

Integrated Anaerobic-Aerobic Sequencing Batch Reactors for Unrestricted Reuse Using Greywater Treatment

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Abstract—This work is carried out to evaluate the efficiency of the pilot scale integrated scheme which comprises of an Anaerobic Sequence Batch Reactor (AnSBR) reactor, Aerobic Sequence Batch Reactor (ASBR), and sand filter for the elimination of organic matter and nutrient in synthetic greywater. The treatment effectiveness of the pilot plant was identified based on its pollutant removal efficiency for 12 months. The AnSBR removes 49.64, 64.24, 55.35, 87.82, 54.36, 32.73, 72.61, 34.88, and 72.11% of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Nitrogen (TN), anionic surfactant, Total Phosphorous (TP), Ammonium Nitrogen ($\text{NH}_4^+\text{-N}$), Total Suspended Solids (TSS), Nitrate Nitrogen ($\text{NO}_3^-\text{-N}$) and sulphates, respectively. Moreover, the removal efficiencies are improved to 84.27, 86.04, 80.8, 95.13, 80.55, 90.23, 72.98, and 75.45%, respectively, in the ASBR with an additional aeration period. The removal efficiencies of COD, BOD, TN, anionic surfactant, TP, TSS, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and sulphates have been improved progressively to 89.12, 94.9, 85.15, 99, 86.98, 88.54, 93.52, 94.89, and 80.49%, respectively in the sand filter. In tracer studies, that a total of 29.3% of the salt has been remained in the reactor which suggests a good deal of salt of the integrated system. Furthermore, this hydrodynamic study discloses a moderately low volume (30.3%) for the integrated system with the mean residence time is lesser than theoretical hydraulic residential time. Based on these findings, it is evident that the integrated anaerobic-aerobic system bounded with the sand filter process accomplishes the achievement of efficiency.

Index Terms—Aerobic reactor, anaerobic reactor, greywater, hydrodynamic studies, NaCl purge, sand filter.

I. INTRODUCTION

Global water shortage has been a principal issue over the years because of the population growth combination, increasing lifestyle standard, increased urbanization, nutritional changes, water resources mismanagement, and climate variations [1]. Water management is required to maintain as well as improve water distribution and sanitation. Management of wastewater is important to eliminate water scarcity and to protect all types of ecosystems. The increasing demand for finite and irreplaceable water resources has stimulated innovative plan of action for freshwater governance, including technology innovation for recycling of wastewater. Source separation of wastewater can resolve the

problem of conventional water treatment which requires complex methods for treatment since the several types of wastewater flow from the residential area mixes with clean water and have limited options regarding the recycling of wastewater components. In the source separation process, greywater (bathroom, kitchen, and laundry water), blackwater (urine, faces, and flush water), and yellow water (only urine) are separated from wastewater [2], [3]. Water treatment plants should be able to handle with the changes in the composition of wastewater and the daily variability in flow.

Greywater reuse and recycling can be the essential practice to decrease the demand for drinking water. Reuse of treated greywater can save approximately 50 L of potable water in a common household every single day [4], [5]. Greywater is the discharge that is created by the kitchen sinks, showers, baths, bathroom sinks, and laundry. Characteristics of greywater fluctuate according to the consumer's lifestyle, cultural and social behavior. It has the lowest micro and macro contaminants compared to other wastewaters (e.g., black water). Hence, the source of separation of municipal sewers into grey and black streams has been promoted to maximize the recycling possibility and minimize the required energy for the treatment [6]–[8].

The unconcentrated domestic wastewater streams are produced from laundry facilities, shower, and washbasins constitute the greywater, and greywater involves the kitchen wastewater too [9], [10]. The greywater gives a contribution of 60–75% to domestic wastewater of the total water volume including a release of N, P, K, and organic matter in the rate of 9–14%, 20–32%, 18–22%, and 29–62% respectively [11]. Greywater normally contains a low level of contaminating pathogens. Urine is not included in greywater as it has a negligible quantity of nitrogen, in particulate form derived from organic nitrogen [12]. There are a lot of methods that have been used to remove organic contaminants in greywater including physical, chemical, and biological methods, as shown in Fig. 1.

Physical and substance cycles can crash suspended solids, natural matter, and microbes, however, are generally less equipped for eliminating supplements [13], [14]. Organic cycles can frequently fill in as a superior decision, permitting the expulsion of supplements, keeping away from the utilization of synthetics, lessening the expenses and effects on the climate. Treatments are employed for diminishing the contaminants level in the gravel previously reprocess or the final disposal. They are impurity explicit that is applied to the ordinary process of wastewater treatment grouping including pre-treatment, essential, tertiary and optional treatment. Thus, every system in this process involves the biological or the physio chemical treatment.

Several biological techniques have been applied for

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greywater treatment, including; membrane bioreactor, constructed wetlands, AnSBR, rotating biological contactors (RBC), and ASBR [15]. Among these, the sequential batch reactors (SBR) systems are advantageous due to the possibility to carry out the removal of substrates in a single unit, with a small footprint due to the absence of secondary clarifiers. The effluents produced from SBR treatment of greywater satisfied most of the conventional pollutant standards of wastewater reuse. The SBR scheme is attributed to a high tractability for the operation as well as the time-controlled sequence, which are considered as the necessary pollutant reducing method [16], [17]. The AnSBR process is best fit for performing the greywater anaerobic treatment. Additionally, the AnSBR process can enable the expulsion in an effective manner based on organic loads like BOD₅, oil, COD, and grease. This process is utilized for removing the phosphate and nitrogen compound concentrations. In addition, the biological degeneration of the sludge can be accomplished by the AnSBR, with the production of biogas as a source of green energy [18].

Meanwhile, the aeration method has demonstrated the effectual approach for diminishing the various pollutants in the wastewater. Moreover, the existing developed aeration processes are depending on the air supply for the effective treatment scheme. Abdel-Shafy *et al.* [19], Albalawneh and Chang [20] studied the anaerobic biodegradability of greywater and found 70% biodegradability and removal of nitrogen as 22–30% and phosphorous as 15–21% in the greywater. Moreover, the anaerobic reduction needs further improvement and can be followed by an aerobic system [21]. Abu Ghunmi *et al.* [22] carried out the process of greywater treatment based on the anaerobic–aerobic schemes for the irrigation. The anaerobic and aerobic units achieved 45%, 39% COD removal in summer, and 53%, 64% COD removal in winter respectively. Except for pathogens, aerobic effluent quality agreed using the proposed irrigation guidelines of water quality for water recovered in Jordan.

Gašpariková *et al.* [23] evaluated anaerobic-aerobic wastewater treatment plant operations to have many benefits and it is performed to overcome the limitations of the methods like aerobic and anaerobic. By combining these methods into a single integrated scheme through the anaerobic pre-treatment process as well as aerobic post-treatment process it obtained high efficiency for removing the organic matter, low specific energy needs, biogas development, relatively short confinement period, and low specific development of excess sludge [24]. However, SBR systems are less efficient in eliminating total suspended solids (TSS) despite the high reduction in most of the other organic contaminants in greywater treatment [25]. So, filtration is one of the low-cost techniques used as a post-treatment unit to remove turbidity, colloids, and suspended solids.

The main reason for treating the greywater in low or middle-income countries is because of public health issues concern. If the greywater is not treated then the people in those countries would suffer a lot from the dangerous diseases. Also, the medical facilities are also not as much upgraded in those low. So, to protect people life from diseases, the greywater must be treated. In addition, people in these countries often use greywater because of inadequate

water facilities. Hence, reusing the greywater is a good idea to compensate for the inadequate water facilities, but that greywater should be treated before reuse.

The objective of the present research work is summarized as follows,

- To treat the greywater for reuse, a novel frame work has been proposed.
- To examine the purity of the greywater after the process of treatment.
- To evaluate long-term performance while removing the organic matter, suspended solids, and nutrients.
- To estimate hydrodynamic characteristics of the greywater treatment in the integrated system.
- To compare the proposed greywater treatment design with existing models.

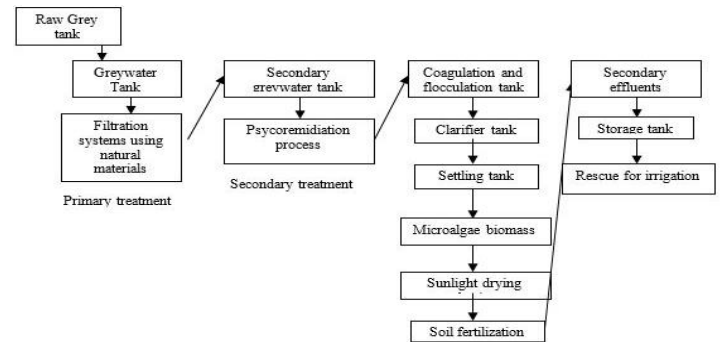


Fig. 1. Hybrid system for treatment of household greywater [26].

II. MATERIALS AND METHODS

All the experimental investigations were carried out using synthetic greywater in a pilot plant fabricated in the environmental engineering lab, National Institute Technology Karnataka (NITK), Surathkal, India.

A. Integrated Greywater Treatment Plant Design and Operation

TABLE I: DESIGN OF HOLDING TANK, ANSBR REACTOR, ASBR, AND SAND FILTER

Operational parameters	Diameter (m)	Height (m)	Total volume (m ³)
Holding tank	0.4	0.77	0.2
AnSBR	0.55	0.87	0.2
ASBR	0.55	0.87	0.2
Sand Filter	0.30	0.53	0.04

The integrated greywater treatment plant consists of two same size greywater influent holding tanks, namely, the AnSBR, and the ASBR followed by a sand filter, to exterminate suspended solids and coarse organic matter from the water that is treated by anaerobic reactor, which is given in Fig. 2. The design detail of the whole integrated greywater treatment is shown in Table I. The entire setup was made of non-transparent PVC tanks. The treatment unit has been operated with an automated configuration of 6 cycles. The typical duration of each cycle is four hours, with 24-hour Hydraulic Retention Time (HRT). This process has been subsequently channeled using ASBR fitted through the aeration pump that is diversified for 12h to achieve the desired final effluent quality with the loading rate of 2.6

kgBOD₅/m³/day. In ASBR, air flowrate is provided using air pump with maximum of 660 L/h and dissolved oxygen concentration is maintained at 1-3 mg/L.

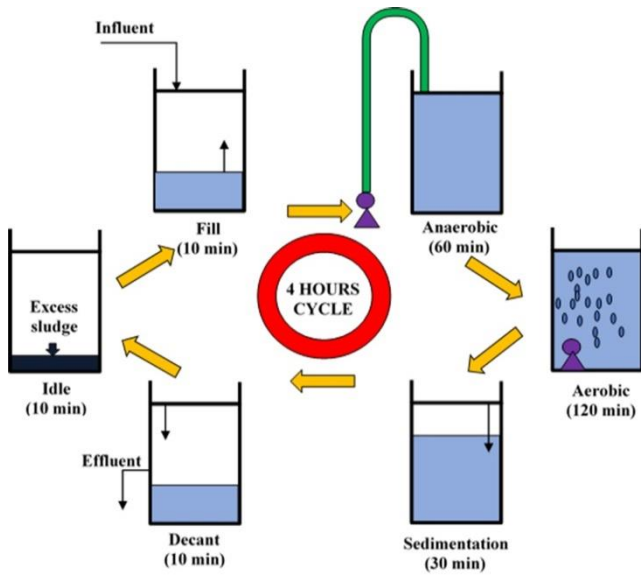


Fig. 2. Typical layout and operating procedure for greywater treatment using a combined anaerobic-aerobic-sand filter system.

B. Feed and Sludge Preparation

Synthetic greywater is prepared by mixing arrowroot powder (starch), detergent, Urea (laboratory/analytical grade), Potassium dihydrogen phosphate, liquid handwash and milk powder to feed the pilot-scale plant. The quantity of feed sample is around 100 L/day which inflows into the integrated system. In this Sequencing Batch Reactor (SBR) the feed has been provided in a multi-stage. So, the flow rate is maintained at around 0.85 L/min in each cycle.

On the other hand, the inoculum was supplemented with macronutrients, micronutrients, and pH was adjusted to 7.5-8 before filling the reactor. Subsequently, the anaerobic reactor was filled with 100 L of anaerobic sludge at mixed liquor volatile suspended solids (MLVSS) concentration of 1000-1500 mg/L. Meanwhile, the aerobic reactor was filled with 100 L of aerobic sludge at MLVSS concentration of 1500-2000 mg/L on day one of operation.

C. Sand Filter Media

The gravel and sand provided in sacks were washed in tap water thoroughly before filling in the plastic drum. The empty Volume (up to the outlet) of the tank is 70 L. There were two grades of gravel and one grade of sand provided. Take 20 L of the biggest gravel and spread it evenly in the tank. On top of it, the smaller gravel was spread (20 L). Finally, on top of it, for the volume of 10 L, the sand particles of 1-2 mm were spread. The sand provided in sacks was sieved in standard sieve sizes (1-2 mm), followed by thorough washing in tap water to remove dirt. The filling of gravel and sand was carried out with constant tapping and spread evenly. The media selection and design parameters of the sand filter have been represented in Table II.

The relationship among dry density, specific gravity and void ratio is shown in (1):

$$\rho_d = \frac{G \rho_w}{1+e} \quad (1)$$

where G is specific gravity, e is void ratio, ρ_d is dry density (kg/m³) and ρ_w is density of water (kg/m³)

The porosity of the filter media was then determined based on void ratio is given as follows (2):

$$n = \frac{e}{1+e} \quad (2)$$

where n = porosity (%).

The calculations of each layer as well as overall void ratio and porosity of the entire sand filter are described as follows.

- Bottom layer (20 mm size crushed stone)

Specific gravity (G) = 2.884

Water density (ρ_w) = 1000 kg/m³

$$\text{Dry density } (\rho_d) = \frac{\text{Weight of 20 mm size crushed stone}}{\text{Unit Volume}} = \frac{1.55 \text{ kg}}{1 \text{ L}} = 1550 \text{ kg/m}^3$$

$$\text{From (1), } 1550 = \frac{2.884 \times 1000}{(1+e)}$$

Void ratio (e) = 0.86

$$\text{From (2), Porosity (n)} = \frac{e}{1+e} = \frac{0.86}{1.86} = 0.4623 \text{ (or 46.23\%)}$$

TABLE II: CHARACTERISTICS OF THE FILTER MEDIA

Layer	Depth (m)	Filter medium	Grain size curve analysis
Bottom layer	0.21	Crushed stone (20 mm size)	D ₁₀ = 13.68 mm
			D ₃₀ = 17.66 mm
Transition layer	0.14	Crushed stone (12 mm size)	D ₆₀ = 26.46 mm
			C _U = 1.93
Top layer	0.1	Coarse sand (1-2 mm size)	C _C = 0.86
			e = 0.86
			n = 46.23%
			D ₁₀ = 6.98 mm
			D ₃₀ = 10.3 mm
			D ₆₀ = 11.48 mm
			C _U = 1.65
			C _C = 1.32
			e = 0.713
			n = 41.6%
			D ₁₀ = 1.0 mm
			D ₃₀ = 1.4 mm
			D ₆₀ = 1.83 mm
			C _U = 1.85
			C _C = 3.69
			e = 0.476
			n = 32.25%

- Transition layer (12 mm size crushed stone)

Specific gravity (G) = 2.878

Water density (ρ_w) = 1000 kg/m³

$$\text{Dry density } (\rho_d) = \frac{\text{Weight of 12 mm size crushed stone}}{\text{Unit Volume}} = \frac{1.68 \text{ kg}}{1 \text{ L}} = 1680 \text{ kg/m}^3$$

$$\text{From (1), } 1680 = \frac{2.878 \times 1000}{(1+e)}$$

Void ratio (e) = 0.713

$$\text{From (2), Porosity (n)} = \frac{e}{1+e} = \frac{0.713}{1.713} = 0.416 \text{ (or 41.6\%)}$$

- Top layer (1-2 mm size coarse sand)

Specific gravity (G) = 2.605

Water density (ρ_w) = 1000 kg/m³

$$\text{Dry density } (\rho_d) = \frac{\text{Weight of 1-2 mm size coarse sand}}{\text{Unit Volume}} = \frac{1.765 \text{ kg}}{1 \text{ L}} = 1765 \text{ kg/m}^3$$

$$\text{From (1), } 1765 = \frac{2.605 \times 1000}{(1+e)}$$

$$\text{Void ratio (e)} = 0.476$$

$$\text{From (2), Porosity (n)} = \frac{e}{1+e} = \frac{0.476}{1.476} = 0.3225 \text{ (or 32.25 \%)}$$

- Overall sand filter (3 layers combined)

$$\text{Specific gravity (G)} = 2.7$$

$$\text{Water density } (\rho_w) = 1000 \text{ kg/m}^3$$

$$\text{Dry density } (\rho_d)$$

$$= \frac{\text{Weight of (20 mm crushed stone+12 mm crushed stone+1-2 mm coarse sand)}}{\text{Unit Volume}} = \frac{1.55 \text{ kg}}{1 \text{ L}} + \frac{1.68 \text{ kg}}{1 \text{ L}} + \frac{1.765 \text{ kg}}{1 \text{ L}} = 1665 \text{ kg/m}^3$$

$$\text{From (1), } 1665 = \frac{2.7 \times 1000}{(1+e)}$$

$$\text{Void ratio (e)} = 0.622$$

$$\text{From (2), Porosity (n)} = \frac{e}{1+e} = \frac{0.622}{1.622} = 0.3835 \text{ (or 38.35 \%)}$$

D. Sampling and Analysis

Here, four numbers of sampling points are used for collecting samples of greywater on two times in a week. The sampling locations were preparation tanks, AnSBR effluent, ASBR effluent and effluent of the sand filter and for gathering the samples of wastewater for performing the physicochemical analysis.

Moreover, the collected samples have to label as well as subject for the quality analysis, and usually stored in the deep freeze. Additionally, the parameters like total dissolved solids (TDS), pH, Temperature, and electrical conductivity (EC) are calculated with the use of HANNA digital instruments. Moreover, BOD, Turbidity, ammonium nitrogen $NH_4^+ - N$ (Nessler method), TSS, anionic surfactants, sulphates, total phosphorous (TP), and nitrate nitrogen ($NO_3^- - N$) (Brucine method), chemical oxygen demand (COD) (potassium dichromate reactor digestion), are performed under the important methods based on the investigation of water as well as wastewater procedures. Furthermore, Persulfate method (4500-N C) has been used to analyze the total nitrogen (TN) concentration in the influent and effluent samples [27].

E. Tracer Studies

The tracer experiment is defined as an indirect process for calculating the flow, characterizing sludge, and the properties of filter media. The feed water has supplied to the tap water furnace at a constant flow rate that maintains a 24-hour HRT while performing the tracer inspection. Additionally, this experimentation is processed after 12 months of the system operation. Moreover, for testing, the samples are obtained continuously using the outlet chamber until the pulse tracer was added to the influx stream and at least twice the HRD or tracer's concentration was reached [28]. Also, this experimentation in the integrated mechanism was analyzed by influencing with sodium chloride (NaCl) that is combined using the influential (electrical conductivity (EC) initial pulse of 733 S), the EC was monitored as the pilot plant exited each cycle, i.e. using the EC return to create the turning curve 4 hours [29]. Subsequently, the NaCl concentration has been computed based on the NaCl balance in the reactor.

The exit tracer sample time (D) and concentrations (C) are normalized through theoretical hydraulic retention time (D), and input tracer concentration (C 0) respectively. Also, the

Mean retention time (\bar{t}), variance (σ^2), dimensionless time (θ), $F(t)$, and dispersion number (D/UL) are determined by (3), (4), (5), (6), (7) and (8).

$$\text{Mean retention time, } \bar{t}, \min = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} \quad (3)$$

$$\text{Variance, } \sigma^2 = \frac{\int_0^\infty (t - \bar{t})^2 \times C(t)dt}{\int_0^\infty C(t)dt} \quad (4)$$

$$\sigma_\theta^2 = \frac{\sigma^2}{\bar{t}^2} \quad (5)$$

$$\text{Dispersion number, D/UL} = \sigma_\theta^2/2 \quad (6)$$

$$F(t) = \frac{\text{Tracer}_{\text{before}} - \text{Tracer}_t}{\text{Tracer}_{\text{before}} - \text{Tracer}_{\text{after}}} \quad (7)$$

$$\text{Dimensionless time, } \theta = T/\bar{t} \quad (8)$$

An amount of dead spots in the integrated system is estimated based on the mean and theoretical HRT ratio that is given in (9).

$$V_d = \left(1 - \frac{\bar{t}}{t}\right) \times 100 \quad (9)$$

III. RESULTS AND DISCUSSION

A. Performance Evaluation of Integrated Greywater Treatment

The daily sampling program was developed for collecting the synthetic greywater for identifying the features like physical and chemical. Subsequently, the values of pH, EC, COD, BOD₅, $NH_4^+ - N$, anionic surfactants, and TP for synthetic greywater were 7.1, 262.35, 347.87, 262.35, 24.26, 46.44, and 6.53 mg/L, separately. The nitrate-nitrogen ($NO_3^- - N$) and the TN were 8.8 and 40.73 mg/L. Hence, the obtained results are demonstrated the strength of greywater, which average value is high.

B. AnSBR Pilot Plant Reactor

The AnSBR process is utilized in this work for removing the anionic surfactants in the range as 84.6%. The AnSBR features are mentioned in Table III.

The COD as well as BOD₅ removal has been removed from 356 to 163.2 and 252.8-96 mg/L that are corresponding to the 54.15 and 62.02% removal rate. Valuable degradation of organic loads can be achieved due to the anaerobic nature of UASP, and they are converted to biogas. Subsequently, the BOD₅/COD average ratio is 0.59 (i.e., lower than 0.75 in the raw greywater) in the AnSBR treated effluent. It reduces due to the fact that the rate of removal of organic loads as BOD₅ (62.02%) that is higher than chemical load as COD (54.15%). However, the ratio of BOD₅/COD in AnSBR treated effluent is still enough to achieve further organic degradation in the

biological treatment.

TABLE III: THE ANAEROBIC TREATMENT EFFECTS ON CHEMICAL AND PHYSICAL PROPERTIES OF GREYWATER BY ANSBR PARAMETERS

Parameters	Unit	N	Synthetic greywater (average)	AnSBR effluent	
				Concentration	Efficiency (% R)
TSS	mg/L	10	142.3±6.09	114.4±5.5	19.60
Anionic Surfactant	mg/L	10	46.44±18.19	7.15±1.06	84.60
COD	mg/L	10	356±29.51	163.2±23.61	54.15
BOD ₅	mg/L	10	252.8±28.02	96±21.33	62.02
BOD ₅ /COD	Ratio	10	0.71±0.09	0.59±0.13	-
TP	mg/L	10	6.73±0.69	4.71±0.47	30.00
TN	mg/L	10	39.94±3.23	32.82±1.8	17.83

The inadequate reduction of the TSS, TN, and TP are extended at 19.6%, 17.83%, and 30 %, respectively. These decreases were from 142 to 114.4 mg/L for TSS, from 39.94 to 32.82 for TN, and from 6.73 to 4.71 mg/L for TP. Additionally, the AnSBR is utilized for removing the anionic surfactants, BOD₅ and COD, it is still weak in removing TSS, TN, and TP. The calculated COD/TN/TP in the present effluent is 34.65/6.96/1, which is in correlation with the values reported by Tchobanoglous *et al.* [30]. This indicates that there can be very few chances to treat biologically further.

So, AnSBR needs to be modified to bring down the contaminant load. Moreover, the AnSBR influent should be treated by modified AnSBR to reduce the nutrient load on the aerobic system. To obtain the lower total nitrogen limits by

biodegradation, biodegradable carbon sources are available immediately for use by refuse organisms. So, it was decided to develop the multistage flow for the AnSBR system, aided with internal circulation in the pilot plant to improve the biological treatment and the further treatment as the aerobic system to remove the concerned pollutants.

C. Greywater Treatment Using ASBR Pilot Plant Reactor

The variable aeration times effects of 15-120min are mentioned in Table IV. Thus, the obtained outcomes are demonstrated the high aeration time and the pollutant reduction. Thus, it is used for absorbing the organic matter from the used greywater while enhancing the existing bacteria.

The biological treatment cannot be suitable for further treatment, since the BOD₅/COD ratio is 0.49 at the maintained aeration time of 120 minutes. The performance of the combined anaerobic-aerobic was found to be limited as far as TSS removal was concerned, they do not comply with local regulatory standards for reuse in irrigation mentioned in Table V. As a result, postoperative treatment was required to control the treated of the combined anaerobic-aerobic treatment process. So, there was a need to select one of the physical treatments, which is capable of low cost, low energy, and less polluting, in operation. Meanwhile, the filtration unit is used to remove turbidity, colloids, suspended solids, and remove microbes present in the biologically treated effluent.

D. Up-Flow Sand Filter (UFSF) Performance

The UFSF efficacy for aerobic waste treatment is given in Table VI. Concentrations of COD, BOD₅, TN, TP, anionic surfactants, and TSS ranged from 30 to 45, 7 to 20, 2 to 4, 0.7 to 1, 0 to 1, and 6 to 8mg/L, respectively. The efficiency of the system for removing these parameters is 30.87, 38.04, 60.99, 33.07, 81.85, and 81.09%, respectively.

TABLE IV: AERATION EFFECT AT DISSIMILAR TIMES ON THE CHARACTERISTICS OF CHEMICAL AND PHYSICAL BY ANSBR EFFLUENT

Constraints	Unit	N	AnSBR effluent (average)	Aeration time (min)									
				15		30		60		90		120	
				Conc.	%R	Conc.	%R	Conc.	%R	Conc.	%R	Conc.	%R
TSS	mg/L	10	94±3.4	~88	6.38	~79	15.96	~68	27.66	~53	43.62	~40	57.45
COD	mg/L	10	176±16.86	~159.8	9.24	~148.65	15.52	~135.34	24.1	~88.54	49.69	~44.8	74.5
BOD ₅	mg/L	10	99.2±23.61	~83	16.33	~76	23.39	~70	29.44	~48	51.61	~22	77.82
BOD ₅ /COD	Ratio	10	-	51.94	-	51.13	-	51.72	-	54.21	-	0.49	-
TP	mg/L	10	3.11±0.33	-	-	-	-	-	-	-	-	~1.32	57.55
TN	mg/L	10	19.82±2.03	~16.8	15.24	~14.2	28.35	~11.6	41.47	~9.1	54.09	~7.48	62.26

*Every AnSBR value effluent parameter is defined based on mean value ± SD

E. Organic Matter and Nutrient Removal of the Integrated Greywater Treatment Plant

At anaerobic, aerobic, and sand filter conditions, the influent COD concentration was maintained at 347.87 mg/L at the pilot plant. Operating conditions were maintained at COD/N/P ratio of 53.27/6.23/1, HRT=24hrs. X=1-2 g/L and DO=3.5-4.5mg/L; the outgoing COD concentration decreases to 175.2 mg/L giving the AnSBR a removal capacity of 49.64%. The maximum COD removal capacity is

84.27% that is attained for ASBR. From Fig. 3(a), proves that the removal capacity enhances through increasing influential COD concentration. The pilot-plant showed a total removal of 89.12% of COD after the sand filtration phase, at organic loading rates measuring 3.5 kg COD/m³/day.

In the present study, the mean ratio of BOD/COD in the influent greywater was 0.74 to 0.76. Therefore, there was the right amount of biodegradable organic matter presented in greywater, which can be consumed or biodegraded by bacteria during the anaerobic and aerobic stages. The effluent

BOD concentration decreased to 92.98 mg/L yielding a removal efficiency of 64.24% in AnSBR. The BOD removal efficiency of aerobic effluent was obtained around 86.04% in ASBR. From the final waste generated from the sand filter,

the BOD concentration was reduced to 13.26 mg/L, which gave the ability to remove 94.9% of the 2.6 kg BOD/m³/day (Fig. 3b) measured organic loading rates.

TABLE V: TREATED GREYWATER REUSE IN IRRIGATION GUIDELINES AND REGULATIONS [1], [20]

Constraint	India		US EPA		Australia		Italy		Jordan		China	
	Irrigation	Reuse	Irrigation	Reuse	Irrigation	Reuse	Irrigation	Reuse	Irrigation	Reuse	Irrigation	Reuse
Total Suspended solids mg/l, Max.	200	200	30	—	—	—	—	10	150	50-150	—	10.0-50.0
pH	5.5-9	6.0-9.0	6.0-9.0	6.0-9.0	4.5-9	—	—	6.0-9.5	6.0-9.0	6.0-9.0	—	6.0-9.0
BOD	30	30	30	10	20	20	—	20	300	30-300	—	10.0-20.0
COD	—	—	—	—	—	—	—	100	500	100-500	—	15
Turbidity	20	2	5	5	30	10	—	—	25	2.0-10.0	—	10
TN	30	10	—	—	—	—	—	15	70	50-70	—	15-20
TP	6.0-8.0	1	—	—	—	—	—	2	—	30	—	1.0-5.0

TABLE VI: THE UFSF EFFECT OF GREYWATER ON CHEMICAL AND PHYSICAL PROPERTIES

Parameters	Unit	N	Aerobic effluent	UFSF effluent	
				Concentration	Efficiency (% R)
TSS	mg/L	10	38.34±3.25	7.25±0.87	81.09
Anionic Surfactant	mg/L	10	2.26±1.9	0.41±0.5	81.85
COD	mg/L	10	54.75±15.22	37.85±7.28	30.87
BOD ₅	mg/L	10	21.40±12.85	13.26±6.12	38.04
TP	mg/L	10	1.27±0.64	0.85±0.12	33.07
TN	mg/L	10	7.82±3.2	3.05±0.87	60.99

*Each value of the parameter is described as the mean value ± SD

The effluent of TN concentration decreased to 18.19 mg/L yielding a removal efficiency of 55.35% in AnSBR. The TN removal efficiency of aerobic effluent was obtained around 80.8% in aerobic SBR. From the final effluent generated from the sand filter, the concentration of TN was reduced to 6.05 mg/L yielding a removal efficiency of 85.15% (Fig. 4).

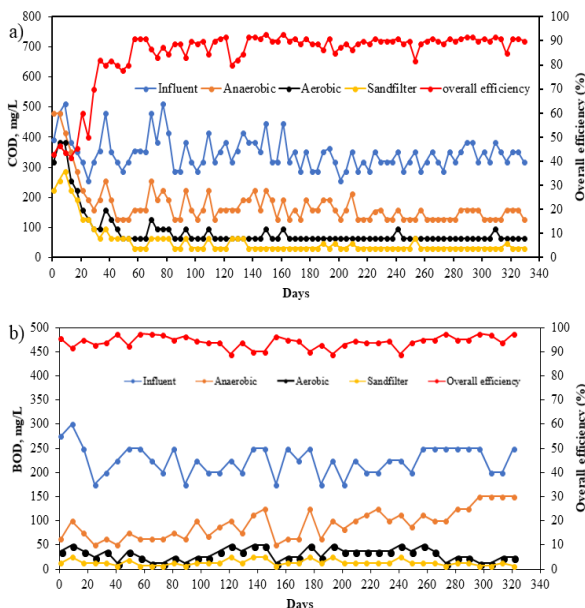


Fig. 3. Overall removal efficiencies of organic matter (a) COD (b) BOD in anaerobic, aerobic, and sand filter stages.

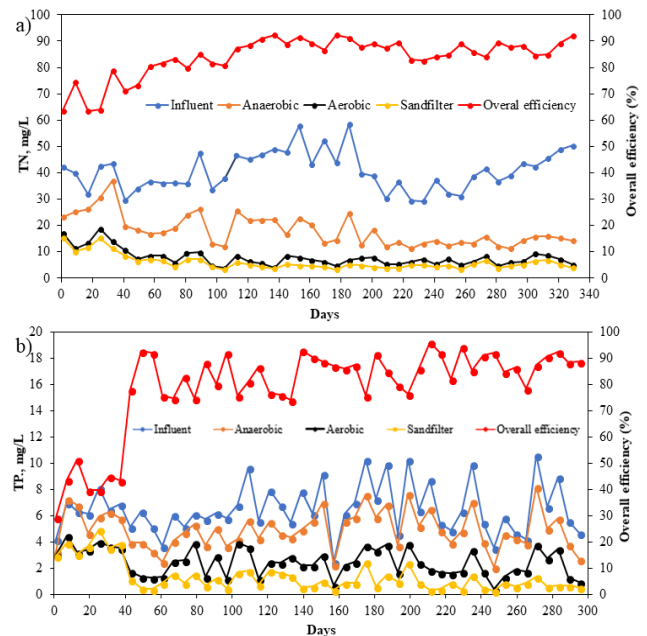


Fig. 4. Overall removal efficiencies of nutrients (a) TN (b) TP in anaerobic, aerobic, and sand filter stages.

The overall performance of the integrated system is shown in Table VII. The pilot plant has been controlled and monitored with the observation of pH conditions since the micro-organisms in biological treatment depend on the optimal pH values. The dissolved solids concentrations have not exceeded more than 1000 mg/L, which satisfied the effluent standards' limits. The anionic surfactant, TP, $NH_4^+ - N$, $NO_3^- - N$, TSS, and sulphates concentrations decreased to 5.66, 2.98, 16.32, 2.41, 92.4, and 10.92 mg/L, yielding the removal efficiency of 87.82, 54.36, 32.73, 72.61, 34.88, and 72.11 %, respectively, in AnSBR. Of these contaminants, TSS and $NH_4^+ - N$ have been shown inadequate removal during the anaerobic phase due to the decomposition of nitrogenous organic matter (Yang et al. 2015). The removal efficiencies of anionic surfactant, TP, $NH_4^+ - N$, $NO_3^- - N$, TSS, and sulphates were obtained to be 95.13, 80.55, 90.23, 72.98, and 75.45%, respectively, in ASBR.

TABLE VII: EFFECT OF GREY WATER OVERALL TREATMENT OF CHEMICAL AND PHYSICAL CHARACTERISTICS

Parameter	Unit	N	Feeding Tank	Anaerobic effluent		Aerobic effluent		Sand filter effluent		Overall efficiency % R
				Concentration	% R	Concentration	% R	Concentration	% R	
pH		45	7.1±0.39	6.79±0.41	-	7.00±0.32	-	7.15±0.33	-	-
EC	µS/cm	45	262.35±48	584.58±157.3	-	533.97±94	-	551.15±88.7	-	-
Dissolved Oxygen	mg/L	45	4.72±0.6	1.53±0.49	-	3.9±0.53	-	4.9±0.63	-	-
$NH_4^+ - N$	mg/L	45	24.26±2.3	16.32±1.9	32.73	7.26±1.6	55.51	2.78±0.29	61.71	88.54
Nitrate Nitrogen	mg/L	45	8.8±0.95	2.41±0.63	72.61	0.86±0.12	64.31	0.57±0.22	33.72	93.52
TN	mg/L	45	40.73±7.3	18.19±5.9	55.34	7.82±3.2	57	6.05±2.87	22.63	85.15
COD	mg/L	45	347.87±49	175.21±36.7	49.63	54.75±15.22	68.75	37.85±7.28	30.87	89.12
BOD	mg/L	45	260±30.1	92.98±30.02	64.23	21.40±12.85	76.98	13.26±6.12	38.04	94.9
Phosphates	mg/L	45	6.53±1.89	2.98±1.45	54.36	1.27±0.64	57.38	0.85±0.12	33.07	86.98
TSS	mg/L	45	141.9±5.89	92.4±4.5	34.88	38.34±3.25	58.5	16.25±2.12	57.62	88.5
Surfactants	mg/L	45	46.44±18.19	5.66±3.06	87.81	2.26±1.9	60	0.41±0.15	81.8	99.11
Sulphates	mg/L	45	39.15±3.22	10.92±1.36	72.11	9.61±1.12	12	7.64±0.88	20.5	80.48

*The parameter value was defined based on mean value ± SD

The $NH_4^+ - N$ removal efficiency was improved (~55.5) at the aerobic stage due to the adequate nitrification process and also the increase in TSS removal (~58.5%) since the SBR systems are advantageous due to the possibility to carry out the replacement of substrates in a single unit (aeration reactor and secondary clarifier). In the final effluent generated from the sand filter, the concentrations of anionic surfactant, TP, $NH_4^+ - N$, $NO_3^- - N$, TSS, and sulphates were reduced to 0.41, 0.85, 2.78, 0.57, 7.25, and 7.64 mg/L, yielding removal efficiencies of 99, 86.98, 88.54, 93.52, 94.89 and 80.49%, respectively.

F. Hydrodynamic Studies in Integrated System

Like dyes, salts can be used to measure the stay of water in a system. The known quantity and salt concentration are added to a system and measured from an outlet by electrical conductivity changes. Chloride represents an effective tracer because it is relatively inactive and has not been used extensively by biota. Nitrate can be a bad tracer because it can be ingested by biota before leaving the system [31].

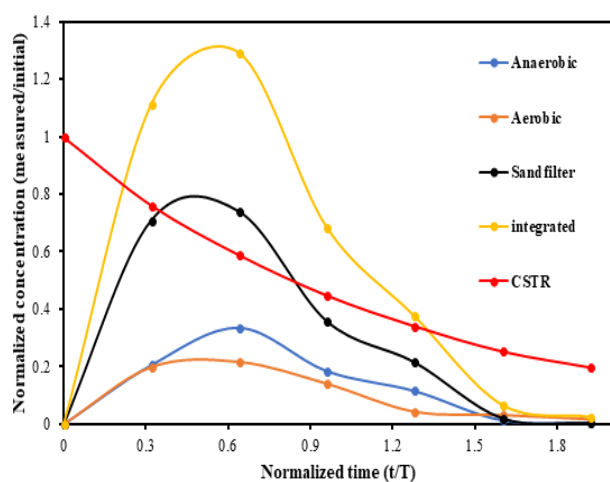


Fig. 5. Normalized time vs normalized concentration.

To analyze the hydrodynamics of the integrated system, residential time distribution (RTD) curves have been arranged by the NaCl solution as a tracer. The electric conductivity of tap water = 70.6 µS/cm, The Electric conductivity of NaCl injected in tap water = 1164.8 µS/cm

(733 mg/L concentration). Electric conductivity of NaCl excluding tap water = 1094.2 µS/cm. Therefore, NaCl concentration (mg/L) = Conductivity value (µS/cm)/0.67. The results of the calculations show that the effluent to total salt ratio is 70.69 %, which is equal to F (t). A good deal of the salt remains in the reactor, which suggests that a total of 29.3% of the salt had already been remained in the reactor.

The utilized test parameters of this process are detailed as below: The influent Q = 100 L/day = 0.0042 m³/h, T=24 h=1440 min. The normalized RTD curves generated by the tracer probe at 24-h HRT are shown in Fig. 5. Moreover, the calculated results of the hydrodynamic properties are detailed in Table VIII. The \bar{t} of the system is 16.73 h that indicates the actual exposure time of the system which is less than HRT.

TABLE VIII: CALCULATION RESULTS FOR TRACER ANALYSIS

S. No	Parameters	Anaerobic	Aerobic	Sand filter
1	Mean retention time, \bar{t} , min	1003.43	996.36	1012.805334
2	Variance, σ^2	122.78	126.78	119.5679126
3	σ^2	0.00012194	0.00012771	0.000116564
4	Dispersion number, D/UL	6.0972E-05	6.38551E-05	5.82818E-05
5	F(t)	0.83	0.8	0.83
6	Dimensionless time, θ	1.44	1.45	1.42

The dead space of the model acts as the necessary part that can affect the \bar{t} and integrated system efficiency. Moreover, 30.3% dead space was identified in the system that demonstrating the substrate satisfactory distribution within the integrated system. Furthermore, a plug-flow regime suggested that the lower value of D/UL obtained for anaerobic tank, aerobic tank, and sand filter as 6.0972E-05, 6.38551E-05, and 5.82818E-05, respectively, may be considered to have this structure [28].

Moreover, F (t) values of effluent salt ratio from the anaerobic tank, aerobic tank, and sand filter to the inlet are 0.83, 0.8, and 0.83. The results show that the leftover NaCl of total salt in the anaerobic tank, aerobic tank, and sand filter is 17%, 20%, and 17%, respectively. Comparison of organic matter and nutrient removal efficiencies of integrated

anaerobic, aerobic, and sand filter system and other combined biological treatment systems for greywater are detailed in Table IX.

TABLE IX: COMPARISON OF ORGANIC MATTER AND NUTRIENT REMOVAL EFFICIENCIES OF INTEGRATED ANAEROBIC, AEROBIC, AND SAND FILTER SYSTEM AND OTHER COMBINED BIOLOGICAL TREATMENT SYSTEMS FOR Greywater

Reference	Technology	Organic loading rate		HRT (h)	Removal efficiency (%)				
		Kg COD/m ³ *day	Kg BOD /m ³ *day		COD%	BOD%	NH ₄ ⁺ -N%	TN%	TP%
Present Study	Integrated anaerobic, aerobic, and sand filter	3.5	2.6	24	89.12	94.9	88.54	85.15	86.98
Priyanka <i>et al.</i> [32]	Sequencing batch reactor	-	-	24	96.2	97.38	81.68	-	72
Abdel-Shafy <i>et al.</i> [19]	Anaerobic/aerobic integration via UASB/enhanced aeration	1.93	1.1	24	98.4	98.3	95.3	94	90.5
Tombola <i>et al.</i> [8]	Sequencing batch biofilm reactor	-	-	24	86.5	-	98.4	71.4	-
Eslami <i>et al.</i> [26]	Integrated fixed-film activated sludge (IFAS)	0.11-1.3	-	8.1	93	85	-	90	87
Saidi <i>et al.</i> [33]	Multistage moving bed biofilm reactor	3.4	2.8	28.8-38.4	94.5	99.4	99.7	63	14
Abdel-Shafy <i>et al.</i> [18]	Anaerobic/aerobic integration via UASB and MBR	1.93	1.1	7.5-10.5	97.8	97.4	94.5	-	89.8
Merz <i>et al.</i> [34]	Membrane bioreactor technology	0.09-0.21	-	9-18	85	94	72	-	19
Hernández Leal <i>et al.</i> [35]	Aerobic treatment	0.15-8	-	12-24	90	-	-	-	-
Friedler <i>et al.</i> [36]	Screening, Rotating biological contractors, Chlorination	-	-	-	75	96	96	-	58

IV. CONCLUSION

Greywater can be reused for irrigation if satisfactory and appropriate treatment is obtained using the integrated treatment methods provided. The integrated aerobic-aerobic sequence batch reactor for greywater treatment is a practical, low cost and feasible process. The use of an integrated system provides the following greywater purification efficiency based on the following findings.

- The removal capacity of the pilot plant for COD, BOD, anionic surfactants, TN, TSS and TP is 89%, 95%, 99%, 85%, 88.5 and 87% respectively.
- The integrated system provided significant removal performance of anionic surfactants, COD, BOD, TN, and TP, while the system maintained at COD/N/P is 53.27/6.23/1, X (MLVSS) in the range 1-1.5 g/L, HRT-24 hrs., DO in the scope of 2.5-4.5 mg/L and OLR of 3.5 kg COD/m³. d (2.6 kg BOD/ m³. d).
- The mean residence time (\bar{t}) was 16.73 h, which is less than the theoretical HRT (T). Furthermore, the dead space size of the whole system is about 30.3%, which represents a moderately low value the integrated systems. In future to optimize the greywater treatment parameter and time consumption, a hybrid optimization will be implemented in this greywater treatment model. Hence, the greywater treatment design could be enhanced and will get optimized result.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Sarath Chandra Pragada: Conceptualization; Formal analysis; Methodology; Conducted the research; Analyzed the data; validation; Visualization – original draft. Arun Kumar Thalla: Conceptualization; Investigation; Funding acquisition; Supervision; Writing – review & editing. All authors had approved the final version.

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