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"Nutrient Removal from Dairy Wastewater by Aerobic Sequencing Batch Reactor (Sbr)"

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Abstract
India's dairy industry generates nutrient-rich wastewater that poses serious environmental risks if untreated. This study evaluates the performance of an aerobic Sequencing Batch Reactor (SBR) for treating dairy effluents under Indian conditions. The system's efficiency in removing BOD, COD, nitrogen, phosphorus, and solids was assessed with varying time cycles. Results highlight the SBR as a compact, cost-effective, and efficient solution for decentralized wastewater treatment in the dairy sector.

Keywords: Dairy industry, SBR, Nutrition removal, HRT

1. Introduction

India's dairy industry holds a vital position in the national economy, being the largest milk producer globally, with an annual production exceeding 230 million tons as of 2022–2023 (NDDB - 2023). This sector supports the livelihoods of millions of farmers, particularly in rural and semi-urban regions, and plays a key role in ensuring food security and nutritional health. However, the rapid growth of dairy processing units has also intensified concerns over environmental sustainability, especially the management of high-strength wastewater generated during various processing stages.

Dairy wastewater is typically characterized by high biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and significant concentrations of nitrogen and phosphorus. These pollutants originate from milk spillage, equipment washing, pasteurization processes, CIP (clean-in-place) systems, and sanitizer residues (Gupta, R., & Mittal, A. K. (2020)). If inadequately treated and discharged into water bodies, such effluents lead to eutrophication, oxygen depletion, and deterioration of water quality, posing serious risks to aquatic life and public health.

In India, many small- and medium-scale dairy units operate with limited financial and technical capacity, resulting in either partial treatment or direct discharge of untreated effluents into nearby drains or natural streams. Conventional treatment technologies such as activated sludge processes (ASP) often demand high maintenance, skilled labor, and space, making them less suitable in rural Indian contexts.

Hence, there is an urgent need for cost-effective, energy-efficient, and decentralized treatment solutions that can efficiently handle nutrient-rich wastewater.

The Sequencing Batch Reactor (SBR) process has emerged as a promising alternative for the treatment of dairy effluents due to its flexibility in operation, compact footprint, and ability to simultaneously remove organic matter, nitrogen, and phosphorus. SBRs operate in time-sequenced phases (fill, react, settle, decant, and idle) within a single reactor unit, enabling tailored process control and high treatment efficiency, even with variable wastewater loads (Mohan, S. V., Rao, N. C., & Sarma, P. N. (2018)).

Particularly, the aerobic SBR configuration supports aerobic microbial activity that facilitates the oxidation of ammonia to nitrate (nitrification) and partial removal of phosphorus through biological uptake. This process aligns well with the Indian climatic conditions, where ambient temperatures support robust microbial metabolism year-round, thus enhancing biological nutrient removal performance.

This study explores the efficiency of an aerobic SBR system in treating dairy wastewater under typical Indian operating conditions. The present study deals with nutrient removal from dairy wastewater by aerobic SBR. The performance evaluation for optimization of the time cycle and HRT of dairy wastewater is studied.

2. Technological Basis of SBR

The Sequencing Batch Reactor (SBR) is a time-sequenced modification of the conventional activated sludge process, designed to treat wastewater in batch mode within a single tank. This configuration integrates equalization, biological oxidation, sedimentation, and decantation in a controlled cycle consisting of five phases: Fill, React, Settle, Decant, and Idle (Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2014)).The batch operation allows for greater control over operational parameters, making SBR particularly suitable for wastewater with fluctuating flow and composition, such as dairy wastewater.

Dairy wastewater typically exhibits high organic loading, with BOD_5 levels ranging from 800–2000 mg/L, COD from 1500–4000 mg/L, and significant amounts of nutrients including TKN (80–120 mg/L) and total phosphorus (10–40 mg/L) (Kushwaha, J. P., Srivastava, V. C., & Mall, I. D. (2011)). During the aerobic React phase, heterotrophic microorganisms degrade organic matter, while autotrophic nitrifiers convert ammonia to nitrate. By incorporating an anoxic phase, SBR systems can also achieve denitrification, and with suitable anaerobic-aerobic sequencing, biological phosphorus removal (EBPR) can be facilitated through the action of polyphosphate-accumulating organisms (PAOs) (Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2014)).

Given the variable nature of dairy wastewater, the space limitations, and the need for low-maintenance systems in many parts of rural and peri-urban India, SBR presents itself as a technically feasible and sustainable solution for medium- and small-scale dairy units across the country.

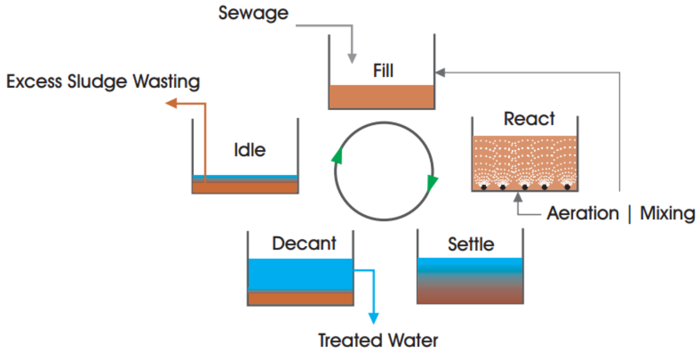

Figure 0- SBR Operating Principle

3. Objectives

SBR treatment is efficient in nutrient removal of Domestic Wastewater. It has been used as good alternative for the conventional treatment processes. Hence study of this treatment options may hold good for Dairy wastewater. Thus to check compatibility of SBR for dairy wastewater the following objectives are worked on.

i. To analyze the characteristics of raw and primary treated dairy wastewater.
ii. To develop an experimental set up for aerobic SBR for primary treated dairy wastewater.
iii. To optimize the cycle regime and HRT for nutrient removal in aerobic SBR.
iv. To study the process kinetics for nitrification and de-nitrification in aerobic SBR.

4. Host Industry Profile

4.1 Technical Introduction

The milk coming from various dairies is first of all collected at the Raw Milk Revolution Department (RMRD). Sample is taken from milk collected from each institute to measure fat and water percentage. Total stock of milk is cooled at 4^0C and stored in containers. As per requirement the milk is then taken to pasteurization department where it is pasteurized and then stored again in separate tanks. Major part of this pasteurized milk is then used for packaging. Remaining part is used to produce local packaging as well as other products like- Paneer, Shrikhand, Curd, Flavored milk, Ghee, Butter produced products are first stored in the Cold Storage Room and then distributed to the market according to the needs. All the vessels, cans and truck containers are sterilized or cleaned with the help of hot water produced by boiler. Also Plant Heat Exchanger (PHE) which is located at pasteurization unit is cleaned after every 8hrs shift by hot water and acid. Cleaning in Place (CIP) is done after every 24hrs. All the waste water along with mixed pollutants is then drained using drainage system to ETP where it is digested anaerobically and further aerobically treated to produce Biogas and fertilizers so that water is purified and then let for agricultural use.

4.2 Production overview

1	Milk reception capacity	40,000 liters/day (Raw)
		35,000 liters/day (Chilled)
2	Milk process capacity	75,000 lakh liters/day
3	Desi butter manufacturing:	
	• CBMM	3 MT/day
	• Top Churn	1 MT/day
4	Ghee Manufacturing	2 MT/day

5	Packaging lines:	
	• Milk packaging	70,000 liters/day
	• Rollatainer machine (Cartoons)	2 MT/day
	• Ghee packaging (pouch)	1.5 MT/day
	• Table butter packaging:	
	• In 500 gm.	2 MT/day
	• In 100 gm.	1 MT/day
6	Storage capacity:	
	• Milk (Packed Milk)	75,000 liters
	• Desi butter	10 MT
	• Ghee	5-10 MT
7	Total Project Investment:	
	• OF - I/II	4 Crore
	• OF - III	10 Crore

Table 1 – Host Industry Production Details

5. Sources of Wastewater in the Dairy Industry

The dairy industry generates a significant amount of wastewater primarily due to the use of water in processing, cleaning, and sanitizing operations. Major sources include milk reception areas, where spillage and cleaning of tankers and storage vessels occur. During pasteurization, homogenization, and other milk processing stages, losses of milk and its by-products such as cream, whey, and butterfat contribute to the organic load in wastewater. Cheese and butter production units discharge substantial volumes of wash water, brine, and whey. Cleaning-In-Place (CIP) systems, which involve frequent cleaning of pipelines, tanks, and equipment using alkaline and acidic solutions, are also a major contributor to wastewater generation. Additional wastewater arises from packaging sections due to washing and rinsing of containers, and from utility sections like cooling towers and condensate drainage. The resulting effluent is typically characterized by high biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, and fluctuating pH values, posing serious challenges to treatment and disposal (Tchobanoglous et al., 2003; CPCB, 2016; Kushwaha et al., 2011).

5.1 Range of Dairy Wastewater parameters.

Parameter	Range
pH	6.5 – 8.5
BOD	900 – 1200 mg/l
COD	2500 – 3000 mg/l
TDS	550 – 1000 mg/l

Table 2- Dairy wastewater parameters

5.2 Research Problem

Dairy wastewater is organic it contains milk constituents- casein, salts (inorganic), detergents too. These contribute high BOD-COD. Dairy wastewaters implies rapid decompose results deplete dissolved oxygen and resulted in heavy anaerobic conditions with foul odors. Higher of such compounds concentrations are toxic to aquatic ecosystem. Nitrogen originates from milk is in organic nitrogen, urea and nucleic acids, Phosphorus as orthophosphate and polyphosphate along organic forms. Excess nutrients results in eutrophication.

5.3 Flow Chart of Effluent Treatment Plant of host Industry

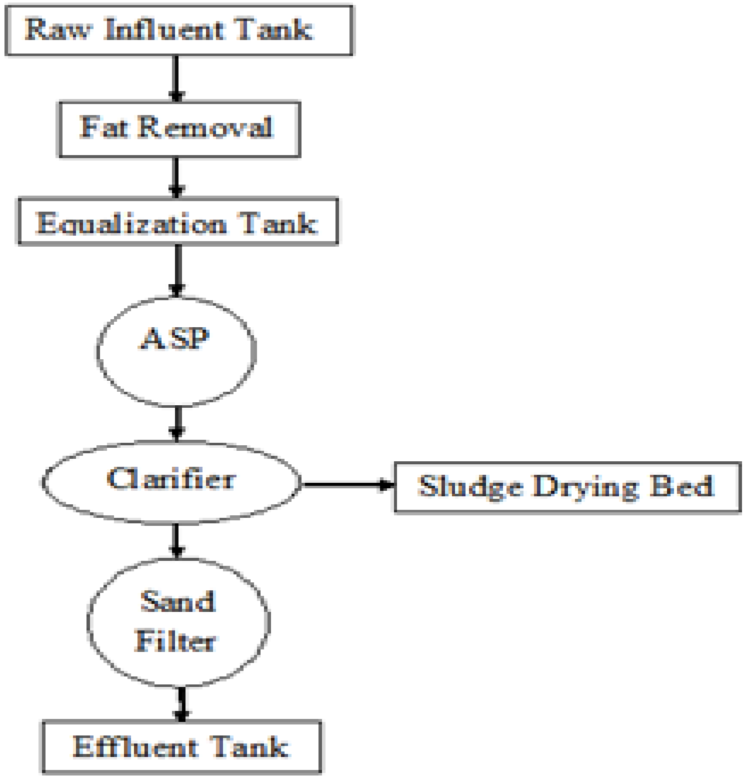

Figure 2- Flow chart of ETP of host industry

6. Operation of SBR

After commissioning, activating microbes in the reactor unit, Operated with one Cycle (4Hrs) per day, Distribution of time for various cycles of operation are for 4, 5, 6, 7, and 8 Hours cycle is as follows.

Sr. No	Steps	Time				
		4 Hours	**5 Hours**	**6 Hours**	**7 Hours**	**8 Hours**
1	Fill Mix (25%)	60	75	90	105	120
2	React (35%)	84	105	126	147	168
3	Settle (20%)	48	60	72	84	96
4	Decant (15%)	36	45	54	63	72
5	Idle (5%)	12	15	18	21	24
	Total	240	300	360	420	480

Table 1- Time Distribution of Various Cycles in SBR

The reactor was operated with 6 cycles as described below.

In the first Cycle of study, Sequencing Batch Reactor was operated in five steps viz. Fill & Mix, Fill & React, React, Settle and Decant for 4Hrs duration. This Cycle was operated four times. The inlet and outlet sample were analyzed for pH, COD, BOD, TKN, P, TDS and TSS.

In the second Cycle of study, Sequencing Batch Reactor was operated in five steps. Fill & Mix, Fill & React, React, Settle and Decant for 5hrs duration. This Cycle was operated four times. The inlet & outlet sample were analyzed for pH, COD, BOD, TKN, P, TDS and TSS.

In the third Cycle of study, Sequencing Batch Reactor was operated in five steps viz. Fill & Mix, Fill & React, React, Settle and Decant for 6Hrs duration. This Cycle was operated four times. The inlet & outlet sample were analyzed for pH, COD, BOD, TKN, P, TDS and TSS. In the fourth Cycle of study, Sequencing Batch Reactor was operated in five steps viz. Fill & Mix, Fill & React, React, Settle and Decant for 7Hrs duration. This Cycle was operated four times. The inlet & outlet sample were analyzed for pH, COD, BOD, TKN, P, TDS and TSS.

6.1 Analysis of influent and effluent

The inlet and outlet samples of SBR model were analyzed for different parameters which will decide the characteristics of waste water and hence removal efficiency is studied. For parameters are as follows:

a. pH
b. Biochemical Oxygen Demand (BOD)
c. Chemical Oxygen Demand (COD)
d. Total Kjeldhal Nitrogen (TKN)
e. Phosphorus (P)
f. Total Suspended Solids (TSS)
g. Total Dissolved Solids (TDS)

In each Cycle of SBR inlet-outlet samples were collected and analyzed for each parameter mentioned above. All the analyses were carried out with standard procedures and chemicals. Samples were collected on site, immediately analyzed for all the parameters, hence no sample preservation techniques of were adopted.

Parameter	Standards prescribed		
	Inland	Public sewers	For irrigation
pH	5.5 - 9.0	5.5 - 9.0	5.5 - 9.0
Total Dissolved Solids, mg/l, max.	2100		
Total Suspended Solids, mg/L, max.	100	600	200
Oil and grease, mg/L, max.	10	20	10
BOD (5 day at 200), mg/L max.(BOD_5)	30	350	100
Chemical Oxygen Demand (COD)	250		

Table 4- MPCB Standards

6.2 Dairy Wastewater Characteristics

Parameter	Influent	MPCB Limit
pH	9.8	5.5-7.5
BOD	839	<100
COD	1700	<250
TDS	2156	<2100
SS	276	<100
O & G	42	<10
Chloride	310	<600
Sulfate	418	<1000

Table 5 - Characteristics of dairy wastewater from host dairy

7. Discussion on Results

7.1 Four Hours Cycle

Sr. No	Steps	Time In Minutes
1	Fill Mix (25%)	60
2	React (35%)	84
3	Settle (20%)	48
4	Decant (15%)	36
5	Idle (5%)	12
	Total	240

Table 0- Four hours cycle operation

Day	Day 1		Day 2		Day 3		Day 4		Average		Average % Removal
Parameter	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
pH	8.65	7.13	8.56	7.23	8.21	7.26	7.54	7.32	7.62	7.20	
BOD	1093	641	946	598	978	603	1031	662	1068	626	41.33
COD	2679	1509	2724	1624	2837	1589	2773	1649	2753.2	1592.7	42.14

TKN	154.1	92.1	151.7	94.7	159.2	98.8	157.6	96.9	155.6	95.62	38.54
P	6.43	3.71	5.52	3.32	5.29	3.08	5.87	3.56	5.77	3.43	40.55
TDS	2056	1426	1960	1312	1839	1378	1995	1321	1962.5	1359.3	30.73
TSS	438	336	375	283	480	392	395	297	422	263.2	37.66

Table 7- Four hours cycle observations

For a 4-hour cycle operation, the treatment process demonstrated moderate removal efficiencies across key wastewater quality parameters. The influent Biochemical Oxygen Demand (BOD_5) was 1093 mg/L, which was reduced to 641 mg/L, resulting in a BOD_5 removal efficiency of 41.33%. Similarly, the Chemical Oxygen Demand (COD) decreased from 2753 mg/L to 1593 mg/L, achieving a removal efficiency of 41.33%. Total Kjeldahl Nitrogen (TKN) levels dropped from 155.6 mg/L to 95.62 mg/L, corresponding to a relatively low removal efficiency of 38.54%, indicating limited nitrification and denitrification under the current aeration period. The influent phosphorus concentration of 5.77 mg/L was reduced to 3.43 mg/L, with a removal efficiency of 40.55%. Total Dissolved Solids (TDS) declined from 1962.5 mg/L to 1359.3 mg/L, yielding a removal efficiency of 41.33%; however, further reduction may require advanced treatment methods such as membrane filtration or ion exchange. Total Suspended Solids (TSS) was reduced from 1093 mg/L to 641 mg/L, showing the lowest removal efficiency among all parameters at 37.66%.

7.2 Five Hours Cycle

Sr. No	Steps	Time In Minutes
1	Fill Mix (25%)	75
2	React (35%)	105
3	Settle (20%)	60
4	Decant (15%)	45
5	Idle (5%)	15
	Total	300

Table 8 - Five hours cycle operation

Day	Day 1		Day 2		Day 3		Day 4		Average		Average % Removal
Parameter	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
pH	7.83	7.13	7.51	7.23	7.88	7.26	7.69	7.32	7.62	7.20	
BOD	1113	422	1046	403	1078	418	1031	432	1067	418.8	60.74
COD	2619	1044	2704	10675	2867	1092.9	2743	1096.8	2733.2	1093.2	60.01
TKN	142.7	57.9	145.1	59.3	147.2	60.1	152.2	64.4	146.8	60.42	59.20
P	6.49	2.52	5.97	2.37	6.31	2.48	5.59	2.32	6.09	2.42	60.26
TDS	2039	1249	1969	1226	1889	1211	1969	1224	1966.5	1227.6	37.57
TSS	412	249	362	211	471	273	388	233	408.3	242	40.72

Table 9 - Cycle observations for five hours

For a 5-hour cycle operation, the treatment process exhibited improved removal efficiencies across key wastewater parameters compared to the 4-hour cycle. The Biochemical Oxygen Demand (BOD_5) in the first sample was reduced from 1067 mg/L to 418.8 mg/L, and in the second sample from 1046 mg/L to 403 mg/L, resulting in an average BOD_5 removal efficiency of **60.74%**, indicating an improvement due to extended aeration. The Chemical Oxygen Demand (COD) decreased from 2619 mg/L to 1044 mg/L, achieving an overall removal efficiency of **60.01%**. Total Kjeldahl Nitrogen (TKN) concentrations reduced from 142.7 mg/L to 57.9 mg/L and from 145.1 mg/L to 59.3 mg/L in two separate samples, yielding an average removal efficiency of **59.20%**. Phosphorus levels declined from 6.49 mg/L to 2.52 mg/L and from 5.97 mg/L to 2.37 mg/L, with an average removal efficiency of **60.26%**. Total Dissolved Solids (TDS) were reduced from 2039 mg/L to 1249 mg/L in one sample and from 1969 mg/L to 1226 mg/L in another, resulting in an average TDS removal efficiency of **37.57%**, suggesting that further reduction may require advanced filtration techniques. Total Suspended Solids (TSS) decreased from 412 mg/L to 249 mg/L and from 362 mg/L to 211 mg/L, corresponding to an average removal efficiency of **40.72%**.

7.3 Six Hours Cycle

Sr.No	Steps	Time in Minutes
1	Fill Mix (25%)	90
2	React (35%)	126
3	Settle (20%)	72
4	Decant (15%)	54
5	Idle (5%)	18
	Total	360

Table 10- Six hours cycle operation

Date	Day 1		Day 2		Day 3		Day 4		Average		Average % Removal
Parameter	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
pH	7.73	7.3	7.41	7.33	7.78	7.36	7.76	7.32	7.62	7.20	
BOD	1124	225	1078	229	1094	236	1141	237	1109.4	220	**80.16**
COD	2632	551	2698	539	2876	562	2742	544	2749.5	549	**80.04**
TKN	142.1	32.2	145.4	34.6	134.6	29.4	139.2	31.8	140.32	32.02	**77.19**
P	7.31	1.49	6.53	1.42	5.96	1.22	6.42	1.33	6.55	1.36	**79.61**
TDS	2016	1109	1869	1016	1989	1029	2041	1121	1978.5	1068	**46.1**
TSS	403	213	374	186	462	241	386	203	406.2	210	**48.30**

Table 11- Cycle observations for six hours

For the 6-hour cycle operation, the wastewater treatment process demonstrated significantly improved removal efficiencies across all analyzed parameters. The Biochemical Oxygen Demand (BOD_5) was reduced from 1124 mg/L to 225 mg/L in one sample, and from 1078 mg/L to 229 mg/L in another, yielding an average BOD_5 removal efficiency of 80.11%. While this represents a considerable improvement, further enhancement is necessary to meet the effluent discharge standards prescribed by the Central Pollution Control Board (CPCB). The Chemical Oxygen Demand (COD) was lowered from 2632 mg/L to 551 mg/L and from 2698 mg/L to 539 mg/L across two samples, resulting in an average

COD removal efficiency of 80.04%. Total Kjeldahl Nitrogen (TKN) concentrations decreased from 142.1 mg/L to 32.2 mg/L and from 145.4 mg/L to 34.6 mg/L, with an average removal efficiency of 77.19%, indicating improved nitrification and nitrogen removal. Phosphorus levels dropped from 7.31 mg/L to 1.49 mg/L, achieving an average removal efficiency of 79.61%; this performance is closely linked to enhanced BOD and nitrogen reduction during the extended cycle. Total Dissolved Solids (TDS) were reduced from 2016 mg/L to 1109 mg/L and from 1869 mg/L to 1016 mg/L in two samples, resulting in an average TDS removal efficiency of 46.10%, though further improvement may require the use of advanced filtration or membrane processes. Total Suspended Solids (TSS) decreased from 403 mg/L to 213 mg/L and from 374 mg/L to 186 mg/L, corresponding to an average removal efficiency of 48.30%. Overall, the 6-hour aeration cycle significantly enhanced pollutant removal efficiencies, making it a more effective operational mode compared to shorter durations.

7.4 Seven Hours Cycle

Sr. No	Steps	Time In Minutes
1	Fill Mix (25%)	75
2	React (35%)	105
3	Settle (20%)	60
4	Decant (15%)	45
5	Idle (5%)	15
	Total	300

Table 12- Seven hours cycle operation

Day	Day 1		Day 2		Day 3		Day 4		Average		Average % Removal
Parameter	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
pH	7.63	7.21	7.56	7.39	7.71	7.44	7.82	7.29	7.73	7.38	
BOD	1124	48.1	1178	51.3	1181	54.6	1163	58.2	1161.5	52.78	**95.40**
COD	2622	103	2693	99	2898	110	2739	108	2736.5	105	**96.16**
TKN	138.2	10.2	141.7	9.8	143.6	10.8	146.7	9.4	142.5	10.05	**92.94**
P	5.44	0.37	4.12	0.36	6.96	0.41	5.32	0.38	5.46	0.38	**93.04**
TDS	2026	969	1889	907	1973	928	2064	954	1988	926.5	**53.39**
TSS	419	186	344	153	483	201	398	181	411	180	**56.20**

Table 13 - Seven hours cycle operation

In the 7-hour cycle operation, the treatment process demonstrated highly effective removal efficiencies across all tested parameters. The Biochemical Oxygen Demand (BOD_5) was reduced from 1124 mg/L to 48.1 mg/L and from 1178 mg/L to 51.3 mg/L in two samples, resulting in an impressive average BOD_5 removal efficiency of 95.40%. The Chemical Oxygen Demand (COD) declined from 2622 mg/L to 103 mg/L and from 2693 mg/L to 99 mg/L, with an average removal efficiency of 96.16%. Total Kjeldahl Nitrogen (TKN) was lowered from 138.2 mg/L to 10.2 mg/L and from 141.7 mg/L to 9.8 mg/L, yielding an average TKN removal efficiency of 92.94%, indicating efficient nitrification and nitrogen removal processes. Phosphorus concentrations were reduced from 5.44 mg/L to 0.37 mg/L and from 4.12 mg/L to 0.36 mg/L, with an average removal efficiency of 93.04%, closely aligned with the improved BOD and nitrogen removal. Total Dissolved Solids (TDS) decreased from 2026 mg/L to 969 mg/L, achieving a 53.39% removal efficiency, which may still require advanced treatment for further reduction. Total Suspended Solids (TSS) dropped from 419 mg/L to 186 mg/L and from 344 mg/L to 153 mg/L, yielding an average TSS removal efficiency of 56.20%. Notably, the final TSS concentrations remained below 200 mg/L, significantly better than the CPCB effluent standard of 500 mg/L, highlighting the high performance of the treatment process during the 7-hour cycle.

7.5 Eight Hours Cycle

Sr. No	Steps	Time In Minutes
1	Fill Mix (25%)	120
2	React (35%)	168
3	Settle (20%)	96
4	Decant (15%)	72
5	Idle (5%)	24
	Total	480

Table 14 - Eight hours cycle operation

Day	Day 1		Day 2		Day 3		Day 4		Average		
Parameter	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Average % Removal
pH	7.5	7.2	7.58	7.4	7.6	7.32	7.88	7.4	7.64	7.33	
BOD	1100	50	1230	55	1123	52	1166	55	1154.7	53	**95.41**
COD	2589	99	2693	87	2898	110	2739	108	2729.7	101	**96.30**
TKN	142	11	193	10.2	148	11.3	133	10.6	154.00	10.775	**93.00**
P	6.23	0.32	4.23	0.44	6.9	0.5	5.32	0.29	5.67	0.3875	**93.17**
TDS	2030	1023	1669	726	1883	856	2003	863	1896.2	867	**54.28**
TSS	423	102	433	215	443	198	403	188	425.50	175.75	**58.70**

Table 15 - Eight Hours Cycle Operation

In the 8-hour cycle operation, the wastewater treatment process sustained high removal efficiencies across all measured parameters. The Biochemical Oxygen Demand (BOD_5) was reduced from 1166 mg/L to 55.1 mg/L, resulting in an average BOD_5 removal efficiency of 95.00%, indicating excellent organic matter degradation. The Chemical Oxygen Demand (COD) decreased from 2589 mg/L to 99 mg/L, achieving an average removal efficiency of 96.30%, reflecting effective oxidation of both biodegradable and non-biodegradable organics. Total Kjeldahl Nitrogen (TKN) was reduced from 142 mg/L to 11 mg/L, corresponding to an average removal efficiency of 92.94%, demonstrating efficient nitrification under extended aeration. Phosphorus concentrations declined from 6.23 mg/L to 0.32 mg/L, with an average removal efficiency of 93.17%, benefiting from enhanced BOD and nitrogen removal processes. Total Dissolved Solids (TDS) were reduced from 2030 mg/L to 1023 mg/L, resulting in a 54.28% reduction, which may still require tertiary treatment for further compliance. Total Suspended Solids (TSS) showed a notable decline from 423 mg/L to 102 mg/L, corresponding to 58.70% removal efficiency. The final TSS concentrations remained well below the CPCB effluent standard of 500 mg/L, confirming the high performance of the treatment system during the 8-hour cycle.

7.6 Efficiency of Cycles

A detailed evaluation of the treatment process across varying aeration durations (4 to 8 hours) reveals a progressive enhancement in the removal efficiency of key wastewater parameters with increased cycle time.

In the 4-hour cycle, the influent BOD_5 concentration of 1093 mg/L was reduced to 641 mg/L, achieving a removal efficiency of 41.33%. COD was reduced from 2753 mg/L to 1593 mg/L (41.33%), while TKN declined from 155.6 mg/L to 95.62 mg/L (38.54%). Phosphorus decreased from 5.77 mg/L to 3.43 mg/L (40.55%), TDS from 1962.5 mg/L to 1359.3 mg/L (41.33%), and TSS from 1093 mg/L to 641 mg/L (37.66%). These values indicate limited biological activity under shorter aeration, suggesting underperformance in organic and nutrient removal.

The 5-hour cycle showed moderate improvement. BOD_5 removal improved to 60.74% (1067 mg/L to 418.8 mg/L and 1046 mg/L to 403 mg/L), and COD removal to 60.01% (2619 mg/L to 1044 mg/L). TKN decreased from 145.1–142.7 mg/L to around 58 mg/L, with an average removal of 59.20%. Phosphorus was reduced from 6.49–5.97 mg/L to ~2.4 mg/L (60.26%), TDS from ~2000 mg/L to ~1230 mg/L (37.57%), and TSS from ~400 mg/L to ~230 mg/L (40.72%), reflecting better microbial activity and nutrient uptake.

With the 6-hour cycle, removal efficiencies further improved. BOD_5 declined from 1124 mg/L to 225 mg/L and 1078 mg/L to 229 mg/L (80.11%). COD was reduced from 2632–2698 mg/L to ~ 545 mg/L (80.04%) and TKN from ~144 mg/L to ~33 mg/L (77.19%). Phosphorus fell from 7.31 mg/L to 1.49 mg/L (79.61%). TDS removal increased to 46.10% and TSS to 48.30%, with final TSS well below 200 mg/L, indicating efficient biomass settling.

In the 7-hour cycle, BOD_5 removal reached 95.40% (1124–1178 mg/L to ~50 mg/L), COD to 96.16% (2622–2693 mg/L to ~100 mg/L), and TKN to 92.94% (from ~140 mg/L to ~10 mg/L). Phosphorus was reduced to 93.04%, with final values near 0.36 mg/L. TDS dropped by 53.39%, while TSS removal efficiency rose to 56.20%. Final TSS concentrations (~153–186 mg/L) were significantly below the CPCB standard of 500 mg/L, validating the effectiveness of the extended aeration.

The 8-hour cycle maintained similar high efficiency. BOD_5 dropped from 1166 mg/L to 55.1 mg/L (95.00%), and COD from 2589 mg/L to 99 mg/L (96.30%). TKN declined from 142 mg/L to 11 mg/L (92.94%), and phosphorus from 6.23 mg/L to 0.32 mg/L (93.17%). TDS reduction slightly improved to 54.28%, and TSS decreased from 423 mg/L to 102 mg/L (58.70%), confirming optimal solids settling.

Overall, the analysis clearly demonstrates a strong correlation between aeration duration and pollutant removal efficiency. While 4-hour and 5-hour cycles provided partial treatment, significant improvements were observed at 6 hours and beyond, especially for nitrogen and phosphorus. The 7-hour and 8-hour cycles consistently achieved effluent qualities within CPCB norms, with BOD_5 and TSS levels below critical limits, establishing these durations as optimal for enhanced biological treatment.

8. Conclusions

1. Efficiency was developed without using chemicals.
2. The study demonstrated SBR with 7 hours cycle is optimal with dairy wastewater treatment for nutrient removal.
3. In this study, the TDS and TSS removal efficiency is very low compared with BOD, COD TKN, and Phosphorus.
4. With Variation in operating Cycle, along conditions, SBR Technology as a flexible tool for the treatment of Wastewater with many changing compositions.
5. The aeration process is must during the Fill and react phase only, thus unit to be sized for higher flow rates too.
6. SBR technology gives the flexibility to bring wastewater parameters within MPCB Prescribed Standards.

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