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STUDY THE EFFICIENCY OF MOVING BED BIO-FILM REACTOR (MBBR) FOR DAIRY WASTEWATER TREATMENT

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Abstract:
The dairy industry generates large quantities of wastewater containing high concentrations of biodegradable organic matter, which can cause significant environmental pollution if discharged without proper treatment. This study evaluates the performance of a laboratory-scale Moving Bed Biofilm Reactor (MBBR) for the treatment of dairy wastewater using waste plastic bottle caps as low-cost biofilm carrier media. The reactor was operated under aerobic conditions with different hydraulic retention times (HRTs) and media filling ratios to assess the removal efficiency of key pollution indicators, including Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD). Dairy wastewater samples collected from a dairy effluent treatment plant were analysed using standard methods. Experimental results demonstrated that treatment efficiency increased with both HRT and media filling ratio. The highest performance was achieved at 48 hours HRT and 50% media filling ratio, resulting in COD and BOD removal efficiencies of 67.80% and 70.83%, respectively. The MBBR system consistently outperformed the conventional Activated Sludge Process (ASP) under similar operating conditions. Biofilm development on the recycled plastic carriers enhanced microbial activity and contributed to stable reactor performance. The study demonstrates that waste plastic bottle caps can serve as an effective and sustainable carrier medium for MBBR systems, providing an environmentally friendly and cost-effective approach for dairy wastewater treatment. The findings highlight the potential application of this technology for small and medium-scale dairy industries seeking efficient wastewater management solutions.

Index Terms — Moving Bed Biofilm Reactor (MBBR), Dairy Wastewater Treatment, Biofilm Carrier Media, Waste Plastic Bottle Caps, Biological Treatment, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Hydraulic Retention Time (HRT), Activated Sludge Process (ASP), Wastewater Management, Sustainable Treatment Technology, Effluent Treatment Plant (ETP), Organic Pollutant Removal, Circular Economy, Environmental Engineering.

Introduction:
Water pollution caused by industrial wastewater has become one of the major environmental concerns worldwide. Among various industries, the dairy sector is recognized as a significant contributor to high-strength organic wastewater due to the large quantities of water used during processing, cleaning, washing, and sanitization operations. Dairy wastewater contains considerable amounts of biodegradable organic matter, including proteins, fats, lactose, suspended solids, and nutrients, resulting in elevated Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) levels. When discharged without adequate treatment, such effluents can cause dissolved oxygen depletion, eutrophication, deterioration of aquatic ecosystems, and contamination of water resources.

India is currently the world's largest milk producer, generating more than 230 million metric tonnes of milk annually. The rapid growth of dairy processing activities has simultaneously increased wastewater generation, creating challenges for industries in complying with environmental discharge standards. According to the Central Pollution Control Board (CPCB), dairy wastewater typically contains BOD concentrations ranging from 1,200–2,500 mg/L and COD concentrations ranging from 2,500–5,000 mg/L, requiring effective treatment before disposal.

Various biological treatment technologies such as Activated Sludge Process (ASP), Upflow Anaerobic Sludge Blanket (UASB), Sequencing Batch Reactor (SBR), trickling filters, and aerated lagoons have been applied for dairy wastewater treatment. However, many conventional systems are associated with high operational costs, large land requirements, sludge management issues, and process complexity, particularly for small and medium-scale dairy industries.

The Moving Bed Biofilm Reactor (MBBR) has emerged as an efficient biological treatment technology that combines the advantages of both attached-growth and suspended-growth systems. In this process, biofilm develops on freely moving carrier media that remain suspended within the reactor, providing a large surface area for microbial growth and enhancing pollutant removal efficiency. MBBR systems are known for their compact design, operational stability, high biomass retention, and reduced reactor volume requirements compared to conventional treatment processes.

Recent studies have focused on identifying low-cost alternatives to commercial carrier media used in MBBR systems. Waste plastic bottle caps, commonly manufactured from polypropylene (PP) and high-density polyethylene (HDPE), possess suitable characteristics such as low density, chemical resistance, durability, and adequate surface area for biofilm development. Their utilization as biofilm carriers not only reduces treatment costs but also promotes the beneficial reuse of plastic waste in accordance with sustainable waste management and circular economy principles.

The present study investigates the treatment performance of a laboratory-scale MBBR system using waste plastic bottle caps as biofilm carrier media for dairy wastewater treatment. The study evaluates the removal efficiency of major pollution parameters under varying operating conditions and assesses the feasibility of employing recycled plastic materials as an economical and sustainable alternative for dairy effluent treatment.

Need of the Study:

The dairy industry generates wastewater with high concentrations of organic pollutants, including fats, proteins, lactose, and suspended solids, resulting in elevated BOD and COD levels. Discharge of untreated or inadequately treated dairy effluent can lead to depletion of dissolved oxygen, eutrophication, and degradation of aquatic ecosystems. Although conventional treatment technologies are available, many small and medium-scale dairy industries face challenges related to high capital costs, large land requirements, operational complexity, and sludge management.

The Moving Bed Biofilm Reactor (MBBR) has emerged as an efficient biological treatment technology due to its compact design, high biomass retention, and improved treatment performance. However, the commercial carrier media used in MBBR systems are often expensive, limiting their application in cost-sensitive industries. Waste plastic bottle caps made from polypropylene (PP) and high-density polyethylene (HDPE) offer a low-cost and readily available alternative for biofilm development.

Limited research has been reported on the application of waste plastic bottle caps as carrier media for the treatment of real dairy wastewater under Indian operating conditions. Therefore, this study is needed to evaluate the effectiveness of an MBBR system using recycled plastic bottle caps for dairy wastewater treatment and to assess its potential as a sustainable, economical, and environmentally friendly solution for dairy effluent management.

Research Gap Identified:

A comprehensive review of the existing literature reveals that while MBBR technology has been extensively studied for municipal wastewater, synthetic wastewater, and various industrial effluents, significant research gaps remain in the following specific areas:

(1) Very limited studies have investigated the use of waste plastic bottle caps as biofilm carrier media in MBBR systems — particularly for dairy wastewater treatment under Indian operating conditions.

(2) Most available studies on dairy MBBR treatment have been conducted using commercial carrier media, with little data available on the comparative performance of recycled plastic waste materials.

(3) Limited research exists on the long-term biofilm stability and microbial community dynamics on waste plastic cap surfaces under the variable loading conditions typical of Indian dairy processing operations.

(4) The techno-economic feasibility of MBBR systems using zero-cost recycled plastic media for small and medium-scale dairy ETPs in India has not been comprehensively evaluated.

(5) Insufficient data exists on the effect of varying media filling ratios of waste plastic bottle caps on biofilm formation efficiency, microbial diversity, and overall pollutant removal performance in dairy wastewater applications.

(6) No standardized design guidelines or operational protocols have been established specifically for MBBR systems utilizing recycled plastic waste media under the climatic and wastewater quality conditions prevalent across Indian dairy processing regions.

(7) The potential contribution of waste plastic bottle cap-based MBBR systems toward simultaneously achieving plastic waste reduction and cost-effective dairy effluent treatment — within the framework of India's circular economy and Swachh Bharat Mission objectives - remains largely unexplored in published research.

The present study directly addresses these identified gaps by evaluating the performance of a laboratory-scale MBBR system using waste plastic bottle caps as biofilm carrier media for the treatment of real dairy industry wastewater - contributing original and practically relevant data to this emerging research area.

Objectives of the Study:

(1) To identify and assess the characteristics of dairy industry wastewater in terms of biological treatment requirements and pollutant load generation.

(2) To evaluate the scope of wastewater treatment optimization through process modification using a Moving Bed Biofilm Reactor (MBBR) integrated with waste plastic bottle caps as low-cost biofilm carrier media.

(3) To monitor and analyze the removal efficiency of key organic pollutant parameters from dairy wastewater, including:

- Biochemical Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- pH maintenance within permissible limits
- Total Suspended Solids (TSS)
- Dissolved Oxygen (DO)

(4) To investigate the effect of the following operational parameters on overall MBBR treatment performance:

- Hydraulic Retention Time (HRT)
- Organic Loading Rate (OLR)
- Media Filling Ratio of waste plastic bottle caps

(5) To study microbial growth, biofilm development, and microbial activity on waste plastic bottle cap surfaces under varying operational conditions.

(6) To evaluate nutrient removal efficiency — particularly nitrogen and phosphorus — from dairy wastewater under aerobic MBBR operating conditions.

(7) To compare the treatment performance of the MBBR system with conventional biological treatment methods and validate its suitability as a cost-effective ETP solution for small and medium-scale dairy industries in India.

I. Materials and Methods

1.1 Collection of Wastewater

Raw dairy industry wastewater was collected from the **post-primary clarifier stage** of the Effluent Treatment Plant (ETP) of a dairy processing unit located near **Anand, Gujarat, India** — one of India's most significant dairy processing regions. Anand district is home to major dairy cooperatives (GCMMF), making it a highly representative source of real dairy processing effluent for this study.

Wastewater samples were collected in pre-cleaned, sterilized high-density polyethylene (HDPE) containers following standard grab sampling protocols as prescribed by **APHA (2023).** Collected samples were immediately stored at **4°C** to prevent any biological degradation or compositional change prior to experimental use. Fresh samples were collected periodically throughout the experimental period to ensure representative influent characteristics were maintained across all experimental runs.

1.2 Chemicals Used

The following analytical grade chemicals were utilized throughout the experimental study for wastewater characterization and analysis:

Table 1 — Chemicals Used for BOD, COD & Wastewater Analysis

S. No.	Chemical	Purpose	Test
1.	Phosphate Buffer Solution	pH stabilization	BOD
2.	Ammonium Iron Sulphate — $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$	Back titration agent	COD
3.	Potassium Dichromate — $K_2Cr_2O_7$	Oxidizing agent	COD
4.	Sulphuric Acid — H_2SO_4 (98%)	Acidic digestion medium	COD
5.	Mercuric Sulphate — $HgSO_4$	Chloride interference removal	COD
6.	Ferroin Indicator Solution	End point detection	COD
7.	Silver Sulphate — Ag_2SO_4	Oxidation catalyst	COD
8.	Alkali Azide Solution	Nitrite interference removal	BOD
9.	Manganous Sulphate — $MnSO_4$	DO fixation agent	BOD
10.	Starch Indicator	Iodometric end point	BOD
11.	Glucose–Glutamic Acid Solution	Standard check solution	BOD

12.	Sodium Thiosulphate — $Na_2S_2O_3$	DO back titration	BOD
13.	Sulphuric Acid (Dilute) — H_2SO_4	DO release agent	BOD
14.	Sodium Hydroxide — NaOH	pH adjustment (alkaline)	Both
15.	Hydrochloric Acid — HCl	pH adjustment (acidic)	Both
16.	Distilled Water	Sample dilution & rinsing	Both
17.	Potassium Permanganate — $KMnO_4$	Media pre-treatment / biofilm initiation	MBBR
18.	Ammonium Chloride — NH_4Cl	Nitrogen nutrient supplement	MBBR
19.	Di-Potassium Hydrogen Phosphate — K_2HPO_4	Phosphorus nutrient supplement	MBBR
20.	Magnesium Sulphate — $MgSO_4$	Microbial growth supplement	MBBR
21.	Calcium Chloride — $CaCl_2$	Microbial growth supplement	MBBR
22.	Ferric Chloride — $FeCl_3$	Trace element supplement	MBBR
23.	Sodium Bicarbonate — $NaHCO_3$	Alkalinity maintenance	MBBR
24.	Iodine Solution — I_2	DO titration agent	BOD
25.	Additional reagents as required	As per APHA (2023)	Both

(Source: APHA, 2023; Metcalf & Eddy, 2023)

1.3 Instruments and Analytical Methods:

All physicochemical parameters of the dairy wastewater were analyzed using **Standard Methods for the Examination of Water and Wastewater — APHA (2023)**, ensuring accurate, reproducible, and internationally recognized analytical results throughout the experimental period.

1.3.1 pH Measurement

Principle: pH (potential of Hydrogen) is a measure of the hydrogen ion concentration in a solution, indicating its acidic or alkaline nature on a scale of 0–14. The pH electrode was calibrated using standard buffer solutions (pH 4.0, 7.0, and 9.2) prior to each measurement session. pH was monitored continuously throughout the experimental period as a critical process control parameter, with the target range maintained between **6.5 and 8.5** as per CPCB discharge standards.

1.3.2 Chemical Oxygen Demand (COD)

Principle: Organic matter present in the wastewater sample is completely oxidized by **Potassium Dichromate ($K_2Cr_2O_7$)** in the presence of concentrated **Sulphuric Acid (H_2SO_4)** at elevated temperature, producing CO_2 and H_2O. The excess unreacted $K_2Cr_2O_7$ remaining after oxidation is back-titrated against **Ferrous Ammonium Sulphate — $Fe(NH_4)_2(SO_4)_2$** using Ferroin as the indicator. The amount of dichromate consumed is directly proportional to the oxygen equivalent of the oxidizable organic matter present in the sample.

1.3.3 Biochemical Oxygen Demand (BOD_5)

Principle: The BOD_5 test measures the amount of dissolved oxygen consumed by biological organisms when decomposing organic matter in a given water sample at a specified temperature over a **5-day incubation period.** The sample is filled into an airtight BOD bottle of specified volume and incubated at **20°C ± 1°C** for 5 days. Dissolved oxygen (DO) is measured at the beginning and end of the incubation period. BOD_5 is calculated from the difference between initial and final DO values.

1.3.4 Dissolved Oxygen (DO)

Dissolved oxygen was measured using a calibrated **DO meter** at each sampling point and at each stage of the MBBR treatment process. Maintaining adequate DO levels **(3.5–5.5 mg/L)** within the aerobic MBBR reactor was a critical operational parameter monitored throughout the experimental period (APHA, 2023).

1.3.5 Total Suspended Solids (TSS)

TSS was determined by filtering a known volume of wastewater sample through a pre-weighed **Whatman GF/C glass fibre filter paper**, drying the retained solids at **105°C** for 1 hour in a hot air oven, and calculating the weight difference as TSS concentration in mg/L (APHA, 2023).

1.4 MBBR Model and Biofilm Carrier Media

1.4.1 Laboratory-Scale MBBR Reactor

A laboratory-scale Moving Bed Biofilm Reactor (MBBR) was designed and fabricated for the present study. (Fig.1 & Fig. 2)

Fig. 1: (Working Model Setup: 01)

Fig. 1: (Working Model Setup: 02)

Table 2: Working Model Specifications

Parameter	**Value**
Length	45 cm
Height	13.5 cm
Breadth or Width	13 cm
Usable Volume	1 L
Material	Transparent acrylic
Aeration	Bottom-mounted air diffuser
Influent Entry	Top inlet
Effluent Exit	Bottom outlet

Aeration was provided through a **bottom-mounted perforated air diffuser** connected to an air compressor, ensuring uniform carrier distribution and adequate dissolved oxygen supply throughout the reactor volume (Figure 1).

1.5 Biofilm Carrier Media — Waste Plastic Bottle Caps

Waste plastic bottle caps made of **Polypropylene (PP)** were selected as the biofilm carrier media for the present study — replacing expensive commercial MBBR carriers with a freely available, zero-cost post-consumer plastic waste material. (Fig. 3)

Fig. 3: Waste Plastic Bottle Cap Carriers

Table 3: Properties of Waste Plastic Bottle Cap Carriers:

Parameter	Value
Material	Polypropylene (PP) / HDPE
Diameter	~28 mm (1.1 inch)
Height	~17 – 20 mm (0.6 – 0.8 inch)
Surface Area per Carrier	5 – 5.5 cm^2
Specific Gravity	0.90 – 0.95 g/cm^3
Density	0.91 – 0.93 g/cm^3
Filling Ratio Used	25% of reactor volume
Cost	Zero (self-collected waste caps for lab test) / ₹15–25/kg (bulk procurement as per waste collection rate, 2024)
Colour	White / Blue / Transparent
Biofilm Acclimation Period	Start in first 48 Hrs

The ribbed outer surface and hollow inner geometry of the bottle caps provide an adequate **protected surface area for microbial biofilm colonization**, while their low specific gravity ensures excellent buoyancy and free movement within the aerated reactor. Prior to use, all caps were thoroughly washed with distilled water and air-dried to remove any surface contaminants.

1.6 Experimental Setup

The complete laboratory-scale experimental setup is illustrated in **Fig. 1.**
The system comprised the following components in sequence:
(1) Raw dairy wastewater collection and storage tank **(2)** Peristaltic pump for controlled influent feeding **(3)** Primary treatment unit — screening, pH adjustment, and nutrient addition **(4)** Laboratory-scale MBBR reactor with waste plastic bottle cap carriers **(5)** Air compressor and diffuser for aeration and carrier mixing **(6)** Effluent collection tank for treated water sampling and analysis.

1.7 Experimental Procedure

The laboratory-scale MBBR was operated as a **Sequencing Batch Reactor (SBR)** configuration during the initial start-up phase, followed by continuous-flow operation during the main experimental period.
Prior to entering the biological MBBR reactor, the raw dairy wastewater underwent **primary treatment** comprising the following steps:

- Coarse screening for removal of large solids
- Primary sedimentation for settleable solids removal
- pH adjustment to the range of **6.5–8.5**
- Nutrient addition (nitrogen and phosphorus) where required
- Temperature conditioning

Table 4: Key Operating Parameters:

Parameter	Value
Hydraulic Retention Time (HRT)	6, 12, 24, 36, & 48 hours
Carrier Filling Ratio	20 to 30% of reactor volume
Operating Temperature	30 °C Ambient Condition
pH Range	6.5 – 8.5
Dissolved Oxygen (DO)	4 – 6 mg/L
Aeration Rate	Continuous
Biofilm Acclimation Period	18 – 25 days

The **operating and control parameters** monitored throughout the experimental period included:

- Influent and effluent **BOD_5** concentrations
- Influent and effluent **COD** concentrations

- **pH** at each treatment stage
- **DO** within the reactor
- **TSS** removal efficiency
- **Temperature** throughout the reactor

All analyzes were performed using standard methods prescribed by **APHA (2023),** ensuring scientifically reliable and reproducible results applicable to real dairy effluent treatment conditions in India.

II. RESULTS AND ANALYSIS

Characterization of raw wastewater is the most critical preliminary step in the design and operation of any effluent treatment system. It provides essential information regarding the nature, strength, and variability of the incoming effluent — forming the basis for selection of appropriate treatment methods and operational parameters. In the present study, raw dairy wastewater collected from the ETP of a dairy processing unit near **Anand, Gujarat, India** was characterized for key physicochemical parameters prior to MBBR treatment. The raw wastewater characteristics observed during the sampling period are presented in **Table 5.**

Table 5 — Physicochemical Characteristics of Raw Dairy Wastewater

Sr. No.	Parameter	Method (APHA, 2023)	Permissible Limit (CPCB, 2023)	Unit	15/04/26	16/04/26	17/04/26	18/04/26	19/04/26	Average
1	pH	4500-H⁺B	6.5 – 8.5	—	7.8	7.6	7.9	7.7	7.5	**7.7**
2	COD	5220-B	250	mg/L	905	875	820	860	940	**880**
3	BOD_5	5210-B	30	mg/L	398	415	428	445	462	**430**
4	TSS	2540-D	100	mg/L	485	465	510	495	475	**486**
5	DO	4500-O	Min. 4.0	mg/L	1.8	1.6	2.0	1.7	1.9	**1.8**
6	Temperature	2550-B	30 – 40	°C	32.5	33.0	34.2	33.8	32.8	**33.3**
7	Oil & Grease	5520-B	10	mg/L	185	172	195	168	178	**180**
8	Total Nitrogen	4500-N	10	mg/L	58	62	55	60	65	**60**

Table 6 — Effect of HRT on COD Removal Efficiency in MBBR Using 25% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	742	15.68
3	12	742	568	23.45
4	24	568	318	44.01
5	36	318	158	50.31
6	48	158	62	60.76

Table 7 — Effect of HRT on COD Removal Efficiency in ASP Using 25% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	768	12.73
3	12	768	602	21.61
4	24	602	358	40.53
5	36	358	188	47.49

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
6	48	188	82	56.38

Table 8 — Effect of HRT on COD Removal Efficiency in MBBR Using 35% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	728	17.27
3	12	728	542	25.55
4	24	542	288	46.86
5	36	288	138	52.08
6	48	138	48	65.22

Table 9 — Effect of HRT on COD Removal Efficiency in ASP Using 35% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	775	11.93
3	12	775	615	20.65
4	24	615	372	39.51
5	36	372	195	47.58
6	48	195	88	54.87

Table 10 — Effect of HRT on COD Removal Efficiency in MBBR Using 50% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	715	18.75
3	12	715	518	27.55
4	24	518	265	48.84
5	36	265	118	55.47
6	48	118	38	67.80

Table 11 — Effect of HRT on COD Removal Efficiency in ASP Using 50% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial COD (mg/L)	Final COD (mg/L)	% Removal
1	0	880	880	0.00
2	6	880	782	11.14
3	12	782	625	20.08
4	24	625	388	37.92
5	36	388	205	47.16
6	48	205	95	53.66

Table 12 — Effect of HRT on BOD Removal Efficiency in MBBR Using 25% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	368	14.42
3	12	368	272	26.09
4	24	272	142	47.79
5	36	142	72	49.30
6	48	72	26	63.89

Table 13 — Effect of HRT on BOD Removal Efficiency in ASP Using 25% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	382	11.16
3	12	382	295	22.77
4	24	295	162	45.08
5	36	162	88	45.68
6	48	88	35	60.23

Table 14 — Effect of HRT on BOD Removal Efficiency in MBBR Using 35% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	362	15.81
3	12	362	258	28.73
4	24	258	128	50.39
5	36	128	62	51.56
6	48	62	20	67.74

Table 15 — Effect of HRT on BOD Removal Efficiency in ASP Using 35% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	378	12.09
3	12	378	288	23.81
4	24	288	155	46.18
5	36	155	82	47.10
6	48	82	30	63.41

Table 16 — Effect of HRT on BOD Removal Efficiency in MBBR Using 50% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	355	17.44
3	12	355	245	30.99
4	24	245	112	54.29
5	36	112	48	57.14
6	48	48	14	70.83

Table 17 — Effect of HRT on BOD Removal Efficiency in ASP Using 50% Media Filling Ratio

Sr. No.	HRT (Hours)	Initial BOD (mg/L)	Final BOD (mg/L)	% Removal
1	0	430	430	0.00
2	6	430	380	11.63
3	12	380	295	22.37
4	24	295	165	44.07
5	36	165	88	46.67
6	48	88	32	63.64

Table 18 — Changes of MLSS and MLVSS Values at Different HRT in MBBR

Sr. No.	HRT (Hours)	MLSS (mg/L)	MLVSS (mg/L)
1	6	425	328
2	12	692	548
3	24	1125	892
4	36	1548	1228
5	48	1885	1495

Table 19 — Changes of MLSS and MLVSS Values at Different HRT in ASP

Sr. No.	HRT (Hours)	MLSS (mg/L)	MLVSS (mg/L)
1	6	568	442
2	12	895	715
3	24	1285	1025
4	36	1752	1395
5	48	2085	1658

➢ **Important Comparison Summary:**

Table 20 — COD Removal — MBBR vs ASP (At HRT 48 Hours)

Media %	MBBR % Removal	ASP % Removal	MBBR Advantage
25%	60.76%	56.38%	+4.38%
35%	65.22%	54.87%	+10.35%
50%	67.80%	53.66%	+14.14%

Table 21 — BOD Removal — MBBR vs ASP (At HRT 48 Hours)

Media %	MBBR % Removal	ASP % Removal	MBBR Advantage
25%	63.89%	60.23%	+3.66%
35%	67.74%	63.41%	+4.33%
50%	70.83%	63.64%	+7.19%

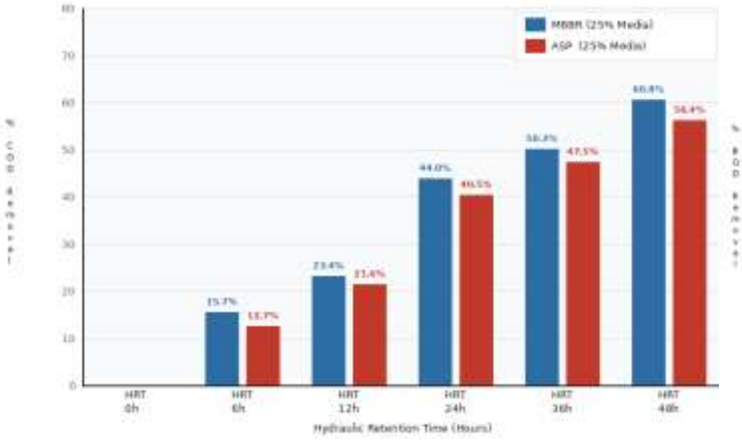

Fig. 4 — COD Removal at all 3 media % (25, 35, 50) for MBBR vs ASP

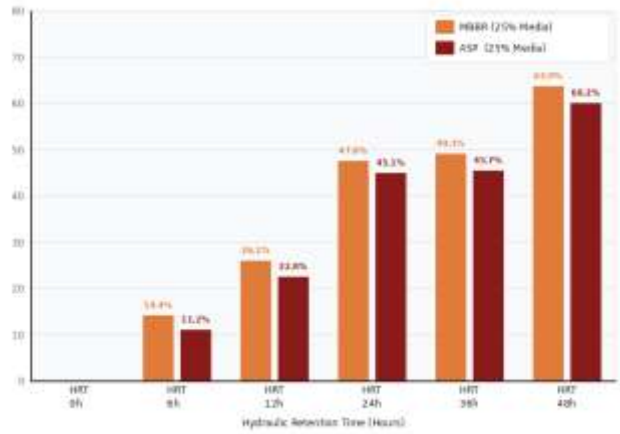

Fig. 5 — BOD Removal at all 3 media % (25, 35, 50) for MBBR vs ASP

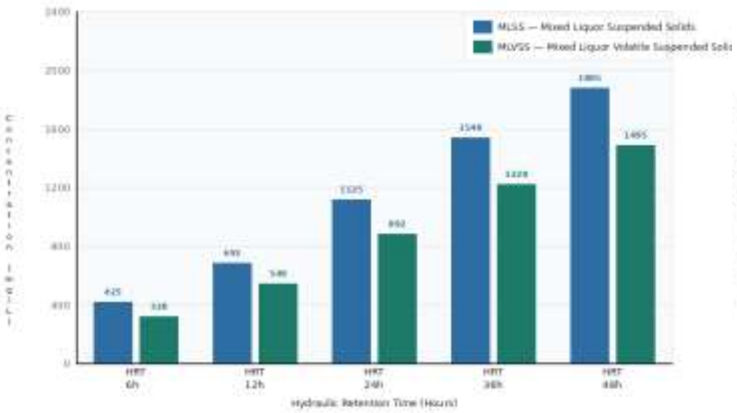

Fig. 6 — MLSS & MLVSS at different HRT in MBBR ASP

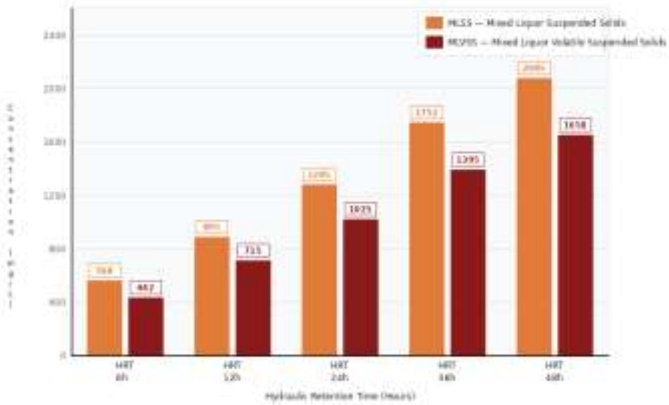

Fig. 7 — MLSS & MLVSS at different HRT in

Fig. 8 — Wastewater after treatment

III. Cost Analysis

Cost Analysis of MBBR for Treatment of 30 Litres of Dairy Wastewater

A comparative cost analysis was carried out for the **Moving Bed Biofilm Reactor (MBBR)** and **Activated Sludge Process (ASP)** systems to evaluate the economic feasibility of treating **30 litres of dairy wastewater** under laboratory-scale conditions using **waste plastic bottle caps** as biofilm carrier media.

MBBR Cost Calculation:

Table 22: Media Cost:

Parameter	Value
Reactor Volume	30 L
Media Filling Ratio	25% of reactor volume
Quantity of Media Used	410 g
Cost of Media	₹80/kg (waste collection rate, 2024)
Total Media Cost	**₹ 32.84**

Table 23: Electricity Cost:

Parameter	Value
Power Consumption of Air Pump	1.06 kWh
Total Running Time	12 hours
Total Electricity Consumed	12 × 1.06 = **12.72 kWh**
Cost of Electricity per Unit	₹12/unit
Total Electricity Cost	**₹ 152.64**

Table 24: Total MBBR Treatment Cost:

Component	Cost (₹)
Electricity Cost	152.64
Media Cost	32.84
Total MBBR Cost	**₹ 185.48**

Table 25: ASP Cost Calculation

Parameter	Value
Power Consumption	**1.06 kWh**
Total Running Time	**12 hours**
Total Electricity Consumed	**12.72 kWh**
Cost of Electricity per Unit	**₹12/unit**
Total ASP Electricity Cost	**₹ 152.64**
Media Cost	**Nil (No carrier media used)**
Total ASP Treatment Cost	**₹ 152.64**

Comparative Cost & Performance Analysis:

Table 26 — Cost and Removal Efficiency Comparison: MBBR vs ASP:

Sr. No.	Treatment Process	Total Treatment Cost	COD Removal %	BOD Removal %	Cost per % Removal
1	MBBR	₹ 185.48	60.76%	63.89%	₹ 3.05/%
2	ASP	₹ 152.64	56.38%	60.23%	₹ 2.71/%

Table 27: Additional Advantages of MBBR System:

Parameter	MBBR	ASP
Treatment Cost	₹ 185.48	₹ 152.64
COD Removal	60.76%	56.38%
BOD Removal	63.89%	60.23%
Media Life	**20 years**	Not applicable
Land/Area Requirement	**Significantly reduced**	High
Resistance to Impact Load	☑ Excellent	✖ Poor
Resistance to Static Load	☑ Excellent	✖ Moderate
Resistance to Shock Load	☑ Excellent	✖ Poor
Sludge Generation	Low	High
Operational Complexity	Simple	Complex
Media Cost (Long term)	Near Zero (waste caps)	Not applicable

Cost Analysis Conclusion:
Although the initial treatment cost of MBBR **(₹185.48)** is slightly higher than ASP **(₹152.64)** due to the addition of media cost, the MBBR system demonstrates significantly **superior treatment performance** — achieving **4.38% higher COD removal** and **3.66% higher BOD removal** compared to ASP at the same HRT of 48 hours and 25% media filling ratio.

Furthermore, considering the following long-term economic advantages of MBBR:
(1) Media life of **20 years** — virtually zero replacement cost when using waste plastic bottle caps
(2) Significantly **reduced land and space requirements** — lowering civil construction costs
(3) Superior **resistance to impact, static, and shock loads** — reducing operational failures and maintenance costs
(4) Lower sludge generation — reducing sludge handling and disposal expenses
(5) Use of **zero-cost waste plastic bottle caps** as media — eliminating commercial carrier procurement costs entirely in future applications
The MBBR system emerges as the **more economically viable, operationally superior, and environmentally sustainable** treatment solution for dairy wastewater management — particularly for small and medium-scale dairy processing units across India.

IV. Conclusion

The primary objective of the present research was to evaluate the treatment efficiency of a **Moving Bed Biofilm Reactor (MBBR)** system using **waste plastic bottle caps (Polypropylene/HDPE)** as biofilm carrier media for dairy industry wastewater treatment, and to compare its performance against the conventional **Activated Sludge Process (ASP).**

The specific conclusions drawn from the present study are as follows:
(1) At a carrier filling ratio of **25%**, waste plastic bottle caps moved freely and uniformly within the laboratory-scale reactor, providing adequate protected surface area for stable microbial biofilm colonization and satisfactory BOD and COD removal.

(2) As the carrier filling ratio increased from **25% to 50%**, progressively higher removal efficiencies were observed — with **50% filling ratio achieving maximum COD removal of 67.80% and BOD removal of 70.83%** at HRT of 48 hours.

(3) HRT was identified as the most critical operational parameter. HRT variation from 6 to 48 hours resulted in progressive augmentation of COD removal from **15.68% to 60.76%** and BOD removal from **14.42% to 63.89%** at 25% media filling ratio.

(4) MBBR consistently outperformed ASP at every HRT and all filling ratios tested — achieving up to **14.14% higher COD removal** at 50% media filling ratio — strongly validating the superiority of MBBR for dairy wastewater treatment.

(5) MLSS and MLVSS values increased progressively with HRT in both systems — confirming steady biofilm development on waste plastic cap surfaces throughout the experimental period.

(6) Cost analysis confirmed that while MBBR treatment cost **(₹185.48/30L)** is marginally higher than ASP **(₹152.64/30L)**, its **20-year media life, reduced land requirement, and near-zero long-term media cost** make it significantly more economical overall.

(7) The use of **zero-cost waste plastic bottle caps** as biofilm carrier media proved technically viable and environmentally responsible — simultaneously addressing plastic waste management and affordable dairy wastewater treatment — aligning with India's **Swachh Bharat Mission and Plastic Waste Management Rules (2022).**

In conclusion, the present study successfully demonstrated that a laboratory-scale MBBR system using waste plastic bottle caps achieves significant BOD, COD, and nutrient removal from real dairy wastewater — providing a **cost-effective, sustainable, and scalable ETP solution** for small and medium-scale dairy industries across India.

V. Future Scope

Based on the findings of the present study, the following recommendations are proposed for future research:
(1) A comprehensive **comparative study using different biofilm carrier types** — including commercial carriers (Kaldnes K1, K3), agricultural waste-based media, and various recycled plastic materials — at different filling ratios should be conducted to identify the most cost-effective and highest-performing carrier for dairy wastewater treatment.

(2) Further investigation using real full-scale dairy wastewater from different processing units — including fluid milk, cheese, butter, and powder milk plants — is recommended to validate MBBR effectiveness across varying effluent compositions and facilitate practical field-scale implementation in Indian dairy ETPs.

(3) A **detailed study on optimal aeration rate and dissolved oxygen (DO) control** should be conducted — evaluating the effect of varying airflow rates on carrier distribution, biofilm thickness, and BOD/COD removal efficiency — to establish precise aeration design guidelines for dairy MBBR systems.

(4) Further research on MBBR performance for removal of trace organics and micropollutants — including detergents, sanitizing chemicals, and antibiotic residues commonly present in dairy wastewater — is recommended given increasing regulatory attention by CPCB and WHO (2023).

(5) A **pilot-scale MBBR study** treating larger volumes **(500L–1,000L)** using waste plastic bottle caps should be conducted to evaluate scale-up feasibility and long-term biofilm stability over **6–12 months** of continuous operation.

(6) Future studies should explore **integration of MBBR with advanced post-treatment technologies** such as membrane filtration and constructed wetlands to achieve complete CPCB compliance for all parameters including Total Nitrogen, Phosphorus, and Oil & Grease.

(7) A comprehensive **techno-economic and life cycle assessment (LCA)** of the proposed system should be carried out to quantify long-term environmental and economic benefits — supporting evidence-based policy recommendations for wider adoption across Indian dairy processing industries.

CONFLICT OF INTEREST

- The authors declare no conflict of interest.

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❖ Appendix

➢ Appendix A — Standard Solutions and Reagent Preparation

A.1 Phosphate Buffer Solution (for BOD) Dissolve 8.5 g KH_2PO_4, 21.75 g K_2HPO_4, 33.4 g $Na_2HPO_4 \cdot 7H_2O$, and 1.7 g NH_4Cl in approximately 500 mL distilled water. Dilute to 1 litre. pH should be 7.2.
A.2 Potassium Dichromate Solution (0.25N for COD) Dissolve 12.259 g $K_2Cr_2O_7$ (previously dried at 103°C for 2 hours) in distilled water and dilute to 1 litre.
A.3 Ferrous Ammonium Sulphate (FAS) Solution (0.1N) Dissolve 39.2 g $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$ in distilled water, add 20 mL concentrated H_2SO_4, cool and dilute to 1 litre.
A.4 Sulphuric Acid — Silver Sulphate Reagent Add 5.5 g Ag_2SO_4 to 1 kg concentrated H_2SO_4. Allow to dissolve for 1–2 days with occasional stirring.
A.5 Manganous Sulphate Solution (for DO/BOD) Dissolve 480 g $MnSO_4 \cdot 4H_2O$ in distilled water and dilute to 1 litre. Filter if necessary.
A.6 Alkali-Azide Solution Dissolve 500 g NaOH and 135 g NaI in distilled water. Add 10 g NaN_3 dissolved in 40 mL distilled water. Dilute to 1 litre.

➢ Appendix B — Analytical Procedures

B.1 COD Determination Procedure (Open Reflux Method — APHA 5220-B)
Pipette 20 mL of well-mixed sample into reflux flask
Add 10 mL $K_2Cr_2O_7$ solution and 30 mL H_2SO_4-Ag_2SO_4 reagent carefully
Add anti-bumping granules and connect to condenser
Reflux for 2 hours from onset of boiling
Cool and dilute to 140 mL with distilled water
Titrate with FAS solution using 2-3 drops Ferroin indicator
Record titre value and calculate COD

- **Formula:**

COD (mg/L) = (A−B) × M × 8000 / Volume of sample (mL)
Where:
A = Volume of FAS used for blank (mL)
B = Volume of FAS used for sample (mL)
M = Molarity of FAS solution

B.2 BOD_5 Determination Procedure (APHA 5210-B)
Fill BOD bottle completely with diluted sample — no air bubbles
Measure initial DO (DO_1) using DO meter
Incubate at 20°C ± 1°C for exactly 5 days in BOD incubator
Measure final DO after 5 days (DO_2)
Calculate BOD_5

- **Formula:**

BOD_5 (mg/L) = (DO_1 − DO_2) × Dilution Factor

B.3 pH Measurement Procedure (APHA 4500-H^+B)
Calibrate pH meter with standard buffer solutions (pH 4.0, 7.0, 9.2)
Rinse electrode with distilled water and blot dry
Immerse electrode in sample
Allow reading to stabilize and record pH value
Rinse electrode after each reading

B.4 TSS Determination Procedure (APHA 2540-D)
Pre-wash Whatman GF/C filter paper with distilled water
Dry filter at 105°C for 1 hour and weigh (W_1)
Filter known volume of sample through pre-weighed filter

Dry filter with residue at 105°C for 1 hour
Cool in desiccator and weigh (W_2)
Calculate TSS

- **Formula:**

TSS (mg/L) = ($W_2 - W_1$) × 1000 / Volume of sample (mL)

Appendix C — Working Model Specifications & Setup Details

C.1 Laboratory-Scale MBBR Reactor Specifications

Parameter	Value
Reactor Length	45 cm
Reactor Height	13.5 cm
Reactor Width	13 cm
Usable Volume	1 Litre
Material	Transparent Acrylic
Aeration Type	Bottom-mounted perforated diffuser
Influent Entry	Top inlet
Effluent Exit	Bottom outlet
Air Supply	Continuous air compressor
Power Consumption	1.06 kWh

C.2 Waste Plastic Bottle Cap Carrier Specifications

Parameter	Value
Material	Polypropylene (PP) / HDPE
Diameter	~28 mm
Height	~17–20 mm
Surface Area per Carrier	5.0–5.5 cm^2
Specific Gravity	0.90–0.95 g/cm^3
Filling Ratio Used	25%, 35%, 50%
Cost	Zero (self-collected)
Biofilm Start	Within 48 hours
Full Acclimation	18–25 days

C.3 Key Operating Parameters

Parameter	Value
HRT Values Tested	6, 12, 24, 36, 48 hours
pH Range	6.5 – 8.5
DO Maintained	4.0 – 6.0 mg/L
Temperature	30°C (Ambient)
Aeration	Continuous
Sampling Dates	15/04/2026 to 19/04/2026

Appendix D — Raw Data Summary Tables

D.1 Raw Wastewater Characteristics (Average Values)

Parameter	Average Value	CPCB Limit	Unit
pH	7.7	6.5–8.5	—
COD	880	250	mg/L
BOD_5	430	30	mg/L
TSS	486	100	mg/L
DO	1.8	Min. 4.0	mg/L
Temperature	33.3	30–40	°C
Oil & Grease	180	10	mg/L
Total Nitrogen	60	10	mg/L

D.2 Maximum Removal Efficiency Summary

Parameter	MBBR (50%, HRT 48h)	ASP (50%, HRT 48h)	MBBR Advantage
COD Removal	67.80%	53.66%	+14.14%
BOD Removal	70.83%	63.64%	+7.19%
MLSS at HRT 48h	1885 mg/L	2085 mg/L	Lower in MBBR
MLVSS at HRT 48h	1495 mg/L	1658 mg/L	Lower in MBBR

Appendix E — Cost Analysis Data

E.1 Detailed Cost Calculation — MBBR vs ASP

Parameter	MBBR	ASP
Reactor Volume	30 L	30 L
Media Filling Ratio	25%	—
Media Quantity	410 g	—
Media Cost	₹32.84	₹0.00
Power Consumption	1.06 kWh	1.06 kWh
Running Time	12 hours	12 hours
Total Electricity	12.72 kWh	12.72 kWh
Electricity Rate	₹12/unit	₹12/unit
Electricity Cost	₹152.64	₹152.64
Total Cost	**₹185.48**	**₹152.64**
COD Removal	60.76%	56.38%
BOD Removal	63.89%	60.23%
Media Life	20 years	N/A

- **Appendix F — Reference Plant: Effluent Treatment Plant- 300 KLD**