$, the GF-BAF demonstrated superior removal of TDS due to permeability, adsorption, bio-film formation, and bacterial activity in the finer pores of the media. The dual media filter, NZGF-BAF, facilitates processes such as absorption, adsorption, ion exchange, and biofilm development, ultimately leading to better removal of all contaminants. To further optimize the treatment process, Response Surface Methodology (RSM) was employed to identify the optimal operational parameters, including HRT, C/N ratio, aeration rate, and filter depth, for maximizing the removal of contaminants such as COD, BOD, $\text{NH}_3\text{-N}$, turbidity, and TDS. Experiments conducted using the NZGF-BAF system under optimized conditions (HRT of 3.7 h, C/N ratio of 6.5, aeration rate of 66.2 L/h, and filter media depth of 81.7 cm) attained removal efficiencies of 93% for COD, 98% for BOD, 94% for $\text{NH}_3\text{-N}$, 93% for turbidity, and 67% for TDS. The results indicate that the NZGF-BAF system demonstrates strong potential for efficient greywater treatment under controlled laboratory conditions. However, since real greywater varies in composition, further studies using actual greywater under practical operating conditions are necessary to confirm real-world applicability.

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